The concept of sustainability arises because of the finite and limited resources of the world. This limitation is exacerbated by the continual growth of the world’s population, whose demand on resources increases significantly with time. To overcome this problem, sustainable development, which is defined in the Brundtland Report as “development that meets the needs of the present without compromising the ability of future generations to meet their own needs” is imperative. It refers to the optimal utilization of these resources with the aim of maximizing their usage effectiveness while at the same time minimizing the adverse effect of their use on the environment. This includes conservation and enhancement of resources by gradually changing our approach towards the development and utilization of technologies. The principle of sustainability must be translated into practical engineering projects; otherwise, resources may be completely depleted or the environment may suffer irreversible damage.

In a discussion paper presented by the President of the Institution of Professional Engineers New Zealand (IPENZ) under the auspices of the IPENZ Presidential Task Committee on Sustainability in 2003-04, four key sustainability factors for engineers in the profession were identified:

1. To manage changes in the environment (both local and global) resulting from engineering activities which threaten the continued viability of the planet;
2. To ensure the equal distribution of resources and safety of engineering activities for both current and future generations;
3. To ensure that the skills of professional engineers in problem solving are carried out holistically; and
4. Where practicable, to make good existing problems caused by past failures to follow sustainability principles.

The School of Civil and Environmental Engineering endorses the principle of engineering for sustainability. On the one hand, it inculcates this principle in both her undergraduate and post-graduate students so that they will become engineers with this mindset. The School believes that it is crucial to educate young engineers in this approach from the start so that they will be committed to implement sustainable development.

Research in the School is also carried out using a similar approach so that new and novel ideas are developed for use by the practicing community to promote sustainability. Past environmental failures that were considered technically and economically impractical to remedy are re-examined in innovative research endeavors to determine if they can be resolved. Multi-faceted approaches are investigated in depth by inter-disciplinary team members for innovative ideas which ensure a holistic solution to engineering practices. Thus, a mono-faceted approach with a solely technical view point is discarded in preference to a synergistic approach. Such cooperation amongst researchers from different fields is crucial in ensuring a better understanding of the complexity that exists in a fast changing environment, both at the local and global level. Only with such knowledge can one manage the threat to Earth from, for example, global warming and the consequent rise in sea-level. The optimal use of diminishing resources in the 21st century demands novel ideas beyond classical solutions. Renewable resources and recycled material, which are becoming crucial in everyday engineering practices, are examined and tested by teams in the School to ensure a level of safety that does not endanger public health.

This article summarizes some of the research currently undertaken in the three Divisions of the school, namely,

- Division of Environmental and Water Resources Engineering (EWRE)
- Division of Infrastructure Systems and Maritime Studies (ISMS)
- Division of Structures and Mechanics (SM)

Some of the research programs in progress are as follows:

- Environmental Monitoring towards Sustainability (EWRE)
- Membrane Research (EWRE)
- Recycling and Waster Resources (EWRE)
- Risk Assessment in Sustainable Public Private Partnership (PPP) Infrastructure Projects (ISMS)
- Sustainable Transportation System (ISMS)
- Utilization of Underground Space (ISMS)
- Continuous Structural Health Monitoring using Smart Sensors (SM)
- Safety and Risk Assessment of Offshore Structures with Cracks and Defects (SM)
ENVIRONMENTAL MONITORING FOR SUSTAINABILITY

As part of the effort to protect aquatic environments, water quality monitoring has to be carried out, not only to alert users to potential threats but also to evaluate long-term changes for environmental sustainability. The research focuses on assessing the occurrence and fate of both microbial and chemical contaminants in water, ranging from trace level organic pollutants in reclaimed water, to algal toxins and viral pathogens in surface waters.

In the case of chemical contaminants, there has been increasing public concern over the levels of endocrine disrupting chemicals (EDCs) and other potentially harmful organics detected in aquatic environments. Many of these chemicals have been traced to the discharge of wastewaters in natural ecosystems where adverse developmental and reproductive effects in animal populations have been observed over time. While some of these are well known (e.g. PCBs, chlorinated pesticides and PAHs) with established analytical detection methods, others are emerging and require the development of new procedures for detection. As Singapore embarks on new water initiatives, including reclaiming water from wastewater, converting estuaries into freshwater reservoirs, capturing water from highly urbanized catchments, etc., many important questions arise as to the nature of possible contaminants, their impact on human health and interaction with aquatic ecosystem processes. The emerging organic contaminants targeted in this study include surfactants, such as the alkylphenol polyethoxylates (APEOs) and their derivatives; hormones (e.g. natural and synthetic estrogens); plasticizers (e.g. bisphenol A); pharmaceuticals (e.g. Ibuprofen, Naproxen); perfluorinated compounds (PFOA, PFOS), which are highly non-biodegradable and persistent in the environment, and algal toxins produced by cyanobacteria.

In addition to chemical contaminants, microbial pathogens are also important to protect public health and safety. Our recent focus is on the occurrence of human enteric viruses in surface waters, viable but non-culturable bacterial pathogens and harmful algal blooms which produce toxins (Figure 1a). A number of techniques are employed, including real-time PCR, microarrays, flow cytometry (Figure 1b) as well as traditional culture-based methods. One of the challenges today is to be able to detect target microbes as rapidly as possible, to avoid outbreaks of infectious disease. To this end, we are working on an optical online bacteria detection system for water distribution systems.

MEMBRANE RESEARCH

With ongoing rapid industrialization, the demand for drinking water has increased tremendously in terms of quantity and quality. The scarcity of such a precious resource has increased the need for water reclamation, for the preservation and recovery of drinking water.

However, the presence of contaminants such as natural organic matters (NOMs) and trace organics accumulating in raw water creates a major problem. The coagulation/flocculation and chlorination technology has been widely used for the removal of the contaminants. However, this technology is unable to completely remove them; it also generates large volumes of sludge which requires further treatment and disposal. In addition, aluminium exposure is suspected of playing a part in the onset of Alzheimer’s disease. NOMs have been shown to react with the major disinfectants (chlorine, ozone, chlorine dioxide, chloramines) to produce a host of disinfection by-products, such as trihalomethanes (THMs), haloacetic acids (HAAs), bromoform (CHBr₃), dibromoacetic acid (DBAA), and 2,4-dibromophenol (2,4-DBP), etc, which are carcinogenic.

Figure 1(a). Species of cyanobacteria isolated from a eutrophic reservoir. Blooms of cyanobacteria are not only unsightly; they can cause depletion of dissolved oxygen which can lead to fish being killed. Some species of cyanobacteria are also known to produce toxins which can damage the liver and nervous system.

Figure 1(b). Flow cytometric detection of bacteria cells based on the light scattering and fluorescence characteristics of cells stained with SYTO80.
Civil Engineering Research | 3

Progress has been made with regard to the use of micro/ultra filtration (MF/UF/RO) membranes as an advanced water treatment process for producing high quality drinking water with a small footprint size. However, the commercial filtration membranes have a high fouling tendency caused by the deposition of contaminants such as NOMs as well as trace organics and microorganisms. This is one of the major problems in using filtration membranes for producing drinking water. There is an urgent need to search for new generation membranes which will be able to overcome the existing problems of membrane fouling and leaking of contaminants within the membrane pore.

Nanotechnology

Nanotechnology has great potential in molecular separation applications by offering more precise structural controlled materials. Titanium oxide (TiO$_2$) nanosized particles are a popular photocatalyst which attract much attention from both fundamental research and practical applications with the aim of removing HA from water. However, the nanosized TiO$_2$ photocatalyst has an inherent and significant drawback— that is, the difficulty in separation and recovery. In order to increase the photocatalytic activity of TiO$_2$ and concurrently solve the problem of separation and recovery, it is important to re-design TiO$_2$ structured photocatalytic material. To this end, efforts by our research group have led to the development of an inexpensive, robust and free-standing multifunctional TiO$_2$ nanofibre filtration membrane.

The Membrane

The robust and free-standing multifunctional TiO$_2$ nanofibre membrane is in the form of a “spider web” non-woven fibre. The non-toxic TiO$_2$ nanofibre membrane acts as both filtration membrane and photocatalyst in water technologies (Figure 2).

In the presence of ultraviolet light, the crystalline TiO$_2$ nanofibre is known to produce strong oxidant and exhibit quantum size effects. However, this material also can be used under such a condition. These unique properties give rise to various applications particularly in producing cost effective commercial filtration membranes that could dramatically reduce the cost of water production.

The advantages of the free-standing multifunctional TiO$_2$ nanofibre membrane are:

1. Full surface exposure to UV or solar radiation for self-regeneration, which significantly reduces the membrane fouling problem
2. Concurrent membrane filtration for separation purposes
3. A high surface area, which allows higher adsorption rate of various trace organics and bacteria for improving water quality
4. A higher acid/basic and temperature resistance
5. Environmentally friendly; and longer membrane life span
6. Flexible property which enables the membrane to be formed into various membrane modules for greater flexibility in commercial applications.

Recycling and Waster Resources

Wastes may not be wastes; they are actually misplaced resources. Using proper management system and suitable technologies, waste residues can be converted into reusable/new materials or useful sources of fuels for supplying energy. Such a mindset is critical in ensuring sustainability. Over the years, CEE researchers have been converting waste residues such as copper slag, marine clay, sludge, incineration ashes, and green wastes into reusable construction materials such as pavement blocks, bricks, land reclamation materials, and fertilizers. In the past eight years, CEE researchers (Figure 3) have also embarked on the waste-to-energy research by converting organic waste residues into biofuels including bio-methane, bio-hydrogen, bio-ethanol, bio-diesel, bio-electricity, and bio-crude. Biofuel, which is considered as a clean energy source, can be developed into a key alternative energy source as important as solar energy.

RISK ASSESSMENT IN SUSTAINABLE PUBLIC PRIVATE PARTNERSHIP (PPP) INFRASTRUCTURE PROJECTS

Sustainable infrastructure and environmental projects under “project finance schemes” are regarded as high-risk projects and complex to finance because of the impact on the spreads in the cost of capital. The role of risk assessment during the feasibility and pre-procurement phase is, therefore, essential in order to realistically understand the environmental, social,
technical, political, economic, legal and financial risks involved in the projects.

This research investigates qualitative and quantitative risk modeling techniques and proposes solutions for application in a sustainable infrastructure and environmental context (Figure 4). The focus is on how the risks involved can be assessed realistically, to identify relevant factors for risk modeling purposes, and to recommend risk mitigation and management strategies.

**SUSTAINABLE TRANSPORTATION SYSTEM**

The main issues in developing sustainable transportation systems are energy consumption and pollutant emission. Research in this area, therefore, focuses on establishing baseline values as well as strategies that can minimise fuel consumption and pollutant emission.

Research so far has been primarily in the development of analytical and computer models to assist in the planning and operation of sustainable transportation facilities. These include speed-flow models for analysing road traffic. In air transportation, tools are available for estimating capacity and delays of airfield facilities. A sea space capacity model has also been developed for port planning and management with an aim to identify existing and potential bottlenecks. The availability of these models also allows one to evaluate the effectiveness of potential measures that could reduce congestion and contribute directly to addressing the issues of energy use and pollutants.

For road transportation, efforts are on-going to fine-tune the speed-flow models to reflect the changing traffic environment. A potential area of study is to investigate the impacts of, and infrastructure requirements that would facilitate the use of vehicles powered by clean energy. In air transportation, studies were done to establish the amounts of fuel consumption and pollutant emission due to aircraft ground operations at Changi Airport, both for current and future air traffic levels. Potential reductions in fuel consumption and pollutant emission due to various measures to modify ground operations have been investigated. In sea transportation, the current effort is on the developing a simulation model for estimating delays to vessels within a congested port and generating measures for conflict and congestion resolution.

**UTILIZATION OF UNDERGROUND SPACE**

There is an increasing need to plan and develop strategic underground facilities and infrastructures for various applications in recent years. 3D Geological Information System (3DGIS) can provide a tool to store and access effectively all data supporting 3D geological modelling through an integrated database for the underground spaces.

A scalable borehole database, based on the AGS (Association of Geotechnical & Geoenvironmental Specialists) 3.1 Format, has been designed (Figures, 5a and 5b). This database is incorporated into “3DRock” – a prototype of the 3DGIS software. This prototype, developed under the Underground Technology Rock Engineering (UTRE) Programme, is able to integrate, visualize, measure and analyse the geology of rock caverns for the pre-construction, construction, and post-construction stages.

**Figure 4. Public-Private Partnership (PPP) in Singapore**

**Figure 5(a). Integration of Underground Cavern Infrastructure and Geological Information.**

**Figure 5(b). The 3D Visualization of Borehole Database in 3DRock**
Continuous Structural Health Monitoring using Smart Sensors

There is an increasing demand worldwide for automatic, real-time and continuous structural health monitoring (SHM) systems for civil structures. SHM techniques based on smart sensors such as optical fibre sensors (OFSs) and piezoceramic transducers (e.g. Lead Zirconate Titanate or PZT) have attracted extensive research attention during the last decade. The smart sensors are lightweight, compact, highly reliable, immune to ambient noise and sensitive even to minor changes in structures as compared to conventional instruments. By monitoring the stresses, strains, displacements, temperature and checking the occurrence of damages at critical locations, the smart sensing systems using PZTs and OFSs are able to provide comprehensive monitoring of engineering structures.

Safety and Risk Assessment of Offshore Structures with Cracks and Defects

This MPA-NTU-ABS joint research project investigates the safety and integrity of damaged (cracked) square hollow sections (SHS) tubular welded joints commonly found at the top-side of offshore platforms. It involves finite element analysis and experimental tests to validate the use of the standard BS7910 (2005) assessment procedure for the square hollow section T, Y and K-joints containing fatigue cracks. Based on this model, an automatic mesh generation program is proposed and validated. This model is used to refine the parametric study of the effect of the variables such as the crack shape, crack size and the weld. The ultimate strength formulae for uncracked geometries and the reduction of load bearing area, the plastic collapse loads of cracked SHS T, Y and K-joints under brace end axial loads are derived and validated experimentally and numerically. In accordance with the J-integral approach the failure assessment diagrams (FADs) of the SHS T, Y and K-joints are subsequently constructed.

In the experimental tests, the alternating current potential drop (ACPD) technique shown in Figure 7(a) was used to monitor the fatigue crack propagation initiating from the hot spot stress location. Figure 7(b) shows the cracked SHS welded joints tested to failure under incremental static loads so as to obtain the ultimate collapse loads. The recorded data including the actual crack shape and size shown in Figure 7(c) were then used to validate the existing BS7910 (2005) Level 3A failure assessment diagrams (FADs) accordingly.
Figure 7(b). The ultimate static test of the cracked SHS tubular welded joint

Figure 7(c). Typical crack surface of the SHS tubular welded joint specimen

The School takes pride in the outstanding research achievements/awards of the following staff members:

**APPOINTMENT**

Assoc Prof Lam Soi Hoi was appointed as a Vice President in Intelligent Transportation Society, Singapore.

**AWARDS**

M.C. Bauchemie Award was given to Asst Prof Jong Herman Cahyadi for an outstanding and original paper on “Effect of Preconditioning of Concrete under Accelerated Test” at 31st Conference on Our World in Concrete and Structures, 16-17 August 2006.

Lam, S.L. Jasmine received Best Paper Award for her paper of “Managing Container Shipping Supply Chains” in the *International Association of Maritime Economists Annual Conference*, Melbourne, 12-14 July 2006.

**EDITORSHIP**

Professor Chiew Yee Meng was appointed as a member of the Editorial Board of Journal of the Institution of Engineers, Singapore (IES). He was also appointed as a member of the Editorial Board of Journal of Recent Patents on Mechanical Engineering

**EDITORSHIP**

Assoc Prof Tommy Wong was appointed as an Associate Editor of the Journal of Hydrologic Engineering, American Society of Engineers (ASCE).

He has accepted invitations to join the Editorial Advisory Boards of The Open Civil Engineering Journal, Open Civil Engineering Letters, Open Civil Engineering Reviews, The Open Hydrology Journal, Open Hydrology Letters, and Open Hydrology Reviews. All six journals are published by Bentham Science Publishers.

Assoc Prof Lam Soi Hoi was appointed as an Associate Editor for Transportmetrica Journal, Hong Kong Society for Transportation Studies Ltd.

Assoc Prof Edmond Lo and Assoc Prof Law Wing Keung, Adrian were appointed as an Associate Editor in Journal of Hydro-Environment Research (from 2007 onward)

**INVITED LECTURES**

Assoc Prof Chu Jian was invited to deliver lectures at the following conferences:


Assoc Prof Lam Soi Hoi was an invited speaker at the 14th World Congress on ITS, Beijing, 9-13 October 2007.

Assoc Prof Tan Kang Hai had been invited by organizing Chairman of European cooperation in the field of Scientific and Technical Research (COST) Action C26 to present an invited paper on “Behaviour and modelling of composite columns and beams under fire conditions” held in Czech Technical University, Prague from 30 to 31 March 2007.
RESEARCH CENTRES

Activities of Environmental Engineering Research Centre (EERC) From July 2006 To June 2007

CENTRE ACTIVITIES

EERC actively hosted public seminars and specialized workshops over this reporting period. These seminars were widely attended by researchers and students from CEE and other schools in NTU, including IESE and NIE. The participants were also from industrial sectors and governmental agencies.

Public seminars

1. Broad-based Environmental Enrichment Program (BEEP) 2007 – Hong Kong: An afterview
   NTU, School of CEE, Environmental Engineering Year 4 Students
   Ang Zhi Ching, Andrew
   Chia Chee Guang, Derrick
   Ding Lit Siong
   He Qihui
   Poh Leong Soon
   26 January 2007

2. Algae-based photobioreactors: the new technology platform for resource-efficient pollution control
   Assistant Professor Benoit Guieysse
   School of Civil & Environmental Engineering
   Nanyang Technological University
   1 Feb 2007

3. Indoor air quality at NTU and possible treatment technology: from two preliminary data sets to a complete story
   Assistant Professor Victor Chang
   School of Civil & Environmental Engineering
   Nanyang Technological University
   15 Feb 2007

4. Probing the nano- and micro-scales of reverse osmosis membranes – a comprehensive characterization of membrane physiochemical properties
   Assistant Professor Tang Chuyang
   School of Civil & Environmental Engineering
   Nanyang Technological University
   8 Mar 2007

5. Tendencies in future waste management
   Prof. Dr.-Ing. R. Stegmann
   Hamburg University of Technology
   President, Institute of WasteRessourceManagement
   Germany
   20 Mar 2007

6. Water resources in a changing climate – what are the implications of climate change for Singapore's water infrastructure?
   Bob Sargent
   Head, Chartered Institution of Water and Environmental Management, UK
   21 Mar 2007

7. Monte Carlo simulation of colloidal membrane filtration
   Assistant Professor Jim Chen
   School of Civil & Environmental Engineering
   Nanyang Technological University
   29 Mar 2007

8. Bioenergy as a renewable green and clean energy (Energy forum)
   Assoc Professor Wang Jing-Yuan,
   Nanyang Technological University
   6 June 2007
   Venue: Institute of Southeast Asian Studies
   ** A/P Wang was invited to speak at the Institute of Southeast Asian studies (Energy Forum) with 70 attendees in total; LHZB interviewed him and featured the story on 7 June.

9. Urban environmental management & sustainability (guest lecture series)
   Assoc Professor Wang Jing-Yuan,
   Nanyang Technological University
   21 August 2007
   Venue: Department of Architecture, School of Design and Environment, National University of Singapore

10. New directions in desalination
    Professor Raphael Semiat
    Director of Grand Water Research Institute
    Head of GWRI Rabin Desalination Laboratory
    The Chemical Engineering Department
    Technion - Israel Institute of Technology
    24 Aug 2007

11. Stability of Pseudomonas putida Cultures during the Off-Gas Treatment of Toluene and Benzene
    Dr. Raul Muñoz
    Senior Researcher
    Dept of Chemical Engineering and Environmental Technology
12. Off-Gas Treatment Of Vocs In Two-Phase Partitioning Bioreactors: Potential and Limitations
Dr. Raul Muñoz
Senior Researcher
Dept of Chemical Engineering and Environmental Technology
Valladolid University, Spain
20 Sep 2007

13. Free nitric acid inhibition on nitrous oxide reduction in denitrification & Could polyphosphate-accumulating organisms be glycogen-accumulating organisms?
Dr. Raymond J Zeng
Advanced Water Management Centre
University of Queensland, Australia
7 Dec 2007

Workshop

Project Atmospheric Brown Clouds (ABC) – Water Impact Study Group meeting;
Jointly hosted by EERC and MRC, 24–25 May 2007, NTU
NTU has been designated as the lead institution for the project of “Water Impact Study” as part of the Atmospheric Brown Clouds project of the United Nation Environment Programme (UNEP). UNEP has invited regional scientists to participate in this project held in Singapore 24-25 May, 2007. A/P Tan Soon Keat (D-MRC), A/P Wang Jing-Yuan (D-EERC) and Asst Prof. Victor Chang are part of the team on this project. This was the first of the four workshops on the Water Impact Study of UNEP’s ABC programme in 2007.

Project Atmospheric Brown Clouds (ABC) – Water Impact Study Group meeting;
Jointly hosted by EERC and MRC, 15–16 Sep 2007, NTU
The second Water Impact Study Group meeting was aimed at (i) discussing the chapters of the report by each sub-groups as outlined in the first meeting in May 2007 draft, (ii) sharing among the group members the views and opinion of the ABC science team (ST) members during the ST meeting in August in Korea, and (iii) facilitating further work and compilation of the final report of the water study due December 2007.

International conference

- 4TH IWA Leading Edge Conference on Water and Wastewater Technologies (LET) @ Swissotel The Stamford, Singapore; 3 - 6 JUNE 2007
  NTU Participants: A/Prof Edmond Lo Yat-Man, A/Prof Wang Jing-Yuan, A/Prof Darren Sun and EERC researchers.

- Science team meeting and workshop on Impact Assessment - Project Atmospheric Brown Clouds (ABC) @ Imperial Palace Hotel, Seoul, Korea; 27-29 Aug 2007
  NTU Team: A/P Tan Soon Keat, A/P Wang Jing-Yuan, Asst Prof. Victor Chang and Dr. Wang XiKun.

- RUC meeting @ Tongji University, Shanghai, China; 19–22 Sep 2007
  A/P Wang (D-EERC) was invited to present on environmental research in NTU at the RUC meeting.

- 11th World Congress on Anaerobic Digestion (AD11) - Bioenergy for our future @ Brisbane, Australia; 24-27 Sep 2007
  A/P Wang (D-EERC) and his graduate student, Mr Ding HongBo attended the conference.

Colloquium

EERC hosted a joint colloquium for the delegation from the department of environmental engineering (DEE) of National Cheng Kung University (NCKU) of Taiwan on 2 Nov 2007. The NCKU team comprised of eight professors and six graduate students. Several of the CEE Faculty and researchers attended the colloquium to interact with the NCKU visitors. A number of our faculty members had also given presentation on topics related to their research interests. The joint colloquium has achieved its main objective to let the colleagues from two institutions discuss their common interests and possible collaboration. An MOU was signed between NTU and NCKU on the same day.

NCKU-NTU Colloquium hosted by EERC, 2 Nov 2007. Delegates from the National Cheng Kung University interacted with the school faculty and graduate students.
RESEARCH CENTRES

Community involvement

National Science Challenge 2007
- The annual National Science Challenge, jointly organised by the Agency for Science, Technology and Research, Singapore Science Centre and the MOE, is a major Science competition for Secondary Schools.

EERC was invited by the Singapore Science Centre to host an Outdoor Challenge (on 12 Sep 2007) for the National Science Challenge grand final. The challenge proposed and coordinated by EERC, “Making Nanyang Lake a Sustainable Eco-Lake” was a full day program which comprised of site investigation at the lake followed by laboratory analysis, presentation of findings and proposals on a conceptual master plan by the competing teams. A number of the EWRE faculty staff was invited to be lecturers and judges for the competition.

EERC hosted the outdoor challenge for the grand final of the National Science Challenge 2007.

VISITORS 2007

1. Visit by Dr. Dong, Director of the Institute of Environmental Technology @ Vietnamese Academy of Science and Technology (IES@VAST); 8 January 2007
   During this informal visit, Dr Dong introduced to members of EERC the research activities carried out in IES@VAST.

2. Visit by Scientific Advisory Board Members; 31 January 2007
   Presentations by Prof James O Leckie (SSP) and A/Prof Lo, D-EWT cluster were held at the EERC Annexe lobby followed by Lab tour of the EERC laboratory led by D-EERC.

3. Visit by staff from Institute of Technology, Shimizu Corporation; 7 February 2007
   The visitors were Dr Yashiro, Director; Dr Takashi Tazoh, Deputy Director & Chief Research Manager; Mr Kenji Nakamura. The programme includes presentation by AC (Research) on CEE’s research activities followed by discussion; tour of CEE laboratories and lunch hosted by CEE/NTU. DD-EERC attended the function on behalf of D-EERC.

4. Visit by Dr. Gail Cuthbert Brandt, Associate Vice-President of Academic, University of Waterloo; 6 March 2007
   The visitor was received by Prof Khor Khiam Aik, Director, Office of Research (ORE), Prof Lee Soo Ying, Dean, College of Sciences (CoS) and A/Prof Wang JY, Director of Environment Engineering Research Centre (representing A/P Edmond Lo, Head of EWRE) and gave their presentation.

5. Visit by Ngee An Polytechnic-Centre of Innovation (Environmental and Water Technology) School of Engineering; 7 Mar 2007
   The visitors met with the Division of Environmental and Water Resources Engineering to explore possible areas of collaboration in R & D. Head of EWRE and D-EERC led the visitors through the EERC Research facilities.

6. Visit by academic staff from Nanyang Polytechnic, 8 March 2007
   The NY Poly teaching staff visited EERC facilities (environmental & water resources) and were introduced to our Environmental Engineering program by the Head of EWRE.

   He was invited to be the seminar speaker hosted by EERC while he was in Singapore.

8. Visit by Bob Sargent, President of Chartered Institute of Water & Environment Management; 21 Mar 2007
   Bob Sargent specialises in hydrology, sustainable water resources management and hydro-ecology and he is also the Head of Environmental Services, where he developed the Agency’s environmental strategy. During his stay in Singapore, he would like to set up a meeting with the relevant bodies in universities as well as giving a lecture to the mass audience. He was invited to be the
9. Visit by Sandia National Labs; 22 March 07
A Sandia delegation visited NTU on Thu 22 March. The delegate attended a presentation by EWRE faculty, followed by a tour to RTP facilities.

10. Visit by University of Southampton; 16 April 2007
Southampton is keen to meet with NTU seniors to discuss research tie-ups and teaching exchange. The Delegates consist of Faculty Deans, School Heads, and Senior Administrators. After a general presentation from both institutions there was guided tour to various facilities which include EERC-Annexe, led by D-EERC. The aim of the visit is to develop mutually beneficial research collaborations.

11. Visit by MOE Principals; 16 May 2007
EERC participated in the ‘Learning Journey’ programme, which is part of MOE Principals’ Forum 2007. The visitors were received by the Dean of Admissions and the representatives from the schools. D-EERC and A/Prof Liu Yu led the tour to CEE Environment Laboratories after a briefing by A/Prof Wang JY at EERC.

Purpose: Donor Cultivation. The visitors from STB were given a guided tour to EERC-Annexe facilities and the presentation on “Water Resource Management”.

13. Visit by Dr David Garman, President IWA; 4 June 2007
Dr David Garman, President IWA, visited NTU on 4 June. He was in Singapore for the LET conference. During his visit to NTU, CEE hosted a meeting at the CoE Conference Room with presentations made by the various groups presence followed by discussion on collaboration.

14. Visit by Veolia Environment; 5-6 June 2007
Executives from Veolia Environment visited Singapore 4-7 June 2007. The delegation was led by Robert Bozza, Scientific Advisor to the CTO. Veolia has plans to set up an R&D Centre in Singapore, which could encompass elements of water, waste and energy research. During the visit, they met up with both NTU and IESE to get a feel of the Water R&D here. Membranes and Waste and Energy R&D were research areas they are interested in. This has given them a sense of the capabilities and direction for their proposed R&D centre in Singapore, and perhaps set up some opportunities for collaboration. Water - 5th June from 9.30am-12.00pm (A/Prof Teh, Prof Tay, Prof Fane) Waste and Energy - 6th June from 3.00pm-4.30pm (A/Prof Teh, A/Prof Wang)

The objective of the meeting was to explore ways that NTU and Lereno Bio-Chem Ltd could collaborate in R&D efforts, particularly in developing next generation biofuels. Lereno is one of the four biodiesel producers on Jurong Island. The company’s business plans includes upstream expansion in acquiring and developing palm oil plantations, which would give us access to large amounts of biomass. Developing and producing next generation biofuels from the biomass is part of that vision as well. Research efforts at NTU on pyrolysis and enzymatic conversion of biomass to sugar and bioethanol are areas that were of interest to the company.

16. Visit by Prof Domenico Giardini; 22 June 2005
D-EERC led the visitor through a guided tour of EERC facilities.

17. Visit by Professor Raphael Semiat, 24 August 2007
Raphael Semiat is a professor in the Chemical Engineering Department, Technion, Israel Institute of Technology, Haifa, Israel. He is currently the director of the Grand Water research Institute and in charge of the Rabin Desalination Laboratory within the GWRI. The intention of his visit is to establish good cooperation between the Technion and the universities in Singapore, on water issues.

18. Visit by HE Mdm Zhang Xiaokang and delegates, 11 September 2007
Ambassador Extraordinary and Plenipotentiary of China to Singapore
中国驻新加坡特命全权大使张小康阁下访问南洋理工大学
The School presented (in Chinese) on the achievement in Environment related Research, followed by a guided Lab tour to the Environment Laboratory led by A/P Liu Yu.

19. Visit by Prof. Michal Green; Faculty of Civil and Environmental Engineering, Technion - Israel Institute of Technology, 17 September 2007
Prof. Michal Green has meeting with Prof Ng (ED-NEWRI), A/Prof Teh (Chair), A/Prof Lo (HOD), A/Prof Wang (D-EERC) and several EWRE faculty members.

20. Visit by a delegation from the department of environmental engineering (DEE) of National Cheng Kung University (NCKU) of Taiwan; 2 November 2007
A team comprising of eight professors and six graduate students visited NTU for a joint colloquium. CEE Faculty and researchers were invited to host and interact with the NCKU visitors. A number of our faculty members had also given presentation on topics related to their research interests. The joint colloquium has achieved its main objective to let the colleagues from two institutions discuss their common interests and possible collaboration.

21. Visit by Prof Somerville, the Lee Kuan Yew Distinguished Visitor, 15 November 2007
Prof Somerville’s expertise is on climate change. EERC hosted a tea reception and a presentation by Prof Ng
RESEARCH CENTRES

WJ, ED-NEWRI followed by a guided tour at EERC-Annexe, RTP for the visitor led by D-EERC.

RESEARCH AND DEVELOPMENT

Regional collaboration

- NTU, through EERC, has won the support of the UNEP ABC science team, and UNEP has officially awarded the ABC water impact study project to NTU; seed funding of US$150K has been secured. A/Prof Tan SK and A/Prof Wang JY would be working together on this ABC project with EERC’s support. This project is collaboration under UNEP’s regional university consortium (RUC) that NTU is a member together with 7 other universities in the Asia Pacific region in addressing environmental issues for the Asia Pacific region. It is a sustainable and niche area that EERC can make a significant contribution to NTU, Singapore, and the region.

Industrial collaboration

- ecoWise Pte Ltd has engaged EERC in contract research works on resource recovery.
- Alpha Synovate Pte Ltd has engaged EERC in collaboration work in the area of algae biodiesel and its applications.

Activities of Maritime Research Centre (MRC) from July 2006 to June 2007

New projects - 2007

<table>
<thead>
<tr>
<th>No</th>
<th>Project Title / Description</th>
<th>PI(s)</th>
<th>Collaborating Partners</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Trend and Emerging issues - Maritime technology</td>
<td>Maritime Research Centre</td>
<td>ABS Offshore Technology Centre, Maritime and Port Authority of Singapore</td>
</tr>
<tr>
<td>2</td>
<td>Experimental And Theoretical Studies Of Vortex Shedding Of Side-By-Side Multiple Cylinders.</td>
<td>Cheng Nian Sheng (CEE), Chua Leok Poh (MAE)</td>
<td>ABS Offshore Technology Centre, Maritime and Port Authority of Singapore</td>
</tr>
<tr>
<td>3</td>
<td>Modelling of Wave Run-up, Air-gap and Hydrodynamic Loads of Semi submersible Structures</td>
<td>Huang Zhenhua (CEE)</td>
<td>Keppel FELS Deepwater Technology Group, ABS Offshore Technology Centre, Maritime and Port Authority of Singapore</td>
</tr>
<tr>
<td>4</td>
<td>Real-time Quality Monitoring of Arc Welding Processes</td>
<td>Ling Shih Fu (MAE)</td>
<td>Sembmarine, Maritime and Port Authority of Singapore</td>
</tr>
<tr>
<td>5</td>
<td>Structural Health Monitoring System for Shipyard and Offshore Heavy Cranes</td>
<td>Ma Guowei (CEE)</td>
<td>Sembmarine, ABS Offshore Technology Centre, Maritime and Port Authority of Singapore</td>
</tr>
<tr>
<td>6</td>
<td>Remote Stress Monitoring System (RSMS) for Safe Storage of CNG tank cylinders under High Pressure</td>
<td>Lie Seng Tjhen (CEE), Ma Guowei (CEE)</td>
<td>ABS Offshore Technology Centre, Melchers GMBH &amp; Co., Maritime and Port Authority of Singapore</td>
</tr>
</tbody>
</table>
Activities of Protective Technology Research Centre (PTRC) from July 2006-August 2007

RESEARCH

PTRC has since administered 28 R&D projects and 1 R&D programme totalling $13 million in project value. 23 projects have been completed and 6 on-going.

OUTREACH PROGRAMME

During the reporting period, PTRC has organised an international conference, 5 public seminars, 3 short courses and one workshop. The 2nd international conference on Design and Analysis of Protective Structures was successfully held at the Shangri-La Hotel from 5 to 7 December 2006. Jointly organised by School of CEE and DSTA, the conference attracted 228 participants from 12 countries. The conference had a total of 48 speakers which included 1 Honourable Conference Speaker, 5 Keynote Speakers and 42 Plenary Session Speakers. The Honourable speaker was Professor Lui Pao Chuen, Chief Defence Scientist of DSTA and the keynote speakers were as follows:

Participants seated at Tower Ballroom, Shangri-La Hotel

Mr Richard Lim, Chief Executive, DSTA, giving a welcome speech at the DAPS 2006 dinner

The short course and public seminars organised by PTRC during the reporting period were as follows:

Public seminars

<table>
<thead>
<tr>
<th>S/O</th>
<th>Title</th>
<th>Speakers</th>
<th>Event Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Energy Absorption Capacity of 3D Cellular Materials</td>
<td>Prof Yu Tongxi</td>
<td>05 Jan 07</td>
</tr>
<tr>
<td>2</td>
<td>Research Seminar by UTRE Programme</td>
<td>UTRE Researchers</td>
<td>09 Jan 07</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1. An Xinmei</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>2. Li Jianchun</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>3. Chen Xiliang</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>4. Annamdas Venu</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Gopal Madhav</td>
<td></td>
</tr>
</tbody>
</table>
RESEARCH CENTRES

Public seminars

<table>
<thead>
<tr>
<th>S/O</th>
<th>Title</th>
<th>Speakers</th>
<th>Event Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>Prediction of bumps in deep mines using DEM</td>
<td>Prof Petr Prochazka</td>
<td>08 Feb 07</td>
</tr>
<tr>
<td>4</td>
<td>Tunneling in Rock-Present Technology and Future Challenges</td>
<td>Prof Zhao Jian</td>
<td>28 May 07</td>
</tr>
<tr>
<td>5</td>
<td>Modelling of Explosion Effect on concrete structures: Challenges and Some Recent Studies</td>
<td>Prof Lu Yong</td>
<td>23 Aug 07</td>
</tr>
</tbody>
</table>

Short course

<table>
<thead>
<tr>
<th>S/O</th>
<th>Title</th>
<th>Speakers</th>
<th>Event Date</th>
</tr>
</thead>
</table>
| 1   | Plume, Zone and CFD Modelling of Fires School of CEE, NTU             | 1. Prof Vasily B. Novozhiloy  
2. A/P Tan Kang Hai  
3. A/P Adrian Law | 17 & 18 Jul 06           |
| 2   | The Mechanics and Physics of Advanced Blasting - Waves, Shocks, Fracture, Damage, Impact and Profit, by Professor Hans - Peter Rossmanith, Institute of Mechanics and Mechatronics, Vienna University of Technology Austria, 11 and 12 September 2006 | Prof Hans-Peter Rossmanith | 11 & 12 Sep 06 |
| 3   | Discontinuous Deformation Analysis (DDA) for Rock Mass Stability and Deformation | Dr. Shi Genhua            | 2 & 3 Nov 06 |

Workshop

<table>
<thead>
<tr>
<th>S/O</th>
<th>Title</th>
<th>Speakers</th>
<th>Event Date</th>
</tr>
</thead>
</table>
| 1   | 3-D Geological Information System (GIS) and Engineering Practices    | 1. Dr Geoff Zeiss         
2. Assoc Prof Tor Yam Khoon  
3. Prof Zhu Hehua  
4. Dr Li Xiaojun | 11 & 12 Jan 07           |

DEFENCE TECHNOLOGY PRIZE AWARD

Director of PTRC, Professor Pan Tso-Chien, receiving award trophy from the Minister for Defence, Mr Teo Chee Hian

Left to Right: Assoc Prof Lee Fook Hou (NUS), Prof Pan Tso-Chien (NTU), Mr Ong Yew Hing (DSTA), Prof Lui Pao Chuen (MINDEF) and Minister for Defence, Mr Teo Chee Hian
PTRC is part of the Protective Technology Research Team that had won a Technology Prize Award at the Defence Technology Prize (DTP) Award Ceremony held at the Nanyang Auditorium, NTU, on 3 November 2006. The DTP is MINDEF’s most prestigious award to recognise outstanding contributions in defence science and technology to enhance Singapore’s defence capability. Director of PTRC, Professor Pan Tso-Chien, represented the centre in receiving the award trophy from the Minister for Defence, Mr Teo Chee Hian. Other award recipients from PTRC were Assoc Prof Li Bing, Assoc Prof Lok Tat Seng and Assoc Prof Lu Yong.

Noteworthy R&D milestones by the PTR Team include filed tests to explore new methodologies of blast-resistant structures, which have led to the development of modern protective concepts such as reinforced soil walls and lightweight blast door systems.

Another remarkable PTR Team contribution is in the area of underground ammunition facilities (UAF). Research in UAF has led to the establishment of the Underground Technology and Rock Engineering (UTRE) programme, which focuses on UAF technology for the construction of underground structures in Singapore. Currently, the programme drives researchers, identifies potential underground space applications and protective technology, promotes the use of underground space, and explores new technologies for construction.

Finally, the PTR Team’s award-winning efforts involve a review of state-of-the-art protective materials and advanced technology that protect structures against closed-in blasts and penetrations, as well as an assessment of new materials that could be incorporated into existing buildings for their protection. As an alternative to brittle conventional reinforced concrete and blast loads that can dislodge potentially dangerous concrete debris, the PTR Team has developed cement-based composites, which are more shatter-resistant and have a greater capacity for energy absorption.

INTERNATIONAL VISITORS

PTRC has also received a total of 6 delegations with close to 60 visitors during the reporting period. The delegates were from local as well as foreign governments, universities, and research institutions.

Some of the distinguished foreign visitors whom we have received include the following:

<table>
<thead>
<tr>
<th>S/O</th>
<th>Visitor</th>
<th>Designation</th>
<th>Visit Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Comm James Tan</td>
<td>Commissioner, Civil Service Defence Force</td>
<td>09 Nov 06</td>
</tr>
<tr>
<td>2</td>
<td>Dr Anton Schrafl</td>
<td>Director, Pan Pacific PLC</td>
<td>16 Mar 07</td>
</tr>
<tr>
<td>3</td>
<td>Mr Linus Fast</td>
<td>Programme Manager, FOI Defence &amp; Security, Systems and Technology, Sweden</td>
<td>10 Apr 07</td>
</tr>
<tr>
<td>4</td>
<td>Prof Leonard Ferrari</td>
<td>Provost &amp; Academic Dean, US Naval Postgraduate School</td>
<td>04 Jul 07</td>
</tr>
</tbody>
</table>
A list of approved research projects is summarized below. Readers are welcome to email the respective investigators for more information regarding their work.

<table>
<thead>
<tr>
<th>Project Titles</th>
<th>Principal Investigator</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Internal Project</strong></td>
<td></td>
</tr>
<tr>
<td>Molecular Basis of Formation of Active but Non-Culturable Environmental Bacterial Pathogens. <em>(Collaboration with Curtin University, Australia)</em> <em>(En&amp;Wr)</em></td>
<td>Gin Yew-Hoong Karina <em>(<a href="mailto:cyhgin@ntu.edu.sg">cyhgin@ntu.edu.sg</a>)</em></td>
</tr>
<tr>
<td>Illustration Fouling Mechanism of Ultrafiltration Membrane in Water Treatment System</td>
<td>Darren Sun Delai <em>(<a href="mailto:ddsun@ntu.edu.sg">ddsun@ntu.edu.sg</a>)</em></td>
</tr>
<tr>
<td>Catastrophic Risk Analysis of Infrastructure Systems</td>
<td>New PI: Robert Tiong <em>(<a href="mailto:clktiong@ntu.edu.sg">clktiong@ntu.edu.sg</a>)</em></td>
</tr>
<tr>
<td>Simultaneous Transportation and Inventory Management for Intermodal Freight Transport</td>
<td>Teo Chee Chong <em>(<a href="mailto:TeoCC@ntu.edu.sg">TeoCC@ntu.edu.sg</a>)</em></td>
</tr>
<tr>
<td>Membrane Filtration of Interacting Poly-Disperse Colloidal Particles with Simultaneous Gaseous Bubble Flow</td>
<td>Jim Chen Chin-Kuang <em>(<a href="mailto:JimChen@ntu.edu.sg">JimChen@ntu.edu.sg</a>)</em></td>
</tr>
<tr>
<td>Removal of Trace Contaminants Using Molecularly Imprinted Polymers and Bioreactors</td>
<td>Benoit Guieysse <em>(<a href="mailto:BJGuieysse@ntu.edu.sg">BJGuieysse@ntu.edu.sg</a>)</em></td>
</tr>
<tr>
<td><strong>SEP Project.</strong> Mechanism of Water and Air Flows Through Unsaturated Soil</td>
<td>Harianto Rahardjo <em>(<a href="mailto:chrahardjo@ntu.edu.sg">chrahardjo@ntu.edu.sg</a>)</em></td>
</tr>
<tr>
<td>Failure Modes and Ultimate Strength of Tubular Joints under Elevated Temperatures</td>
<td>Tan Kang Hai <em>(<a href="mailto:CKHTAN@ntu.edu.sg">CKHTAN@ntu.edu.sg</a>)</em></td>
</tr>
<tr>
<td>Estuarine Transport of Fine Suspended Sediments from Urban Tropical Catchments</td>
<td>Lloyd Chua Hock Chye <em>(<a href="mailto:chchua@ntu.edu.sg">chchua@ntu.edu.sg</a>)</em></td>
</tr>
<tr>
<td>Dynamics of Floating Breakwater in Nonlinear Shallow Water Waves</td>
<td>Huang Zhenhua <em>(<a href="mailto:zhhuang@ntu.edu.sg">zhhuang@ntu.edu.sg</a>)</em></td>
</tr>
<tr>
<td>Fouling of Reverse Osmosis and Nanofiltration Membranes by Biological Macromolecules - Probing the Foulant-Membrane and Foulant-foulant Interactions</td>
<td>Tang Chuyang <em>(<a href="mailto:cytang@ntu.edu.sg">cytang@ntu.edu.sg</a>)</em></td>
</tr>
<tr>
<td><strong>External Project</strong></td>
<td></td>
</tr>
<tr>
<td>Safety and Risk Assessment of Offshore Structures Containing Cracks and Defects.</td>
<td>Lie Seng Tjhen <em>(<a href="mailto:cstlie@ntu.edu.sg">cstlie@ntu.edu.sg</a>)</em></td>
</tr>
<tr>
<td>Finite Element Analysis (FEA) Code Checking as per Rules on Marine Classification Societies. <em>(external parties - Six Tee Engineering Group, Germanischer Lloyd)</em></td>
<td>Gho Wie Min <em>(<a href="mailto:cwmgho@ntu.edu.sg">cwmgho@ntu.edu.sg</a>)</em></td>
</tr>
<tr>
<td>Low Speed Manoeuvring of an Ogive Cylinder Using Pulsating Jets.</td>
<td>Law Wing-Keung, Adrian, <em>(<a href="mailto:CWKLAW@ntu.edu.sg">CWKLAW@ntu.edu.sg</a>)</em></td>
</tr>
<tr>
<td>Research and Development of an Operational Tsunami Prediction and Assessment System (OTPAS)</td>
<td>Pan Tso-Chien <em>(<a href="mailto:cpan@ntu.edu.sg">cpan@ntu.edu.sg</a>)</em></td>
</tr>
<tr>
<td>Project Titles</td>
<td>Principal Investigator</td>
</tr>
<tr>
<td>-------------------------------------------------------------------------------</td>
<td>----------------------------------------------------------------</td>
</tr>
<tr>
<td>Development of Analytical Tools for Progressive Collapse Analysis Due to Terrorist Bombing</td>
<td>Tan Kang Hai, (<a href="mailto:ckhtan@ntu.edu.sg">ckhtan@ntu.edu.sg</a>) Li Bing (<a href="mailto:CBLi@ntu.edu.sg">CBLi@ntu.edu.sg</a>)</td>
</tr>
<tr>
<td>TEC Project. Structural Health and Safety Monitoring of Excavation Support Structures using Electro-Mechanical Impedance Technique</td>
<td>Yang Yaowen (<a href="mailto:cywyang@ntu.edu.sg">cywyang@ntu.edu.sg</a>)</td>
</tr>
<tr>
<td>Funding level: $99,000</td>
<td></td>
</tr>
<tr>
<td>Autonomous Verification and Validation for Simulation Modeling Top-up of $38,985 by ST Electronics (Training &amp; Simulation) Pte Ltd. A copy of letter dated 25 Aug 06 was received from Office of Finance.</td>
<td>Yang Yaowen (<a href="mailto:cywyang@ntu.edu.sg">cywyang@ntu.edu.sg</a>)</td>
</tr>
<tr>
<td>Use of Copper slag as a land reclamation fill material in Singapore: Phase 1</td>
<td>Lim Teik Thye (<a href="mailto:cttlim@ntu.edu.sg">cttlim@ntu.edu.sg</a>)</td>
</tr>
<tr>
<td>Soil Improvement for Tree Stability</td>
<td>Harianto Rahardjo (<a href="mailto:chrahardjo@ntu.edu.sg">chrahardjo@ntu.edu.sg</a>)</td>
</tr>
<tr>
<td></td>
<td>Tan Puay Yok</td>
</tr>
<tr>
<td></td>
<td>Leong Eng Choon</td>
</tr>
<tr>
<td></td>
<td>(<a href="mailto:cceleong@ntu.edu.sg">cceleong@ntu.edu.sg</a>)</td>
</tr>
<tr>
<td>Application of an Electromagnetic Field Effect</td>
<td>Law Wing-Keung, Adrian, (<a href="mailto:CWKLAW@ntu.edu.sg">CWKLAW@ntu.edu.sg</a>)</td>
</tr>
<tr>
<td></td>
<td>Tony Fane (<a href="mailto:AGFane@ntu.edu.sg">AGFane@ntu.edu.sg</a>)</td>
</tr>
<tr>
<td>Underground Technology and Rock Engineering (UTRE) Program - Behaviour of Rock Cavern Under Dynamic Loads (This project is a continuation from previous project by Zhao Jian who resigned in 2005). The new PI is ZhaoZY</td>
<td>Zhao Zhiye (<a href="mailto:czzzhao@ntu.edu.sg">czzzhao@ntu.edu.sg</a>)</td>
</tr>
<tr>
<td>Atmospheric Brown Clouds (water budget) – Water impact study</td>
<td>Wang Jing-Yuan (<a href="mailto:jywang@ntu.edu.sg">jywang@ntu.edu.sg</a>)</td>
</tr>
<tr>
<td></td>
<td>Tan Soon Keat</td>
</tr>
<tr>
<td></td>
<td>(<a href="mailto:ctansk@ntu.edu.sg">ctansk@ntu.edu.sg</a>)</td>
</tr>
<tr>
<td>Development of a Quantitative Risk Analysis (QRA) System and Establishment of Quantitative Safety Target for Road Tunnels</td>
<td>Lam Soi Hoi (<a href="mailto:cshlam@ntu.edu.sg">cshlam@ntu.edu.sg</a>)</td>
</tr>
<tr>
<td></td>
<td>Wong Yiik Diew</td>
</tr>
<tr>
<td></td>
<td>(<a href="mailto:cydwong@ntu.edu.sg">cydwong@ntu.edu.sg</a>)</td>
</tr>
<tr>
<td>Experimental and theoretical studies of vortex shedding of side-by-side multiple cylinders</td>
<td>Cheng Nian Sheng (<a href="mailto:cnscheng@ntu.edu.sg">cnscheng@ntu.edu.sg</a>)</td>
</tr>
<tr>
<td></td>
<td>Chua Leok Poh</td>
</tr>
<tr>
<td>Innovative Design of Civil Defence Shelters</td>
<td>Ma Guowei (<a href="mailto:cgwma@ntu.edu.sg">cgwma@ntu.edu.sg</a>)</td>
</tr>
<tr>
<td>Emerging Organic Contaminants in Catchment Surface Waters of the Marina Bay</td>
<td>Karina Gin Yew-Hoong (<a href="mailto:cyghin@ntu.edu.sg">cyghin@ntu.edu.sg</a>)</td>
</tr>
<tr>
<td>Development of an Online Pathogen Detection System</td>
<td>Karina Gin Yew-Hoong (<a href="mailto:cyghin@ntu.edu.sg">cyghin@ntu.edu.sg</a>)</td>
</tr>
<tr>
<td><strong>RGM Project</strong></td>
<td></td>
</tr>
<tr>
<td>Development of Nano-structured Photocatalyst for Membrane Water Treatment (Remarks by Principal Investigator:This project will be managed by SSP Office as it is part of NTU-Stanford-PUB TEC project.)</td>
<td>Darren Sun (<a href="mailto:ddsun@ntu.edu.sg">ddsun@ntu.edu.sg</a>)</td>
</tr>
<tr>
<td>Project Titles</td>
<td>Principal Investigator</td>
</tr>
<tr>
<td>-------------------------------------------------------------------------------</td>
<td>---------------------------------------------</td>
</tr>
<tr>
<td>Finite Element Modeling of Precast Hybrid Steel-Concrete Connections under Seismic Loadings</td>
<td>Yip Woon Kwong (<a href="mailto:cwkyip@ntu.edu.sg">cwkyip@ntu.edu.sg</a>)</td>
</tr>
<tr>
<td>Development of Advanced Research in Civil &amp; Structural Engineering</td>
<td>Pan Tso-Chien (<a href="mailto:cpan@ntu.edu.sg">cpan@ntu.edu.sg</a>)</td>
</tr>
</tbody>
</table>
INTRODUCTION

Carbon finance is the investment in Greenhouse Gas (GHG) emission reduction projects in developing countries and countries with economies in transition within the framework of the Kyoto Protocol’s Clean Development Mechanism (CDM) or Joint Implementation (JI) and with creation of financial instruments that are tradable in carbon market. For many projects that involve renewable energy the benefits are both in needed energy generation and carbon credit revenue. The carbon credits produced by CDM projects are called Certified Emission Reductions ("CERs") and carbon credits produced by JI projects are called Emission Reduction Units ("ERUs"). The credits are monetized when the project developer sells them to a third party (possibly a power generator in an industrialized country) and measured in metric ton CO\textsubscript{2} or CO\textsubscript{2}eq (Carbon Dioxide Equivalent). This is considered a primary market transaction and makes up 85% of the current CER/ERU market.

The difference between CDM and JI is geographical and procedural. A CDM project involves an Annex I (industrialized) entity investing in a project in a Non-Annex I country. A JI project involves one Annex I country investing in a carbon project in another Annex I (industrialized with economies in transition) country.

The CDM is a much larger and more mature mechanism as it has been generating credits since 2004, whereas JI will begin generating credits in 2008. According to the World Bank, in 2006 the CDM market was worth $5.2 Billion and the JI market was worth $141 Million. Both of these markets grew by 300% compared to 2005.

Carbon financing will generate additional revenue from carbon credit which will increase the bankability of projects by reducing the risks of commercial lending or grant finance. Meantime, it has also demonstrated numerous opportunities for collaborating across sectors, and has served as a catalyst in bringing climate issues to bear in projects relating to rural electrification, renewable energy, energy efficiency, urban infrastructure, waste management, pollution abatement, forestry, and water resource management.

The financial benefits as a result of carbon financing will certainly affect the project feasibility study. This study is based a hydro power project in Central Vietnam, Za Hung Hydro Power Plant, which is under validation of CDM project, to demonstrate these impacts on the project financing analysis.

ZA HUNG HYDRO POWER PROJECT

Project overview

The Za Hung Hydropower Project involves the construction of a 30 MW power plant consisting of 2 units of 15 MW each on the A Vuong river in Za Hung commune, Dong Giang district, Quang Nam province. The estimated annual gross power generation is about 110.3 million kWh and about 109.2 million kWh will be fed to the national grid.

The objective of the Za Hung Hydropower Project is to generate renewable electricity utilizing hydroelectric resources in the A Vuong river and sell the generated power to Electricity Corporation of Vietnam (EVN-Who is responsible for national grid management).

The project activity will reduce greenhouse gas (GHG) emission by avoiding electricity generation and CO\textsubscript{2} emissions from national electricity grid. Total expected CO\textsubscript{2} annual emission reduction from the proposed project has been estimated to 634,009 tCO\textsubscript{2} during the crediting period of 10 years.

The project will stimulate and accelerate the development of renewable energy technologies in order to reduce GHG emissions, to protect the environment, to conserve the country energy resources while responding to increasing energy demand and energy resource diversification imperatives necessary for national sustainable economic growth. It is in line with energy policies of Vietnam; therefore it satisfies the sustainable development criteria for CDM project, established by Designated National Authority (DNA) of Vietnam.

Financial analysis

The project started construction in 2006 and targeted to complete by 2009 with an operation life of 40 years. The total investment sums up to USD 31.76 million with a 20-80 Equity-Debt ratio. Discount rate is 10% with a 3-year grace period during construction period and 10 years payback period. Annual operation and maintenance cost is 1.5% of the total investment.
Revenue generated is solely electricity sales in case of absence of carbon finance. The average electricity sales price to Electricity Corporation of Vietnam is US 4 cents/kWh (2.0 Cent/kWh in rainy season and 4.5 Cent/kWh in dry season). That will generate annual revenue of USD 4.37 million during the 40 years operation life.

With carbon finance, the CER credit is estimated to be sold at price of USD 8.4/tCO₂ in the primary market. That will generate additional annual revenue of USD 0.53 million during the 10 years crediting period. This is a conservative estimation as compared with the current Nord Pool open market CER trading price of Euro 16.5 and future average price of Euro 17 for 2008 to 2010.

The internal rate of return (IRR) calculated for with and without carbon finance are 11.63% and 9.53% respectively. Compared with discount rate of 10%, the project financing plan without carbon finance is not feasible whereas with carbon finance, the project financially feasible.

CONCLUSION AND RECOMMENDATION

Carbon finance will have great impacts to project financing feasibility study. The trading or sales of carbon credit, CERs, will generate additional revenue during the early stage of project operation period which will in turn have noticeable contribution to the project net present value (NPV). The total revenue generated from carbon credit commonly will be 10-15% of the total investment. Therefore carbon finance plays an important role in assessment of project financing plan. Apart from the financial benefits, carbon finance also encourages development of clean energy in host countries. These will bring both social and economic gains to the country. A key factor is the Economic Internal Rate of Return (EIRR) which is the quantification of both social and economic benefits and which is also a key assessment criteria in verification of CDM projects. However, the estimation of EIRR is much more complex compared with financing IRR as EIRR need detailed study of the whole social and economic structure of the country. Therefore future study will be carried out on EIRR estimation.

REFERENCES


INTRODUCTION

Multi-project scheduling and linear scheduling are two important and common concepts in the construction industry. These concepts are usually handled separately. However, some companies handle multiple projects in which some projects are repetitive as well. This paper integrates the multi-project scheduling and linear scheduling concepts. Since the nature of the proposed problem is combinatorial, Simulated Annealing is proposed as an optimization tool. A numerical example is used to show the application of the proposed method and to verify the model.

Since CPM is not effective for scheduling of linear projects, some other methods like Line of Balance method (LOB) [1], Vertical Production Method (VPM) [2] and Linear Scheduling Method (LSM) [3] have been developed. LSM is utilized in this research. Practically, resources are limited in construction projects so multiple resource constraints are incorporated in the model by “resource leveling” and “resource allocation”. LSM was introduced by Johnston in 1981 [3] in a highway construction project. Harmelink (1995) [4] established a heuristic algorithm to determine the controlling activities path but without consideration of resource limitations. “Controlling activity path” in linear scheduling is a concept similar to “critical path” in CPM. Controlling activity path is a set of activities that constitute a path and dictate project duration. Mattila (1997) [5] considered resource leveling in a model of highway construction project. He solved the model by using mixed integer programming. Liu (1999) [6] considered single resource allocation and proposed a heuristic solution procedure using the Tabu Search algorithm in his model. The model included two stages. Lue & Hwang (2001) [7] proposed a precast production project and solved it with a genetic algorithm-based model.
Simulated annealing is introduced in 1983 in the science magazine [8] in 1983. This concept has been used in several engineering applications since 1983 but it is introduced to construction management by Chung-I Yen (2005) [9]. He used simulated annealing for optimizing linear scheduling projects with multiple resource constraints. He considered resource allocation and resource leveling simultaneously.

MULTIPLE PROJECTS

The resource-constrained multi-project problem is defined as one in which two or more projects are concurrently active [10]. There are two approaches for scheduling of multi-project situations i.e. multi-project and single project approach. In the former, projects are considered separately, while projects are connected to each other in the latter. The multi-project approach is used in this paper. The first attempt in this field is done by Fendley (1968) and a lot of heuristics have been proposed since 1968.

Various projects are not the same and there are unequal delay penalties. The unequal delay penalties arise if the type of supervision associated with each project is different, or the delay penalties are assigned by the customers, or if the profit contributions of the projects are different [10]. Since projects are different, a weighting factor is defined for each project to be able to produce objective functions in the formulation stage. The weighted factor can be calculated based on the delay penalties.

SIMULATED ANNEALING ALGORITHM

Simulated annealing is based on the similarity between solid annealing process and combinatorial optimization. The algorithm consists of several decreasing temperatures.

Suppose that finding the minimum of the cost function is favorable. Each temperature includes a sequence of iterations. First, the beginning temperature is chosen and the initial solution is selected and the cost function will be calculated. Then a new solution will be created in the neighborhood of the previous solution. New cost function will be calculated. If new cost function is less than the previous one, it will be accepted. If new cost function is more than the previous one, it will be accepted according to Metropolis’s criterion [Metropolis et al., 1953] based on Boltzman’s probability. According to Metropolis’s criterion, if the difference between the cost function values of the current and the newly produced solution (\(\Delta E\)) is equal to or larger than zero, a random number \(\delta\) in [0,1] is generated from a uniform distribution and if

\[
\delta \leq e^{(-\Delta E/T)}
\]

Then the newly produced solution is accepted as the current solution. The number of new solutions which are created in each temperature is as many as the iteration number (termination condition). Iteration number can be a certain number of moves [9]. Then temperature will reduce upon temperature update rule and every above-said step will be iterated until the temperature goes down to the minimum temperature (halting criteria) [8]. The result will be affected by the number of iterations and the speed of reducing temperature. The halting criterion in this research is equation (2).

\[
\text{Temperature} = Te^{(-r)}
\]

Where T is the initial temperature, \(r\) is a cooling ratio, and \(t\) is the number of times that temperature has been used. The chosen \(r\) is 0.1 in this research.

PROBLEM FORMULATION

Assume there are two linear projects with \(N_1 + N_2\) activities, M locations, and I critical resources. \(n\) represents an activity i.e. one of \(\{N_1 + N_2\}\) activities but \(n_1\) and \(n_2\) represents activities of the first and second project respectively. The final program is based on this formulation. These formulas are based on those formulas which are proposed for a single linear project scheduling [9]. The problem is formulated as follows:

Objectives:

\[
\text{MinimizeMax}\left\{w_1 f(n_1, m) + w_2 f(r_2, m)\right\}n_1 = 1...N_1, n_2 = N_1 + 1...N_1 + N_2, m = 1...M\}
\]

\[
\text{Minimize}\sum_{i=1}^{I} \sum_{j=1}^{J} W_i (dp_{i,j} + dm_{i,j}) \quad [9]
\]

Constraints:

- Activities precedence relationships
- Resource availability
- Activities completion

Notations:

- \(dp_{i,j}\): Absolute difference plus value of resource I assignment between day t+1 and day t
- \(dm_{i,j}\): Absolute difference minus value of resource I assignment between day t+1 and day t
- \(W_i\): Weighting factor for resource i
- \(w_i\): Weighting factor of various projects

SOLUTION METHODOLOGY

A two-stage solution-finding procedure [9] is introduced in this section. These two stages are explained briefly. In the first stage a simple feasible solution for each project is proposed. In this method we imagine that activities do not have any overlapping in each project so the first activity of each project in all locations is finished before the second activity of that with the second priority starts and it continues till each project is finished. In the other words, it is the maximum duration for

\[\text{Notations:}\]

\[\text{Constraints:}\]

\[\text{Objectives:}\]

\[\text{SIMULATED ANNEALING ALGORITHM}\]

\[\text{MULTIPLE PROJECTS}\]

\[\text{CONSTRUCTION MANAGEMENT}\]
each project but it guarantees that we have enough resources for activities to be done. It is assumed that resources are fixed for an activity in all locations in this stage.

Simulated annealing is used during the second stage to find the optimized solution. The number of one of the resources of one of the activities is changed in each iteration of the algorithm to find the best allocation. The problem will be solved by multiple-resource allocation algorithm. Next Time Frame (NTF) concept is utilized in solving by considering multiple resource constraint. The resources assigned to a repetitive activity can be varied at different locations within a specified range. The goal is to find best assignment of resources to activities to have the minimum sum of weighted project durations and fluctuation of resources assigned for the projects. So search neighborhood is all possible resource assignments to activities. The maximum and minimum temperatures are 1000 and 1 respectively.

### RESULTS AND CONCLUSION

The problem is written in Java programming language. The program is run 100 times. The average and the most optimized answer and other information which is achieved from 100 implementations are represented in Table 2.

### NUMERICAL EXAMPLE

In this section two projects are introduced as a multi-project problem to be solved by the model which is proposed. Tasks and resources can not be split. Moreover, Resources are assumed to maintain a constant productivity level within a certain range of assignment.

Table 1 lists required information about the proposed artificial projects and their activities. Project 1 consists of activities A to E and project 2 consists of activities F to K. Table 1 also presents information about resources. It is assumed that resources are labors. The maximum number of Labor 1 and 2 are 8 and 6 respectively.

The goal of this problem is to find the best resource assignment combination and the best sequence of activities to minimize the sum of weighted project durations and the fluctuation of resource usage. The main objective is to find the minimum of the sum and the second objective (minimum fluctuation of resource usage) is used when there are two schedules with the same sum.

### Table 1. Required information about activities and required resources

<table>
<thead>
<tr>
<th>Activity</th>
<th>Duration (Days)</th>
<th>Predecessor</th>
<th>L1</th>
<th>L2</th>
<th>Total L1 Required</th>
<th>Activity priority</th>
<th>L1 Range</th>
<th>L2 Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>4</td>
<td></td>
<td>3</td>
<td>2</td>
<td>4*3=12</td>
<td>1</td>
<td>2-4</td>
<td>1-3</td>
</tr>
<tr>
<td>B</td>
<td>2</td>
<td>A (FS0)</td>
<td>2</td>
<td>1</td>
<td>2*2=4</td>
<td>2</td>
<td>1-3</td>
<td>1-2</td>
</tr>
<tr>
<td>C</td>
<td>2</td>
<td>B(FS0)</td>
<td>2</td>
<td>1</td>
<td>2*2=4</td>
<td>3</td>
<td>1-3</td>
<td>1-3</td>
</tr>
<tr>
<td>D</td>
<td>2</td>
<td>C(FS1)</td>
<td>1</td>
<td>1</td>
<td>2*1=2</td>
<td>4</td>
<td>1-2</td>
<td>1-2</td>
</tr>
<tr>
<td>E</td>
<td>1</td>
<td>D(FS0)</td>
<td>1</td>
<td>1</td>
<td>1*1=1</td>
<td>5</td>
<td>1-2</td>
<td>1-2</td>
</tr>
<tr>
<td>F</td>
<td>3</td>
<td></td>
<td>2</td>
<td>1</td>
<td>3*2=6</td>
<td>1</td>
<td>1-3</td>
<td>1-2</td>
</tr>
<tr>
<td>G</td>
<td>2</td>
<td>F (FS0)</td>
<td>1</td>
<td>2</td>
<td>2*1=2</td>
<td>2</td>
<td>1-2</td>
<td>2-4</td>
</tr>
<tr>
<td>H</td>
<td>4</td>
<td>G (FS1)</td>
<td>3</td>
<td>1</td>
<td>4*3=12</td>
<td>3</td>
<td>2-4</td>
<td>1-3</td>
</tr>
<tr>
<td>I</td>
<td>3</td>
<td>H (FS0)</td>
<td>1</td>
<td>1</td>
<td>3*1=3</td>
<td>4</td>
<td>1-2</td>
<td>1-2</td>
</tr>
<tr>
<td>J</td>
<td>1</td>
<td>I (FS0)</td>
<td>1</td>
<td>2</td>
<td>1*1=1</td>
<td>5</td>
<td>1-2</td>
<td>1-3</td>
</tr>
<tr>
<td>K</td>
<td>4</td>
<td>J(FS2)</td>
<td>2</td>
<td>1</td>
<td>4*2=8</td>
<td>6</td>
<td>2-4</td>
<td>1-3</td>
</tr>
</tbody>
</table>

### Table 2. Results of implementations

<table>
<thead>
<tr>
<th>No. of runs</th>
<th>Most Optimized answer</th>
<th>Average</th>
<th>Variance</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>55</td>
<td>68.93</td>
<td>54.93</td>
</tr>
</tbody>
</table>

The following conclusions can be achieved from the results which are prepared.

- A large number of companies which are related to linear projects manage several projects simultaneously so these two concepts should be integrated in a single model.
- Multi-project and Linear scheduling with multiple resources can be integrated and solved simultaneously. This paper proposes a model to solve this problem.
- There are two approaches for scheduling of multi-project situations i.e. multi-project and single project approach. The multi-project approach is used in this paper.
- The model is verified by a successful numerical example. The summary of implementations is summarized in two tables.
REFERENCES


AUTOMATIC 3D MODELING DEVELOPMENT AND APPLICATION FOR HYDRAULIC CONSTRUCTION

Chen Po-Han ( cphchen@ntu.edu.sg)
Nguyen Thi Lan Truc (nguy0050@ntu.edu.sg)

INTRODUCTION

Nowadays, the application of 3D models is increasing in almost every field, especially the AEC (Architecture, Engineering, and Construction) industry. Most 3D models are generated through human manipulation with the use of 3D CAD software. These software packages are very efficient in 3D modeling, but sometimes they are not easy to use and prior experience might be required. Moreover, traditional 3D modeling is time-consuming, as manual input is required for each component as well as for the whole scene.

In the hydraulic engineering domain, 3D models are used not only to illustrate the realistic view before construction, but also to measure the construction’s volume in order to estimate cost based on cut-and-fill volume quantity, concrete volume quantity, etc. Therefore, 3D modeling is crucial and greatly needed in planning hydraulic construction. Since 3D modeling for hydraulic facilities requires accuracy and details, it would need a lot of time, effort and prior experience to manually build the whole model from scratch.

To meet this need, an approach of automatic 3D modeling is proposed to help the user build a 3D model of hydraulic construction in less time and with less manual operation. The easy-to-use features are also provided for those who do not have much experience in 3D modeling.

To demonstrate the proposed approach, an application is developed in the AutoCAD environment to automatically generate a 3D sluice model, an artificial passageway for water fitted with a valve or gate to stop or regulate water flow. With this approach, a 3D model could be automatically generated shortly and accurately from the scratch after the input of data, without much effort and time spent comparing to the traditional method. The AutoCAD environment is taken into account as it is widely used and popular among most users in engineering.

RESEARCH OBJECTIVES

The overall goal is to develop a user-friendly application which could help the users to build a 3D model of a hydraulic construction in less time with less manual operation. The users no longer have to build 3D models step by step. A 3D model could be automatically generated shortly after the input of data.

The application outcome should be precise enough for rendering and volume determination purpose.
CONSTRUCTION MANAGEMENT

METHOD

The application is developed using VisualLISP, a tool for code creation in AutoCAD environment. It is a full-featured, interpretive programming language that can be used to call AutoCAD commands, system variables, and dialog boxes [1]. It can also create user-defined functions and macros in order to facilitate AutoCAD users and increase performance and productivity. The integrated development environment (IDE) offered by VisualLISP reduces the required development time and makes it easier and faster for users and developers to create, debug and deliver AutoLISP-based applications.

Application analyzing and design steps are as follows:

1. To determine the application parameters.
2. To create application’s GUI (Graphical User Interface).
3. To develop application functions and macros.
4. To test and verify the correctness and robustness of the application.

To demonstrate the proposed approach, an application is developed in the AutoCAD environment to automatically generate a 3D sluice model, a model of artificial passageway for water fitted with a valve or gate to stop or regulate water flow.

Determining application parameter

The application parameters (or input data) are the primary dimensions of the sluice, the type for each sluice component, and the position of the sluice model in the AutoCAD environment.

A sluice structure is usually constructed by several components and each component is designed according to its function (Figure 1). Hence, each component has its specific shape that is determined by its dimensions. However, some dimensions are crucial as they determine the component’s shape. Therefore, all the crucial dimensions for each component should be identified and selected as its input parameters. The fewer the number of parameters are, the more user-friendly the application. Other dimensions are extrapolated from the primary ones or from other sources according to the constraints of the criteria and the relations among components.

Options refer to the different types of components available for selection, such as sluice gates, piers, and so on. The options enable the users to model various types of sluices.

To locate the sluice model in AutoCAD, an insertion point is required. The insertion point is also needed to align and assemble all the components together to form a complete sluice model.

Creation of application GUI

Based on the number of input parameters corresponding to each component, an application GUI (Graphical User Interface) could be developed to allow people to interact with the application. The application GUI comprises widgets such as graphical icons, visual indicators along with text, labels or text navigation to present the information and actions available to users.

As VisualLISP does not support GUI’s wizard (which leads users through a sequence of steps to build their own application interface), the Dialog Control Language (DCL) is introduced instead to perform this function. DCL, a built-in GUI mini language for creating simple graphical dialogs within AutoCAD, allows the user to interact with the AutoCAD environment through basic widgets called tiles, such as edit boxes, buttons, checkboxes, radio buttons and list boxes. In order to develop a dialog with DCL, all tiles involved in this dialog have to be constructed in a hierarchical tree in an inverted order. Specifically, a parent tile has to contain children tiles, successively. After that, DCL relies on the tree to develop the corresponding GUI. The hierarchical tree needs to build prior to GUI programming. Figure 2 is an example of developing a GUI for a component through hierarchical tree of tiles.

After all needed GUIs are created with DCL, they are in the DCL format. Therefore, VisualLISP is used to make GUls appeasable by calling the DCL files through VisualLISP commands.
CONSTRUCTION MANAGEMENT

Development of application functions and macros

The process behind GUI’s widgets is undertaken by application functions or macros. Each function or macro carries a specific task. In this application, functions and macros are used to automatically implement 3D modeling and build a 3D sluice model, instead of step-by-step manual input and operation. As the VisualLISP programming language is able to call AutoCAD commands, system variables and dialog boxes, the functions written by VisualLISP are able to generate and modify AutoCAD objects as well as to display GUIs to the user in the AutoCAD environment.

To generate a component, there are several steps. First of all, the function for component generation would retrieve input parameters and any other return values from other functions. It would then calculate its own variables. Afterwards, AutoCAD commands would be called to generate (to draw, modify, assemble, etc.) the 3D object based on the function’s variables. The object is generated from simple to complex or from 2D to 3D.

Each component is constructed through one or several functions, depending on the complexity of the component. Some functions could be re-triggered to carry out a specific task for different components. To avoid repetitiveness of commands in some functions, macro is used to make the program less tedious and less error-prone, as well as to simplify the writing, reading and understanding of the program. Macro is a sequence of commands which are grouped sequentially to act as a single command. Therefore, repetitive commands which carry out the same work could be built into a function and this function could be called each time it is needed.

Let’s take a look at the instance in Figure 3 and see how to automatically generate a retaining wall using VisualLISP functions. The generation procedure is as follows and depicted in Figure 6.

- Create a function to generate a basic block of the retaining wall
  - Call AutoCAD commands to draw the 2D boundary and the extruding path which is used to extrude the boundary to a 3D block.
  - Determine the position of the 2D boundary and the extruding path according to an existent mark. Then use the AutoCAD command to place them in the proper positions.
  - Call the “extrude” command in AutoCAD to extrude the 2D boundary along the extruding path to complete the block of a retaining wall.

- Create a function to trim any unnecessary parts of the 3D block
  - From existing data, the blocks which represent unnecessary parts are built following the steps in the first function.
  - Call the AutoCAD command to subtract the unnecessary parts from the block.

- Create a function to completely generate two symmetric walls in accordance with relative components.
  - Call the AutoCAD command to mirror the generated wall in the previous function on the opposite side based on the distance between the two symmetric walls. This distance is the width of sluice’s slab.

The core data obtained in one function are kept in some global variables in case they need to be used in other functions.

Test and verification of the application

Test and verify is a crucial and vital part of the development process. The application has been implemented a number of times with different input data and in different viewports to make sure the application operates correctly with provided data. The result is measured and assessed in each generated model in order to minimize the possibility of errors.

The average generation time for each 3D sluice model is around 8 seconds, which is much shorter than the average required time for step-by-step manual operation by an experienced professional. The average time needed for step-by-step manual operation is about 7 to 8 hours.

RESULTS

The application result is the generated 3D sluice model. The 3D sluice model has exactly the same components as the real sluice structure. Therefore, it can be used to render a realistic view of the sluice and the model’s volume could be used for cost estimation. Figure 4 depicts a plain 3D sluice model for volume determination. Some rendered products of application results are introduces in Figure 5.
CONSTRUCTION MANAGEMENT

Figure 4. A plain 3D sluice model for cost estimation based on the model’s volume

To demonstrate, an application is tailored for 3D sluice modeling. This application is developed using the VisualLISP programming language and embedded in AutoCAD. Hence, users are able to call the application in the AutoCAD environment as an embedded AutoCAD utility. By using this application, the 3D sluice model will be automatically generated in just a few seconds, saving much time and effort compared to traditional step-by-step manual input and operation.

In fact, there are many 3D modeling software products available in the market. However, those software products are not tailor-made for any specific area and users need time to get used to the software before engaging in production. This paper also concentrates on this issue, therefore easy-to-use features including user-friendly GUIs and visual indicators are provided in the demonstrated application. As this is a built-in AutoCAD application, its result has the same format as user’s work format. Therefore, both types of information are stored in one place and are able to work in one environment. Moreover, users can use AutoCAD utilities to improve the 3D model such as adding additional objects or modifying model’s components.

This kind of application is easy to develop as well as to amend. Therefore developers could apply the idea to other areas. For future work, this application could be extended to other hydraulic facilities and augmented with more practical issues such as more interactions with GUIs and data, automatic determination of model’s volume and so on.

REFERENCES

CONCLUSION

In today’s highly demanding AEC market and industry, products that could improve productivity, save time, and especially save money are keenly looked for. This paper introduces a way that uses Computer-Aided Design (CAD) to automatically generate 3D models for hydraulic construction. As it takes much time, efforts and expert skills to build 3D models for hydraulic facilities, such as dams and sluices, the development of automatic 3D modeling is necessary.

To demonstrate, an application is tailored for 3D sluice modeling. This application is developed using the VisualLISP programming language and embedded in AutoCAD. Hence, users are able to call the application in the AutoCAD environment as an embedded AutoCAD utility. By using this application, the 3D sluice model will be automatically generated in just a few seconds, saving much time and effort compared to traditional step-by-step manual input and operation.

In fact, there are many 3D modeling software products available in the market. However, those software products are not tailor-made for any specific area and users need time to get used to the software before engaging in production. This paper also concentrates on this issue, therefore easy-to-use features including user-friendly GUIs and visual indicators are provided in the demonstrated application. As this is a built-in AutoCAD application, its result has the same format as user’s work format. Therefore, both types of information are stored in one place and are able to work in one environment. Moreover, users can use AutoCAD utilities to improve the 3D model such as adding additional objects or modifying model’s components.

This kind of application is easy to develop as well as to amend. Therefore developers could apply the idea to other areas. For future work, this application could be extended to other hydraulic facilities and augmented with more practical issues such as more interactions with GUIs and data, automatic determination of model’s volume and so on.

REFERENCES

COMPUTER-AIDED VISUALIZATION FOR RESCUE IN INDOOR ENVIRONMENTS

Chen Po-Han (cphchen@ntu.edu.sg)
Nguyen Thi Lan Truc (nguy0050@ntu.edu.sg)

INTRODUCTION

Effective and rapid finding a way out in emergency is always a problem for occupants who get trapped in indoor environment. In such a case, rescuers often rely on emergency signs or verbal communication to direct trapped people to the exits. However, many problems could arise on the move such as mobile signal interruption, low visible scene caused by dense smoke, etc. These problems might prevent the rescuers to communicate with Command Centre as well as to see the emergency signs and passageway clearly. Moreover, a complex spatial layout with occluded spaces will add more difficult in decision the correct way to take.

To address these problems, this research introduces an
approach which uses visual communication with the aid of Virtual Reality (VR) and Augmented Reality (AR) technology to provide rescuers with effective and efficient real-time direction messages during rescue operation inside indoor environments. Content of the visual support is determined and generated corresponding to the rescuer’s information (current position of rescuer, rescuer’s head orientation) and current environment visibility. It is made up by combining a dynamic You-Are-Here (YAH) map superimposing on either real environment or virtual environment. Dynamic YAH map which presents the comprehensive spatial layout will be rotated in a way that the map’s view is always congruent with the real layout with respect to the reader’s viewing perspective. For a low visibility scene, a virtual environment (VR) is retrieved to enable the rescuer to identify rescue places and escape routes. Alternatively, if the scene is clear then the user could see the real scene (AR) while still keep track of superimposing information (computer-generated). The visualization will be displayed on rescuer’s Head Mounted Display (HMD) in real-time.

To demonstrate the research approach, a visualization system is developed and tested in Level B4 of Block N1 at Nanyang Technological University.

RESEARCH OBJECTIVES

The overall goal is to develop an effective computer-aided visualization for support rescue operation in the context of way-finding in an emergency with which user could read off support information easily and quickly. This thesis has following objectives:

- To study and design an effective visualization based on some crucial principles and criteria of visual communication in emergencies. This visualization could facilitate rescuers perception in an emergency situation, so they can understand the spatial information and grasp the way-finding instructions in less time.

- To find a proper content and format of the visualization in terms of computer-aided visualization. To scrutinize to technical support of Virtual Reality (VR), Augmented Reality (AR) techniques whose advantages could make use to facilitate rescuers in either visible or less visible (dense smoke) environment condition.

- To develop a robust, accurate and reliable way-finding support system in terms of computer-aided visualization system by integrating AR, VR and other supported tools and devices such as networking technology, high performance laptop, HMDs, positioning and orientation trackers, etc …

- To implement, operate and verify such kind of system in a simple indoor environment, namely at level B4 of building N1 in Nanyang Technological University (NTU), Singapore. This implementation could be a case study that could be applied to develop the visualization system for other indoor environments.

DEVELOPMENT CONTENT AND FORMAT FOR DISPLAY ON HEAD MOUNTED DISPLAY (HMD)

This part introduces the research work to develop the effective visual representation for way-finding in emergency situations. The content is determined based on criteria and principles of effective visual communication in emergencies [1]. According to [2], the content to be displayed on HMD should be fulfilled the three following functions:

- To identify places and routes
- To map the spatial layout of an area
- To direct occupants and passengers to routes

In this research, VR and AR are used to provide a visual possibility to easily identify places and routes in any cases of environment visibility. VR facilitates the users in case of visual noise by enabling them to figure out the places and routes through a 3D model which is the 3D replication of the real one. Alternatively, AR achieves this task by enabling the users to see and interact directly with the real scene in case of high visibility. Moreover, rescuers are provided other possibility to identify places and routes through the floor plan on YAH map. Specifically, name of the floor plan and possible escape routes will be explicitly given on the map.

To map the spatial layout of an area, a good design YAH map is introduced to achieve this task. The map components comprise a specific floor layout of an indoor environment, the current location and head orientation of the user and the possible escape routes. In this research, YAH map is introduced as dynamic map in which map’s components are changed in real-time in accordance with the user’s location and orientation in real-time. With ordinary static graphic maps which are normally placed in real environments, the user has to rotate his head or uses mental rotation to interpret the map properly. With the dynamic map, for instance, rescuer could know where he is within the vessel and how he is moving such as from bow (“front”) to stern (“back”) or changing sides from starboard (“right”) to port (“left”). The dynamic map could also rotate itself in order to obtain congruence with the user visual experience.

To direct occupants and passengers to routes and to the exits, the exit signs should be marked explicitly on the floor plan to indicate the place of exit doors or exit staircases. Based on the exit signs and the YAH map, the user could be directed quickly to the exits.

Figure 1 illustrates content of the visualization which is developed for a vessel environment in case of clear scene and low visibility scene with the use of AR and VR technologies, respectively.
CONSTRUCTION MANAGEMENT

Figure 1. Content for display on HMD in case of visible scene and low visible scene, respectively

COMPUTER-AIDED VISUALIZATION SYSTEM

Generally, the visualization system should generate the real-time visualization corresponding to the information obtained from the rescuer.

First of all, a framework as showed in Figure 2 is developed to depict a comprehensive picture of the visualization system including system main features and operation.

Figure 2. Visualization system framework

Framework specifications are as follows:

Input

Input is the data needed by the visualization system in order to generate the proper graphics to achieve the rescue task. There are two types of input data: real-time data and pre-defined data. Real-time data are current position of rescuer, rescuer’s head orientation, current environment condition. Real-time positioning is obtained by a position tracker and real-time orientation detection is obtained by an orientation tracker. Pre-defined data are floor plans and 3D model of the environment. Real-time data are obtained successively during system operation. The pre-defined data should be created in advance by using CAD software such as AutoCAD.

Route determination

Route determination deals with generating possible escape routes from the current position of the rescuer. Therefore, rescuer could easily find out the way to the exit door by following one of the provided routes.

YAH map generation

YAH map and its components are generated based on the input data and generated routes. Specifically, the possible escape routes, current position are visualized and integrated with floor plan to become a specific YAH map at this moment. Map’s orientation is rotated based on the rescuer’s head orientation.

Environment selection

Environment selection depends on the current environment visibility. Depending on either clear scene or low visibility scene, real scene (AR mode) or 3D virtual scene (VR mode) is selected to involve in the visualization, respectively.

Integration

After all components of the visualization are generated, they must be integrated to become a complete visual representation as showed in Figure. Specifically, the YAH map with its sufficient components will superimpose on the selected scene.

Rendering

This is the final process of giving appearance to the visualization. Roughly, this process would combine geometry, light, viewpoint, texture, lighting, shading information and other effects to produce a visible graphic output. This visualization system uses real-time rendering to provide the real-time visualization to the rescuer.

Output visualization

This is the final result of the framework which displays on HMD.
Framework operation

Input data are retrieved from corresponding devices and sources. The position information is used to determine the possible escape routes. Then these routes associate with orientation data and the specific floor plan to generate the YAH map. The next step is to determine which scene should be used to assist the rescuer to recognize his way easily in accordance with the current environment visibility. If the environment is covered with visual noise then the 3D virtual scene would be selected, otherwise the real scene is used instead. The following procedure is to integrate YAH map and the selected scene together in appropriate place. Lastly, the visualization is given appearance via rendering process and could be displayed on rescuer’s HMD.

RESULTS

Based on the general framework, a practical application of visualization system is developed and demonstrated in level B4 of block N1 in Nanyang Technical University. The application is developed by using Java3D and J2SE programming language associated with the use AutoCAD application to create pre-defined input data. Figure 3 shows the devices for the visualization system. They are Ekahau positioning engine, Inertial Cube2 orientation tracker, a small laptop, a webcam and an HMD. Ekahau position engine is actually a software product which is installed to the laptop and it detects the user’s position via wireless signal. Webcam is used to record real scene video for AR mode.

The visual representations which are generated by this visualization system in VR mode are shown in Figure 4.

Figure 5 illustrates the generated visualization in AR mode.

CONCLUSIONS

Through computer-aided visualization approach, this research has a significant impact to provide an effective method for way-finding in emergency. By following the visual representation displayed on HMD, the rescuer could easily find a way out in a short time.

The visualization system will automatically generate and provide real-time visualization support to the rescuer through HMD. Hence the rescuer could feel free to use the system with ease. Moreover, the visualization content is investigated based on human-centric factor, which concentrates on easy-to-perceive aspect. Therefore, the rescuers could quickly perceive and grab the provided information on HMD.

By using the general framework, specific visualization system could be developed based on specific environment input. Therefore, the framework could be utilized for every indoor environment.

REFERENCES

INTRODUCTION

Self-compacting concrete (SCC), a recent innovation in concrete technology, has numerous advantages over conventional concrete. Self-compacting concrete, as the name indicates, is a type of concrete that does not require external or internal compaction, because it becomes leveled and compacted under its self-weight. SCC can spread and fill every corner of the formwork, purely by means of its self-weight, thus eliminating the need of vibration or any type of compacting effort. Self-compacting concrete was originally developed at the University of Tokyo, Japan, in collaboration with leading concrete contractors in the late 1980s [1].

The notion behind developing SCC was the concerns regarding the homogeneity and compaction of conventional cast-in-place concrete within heavily-reinforced concrete structures and to improve the overall strength, durability, and quality of concrete. The SCC is highly flowable and cohesive enough to be handled without segregation. Generally, SCC production needs a high volume of very fine materials in order to make the concrete more flowable and cohesive. For this purpose, fly ash was used as mineral admixtures, in order to ensure adequate rheological properties of the SCC in the absence of any viscosity modifying admixtures. Waste materials such as ground waste glass and construction fines, were used by completely or partially substituting natural sand as fine aggregate. The fresh concrete properties were evaluated through the slump flow, the V-funnel and the box test. Compressive strength and splitting tensile strength of SCC were also determined.

The aim of this work is to investigate the possibility to develop SCC by incorporating waste materials as fine aggregate and binder.

EXPERIMENTAL PROGRAM

In this study, SCC mixes were prepared with Ordinary Portland cement (OPC) and Class F fly ash, with a specific gravity of 3.15 and 1.95 respectively. The average particle size of fly ash is smaller than OPC as shown in Figure 1. Crushed coarse aggregate (5 – 10 mm), sand with a fineness modulus of 3.24, ground waste glass with a fineness modulus of 1.82 and construction fines with a fineness modulus of 1.74 were used. The specific gravity of the coarse aggregate, sand, ground waste glass and construction fines are 2.62, 2.58, 2.32 and 1.18. The superplasticizer (SP) used was a polycarboxylate type with a specific gravity of 1.06.

In order to obtain SCC, twenty two mixtures were prepared employing, alternatively, ground waste glass (G) and construction fines (CF) in partial or fully substitution of sand (S). Reference mixtures (S100), with natural sand, were also prepared. Table 1 shows mixture proportions for all the concrete specimens. The percentage cement replacement by fly ash was kept constant at 30% by weight. The volume fraction of coarse aggregate was also kept constant at 27% of the total volume of concrete. It is slightly lower than the value recommended by Japanese Society of Civil Engineers (JSCE) which is between 28% and 30%. Initially, the volume ratio of fine aggregate to mortar \((V_{FA}/V_{M})\) was kept at 0.42. However, slightly segregation was detected. Therefore, it was increased to 0.48 and kept constant at that value so that the mixture is more cohesive. The unit absolute volume of binder (OPC + fly ash) is between 0.17 and 0.19. It follows the value recommended by JSCE which is in the range of 0.16 to 0.19. The water/binder weight ratio \((W/W_B)\) and the superplasticizer/binder weight ratio \((W_{SP}/W_B)\) were varied until flowable and cohesive concrete mixture was obtained.

In order to prepare all the concrete mixtures, the pan concrete mixer was used. After mixing, the fresh concrete was employed for the determination of slump flow to measure the flowability. Time to 500 mm flow \(T_{500}\) and V-funnel time were determined to measure the speed of flow and hence the viscosity and the box test was also done to measure the passing ability of the concrete mixture. Beside these tests, the visual inspection was employed to detect any bleeding and segregation problems. Slump flow, \(T_{500}\) flow through V-funnel time and box test were performed by following JSCE recommendation [2]. Shapes and dimensions of apparatus for slump flow and \(T_{500}\) measurement, V-funnel test, and box test are shown in Figures 2, 3, and 4 respectively. The acceptance criteria for SCC according to JSCE recommendation is presented in Table 2. From the test results, the concrete mixture which is cohesive and flowable or meets the acceptance
Table 1. Concrete Mixture Proportion

<table>
<thead>
<tr>
<th>Mix Code</th>
<th>Composition</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$V_{FA}/V_M$</td>
</tr>
<tr>
<td>S100(1)</td>
<td>0.42</td>
</tr>
<tr>
<td>S100(2)</td>
<td>0.42</td>
</tr>
<tr>
<td>S100(3)</td>
<td>0.48</td>
</tr>
<tr>
<td>CF50(1)</td>
<td>0.48</td>
</tr>
<tr>
<td>CF50(2)</td>
<td>0.48</td>
</tr>
<tr>
<td>CF50(3)</td>
<td>0.48</td>
</tr>
<tr>
<td>CF50(4)</td>
<td>0.48</td>
</tr>
<tr>
<td>CF75(1)</td>
<td>0.48</td>
</tr>
<tr>
<td>CF75(2)</td>
<td>0.48</td>
</tr>
<tr>
<td>CF75(3)</td>
<td>0.48</td>
</tr>
<tr>
<td>CF100(1)</td>
<td>0.48</td>
</tr>
<tr>
<td>CF100(2)</td>
<td>0.48</td>
</tr>
<tr>
<td>CF100(3)</td>
<td>0.48</td>
</tr>
<tr>
<td>G50(1)</td>
<td>0.48</td>
</tr>
<tr>
<td>G50(2)</td>
<td>0.48</td>
</tr>
<tr>
<td>G50(3)</td>
<td>0.48</td>
</tr>
<tr>
<td>G75(1)</td>
<td>0.48</td>
</tr>
<tr>
<td>G75(2)</td>
<td>0.48</td>
</tr>
<tr>
<td>G75(3)</td>
<td>0.48</td>
</tr>
<tr>
<td>G100(1)</td>
<td>0.48</td>
</tr>
<tr>
<td>G100(2)</td>
<td>0.48</td>
</tr>
<tr>
<td>G100(3)</td>
<td>0.48</td>
</tr>
</tbody>
</table>

criteria for SCC is selected. The air content of fresh concrete from selected mixtures was measured and the selected concrete mixtures were cast. The specimens were cured in water. The compressive strength and splitting tensile strength at 14 days were determined by testing three 150 mm cubes and 150 mm x 300 mm cylinders for each mixture respectively.
CONSTRUCTION TECHNOLOGIES

RESULTS AND DISCUSSION

The workability test results of various concrete mixtures are presented in Table 3. For the reference mixtures (100% natural sand), it was found that by increasing the volume ratio of fine aggregate to mortar \( \left( \frac{V_{FA}}{V_M} \right) \) from 0.42 to 0.48, the slight segregation can be eliminated and hence the concrete mixture is more cohesive. From the workability test results, the concrete mixtures which are cohesive and flowable are selected. They are S100(3), CF50(4), CF75(3), CF100(3), G50(2), G75(3), and G100(3). The V-funnel time of some of these mixtures are lower than 8 seconds (the minimum value according to JSCE recommendation). However, no bleeding and segregation have been detected. Therefore, these mixtures can be considered as SCC which is high flowable and cohesive. From these selected mixtures, some phenomena can be observed. When natural sand is replaced partially or fully by construction fines, higher water/binder ratio or/and higher superplasticizer content are required to obtain the SCC. When the percentage of replacement is higher, it requires higher water/binder ratio or/and higher superplasticizer content. It is due to the smaller particle size of construction fines compared to natural sand. Although, it increases the cohesiveness of concrete mixture, the smaller particle size reduces its consistency. The same phenomena, but in lesser extent, can be seen when ground waste glass was used to replace natural sand partially or fully. The particle size of ground waste glass is similar to construction fines. But ground waste glass has a smooth surface and absorbed less water compared to construction fines. Therefore, the SCC made of ground waste glass requires less water content or/and less superplasticizer compared to those made of construction fines.

Table 2. Acceptance Criteria for SCC

<table>
<thead>
<tr>
<th>Method</th>
<th>Typical Range Of Values</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Minimum</td>
</tr>
<tr>
<td>Slump Flow (mm)</td>
<td>650</td>
</tr>
<tr>
<td>( T_{50} ) (sec.)</td>
<td>2</td>
</tr>
<tr>
<td>V-funnel (sec.)</td>
<td>8</td>
</tr>
<tr>
<td>Box Test, ( H_2-H_1 ), mm</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 3. Workability Test Results

<table>
<thead>
<tr>
<th>Mix Code</th>
<th>Slump Flow (mm)</th>
<th>( T_{50} ) (sec.)</th>
<th>V Type Funnel (sec.)</th>
<th>Box Test, ( H_1-H_2 ), mm</th>
<th>Segregation</th>
</tr>
</thead>
<tbody>
<tr>
<td>S100(1)</td>
<td>700</td>
<td>2.1</td>
<td>11.5</td>
<td>200</td>
<td>Slight</td>
</tr>
<tr>
<td>S100(2)</td>
<td>760</td>
<td>2.0</td>
<td>9.5</td>
<td>280</td>
<td>Slight</td>
</tr>
<tr>
<td>S100(3)</td>
<td>660</td>
<td>2.4</td>
<td>5.7</td>
<td>60</td>
<td>None</td>
</tr>
<tr>
<td>CF50(1)</td>
<td>560</td>
<td>4.7</td>
<td>12.1</td>
<td>30</td>
<td>None</td>
</tr>
<tr>
<td>CF50(2)</td>
<td>570</td>
<td>3.9</td>
<td>11.7</td>
<td>20</td>
<td>None</td>
</tr>
<tr>
<td>CF50(3)</td>
<td>590</td>
<td>4.4</td>
<td>11.2</td>
<td>20</td>
<td>None</td>
</tr>
<tr>
<td>CF50(4)</td>
<td>650</td>
<td>2.4</td>
<td>9.5</td>
<td>15</td>
<td>None</td>
</tr>
<tr>
<td>CF75(1)</td>
<td>580</td>
<td>3.9</td>
<td>7.2</td>
<td>30</td>
<td>None</td>
</tr>
<tr>
<td>CF75(2)</td>
<td>610</td>
<td>3.5</td>
<td>6.7</td>
<td>20</td>
<td>None</td>
</tr>
<tr>
<td>CF75(3)</td>
<td>650</td>
<td>2.3</td>
<td>5.2</td>
<td>10</td>
<td>None</td>
</tr>
<tr>
<td>F100(1)</td>
<td>550</td>
<td>6.9</td>
<td>9.2</td>
<td>60</td>
<td>None</td>
</tr>
<tr>
<td>F100(2)</td>
<td>580</td>
<td>4.6</td>
<td>5.2</td>
<td>35</td>
<td>None</td>
</tr>
<tr>
<td>F100(3)</td>
<td>675</td>
<td>2.3</td>
<td>4.5</td>
<td>30</td>
<td>None</td>
</tr>
<tr>
<td>G50(1)</td>
<td>730</td>
<td>1.6</td>
<td>3.6</td>
<td>5</td>
<td>None</td>
</tr>
<tr>
<td>G50(2)</td>
<td>710</td>
<td>4.6</td>
<td>8.2</td>
<td>10</td>
<td>None</td>
</tr>
</tbody>
</table>
The air content of fresh concrete, compressive strength and splitting tensile strength at 14 days of selected SCC are presented in Table 4. The air content ranges from 5.2% to 6.5%. It is suitable for concrete requiring moderate resistance to frost damage. The compressive strength of SCC made of 100% construction fines is the lowest. It is about 34% of the reference SCC (100% natural sand). The reason is that SCC made of 100% construction fines requires the highest water/cement ratio (0.45). Moreover, construction fines used in this experimental work was only sieved. It has not been washed so that the contaminant has not been removed. The presence of contaminant may reduce the compressive strength. The reduction of compressive strength of SCC made of 100% ground waste glass is less significant. The compressive strength of SCC made of 100% ground waste glass is about 74% of the reference SCC (100% natural sand). The water/cement ratio used for SCC made of 100% ground waste glass is 0.4 which is higher than reference SCC (0.36) and lower than SCC made of 100% construction fines (0.45). The reduction of compressive strength of SCC made of waste material (construction fines or ground waste glass) is less when the percentage replacement of natural sand is decreased. The similar phenomenon can also be seen in splitting tensile strength (as shown in Table 4).

### Table 4. Air Content and Strength Test Results

<table>
<thead>
<tr>
<th>Mix Code</th>
<th>Fresh Concrete</th>
<th>Hardened Concrete At 14 Days</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Air Content (%)</td>
<td>Compressive Strength (MPa)</td>
</tr>
<tr>
<td>S100(3)</td>
<td>5.2</td>
<td>72.33</td>
</tr>
<tr>
<td>CF50(4)</td>
<td>6.2</td>
<td>42.13</td>
</tr>
<tr>
<td>CF100(3)</td>
<td>6.5</td>
<td>24.93</td>
</tr>
<tr>
<td>G50(2)</td>
<td>5.5</td>
<td>61.84</td>
</tr>
<tr>
<td>G100(3)</td>
<td>5.8</td>
<td>53.29</td>
</tr>
</tbody>
</table>

### CONCLUSIONS

Based on the experimental work, it is shown that construction fines and ground waste glass together with Class F fly ash have a high potential for utilization in the manufacturing of SCC. The fine particle of construction fines and ground waste glass improves the cohesiveness of concrete mixtures. However, it increases the required water/cement ratio and/or superplasticizer content to achieve high consistency. Therefore, the strength of SCC made of construction fines or ground waste glass is lower than reference SCC. The reduction of strength is more severe in the case of construction fines. It is due to the higher required water/cement ratio and the presence of contaminant. In order to minimize the reduction of compressive strength, the construction fines or waste glass can be blended with natural sand and construction fines should be washed to remove the contaminant.

### REFERENCES

CONSTRUCTION TECHNOLOGIES

NUMERICAL STUDY OF MOISTURE GRADIENT IN DRYING OF CONCRETE

Sabet Divsholi Bahador (Sabe0001@ntu.edu.sg)
Jong Herman Cahyadi (CHCJong@ntu.edu.sg)

INTRODUCTION

The moisture movement has decisive effects on most of the deterioration process in concrete such as chloride penetration, carbonation, corrosion, leaching, and sulfate attack. Therefore, it may affect the performance of concrete [1]. The water diffusion is due to the moisture gradient within concrete and water evaporation from surface. The drying of concrete is the function of the saturation degree and the pore structure of the concrete. Pore structure of the concrete is affected by cementitious composition, w/c ratio, a/c ratio and curing period.

Despite the numerous works have been done on the subject, few works try to study the effect of various parameters on drying rate of concrete. In this study over 300 samples has been cast and monitored for over one year in various drying conditions. And a numerical model to predict the moisture gradient of concrete with various mix proportion and ambient conditions has been proposed.

NUMERICAL MODELING

Generally, concrete after curing is totally saturated. When concrete is subjected to drying, water in concrete is considered to move through the system of interconnecting capillary pores according to the gradient of vapor pressure which is regarded to vary linearly with saturation degree in the pores of concrete [2]. The saturation degree, $S$, is defined as the percentage of the amount of evaporable water in concrete at the particular time to the amount of evaporable water in saturated concrete ($w_{ev}$).

$$S_{(x,t)} = \frac{w_{ev} - \text{water loss}}{w_{ev}}$$

In which $w_{ev}$, the evaporable water in saturated concrete is equal to the total mixing water minus the water used for hydration of cementitious materials in duration of curing. As it has been mentioned above, concrete after curing is totally saturated. Therefore at time $t=0$, Saturation degree will be equal to 1 through the thickness of the sample. After long period of drying in constant ambient relative humidity, the saturation degree will reach to its stabilized level, $S_f$, and will be uniform through the thickness of the sample. The final saturation degree depends on pore structure of concrete. The relation of final saturation degree with ambient relative humidity for different w/c and a/c has been studied experimentally by some of the researchers [3], [4].

The total gradient of moisture for each element is the difference between the initial saturation degree $S_{(x,t=0)} = 1$ and final saturation degree $S_{(x,t=\infty)} = S_f$. Therefore the saturation degree at the time $t$ and distance $x$ from surface can be written as follow

$$S_{(x,t)} = S_f + (1 - S_f)D_{(x,t)}$$

In which $D_{(x,t)}$ is the function of pore structure of concrete. The boundary conditions to calculate the $D_{(x,t)}$ are as follow

- $0 \leq D_{(x,t)} \leq 1$
- $At \ t = 0 \Rightarrow S_{(x,t)} = S_f$ Then $D_{(x,t=0)} = 1$
- $At \ t = \infty \Rightarrow S_{(x,t)} = S_f$ Then $D_{(x,t=\infty)} = 0$
- $For \ x > 0 \Rightarrow D_{(x,t)} \approx bx^n (b \ and \ m \ are \ constant \ tan \ t)$

The only equation which will satisfy these boundary conditions is as follows

$$D_{(x,t)} = \frac{1}{1 + \frac{t^n}{b x^n}}$$

In which the $n$, $m$, $b$ are the constant related to pore structure of the concrete. Parrott [5] described the effective parameters on drying rate as function of w/c ratio, percentage of blended replacement, time and distance from drying surface. As it has been shown in equation (1), one of the main parameters in calculation of the $S_{(x,t)}$ is the amount of evaporable water in saturated concrete which can be calculated as follow

$$w_{ev} = \text{mixing water} - F \times w_{min}$$

In which $F$ is the hydration degree of concrete and $w_{min}$ is the minimum water needed for fully hydration of concrete. The hydration degree of concrete has been studied by many researchers. Based on Papadakis model [4], the following model for hydration of cement compounds has been proposed.

$$F_t = \alpha_{RH} \left(1 - (1 - K_n t)^{\frac{1}{1 - n}} \right) \left(t(1 - n_t)\right)^{\frac{1}{1 - n_t}}$$

In which $t$ is the curing time (days), RH is the curing relative humidity, $T$ is absolute curing temperature (°K). $R=8.314 J mol^{-1} K^{-1}$ is the universal gas constant and the activation energy $E_a = 38.2 KJ mol^{-1}$. The coefficients ($K_n$ and $n$) for each compound are presented in Table 1.
The parameter related to curing relative humidity ($\alpha_{RH}$) is proposed as follows [6].

\[ \alpha_{RH} = \left[ \frac{RH - 0.55}{0.45} \right]^4 \quad \text{for } RH > 0.55 \]  
\[ \alpha_{RH} = 0 \quad \text{for } RH \leq 0.55 \]  

As reported by many researchers the minimum water needed for fully hydration of concrete is around $w_{min} = 0.23$ [7].

In order to calculate the drying rate constant in equation (3), knowing the effect of affecting parameters on pore structure of concrete is necessary. The w/c ratio has reverse effect on pore structure of concrete. Higher w/c ratio leads to increase in total porosity and pore connectivity. Longer curing period results in denser pore structure of concrete. The effect of mineral admixture is related to percentage of replacement, type and quality of mineral admixture. Generally, replacing the Portland cement partially with mineral admixture will result in lower pore connectivity and denser pore structure. However low quality mineral admixture with insufficient curing period may results in higher pore connectivity. From the experimental work, it was found that the mineral admixture replacement mainly affects the final saturation degree. The activity of mineral admixtures has direct relation with glass phase content. The X-ray diffraction method is used by most of the researchers to measure mineral characteristic of mineral admixtures. The result of the X-ray diffraction method can show the percentage of crystalline phase. Therefore mineral admixtures will have the glass phase content as follows

\[ G_p = (1 - \text{crystalline phase content}) \]  

By using the authors experimental data and Parrott [4] and Papadakis [5] data, the final saturation degree of PC concrete as function of w/c ratio and ambient RH can be described as follows

\[ S_f = 1 - \frac{\frac{w-1}{c}}{1.4[{(\frac{1}{RH})}^{0.3}]} \]  

And in blended cement concrete the final saturation degree will be as follow

\[ S_f = (G_p^{0.3} \left(1 + \frac{1}{\sqrt{75d_n}}\right)^{10p} \left(1 - \frac{\frac{w-1}{c}}{1.4[{(\frac{1}{RH})}^{0.3}]}\right) \]  

In which $d_n$ is the average particle size of mineral admixture and $p$ is the ratio of replacement of PC with mineral admixture.

In equation (3), for normal environment temperature $n=1$ and based on authors experimental data and Parrott equation [5], $b = 0.7F(1-1.3w/c)$ and $m=1.8$. In which F is the hydration degree of concrete calculated above. In one dimensional drying with the maximum distance from drying surface equal to $d$, the total water content of concrete at time $t$ can be calculated as follows

\[ W_t = 2l \int_0^l S_f(x,t) \, dx \]  

In which $W_t$ is the total water content at time $t$ and $l$ is the thickness of the sample. Reduction in saturation degree by time for different w/c ratio and curing period in comparison to simulation result by using the equations (4) has been presented in Figure 1.
CONSTRUCTION TECHNOLOGIES

Figure 3. Effect of curing period

The effect of w/c on distribution of saturation degree is shown in Figure 4. The higher w/c ratio results in faster drying rate. And for lower w/c ratio, due to the denser pore structure, higher saturation degree is expected.

Figure 4. Effect of w/c ratio

As mentioned before, the effect of blended cement concrete on saturation degree of concrete depends on its quality and the percentage of replacement. Figure 5 shows the distribution of saturation degree for the blended cements of author’s experimental work in comparison with PC concrete. The low calcium fly ash (LFA) used in the experiment had low quality and the rate of drying was even faster than normal PC.

Figure 5. Effect of various mineral admixtures

CONCLUSIONS

The moisture gradient through the concrete is affected by saturation degree and pore structure of the concrete. The lower w/c ratio, longer curing period and replacement of good quality mineral admixture will result in denser pore structure and slower rate of drying. In this work new model for distribution of moisture through the concrete with considering many effecting parameters has been proposed.

REFERENCES

REMOVAL OF ENDOCRINE DISRUPTING CONTAMINANTS USING MOLECULARLY IMPRINTED POLYMERS

Benoit Guieysse (bjguiyeysse@ntu.edu.sg)

INTRODUCTION

One of today’s most alarming environmental and human health threats is caused by the increasing occurrence of water contaminants that can be toxic at trace concentration due to the repeated exposure of target populations and the cumulated effects from the many substances simultaneously found. As a typical example, endocrine-disrupting contaminants (EDCs) can cause the feminization of male fish populations in contaminated streams and are even suspected to impair human fertility [1-4]. Water treatment methods capable bringing these contaminant concentrations down to extremely low levels are therefore crucially needed.

The presence of trace contaminants in wastewater effluents and water resources shows conventional water treatment processes are inefficient at removing these substances [5]. For instance, activated carbon adsorption is only efficient for hydrophobic contaminants and considerably limited by the presence of interfering substances such as humic acid [6-8]. Biological treatment at trace concentrations is poorly understood and difficult because microorganisms preferentially metabolize other substances present at higher concentrations [9-10]. Ozonation and advanced oxidation processes are efficient at removing many contaminants but are also limited by the competitive removal of interfering organic matter [6, 11]. Finally, the efficiency of microfiltration and ultrafiltration is limited to hydrophobic pollutants adsorbed to particles whereas nanofiltration and reverse osmosis, which are efficient for most compounds, remains highly energy demanding [12]. Hence, the lack of specificity of current methods considerably reduces their efficiency at trace concentration because most of

Figure 1. A target molecule, for instance an endocrine disrupter, is introduced during the polymerization process of appropriate monomers. These polymerize to form a polymer cage. The print molecule can then be dissociated from the polymer imprint. In the presence of the MIP, the target pollutant is selectively adsorbed without poisoning by interfering molecules. The MIP is then regenerated by solvent elution of the pollutant that is subsequently destroyed.
the adsorption, biodegradation, or oxidation capacity is wasted in the removal of harmless compounds. With this perspective, this project aims to develop a novel highly-efficient method based on selective extraction of the contaminants using artificial molecular receptors, followed by their destruction in bioreactors [13-16].

Molecularly Imprinted Polymers (MIPs) are synthesized by guided polymerization of functional monomers around a target molecule (the template), which leaves a specific recognition site after removal of the template (Figure 1). By using an endocrine disrupter as the template, the adsorbing material synthesized becomes a synthetic analogue to the natural receptors that can remove any molecule having the capacity to bind natural receptors (i.e. any potential endocrine disrupter). For the first time in water treatment, removal is ingeniously based on the same property that makes the pollutants so harmful: their capacity to bind to natural receptors. This is extremely advantageous as it will be impossible to identify, determine the environmental fate and understand the effects of all anthropogenic molecules (and their metabolites) entering the environment. There are today 500 known biochemical receptors at which drugs are targeted and this number is expected to increase up to 20-fold in the near future. New methods that can remove any potentially toxic substance are therefore urgently needed. As an additional outcome, the material developed will also be suitable as highly-efficient selective adsorbents for analytical purposes.

**MATERIALS AND METHODS**

**MIPS synthesis**

MIPs synthesis normally requires a template (i.e. the target contaminant), a monomer, a cross-linker, a solvent (also called porogen) and an initiator. The type and amount of each compound must be optimized in view of the desired selectivity, stability, reproducibility, and cost-efficiency. Table 1 lists

<table>
<thead>
<tr>
<th>Monomer</th>
<th>Crosslinker</th>
<th>Solvent</th>
<th>Molecular Ratio (T:M:C)</th>
<th>Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>4-VP</td>
<td>EDMA</td>
<td>Acetonitrile</td>
<td>1: 4.05: 25.06</td>
<td>65°C, 24h</td>
</tr>
<tr>
<td>MAA</td>
<td>DVB</td>
<td>Toluene:acetonitrile (1:3 v:v)</td>
<td>1: 8: 40</td>
<td>70°C, 24h</td>
</tr>
<tr>
<td>MAA</td>
<td>EDMA</td>
<td>Acetonitrile</td>
<td>1: 8: 6.7</td>
<td>60°C, 24h</td>
</tr>
<tr>
<td>MAA</td>
<td>DVB</td>
<td>Acetone</td>
<td>1: 8: 40</td>
<td>60°C, 24h</td>
</tr>
<tr>
<td>MAA</td>
<td>DVB</td>
<td>Toluene:acetonitrile (1:3 v:v)</td>
<td>1: 8: 40</td>
<td>70°C, 24h</td>
</tr>
<tr>
<td>MAA</td>
<td>EDMA</td>
<td>Acetonitrile</td>
<td>1: 8: 6.7</td>
<td>60°C, 24h</td>
</tr>
<tr>
<td>TFMAA</td>
<td>TRIM</td>
<td>Acetonitrile</td>
<td>1: 8: 8</td>
<td>60°C, 24h</td>
</tr>
<tr>
<td>TFMAA</td>
<td>TRIM</td>
<td>Acetonitrile</td>
<td>1: 8: 8</td>
<td>UV&lt;sub&gt;365&lt;/sub&gt;, 3 h + 60°C, 24h</td>
</tr>
<tr>
<td>TFMAA</td>
<td>TRIM</td>
<td>Acetonitrile</td>
<td>1: 8: 8</td>
<td>UV&lt;sub&gt;365&lt;/sub&gt;, 48h</td>
</tr>
<tr>
<td>TFMAA</td>
<td>TRIM</td>
<td>Acetonitrile</td>
<td>1: 4: 4</td>
<td>UV&lt;sub&gt;365&lt;/sub&gt;, 48h</td>
</tr>
<tr>
<td>MMA</td>
<td>TRIM</td>
<td>Chloroform</td>
<td>1: 8: 8</td>
<td>UV&lt;sub&gt;365&lt;/sub&gt;, 2h, 60°C, 24h</td>
</tr>
<tr>
<td>MMA</td>
<td>TRIM</td>
<td>Acetonitrile</td>
<td>1: 8: 8</td>
<td>UV&lt;sub&gt;365&lt;/sub&gt;, 48h</td>
</tr>
<tr>
<td>MAA</td>
<td>EDMA</td>
<td>Acetonitrile</td>
<td>2: 12: 60</td>
<td>60°C, 16h</td>
</tr>
<tr>
<td>MAA</td>
<td>TRIM</td>
<td>Acetonitrile</td>
<td>1: 1: 5</td>
<td>UV&lt;sub&gt;366&lt;/sub&gt;</td>
</tr>
<tr>
<td>MAA</td>
<td>EDMA</td>
<td>Acetonitrile</td>
<td>1: 4.7: 2.0</td>
<td>UV&lt;sub&gt;350&lt;/sub&gt;</td>
</tr>
<tr>
<td>MAA</td>
<td>EDMA</td>
<td>Acetonitrile</td>
<td>1:8:25</td>
<td>43°C, 20h</td>
</tr>
<tr>
<td>MAA</td>
<td>acetonitrile</td>
<td>1:30:150</td>
<td>4°C, 2h, UV&lt;sub&gt;365&lt;/sub&gt;</td>
<td></td>
</tr>
</tbody>
</table>

MAA = methacrylic acid; TFMAA = 2-(trifluoromethyl) acrylic acid; MMA = methacrylic acid methyl ester; 4-VP = 4-vinylpyridine; DVB = divinylbenzene; TRIM = trimethylolpropane trimethacrylate; EDMA = ethylene glycol dimethacrylate.
examples of mixtures and polymerization conditions that have been used for estradiol imprinting. In this study, a MIP was synthesized by dissolving estradiol (E2, 272.4 mg) as template, methacrylic acid (MAA, 0.68 ml) as monomer, and ethylene glycol dimethacrylate (EDMA, 4.7 ml) as crosslinker in 8 ml of acetonitrile. The solution was sonicated for 5 min and purged with nitrogen for 5 min. The tube was then sealed and the mixture heated at 70°C for 20 h. The resulting polymer monolith was recovered, ground in a mortar, sieved (25-145 μm) and washed four times with methanol. The particles of polymers in methanol were kept under the fume hood until complete evaporation of the methanol. The particles were transferred into a Soxhlet extractor for continuous washing with methanol and kept overnight. The washed polymer was finally dried at room temperature. Non-imprinted polymers (NIPs) were synthesized simultaneously under the same conditions but without adding the template. Another MIP was synthesized according to the same protocol but using 40 ml of an acetonitrile mixture as solvent. This resulted in the polymerization of micro-particles which were recovered by centrifugation and washed as described above. All polymers were characterized by SEM, BET and particle size analysis.

**Mip testing**

Six-millilitre glass Solid Phase Extraction (SPE) columns (Supelco) were packed with 100 mg of MIPs or NIPs. The packed columns were washed with 100 ml of methanol:acetic acid (4:1 v/v). Two liters of 5 μg/l E2 aqueous solution were then percolated through each column using a vacuum manifold (Supelco VisiprepSM SPE) and the columns were eluted three times with 4 ml of methanol:acetic acid (4:1 v/v). The concentration of E2 in each extract was determined by HPLC.

**RESULTS AND DISCUSSION**

MIPs for detection of drugs or hazardous metabolites are currently commercially produced, and the principle of MIP recognition for the detection of environmental pollutants has already been demonstrated. Our preliminary results [13-15] have shown that a MIP synthesized for estradiol removal as model contaminants allowed the complete recovery of this compound from aqueous solutions prepared at 2 ppb. By comparison, other reference materials used as controls (non-imprinted polymers, activated carbon, silica-based adsorbent) were less efficient (<80%) especially when interfering organic compounds were present in the system. Finally, we have also shown that only the MIP was capable of removing the endocrine disrupting activity (caused by undetected compounds) from a real waste water sample [14]. These results have shown 1) the higher efficiency of the imprinted material, 2) its higher selectivity, and 3) its capacity to remove endocrine activity without prior knowledge of the compounds involved.

The MIPs synthesized in this study are still under evaluation. However, preliminary data confirm the selective removal of E2 by the MIPs as compared to the NIPs. SEM and particle size analysis showed that the polymer synthesized by precipitation polymerization has an average size of 1-2 μm. This small size, as compared to the polymer particles obtained from the monoliths, should improve adsorption capacity and template recovery but might cause clogging problems under real case applications. This is currently under investigation.

**Acknowledgments**

This project is supported by NTU Start Up Grant (SUG) 39/06.

**REFERENCES**


INTRODUCTION

Reverse osmosis and nanofiltration membranes are increasingly used in water treatment and wastewater reclamation. Many commercial RO and NF membranes are thin film composite (TFC) polyamide (PA) membranes formed by an interfacial polymerization process [1]. A typical TFC polyamide membrane comprises a dense polyamide thin layer of ~100 nanometers thick on top of a microporous polysulfone (PS) support (Figure 1). The performance of composite reverse osmosis (RO) and nanofiltration (NF) membranes is determined by the ultra-thin dense rejection layer [1-3]. Characterization of this critical layer becomes a high priority research area, driven by the increasing popularity of membrane water purification. Membrane characterization is essential to understand the structure of the layer and its interaction with molecular species of interest (e.g., trace organics and foulants). This is also the basis for subsequent optimization to achieve superb fouling resistance and rejection efficiency.

Characterization of TFC membranes is complicated due to their multilayered structures (Figure 1) and the highly non-homogenous nature of the polyamide rejection layer [1]. Many commercial RO and NF membranes are produced based on proprietary recipes whose exact chemistry and processes are not disclosed, which greatly limits membrane end users’ understanding of their transport and fouling behaviors. For example, the application of a thin surface coating layer (several tens of nanometers) on some commercial membranes can drastically change many properties at once, such as increased hydrophilicity, reduced surface roughness, and reduced charge density [3, 4]. Identification of such a coating layer is almost impossible without a comprehensive suite of characterization tools. In many cases, characterization tools spanning multiple length scales from sub-nanometer (molecular scale) to a few hundred micrometers are needed for positive identification.

The purpose of this study was to identify coating layers for some commercial RO and NF membranes and to investigate the effect of coating layer on membrane properties. The differences between coated and uncoated commercial membranes are discussed, and the implications in membrane fouling are emphasized.
EXPERIMENTAL

Materials

Three brackish water RO membranes (ESPA3, LFC1, and BW30) and one NF membrane (NF90) were evaluated in the current study. BW30 and NF90 were provided by Dow FilmTec© (Minneapolis, MN), and ESPA3 and LFC1 were obtained from Hydranautics/Nitto Denko© (Oceanside, CA). All chemicals were of analytical grade, and MilliQ water had a resistivity of 18.2 Mohm-cm.

Membrane Characterization

Membrane samples were characterized by X-ray photoelectron spectroscopy (XPS), attenuated-total-reflection Fourier-transform-infrared spectroscopy (ATR-FTIR), and contact angle and streaming potential measurements. Full details on the measurement procedures have been previously reported by Tang and coworkers [2-6].

Atomic force microscopy for adhesion force measurement

Atomic force microscopy (AFM) was used to perform the adhesion force measurement. AFM force measurement is commonly employed to examine the interaction between particles and a substrate at nanometer scales, and such information is very useful for studying membrane fouling [7]. A greater adhesion force between the foulant surrogate (the functionalized colloidal tip) and the membrane surface indicates a greater fouling tendency [7].

The colloidal cantilever used in this study was surface-functionalized with carboxylic groups (-COO−) and had a spring constant of 0.12 N/m (Figure 2). The cantilever was mounted in an AFM and brought into contact with clean membrane surfaces by a piezoelectric motor. The cantilever was subsequently lifted and its deflection was monitored by a photosensitive diode. The adhesion force was determined as the production of the spring constant and the measured cantilever deflection.

RESULTS AND DISCUSSIONS

Figure 3 shows the XPS spectra for membranes BW30 and ESPA3. The spectrum for ESPA3 was typical for fully aromatic polyamide chemistry [3, 4]. On the other hand, membrane BW30 had significantly lower signal for nitrogen but much stronger signal for oxygen. The elemental composition of BW30, based on the XPS measurement, differed greatly from that expected for cross-linked polyamide [3, 4]. Interestingly, FTIR results show that the two membranes had nearly identical chemistry for the rejection layer [4]. This suggests that membrane BW30 was probably covered with an oxygen-rich coating layer, noting that the penetration depth of XPS is 1-5 nm while that for ATR-FTIR is several hundreds of nanometers. Further electron microscopy confirmed the presence of such a coating layer for BW30 [3], and additional analysis by XPS and FTIR shows that the coating layer was likely a neutral aliphatic polyalcohol with a carbon to oxygen ratio ~ 2 [3, 4]. A similar coating layer was also identified for membrane LFC1, but membranes ESPA3 and NF90 did not possess such a coating.

Membrane surface properties, such as hydrophilicity and surface charge density, are largely determined by the topmost atomic layers. Consequently, the application of a surface coating can greatly affect these properties. As shown in Figure 4, the coated BW30 had a much lower contact angle (26°) as compared to that of the uncoated ESPA3 (43°). Streaming potential analysis revealed that BW30 was not slightly charged at circumneutral pHs (zeta potential = -5.2 mV at pH 7) as compared to the negatively charged ESPA3 (zeta potential = -16.3 mV at pH 7) [8]. Such reduced surface charge and enhanced hydrophilicity were consistent with the
chemical nature of a neutral polyalcohol coating.

As a result of their enhanced hydrophilicity and lower surface charge density, the adhesion forces between the surrogate foulant (the carboxylated particle) and the membrane surfaces were reduced by two orders of magnitude for the coated membranes BW30 and LFC1 (Figure 5), indicating that these membrane were more fouling resistant than the uncoated ones. In contrast, ESPA3 and NF90 had much greater adhesion force, which suggests that a particle will likely stick tightly onto the membrane surfaces once they are in contact – an important promoting factor for significant fouling [7].

Conclusions

Multiscale characterization can provide insightful information on the physical and chemical nature of membranes and the resulting membrane properties and performances. In the current study, a neutral polyalcohol coating layer was identified for two commercial TFC PA membranes (BW30 and LFC1). These membranes had improved hydrophilicity and reduced charge density, which greatly enhanced their anti-fouling ability as suggested by AFM adhesion force measurement. Additional static adsorption, fouling, and trace organics rejection experiments are being performed to evaluate the effect of the coating on membrane fouling and rejection behaviors. Further research will focus on synthesizing and optimizing coatings for both reverse osmosis and nanofiltration membranes.

Figure 5. AFM adhesion force measurement for coated (BW30 and LFC1) and uncoated (ESPA3 and NF90) membranes

REFERENCES

INTRODUCTION

Excessive levels of oxyanions such as arsenate, borate, chromate, etc. have been found in the natural environment [1], irrigation drainage water [2] and industrial wastewater [3]. The majority of these oxyanions are harmful to both humans and wildlife. For example, exposure to chromium can cause diseases such as irritation of skin, respiratory tract, lung carcinoma and probably liver damage. These oxyanions have high solubilities and are usually mobile at the circumneutral to alkaline pH values typical of most hydrogeological environments. Thus, the development of an efficient method for removing these oxyanions is of great importance.

Recently, layered double hydroxides (LDHs) have attracted increasing interest for their potential use in water and wastewater treatment. LDHs are lamellar mixed hydroxides containing positively-charged main layers and the net positive charge is compensated by the anions in the interlayer region. The structure of LDH is shown in Figure 1. The most interesting properties of LDH include their large surface area, high anion exchange capacity and good thermal stability.

While some literature is available on the adsorption of oxyanions by LDHs [4, 5], little information is available on the adsorption of oxyanions by nano-scale LDH. The present study was intended to: (1) prepare nano-scale LDH by a simple method and characterize them with various analytical techniques; and (2) evaluate its oxyanions adsorption behavior and stability throughout the adsorption process.

MATERIALS AND METHODS

In this study, a simple but efficient method involving a fast coprecipitation followed by hydrothermal treatment has been used to prepare stable homogeneous nano-scale LDH for oxyanions removal. The commercial micro-scale LDH was purchased from a chemical company. Both LDHs were characterized by several physicochemical techniques, namely CHN, ASAP, XRD, PCS, FTIR, SEM, EDX, TEM, HRTEM, and SAED. The adsorption behaviors of oxyanions were examined using batch adsorption technique. The adsorption behaviors included adsorption isotherm study, time-dependent adsorption study, and pH-dependent adsorption study. The stability of the LDHs was also monitored during the adsorption process.

RESULTS AND DISCUSSION

The nitrogen adsorption-desorption experiments confirmed that both nano-scale and commercial LDHs were typical of mesoporous materials. Nano-scale LDH displayed higher surface area, larger pore volume, larger pore size and narrower particle size range than commercial LDH (Table 1). Nano-scale LDH has also a smaller crystallite size (<10 nm). Both the TEM and SEI images depicted that nano-scale LDH particles were well shaped in hexagonal form with a lateral size of 40-100 nm (Figures 2(a) and 2(b)).

Table 1. Characteristics of nano-scale LDH and commercial LDH

<table>
<thead>
<tr>
<th>Material</th>
<th>Surface Area (m²/g)</th>
<th>Pore Volume (cm³/g); Pore size (nm)</th>
<th>Particle Size Range (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nano-scale LDH</td>
<td>127</td>
<td>0.312; 8</td>
<td>38-396</td>
</tr>
<tr>
<td>Commercial LDH</td>
<td>56</td>
<td>0.038; 3</td>
<td>22-564</td>
</tr>
</tbody>
</table>

Figure 1. Schematic representation of the LDH structure

Figure 2. (a) TEM image of the nano-scale LDH and (b) SEI image of the nano-scale LDH
ENVIRONMENTAL

(Figure 3(a) demonstrates that nano-scale LDH exhibited remarkably higher oxyanions adsorption percentages than commercial LDH. Nano-scale LDH showed an oxyanion preference in the order of HV$_2$O$_7^{3−}$ > CrO$_4^{2−}$ > HAsO$_4^{2−}$ > MoO$_4^{2−}$ > B(OH)$_4^{−}$ (Figure 3(b)). The adsorption data of oxyanions on the nano-scale LDH showed a suitable fit to the Langmuir isotherm ($r^2$ > 0.97) except for borate. The maximum adsorption capacity of nano-scale LDH for the oxyanions ranged from 70 to 121 mg/g. The fast and slow reaction phases observed in the time-dependent adsorption study for nano-scale LDH indicated that two mechanisms were involved in the adsorption, namely adsorption on the external surface and anion exchange in the interlayer region. The pH effect on the oxyanions adsorption was found to be dependent on the types of oxyanions. The incorporation of oxyanions onto nano-scale LDH was confirmed by the FTIR analysis. From the material stability study, the percentage of the precursor metals released from nano-scale LDH was <3% throughout the adsorption process.

CONCLUSIONS

This study suggests that the low-cost and eco-friendly nano-scale LDH is a stable and effective adsorbent for oxyanions removal. The preference of nano-scale LDH for oxyanions is mainly dependent on the oxyanions electronegativity and geometry.

REFERENCES


REMOVAL OF ANTIBIOTICS BY GAC ADSORPTION

Shen Liang (shen0042@ntu.edu.sg)
Liu Yu (cyliu@ntu.edu.sg)

INTRODUCTION

Antibiotics, a common type of pharmaceutical product, which are specially designed to control bacterial infection in humans and animals, have been found in surface water, groundwater and sewage treatment plant effluents (Giger, 2003). This implies that antibiotics cannot be completely eliminated during biological treatment, and they are subsequently emitted into receiving water systems. Thus, it is necessary to treat the effluents containing antibiotics adequately before discharging.
them to receiving water systems. Among possible technologies that have great potential to remove pharmaceutical products in wastewater, sorption is one of the more popular methods. This work aimed to investigate the adsorption of three typical clinical antibiotics including Penicillin G (PCG), Ampicillin (AmP) and Cephaloridin C (CPC) by granular activated carbon (GAC).

MATERIALS AND METHODS

GAC with a mean size of 2.8 mm was obtained from Calgon Carbon Corporation (USA), with a specific surface area of 1000 m$^2$/g (by BET N$_2$ adsorption), an apparent density of 450 kg/m$^3$, and a particle density of 650 kg/m$^3$. Three kinds of antibiotics, PCG, AmP and CPC were purchased from Sigma-Aldrich Pte Ltd (Singapore). Batch adsorption experiments were carried out with a GAC dose of 1 to 10 g/L, while the antibiotic concentration varied in the range of 10 to 200 mg/L. The solution pH and temperature were kept at neutral and 25°C respectively for all the tests. The antibiotic concentration was measured by HPLC or UV spectrophotometer.

RESULTS AND DISCUSSION

Adsorption isotherm

In this study, the Freundlich and Langmuir isotherm equations were used to fit the adsorption data of three model antibiotics, and results were summarized in Table 1.

Freundlich isotherm:  
$$q_e = K_F C_e^{1/n}$$  
(1)

Langmuir isotherm:  
$$q_e = q_m \frac{K_L C_e}{K_L C_e + 1}$$  
(2)

where $K_F$ is the Freundlich constant indicating the adsorption capacity, $1/n$ is the heterogeneity factor indicating adsorption intensity; $K_L$ is the Langmuir adsorption constant (L/mg) and $q_m$ is the maximum adsorption capacity (mg/g).

It was found that the Langmuir isotherm could provide a better description of all the results than the Freundlich isotherm, as indicated by a higher correlation coefficient, while the GAC adsorption capacity of antibiotics were in the order of PCG>AmP>CPC.

![Graph showing kinetics of AmP adsorption by GAC at C$_0$=200 mg/L and X=5g/L](image)

**Figure 1.** Kinetics of AmP adsorption by GAC at C$_0$=200 mg/L and X=5g/L

Table 1. Equilibrium parameters for antibiotics adsorption by GAC at 25°C

<table>
<thead>
<tr>
<th>Antibiotics</th>
<th>Freundlich isotherm</th>
<th>Langmuir isotherm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$K_F$</td>
<td>$1/n$</td>
</tr>
<tr>
<td>PCG</td>
<td>62.64</td>
<td>0.31</td>
</tr>
<tr>
<td>AmP</td>
<td>12.86</td>
<td>0.44</td>
</tr>
<tr>
<td>CPC</td>
<td>11.51</td>
<td>0.30</td>
</tr>
</tbody>
</table>

Adsorption Kinetics

Besides the commonly used pseudo-first order and pseudo-second order kinetic models, we proposed the following general rate law equation for the adsorption of antibiotics by GAC (Liu and Shen 2007):

$$\frac{d\lambda}{dt} = k_x \lambda^x$$  
(3)

where $k_x$ is the rate constant and $x$ is the adsorption reaction order.

It appears from Figure 1 that the general rate law equation can offer a better prediction than the pseudo-1st and pseudo-2nd order equations. Moreover, the value of $x$ was estimated as 1.25 that is close to 1 implying that Eq. 3 in this case could be reasonably approximated by the pseudo-1st order kinetic equation.

CONCLUSION

This study reveals that antibiotics can be effectively removed by GAC adsorption. The Langmuir isotherm and the general rate law equations would provide the satisfactory description of the equilibrium and kinetic data respectively.
THE RECOVERY OF PHOSPHORUS IN WATER RECLAMATION PLANTS USING MICROBIAL REDUCTION OF IRON ORE

Volodymyr Ivanov (CVIvanov@ntu.edu.sg)
Kuang Shengli (KUAN0010@ntu.edu.sg)

INTRODUCTION

Phosphorus discharged from water reclamation plants is the main factor causing eutrophication of water bodies. Meanwhile, the emission limits for phosphorus discharge are becoming more stringent. Precipitation of phosphate with ferric or ferrous salts is an important method used in water reclamation plants worldwide, but the disadvantages of this method are the high cost of chemicals (about US$1015 per ton of iron calculated as liquid FeCl₃) and the difficulties in further treatment of metal-containing sludge [1].

Return liquor (also called reject water, digester supernatant or sludge digester liquid) is produced by the dewatering of sludge from an anaerobic digester. It is returned to the aeration tank and can contribute from 40% to 60% of the main stream of sewage [2]. If phosphorus in the return liquor is removed, the load of phosphorus in the aeration tank is reduced significantly and hence, probably, the concentration of phosphorous in effluent can be diminished to low level.

An innovative biotechnology, BioIronTech [3 - 4], could remarkably decrease the cost of ferrous or ferric reagents for phosphorus precipitation in water reclamation plant due to the production of ferrous ions by iron-reducing bacteria (IRB) from cheap iron ore (US$140 per ton of iron). IRB can use Fe(III) as an electron acceptor and reduce it to dissolved Fe(II) by oxidation of different organic substrates or H₂ under anaerobic conditions [5-6]. Theoretically, microbially produced ferrous ions from iron ore will react with phosphate in the return liquor and form a precipitate, which could be recovered by settling and used as fertilizer [3]. The aim of the research was to examine the feasibility of phosphorus precipitation from the return liquor using bioreduction of iron ore.

MATERIALS AND METHODS

The return liquor generated by the vacuum centrifugation of anaerobic sludge was collected from a wastewater reclamation plant in Singapore. The iron ore, with iron content 60% (w/w) and hematite as the major mineral, was supplied from China.

The experiment was performed in batch culture with iron ore particles of different sizes. Five ranges of particles size of iron ore were 30~40 mm, 14~20 mm, 5.7~9.5 mm, 2.0~2.8 mm and 0.5~0.7 mm, respectively. 1 kg iron ore particle and 4.5 L return liquor were added into each bioreactors of 5L plastic carboy bottle with spigot and 0.5 L anaerobic sludge was used as inoculums to each experimental bioreactor and no iron ore was added in the control bioreactor.

The bioreactors were placed at 35°C. Batch cultivation was continued for 28 days. The concentration of total ferrous iron, dissolved phosphate and dissolved total organic carbon (TOC) of the mixed liquor were measured every 3 or 4 days.

RESULTS AND DISCUSSION

Fe(II) production

For all 5 experiments, the concentrations of total Fe(II) increased (data not shown). The reactor with the smallest...
size of iron ore particles had the highest ferrous production rate. The highest Fe(II) concentration was 550 mg L\(^{-1}\). The total Fe(II) concentrations in the control bioreactor did not change.

The ferrous production rate linearly correlated with the specific surface area of iron ore particles (Figure 2). The specific surface area of iron ore particles was the key factor affecting the iron ore reduction rate.

**Phosphorus removal**

For all experimental reactors, the concentration of dissolved phosphate decreased (Figure 3). The reactors with the biggest sizes of iron ore had the lowest phosphorus removal rate. The bioreactors with iron ore sizes of 7.6 mm, 2.4 mm and 0.6 mm had a phosphorus removal rate of 61 mg L\(^{-1}\) and a phosphorous removal efficiency of 90%. The phosphate concentration in the control reactor was almost unchanged. The phosphorus removal rate depends on specific surface area of iron ore particles by the curve with saturation.

**TOC removal**

The dissolved TOC of return liquor could be removed by 90%, except in the bioreactor with 0.6 mm iron ore particles (Figure 4). Dissolved TOC was removed faster in the bioreactors with the biggest iron ore particles of 35 mm, 17 mm and 7.6 mm, than in the bioreactors with the smallest iron ore particles of 2.4 mm and 0.6 mm. It is suggested that the removal of TOC from return liquor was not contributed by IRB, but by some other bacterial group competing with IRB for electron donors.

**CONCLUSIONS**

1. The crystalline hematite of iron ore can be reduced by iron-reducing bacteria using organic matter of return liquor. The rate of bioreduction is proportional to the specific surface area of iron ore particles.
2. Phosphorus removal efficiency of 90% could be obtained in the bioreactors with iron ore particle sizes of mean size smaller than 7.6 mm. The TOC of return liquor could also be removed by 90% with this process.

This study demonstrated the feasibility of iron ore bioreduction in wastewater treatment, which can be used for the removal of phosphorus and organic matter from return liquor. From the scientific point of view, this data shows a new aspect of the interaction between the biogeochemical cycles of phosphorous, iron and carbon.

**REFERENCES**

EFFECT OF PROTEIN ON BIOHYDROGEN PRODUCTION FROM STARCH OF FOOD WASTE

Ding Hong-Bo (ding0012@ntu.edu.sg)
Wang Jing-Yuan (jywang@ntu.edu.sg)

INTRODUCTION

Attention has been paid most to carbohydrate rich industrial or domestic wastewaters for biohydrogen production. In the laboratory studies, simple carbohydrates such as glucose and sucrose were used as carbohydrate substrates in media to simulate the wastewaters. However, few studies paid attention to the importance and effects of protein on biohydrogen production. Bai et al. (2004) used different ratios of glucose and peptone as multiple substrates to investigate the roles played by carbohydrate and protein in hydrogen fermentation from artificial wastewater and demonstrated that suitable ratios of glucose and peptone improved the growth of hydrogen producing bacteria. Many agricultural wastes, industrial and domestic food wastes contain starch, which is the most appropriate organic source for biohydrogen production. Starch containing solid waste is easier to process for carbohydrate and hydrogen gas formation. The complex nature of such solid wastes may affect the attempted biohydrogen production. For example, food wastes contain carbohydrates and a certain amount of proteins. In real practices of solid waste fermentation, hydrogen fermentation reactors may receive different types of organic wastes from time to time. The fluctuation of protein content in the feed may impose different effects on the biohydrogen production from the carbohydrate content in the same feed. An understanding of the extent of the protein effect can provide vital information on reactor design and process operation of biohydrogen production. This paper discusses the influence of protein content on the biohydrogen production from carbohydrates, especially from starch in the same organic source. For simplicity, rice as a starch source and soybean residue as a major protein source were mixed to achieve various combinations of starch and protein contents. The biohydrogen production from different mixtures was evaluated to understand the effect of protein on biohydrogen production.

MATERIALS AND METHODS

To harvest anaerobic spore-forming hydrogen-producing clostridia, anaerobic sludge taken from a continuously-operated 100 L methanogenic bioreactor was used. It was heated for 2 h at 103°C to inactivate hydrogen consumers (Lay et al., 1999). The experiments were performed at 37°C using the 250-mL glass bottles as lab bioreactors. A water bath with orbital shaker was used to maintain temperature and provide shaking at 50 rpm. A constant pressure manometer (BS ISO 14853:2005, 2005) was adopted to measure the volume of biogas. Characteristics of rice and soybean residues used as starch-rich and protein-rich substrates, respectively, are shown in Table 1. The mixtures of rice and soybean residue were prepared to obtain different ratios of starch and protein (w/w): 11.7 (M01), 11.4 (M02), 10.0 (M03), 8.8 (M04), 4.5 (M05), 2.8 (M06), 1.7 (M07), 0.6 (M08), 0.4 (M09), 0.3 (M10), and 0.2 (M11). 200 ml of 5% slurries were prepared from every substrate mixture and placed in lab bioreactors. No rice and soybean were added into M12 used as the biotic control. Mineral medium was prepared (Bahl et al., 1986). 1 ml of mineral medium, 50 ml heat-shocked anaerobic sludge and 0.07M phosphate buffer were added to each lab bioreactor. pH was initially adjusted to 6.5 and allowed to drop during batch fermentation.

<table>
<thead>
<tr>
<th>Table 1. Characteristics of rice and soybean residue</th>
</tr>
</thead>
<tbody>
<tr>
<td>% of total solid</td>
</tr>
<tr>
<td>Rice</td>
</tr>
<tr>
<td>Soybean residue</td>
</tr>
</tbody>
</table>

Results And Discussion

The specific hydrogen production potential was plotted against starch/protein ratio in Figure 1. The amount of hydrogen produced, which was plotted as the reference, seemed to be
The protein content also affected the biohydrogen production through the influence on pH change. All the experiments were stopped at the 45th when there was no more biohydrogen production. The final pH values and calculated pH changes (negative sign) are plotted in Figure 3a. M01 through M06 experienced a significant pH decrease of roughly 2 units. Meanwhile, M08 through M11 experienced less pH decrease, and the final pHs in these bioreactors were higher than 6. The final pH in M07 was around 5 and experienced a moderate pH decrease of 1.5 pH units.

Readily available organic nitrogen, such as dissolved proteins and amino acids resulting from anaerobic degradation, directly meets the nitrogen requirement for microorganism growth. Brosseau et al. (1986) observed that hydrogen production and cell growth occurred simultaneously. Bai et al. (2004) reported that optimal hydrogen production and cell growth were both observed in the fermentation of one of the multiple liquid substrate combinations, 3 g-COD/L glucose plus 2 g-COD/L peptone. Relative high protein content could enhance the biohydrogen production through the direct organic nitrogen supply to microorganisms. In Figure 2a, the soluble protein concentration in M07 at starch/protein of 1.7 was maintained at 200-250 mg/L for 20 h, while the concentration in M01 at the highest starch/protein ratio of 11.7 was much lower and nearly the same as the control in M12. The microorganisms in M01 and M12 might need to synthesize necessary organic nitrogen matter first from inorganic nitrogen ammonia. Although the medium containing ammonia as inorganic nitrogen at around 400 mg NH$_4^+$-N/L has been provided equally to each bioreactor, in Figure 2b, ammonia concentration in M01 decreased from 400 to 200 mg NH$_4^+$-N/L in 45 h. In contrast, M07, with starch/protein ratio of 1.7 had a stable ammonia concentration above 600 mg NH$_4^+$-N/L in the whole process. Therefore the advantage of readily available organic nitrogen was obvious. The same conclusion was drawn in Bai et al. (2004).

**Figure 1.** Specific hydrogen production potential, hydrogen production rate, and hydrogen volume

**Figure 2.** Change of (a) soluble protein concentration and (b) change of ammonia concentration

The protein content also affected the biohydrogen production through the influence on pH change. All the experiments were stopped at the 45th when there was no more biohydrogen production. The final pH values and calculated pH changes (negative sign) are plotted in Figure 3a. M01 through M06 experienced a significant pH decrease of roughly 2 units. Meanwhile, M08 through M11 experienced less pH decrease, and the final pHs in these bioreactors were higher than 6. The final pH in M07 was around 5 and experienced a moderate pH decrease of 1.5 pH units.

**Figure 3.** (a) Final pH values and pH changes and (b) effect of protein/starch ratio on pH change.
Organic nitrogen in proteins is transformed into inorganic ammonia nitrogen in anaerobic degradation. Ammonia and amino groups released from proteins could maintain suitable pH by the alkalinity produced:

\[ R - NH_2 \rightarrow NH_4^+ + HCO_3^- + xCO_2 + yH_2O \]

The potential pH decrease imposed by volatile fatty acids was buffered by the bicarbonate produced. As long as the biodegradation of protein accompanies the overall organic biodegradation, the pH could be stabilized at a certain level. Such equilibrium can be prospected by evaluating the protein/starch ratio. In Figure 3b, it is found that to maintain a pH decrease within 0.5 pH unit, the protein/starch has to be greater than 2. Lay (2000) demonstrated that the pH-window for optimal hydrogen production from carbohydrates may be so narrow that a half unit decrease in pH may cause a 50% decrease in hydrogen production from the optimum.

CONCLUSIONS

This study demonstrated some important effects of protein on biohydrogen production from starch. It was found that the maximum specific hydrogen production potential, 0.99 mol H\textsubscript{2}/mol initial starch as glucose, and maximum specific hydrogen production rate, 530 ml H\textsubscript{2}/h g-VSS, occurred at a starch/protein ratio of 1.7. The presence of protein in the food waste not only provided buffering capacity to neutralize the volatile fatty acids as concurrent products, but also enhanced the production by providing readily available organic nitrogen in the form of soluble protein and amino acids to microorganisms.

REFERENCES


INTRODUCTION

A two-phase anaerobic digestion system has been considered to be more effective for the treatment of solid food wastes than a single-stage digestion process (Verrier et al., 1987). The principle of the two-phase anaerobic process is the separation of liquefaction/acidification (fermentation) and acetogenesis/methanogenesis phases (Pohland and Ghosh, 1971). For the treatment of solid food waste, the aim of liquefaction/acidification is hydrolysis and acidogenic fermentation to obtain a liquid fraction with dissolved organics, which are degraded further in the acetogenesis/methanogenesis phase.

Hydrolysis and liquefaction of organic waste is often a rate-limiting step in the anaerobic process (Shin et al., 2001). To increase solubilization, thermal pre-treatment of food waste can be used. Solubilization of organic matter can be increased also due to cell disruption. In addition, freezing of organic matter at low temperature leads to intracellular ice crystals formation causing damage of cell membranes and cell disruption (Thomashow, 1998). The aim of the present research was to study the two-phase anaerobic system for the treatment of food waste, and to evaluate the effect of thermal pre-treatment and freezing/thawing pre-treatment methods on
Two separate batch experiments were conducted with thermal pre-treated food waste (E1) and frozen/thawed food waste (E2). Each batch was accompanied by its separate control (C1 or C2) simultaneously. All the tests were operated in a batch pattern at 35±1°C for 12 days as described previously (Stabnikova et al., 2005). After inoculating with 1 litre anaerobic sludge, the acidogenic reactors were fed with 1 litre distilled water and 800 g fresh or pre-treated food waste. Food waste used in E1 was diluted in 1 litre distilled water and then heated at 150°C for 1 h, whereas the food waste used in E2 was frozen for 24 h at -20°C and then thawed for 12 h at 25°C.

**RESULTS AND DISCUSSION**

Thermal pre-treatment was able to improve the structure of food waste, i.e. increased porosity and decreased bulk density, thickness and volume of the material. After heating at 150°C for 1 hour, cavities appeared, and the structure of vegetable roots became loose (Figure 2A, B). Thermal pre-treatment significantly enhanced the content of soluble organic materials in the food waste as the initial soluble COD concentrations were 3.5 g/l and 7.6 g/l in C1 and E1, respectively.

The highest soluble COD and VFA concentrations in the leachate from the acidogenic reactor treating fresh food waste, observed on the 4th day of the process, were 17.6 g/l and 12.5 g/l (Figure 3A, 3B), respectively. Meanwhile, the soluble COD and VFA concentrations in the leachate from the acidogenic reactor with thermal pre-treated food waste peaked on the 2nd and 3rd day of the process, which were 24.2 g/l and 19.8 g/l, respectively. During the first six days, in comparison with anaerobic treatment of fresh food waste, thermal pre-treatment of food waste increased the total soluble COD production by 13% and total VFA production by 20% in the acidogenic reactor, and also increased the total methane production by 42% in the methanogenic reactor. Use of thermally pre-treated food waste diminished the time to produce the same quantity of methane by 48% in comparison with anaerobic digestion of fresh food waste (Figure 4).

Two identical sets of two-phase systems were used for the treatment of food waste in the present study, each consisting of an acidogenic column reactor and a modified upflow anaerobic sludge blanket methanogenic reactor with recirculation of effluent from the methanogenic reactor into both the acidogenic and methanogenic reactors (Figure 1). The effluent from the methanogenic reactor in the HASL system was divided into two streams: 20% effluent was recycled into the acidogenic reactor to reduce the volume of the effluent to be discharged from the anaerobic system and to avoid water to be added for hydrolysis of food waste to the acidogenic reactor, while 80% effluent was used for the dilution of effluent from the acidogenic reactor to maintain optimal pH for methanogenesis in the methanogenic reactor.

**MATERIALS AND METHODS**

Food waste was collected from a canteen in the university. Waste was shredded into particles with an average size of 6.0 mm. The composition of food waste used in the experiments was as follows (% of wet weight): vegetable roots, 50; orange peels, 20; rice, 15; and noodles, 15. The contents of total solids (TS) were 16.3 and 18.6%; the contents of volatile solids (VS) were 88.0 and 92.9% of TS in the mixed fresh waste in experiment with thermally pre-treated and frozen/thawed food waste, respectively. Anaerobic microbial sludge, used as inoculum for the acidogenic reactor, was collected from an anaerobic digester in a local wastewater treatment plant. Microbial anaerobic granules acclimated with high-concentration volatile fatty acids (VFA)-rich wastewater were inoculated into the methanogenic reactor.

Two identical sets of two-phase systems were used for the treatment of food waste in the present study, each consisting of an acidogenic column reactor and a modified upflow anaerobic sludge blanket methanogenic reactor with recirculation of effluent from the methanogenic reactor into both the acidogenic and methanogenic reactors (Figure 1). The effluent from the methanogenic reactor in the HASL system was divided into two streams: 20% effluent was recycled into the acidogenic reactor to reduce the volume of the effluent to be discharged from the anaerobic system and to avoid water to be added for hydrolysis of food waste to the acidogenic reactor, while 80% effluent was used for the dilution of effluent from the acidogenic reactor to maintain optimal pH for methanogenesis in the methanogenic reactor.

**Figure 1. Schematic diagram of the HASL system: 1, acidogenic reactor, Ra; 2, methanogenic reactor, Rm; 3, peristaltic pump; 4, wet gas meter**

**Figure 2. SEM images of fresh (a) and thermally pre-treated (b) vegetable waste; of fresh (c) and frozen/thawed (d) vegetable waste**

The highest soluble COD and VFA concentrations in the leachate from the acidogenic reactor treating fresh food waste, observed on the 4th day of the process, were 17.6 g/l and 12.5 g/l (Figure 3A, 3B), respectively. Meanwhile, the soluble COD and VFA concentrations in the leachate from the acidogenic reactor with thermal pre-treated food waste peaked on the 2nd and 3rd day of the process, which were 24.2 g/l and 19.8 g/l, respectively. During the first six days, in comparison with anaerobic treatment of fresh food waste, thermal pre-treatment of food waste increased the total soluble COD production by 13% and total VFA production by 20% in the acidogenic reactor, and also increased the total methane production by 42% in the methanogenic reactor. Use of thermally pre-treated food waste diminished the time to produce the same quantity of methane by 48% in comparison with anaerobic digestion of fresh food waste (Figure 4).
improvement was thought to be due to speed up of organic matter hydrolysis.

Freezing/thawing became looser, which caused the increase in dissolved organics concentration. The initial soluble COD concentration was 13.8 g/l in the acidogenic reactor in E2, and increased 1.7 times compared to the control test (C2).

Obviously, both thermal pre-treatment and freezing/thawing pre-treatment enhanced the energy recovery from food waste in terms of methane production. However, external energy was required to implement those pre-treatment processes. An energy balance between the energy required by the pre-treatments and increased energy output was made. If the energy losses from heating and refrigerating processes are not considered, theoretical energy requirement for heating 800 g food waste (TS of 18.6% w/w TS) and 1,000 ml water from 25°C to 150°C was

\[
Q = c_{\text{solid}} m_{\text{solid}} \Delta t + c_{\text{water}} m_{\text{water}} \Delta t = 0.89 \text{ J/g °C} \times 148.72 \text{ g x (150-25) °C} + 4.18 \text{ J/g °C} \times (651.28+1000) \text{ g x (150-25) °C} = 879.33 \text{ kJ.}
\]

Assuming there was no phase change for food waste during freezing, only water was in the form of ice at below 0°C. Theoretical energy for freezing, \(Q = c_{\text{solid}} m_{\text{solid}} \Delta t + L_f m_{\text{water}} = 0.89 \text{ J/g °C} \times 148.72 \text{ g x (25+20) °C} + 334.4 \text{ J/g water} = 2121.8 \text{ kJ.}
\]

\[\Delta H = \Delta H_f + \Delta H_{\text{vap}} \]

\[\Delta H_f = \Delta H_{\text{vap}} \]

\[522.5 \text{ kJ which was required to implement those pre-treatment processes.}
\]

An energy balance between the energy required by the pre-treatment enhanced the energy recovery from food waste treatments and increased energy output was made. If the food waste was subject to the thermal pre-treatment or freezing/thawing procedure. This seems to indicate that there is no net energy generation, while employing pre-treatment procedures compared to the control tests. In addition, it should be realized that the actual energy required by those pre-treatments could be much greater than the calculated theoretical value since thermodynamic efficiency was not considered. For example, the thermodynamic efficiency of the refrigeration cycle, which is proportional to the temperature difference, i.e. the energy required to cool a sample from 25°C to -20°C is much greater than \(C_p x (25 - (-20))\) as assumed. However, optimization of pre-treatment procedures, such as reducing reaction time might result in an enhanced energy recovery. In fact, an external energy input of 522.5 kJ which was required to heat 1000 mL from 25°C to 150°C was likely to be saved if only food waste was heated while following the thermal pre-treatment procedure.

**CONCLUSIONS**

Thermal pre-treatment of food waste at 150°C for 1 hour as well as freezing of food waste for 24 hours at -20°C and then thawing for 12 hours at 25°C facilitated the hydrolytic and fermentation processes in the acidogenic reactor and ensured faster supply of nutrients in the methanogenic reactor. Use of thermal pre-treated food or frozen/thawed food waste reduced operational time of batch digestion by 48% and 42% respectively in comparison with the anaerobic digestion of fresh food waste. Thermal and freezing/thawing pre-
treatment enhanced the production of methane, but there is no net energy output as the energy required by pre-treatment procedures is considered.

REFERENCES

ABSTRACT

Standard Proctor compaction of bentonite was carried out and compared with that of using static compaction. A null type axis translation testing method was used to obtain matric suction values of the static compacted bentonite in order to observe the effects of water content and dry density on the matric suction. It was observed that the static compaction tends to be more energy efficient as compared to the standard compaction due to the relatively higher energy losses of the dynamic nature of the compaction. Furthermore, the static compaction curves consist of the rising trend only, which was explained by using the different mechanisms in the compaction processes. The initial matric suction was observed to be decreasing with increasing initial water content, which was explained using the capillary models.

INTRODUCTION

Bentonite is a type of clay which is often used in a civil construction as a landfill cover due to its good waterproofing ability. This layer of bentonite is often required to be compacted to ensure adequate strength under future loadings. Although laboratory compaction testing is often conducted using the standard proctor method, bentonite compaction tends to encounter difficulties due to the instability of the bentonite surface during the impact compaction, which tends to move sideways with every compaction effort. This causes loss of energy during the compaction. As such, an alternative compaction testing method was being suggested to achieve more accurate results.

Reddy and Jagadish (1993) noted that the static compaction tend to produce only the rising portion of the compaction curve, which was due to the difference in the compaction mechanism. During the static compaction, the compression process of the soil was made possible due to the slow and continuous displacement. As such, after passing the optimum water content, water will start to replace the soil and then be squeezed out of the soil under further displacements. Reddy and Jagadish (1993) also observed that the static compaction process tends to be more energy effective as compared to that of the standard proctor compaction due to the much higher energy losses during the impact process. The compaction of the soil generates matric suction, i.e., the difference between the pore air and the pore water pressures. Factors affecting matric suction are pore size of the soil, water content and compressive stress (Vatsala and Murthy, 2002).

However, the compaction behavior of bentonite under the static compaction is not clear enough, therefore, the primary objective of this project was to compare compaction curves of the static compaction and standard proctor compaction method of bentonite. As the second objective, initial matric suction tests were also conducted on selected static compacted samples to observe the effect of the degree of compactness and water content on the initial matric suction of the bentonite.

MATERIALS & METHODS

Figure 1 shows the experimental setup of the static compaction using bentonite as the soil sample in the experiment. The specific gravity of the bentonite is 2.64 and the free swelling is 550%. The plastic limit, liquid limit and plasticity index were 31%, 272% and 241% respectively. The standard compaction test was conducted in accordance to the ASTM D698-00, except a larger hammer was used to reduce the movement of the bentonite.

The measurement of the initial matric suction of bentonite was conducted using a null type axis translation apparatus. After the soil sample was placed into the cell, the pore-water pressure was kept at a constant value of -1 kPa by applying an increasing air pressure into the cell. The difference between the final air pressure applied and the pore water pressure reading at the equilibrium condition is the initial matric suction. In order to reduce the experiment time, the hyperbola method, suggested by Sridharan and Prakash (1985), was used.
EXPERIMENTAL RESULTS AND DISCUSSION

Force vs. Displacement during Static Compaction

Figure 2 shows typical force versus displacement during a static compaction for the water content of 33.47% and dry density of 1.43 Mg/m$^3$. Figure 2 indicates that the slope of the curve tends to be gentler initially, and the gradient becomes steeper as the displacement increases. This was as expected, as the soil would get harder so it was more difficult to reduce the available voids for the compaction. The objective of obtaining the curve is to obtain the energy required to compact the soil to a predetermined dry density for the particular water content. The compaction energy per unit volume was calculated by summing up the area under the force versus displacement graph plotted per unit volume of the specimen.

Effect of Water Content on the Energy of Static Compaction

Figure 3 shows the static compaction energy per unit volume versus water content for various dry densities. During the static compaction process, the soil will be compressed with continuous displacement. A general downward trend was observed with the increasing water content, which is similar to that obtained by Reddy and Jagadish (1993). Each curve also tends to terminate at specific water content, similar to that obtained by Reddy and Jagadish (1993), due to the squeezing out of the soil from the mold.

Comparison of Static and Dynamic Compaction

Figure 4 shows that the relationship of dry density and water content of bentonite for various static compaction energy levels. The curve only contains the rising portion, which is in line with the results observed by Reddy and Jagadish (1993). This was due to different mechanism in the compaction after the optimum water contents, where both the bentonite and water was being squeezed out of the mould in the sheet form during the continuous displacements by the static compaction process. This makes the water content range after the maximum dry density, which is the point where the static compaction curve terminates, not applicable. Also, it could be seen that under the same amount of compaction energy of 0.6 MJ/m$^3$, static compaction was able to compact the soil to a much higher dry density due to the higher energy efficiency as stated by Reddy and Jagadish (1993). From Figure 4, it can be seen that the closest static compaction curve to the standard proctor curve would be around 80KJ/m$^3$. This is about 7.5 times smaller as compared to that of the standard proctor compaction, hence showing that static compaction would be able to save the compaction energy required to densify the soil significantly.

Effect of Water Content on Initial Matric Suction

Figure 5 shows the relationship between initial matric suction and water content for the dry density of 1.35 Mg/m$^3$. Figure 5 indicates that a typical trend of the initial matric suction decreases with the increasing water content which reinforced the results observed by Vatsala and Murthy (2002). This was also explained by Olson and Langfelder (1965) using...
a capillary model. Under higher water contents, the voids are nearly filled with water, hence, it makes the air-water interface relatively flat. This is as compared under the lower water contents where the meniscus starts to form. Reducing the water content implicates the reduction of the radius of the meniscus, and hence causing the pore-water pressure to get more and more negative.

CONCLUSIONS

Based on the experiments and discussion above, the conclusions are:

1. From the comparisons between the static and standard proctor compaction, it was seen that static compaction tends to be more energy efficient.
2. The static compaction curves was also seen to possess the rising portion only, which was explained using the differences in the static and the standard proctor compaction processes.
3. The initial matric suction was found to be decreasing with the increasing water content, whereas irregularity was observed from the effect of dry density on the initial matric suction.

REFERENCES


Effect of Dry Density on Initial Matric Suction

Figure 6 shows initial matric suction of bentonite versus dry density for various water contents. Figure 6 indicates that there is irregularity for the effect of the dry density on the initial matric suction value, which is probably due to a combination effect of the void size and water mass within the soil. Under the lower dry density, the decrease in the voids size may be more influential causing the increase in the initial matric suction. As the soil gets more and more compacted, the effect of the increasing water mass then probably take over, causing the decrease in the initial matric suction.

CONCLUSIONS

Based on the experiments and discussion above, the conclusions are:

1. From the comparisons between the static and standard proctor compaction, it was seen that static compaction tends to be more energy efficient.
2. The static compaction curves was also seen to possess the rising portion only, which was explained using the differences in the static and the standard proctor compaction processes.
3. The initial matric suction was found to be decreasing with the increasing water content, whereas irregularity was observed from the effect of dry density on the initial matric suction.

REFERENCES


Effect of Dry Density on Initial Matric Suction

Figure 6 shows initial matric suction of bentonite versus dry density for various water contents. Figure 6 indicates that there is irregularity for the effect of the dry density on the initial matric suction value, which is probably due to a combination effect of the void size and water mass within the soil. Under the lower dry density, the decrease in the voids size may be more influential causing the increase in the initial matric suction. As the soil gets more and more compacted, the effect of the increasing water mass then probably take over, causing the decrease in the initial matric suction.
INTRODUCTION

Singapore consists of three main rock formations. The Bukit Timah Granite is located in the centre of the island. The sedimentary Jurong Formation is located in southern, southwestern and western part of Singapore. The Old Alluvium forms the eastern part of Singapore. The season in Singapore can be divided into two main seasons, the wetter Northeast Monsoon season from December to March and the drier Southwest Monsoon season from June to September [National Environment Agency, 2007]. The maximum rainfall usually occurs between December and January, whereas July is noted as the driest month [National Environment Agency, 2007].

Climate changes due to an increase in global temperature have resulted in unusually high rainfalls in some parts of the world. On 19 December 2006, Singapore experienced the third highest amount of rainfall (366 mm) in 75 years. This amount of rainfall exceeded the average amount of 284 mm recorded for the entire month of December in the previous year. This heavy rainfall affected the stability of many slopes between December 2006 and January 2007. Eleven slopes failed in December 2006 and three slopes failed in January 2007. All the slopes have a deep groundwater table.

A deep groundwater table and a significant thickness of unsaturated zone above the groundwater table are general characteristics of steep residual soil slopes. Negative pore-water pressures in unsaturated zone are directly affected by variation of flux boundary conditions (i.e., infiltration, evaporation and transpiration) on the slope surface because of climatic changes. Soil properties in the unsaturated soil zone affect the rate of wetting front movement from the slope surface or the rising rate of groundwater table or both during rainfall events.

The characteristics of unsaturated soil properties are different for every slope. As a result, the hydraulic properties of the soil in the unsaturated zone must vary in accordance with the characteristics of unsaturated soil properties. Furthermore, the characteristics of unsaturated hydraulic properties of the soil affect the rates of changes in pore-water pressures, shear strength and factor of safety of slope during and after rainfall. The main objective of this paper is to study the role of hydraulic properties in rainfall-induced slope failures in Singapore.

ASSESSMENT OF SLOPE STABILITY

Numerical analyses were conducted to study the role of rainfall intensity and hydraulic properties in rainfall-induced slope failures in Singapore. In this study, SEEP/W software (Geoslope International Ltd, 2004) was used to observe the changes in pore-water pressure during rainfall. SLOPE/W software (Geoslope International Ltd, 2004) was used to calculate the variation of factor of safety of typical residual soil slopes in Singapore during rainfall.

Typical soil properties of the granitic Bukit Timah Granite residual soil and the sedimentary Jurong residual soil were used to define the soil profiles of both slopes as summarized in Table 1. The slope angle and height for both slopes used in the analyses are typical of slope geometry in Singapore, which is 12 m in height with a slope angle of 31° (Figure 1). The granitic Bukit Timah residual soil has a lower air-entry value and a higher permeability than the sedimentary Jurong residual soil as shown in Figure 2. A typical rainfall of 32 mm/h was applied to both slopes for a period of 6 hours.

Figure 3 shows variations of factor of safety of the granitic Bukit Timah (BT) and sedimentary Jurong (J) residual soil slopes during rainfall with respect to time. The initial factor of safety of the BT slope (1.44) was higher than the initial factor of safety of the J slope (1.32) due to the generally higher shear strength of the BT residual soil. The factor of safety of the BT slope decreased significantly until it reached a minimum value of 0.98 when rainfall stopped (i.e., elapsed time of 6 hours), indicating failure of the BT residual soil slope.
Table 1. Properties of the granitic Bukit Timah and sedimentary Jurong residual soil

<table>
<thead>
<tr>
<th>Properties</th>
<th>Granitic Bukit Timah Residual Soil</th>
<th>Sedimentary Jurong Residual Soil</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total unit weight, $\gamma$ (kN.m$^{-3}$)</td>
<td>19</td>
<td>20</td>
</tr>
<tr>
<td>Liquid Limit, LL (%)</td>
<td>61</td>
<td>54</td>
</tr>
<tr>
<td>Plasticity Index, PI (%)</td>
<td>25</td>
<td>26</td>
</tr>
<tr>
<td>Fines (%)</td>
<td>55</td>
<td>27</td>
</tr>
<tr>
<td>Effective cohesion, $c'$ (kPa)</td>
<td>8</td>
<td>12</td>
</tr>
<tr>
<td>Effective internal friction angle, $\phi'$ (°)</td>
<td>30</td>
<td>35</td>
</tr>
<tr>
<td>Angle indicating the rate of increase in shear strength relative to the matric suction, $\phi^b$ (°)</td>
<td>17</td>
<td>19</td>
</tr>
<tr>
<td>Saturated Permeability, $k_s$ (m.s$^{-1}$)</td>
<td>$6.45 \times 10^{-7}$</td>
<td>$1 \times 10^{-5}$</td>
</tr>
<tr>
<td>Soil type (USCS)</td>
<td>MH</td>
<td>SM</td>
</tr>
</tbody>
</table>

*Figure 1. Typical geometry and soil profile of the granitic Bukit Timah and sedimentary Jurong residual soil slopes*

*Figure 2. Unsaturated hydraulic properties of the granite Bukit Timah and sedimentary Jurong residual soil slopes*
The rapid decrease in the factor of safety of the BT residual soil slope was caused by the high permeability of the soil that allowed rain water to infiltrate quickly to deeper depths, causing a rapid increase in the pore-water pressures in the slope. On the other hand, the factor of safety of the J slope decreased gradually to a value of 1.09 when rainfall stopped (i.e., elapsed time of 6 hours) and continued to decrease to a minimum value of 1.07 at 3 hours after rainfall stopped (i.e., elapsed time of 9 hours). The lower permeability of the J slope caused a slow movement of infiltrating rain water that delayed the occurrence of the minimum factor of safety to some time later after rainfall stopped.

The BT and J residual soil slopes (Figure 1) were reanalyzed using the different permeability functions in Figure 4, but keeping other soil properties the same. The same rainfall intensity of 32 mm/hr was applied to the slope for a duration of 6 hours.

Figure 5 shows that the rate of decrease and recovery in factor of safety of the BT slope is faster than those of the J slope due to the generally higher permeability of the BT residual soil. In addition, a comparison between Figure 4 and Figure 5 shows clearly that a higher permeability resulted in a lower value of minimum factor of safety for both the BT and J slopes. The minimum factor of safety for the BT slope occurred at the end of rainfall for all cases involving different permeability functions (Figure 5a). However, the minimum factor of safety for the J slope occurred at a delayed time after the rainfall ended. The time delay after the end of rainfall became shorter with the increase in the permeability of the J residual soil (Figure 5b).

ROLE OF SATURATED PERMEABILITY IN AFFECTING FACTOR OF SAFETY

A parametric study was carried out to investigate the role of saturated permeability in affecting the variation of factor of safety during rainfall. Different permeability functions were determined using the same soil-water characteristic curve (SWCC) as shown in Figure 2(a), but with different saturated permeability values as presented in Figure 4. Leong et al. (2002) gave a possible range of measured saturated permeability values of the BT residual soil (i.e., \( k_s \) of 1e-5 m/s, 1e-6 m/s and 1e-7 m/s) and the J residual soil (i.e., \( k_s \) of 1e-6 m/s, 1e-7 m/s and 1e-8 m/s). These values were used in generating permeability functions given in Figure 4.

The BT and J residual soil slopes (Figure 1) were reanalyzed using the different permeability functions in Figure 4, but keeping other soil properties the same. The same rainfall intensity of 32 mm/hr was applied to the slope for a duration of 6 hours.

Figure 5 shows that the rate of decrease and recovery in factor of safety of the BT slope is faster than those of the J slope due to the generally higher permeability of the BT residual soil. In addition, a comparison between Figure 4 and Figure 5 shows clearly that a higher permeability resulted in a lower value of minimum factor of safety for both the BT and J slopes. The minimum factor of safety for the BT slope occurred at the end of rainfall for all cases involving different permeability functions (Figure 5a). However, the minimum factor of safety for the J slope occurred at a delayed time after the rainfall ended. The time delay after the end of rainfall became shorter with the increase in the permeability of the J residual soil (Figure 5b).
CONCLUSIONS

Seepage and slope stability analyses have been conducted for two types of residual soil in Singapore: the granitic Bukit Timah residual soil and the sedimentary Jurong residual soil. Field observation indicated that majority of slope failures occurred in the granitic Bukit Timah residual soil slope. The analyses demonstrated that rain water infiltrated the granitic Bukit Timah residual soil slope at a faster rate than the infiltration through the sedimentary Jurong residual soil slope, resulting in the rapid decrease of factor of safety in the granitic Bukit Timah residual soil slope. The differing rates of infiltration are attributed to the higher permeability of the granitic Bukit Timah residual soil compared to the permeability of the sedimentary Jurong residual soil. The parametric study highlighted the importance of proper characterization of permeability function of unsaturated soil as it affects the variation of factor of safety during rainfall and consequently time to failure.

ACKNOWLEDGEMENT

This work was supported by a research grant from the Housing and Development Board and the Nanyang Technological University (NTU), Singapore. The authors gratefully acknowledge the assistance of the Geotechnical Laboratory staff, School of Civil and Environmental Engineering, NTU, Singapore during the experiments and data collections.

REFERENCES

INTRODUCTION

The presence of joints may significantly affect the mechanical behavior of rock masses by reducing their capacity to bear shear and tensile loading. There has been a considerable effort given to the development of accurate, compressive models for rock joint behavior. In this paper, a numerical investigation of the mechanical behavior of initially mated artificial joints with saw-tooth shaped asperities is undertaken using manifold method (MM). The material heterogeneity and geometrical heterogeneity are implemented into the program. The corresponding results indicate that material heterogeneity will reduce the shear strength. However, its effect is limited to within 8%. In contrast, the shear strength can be increased significantly when the geometrical heterogeneity is considered.

MANIFOLD METHOD

The manifold method (MM) was initially developed by Shi in 1992 [1]. The basic structure of MM includes mainly three parts, namely block kinematics, simplex integration and finite cover system.

MM inherits the block kinematics and contact detection and modeling techniques from the discontinuous deformation analysis (DDA) [2]. The contact detection has two constraints: no penetration and no tension between blocks, which are described by inequalities. Using block kinematics, MM can deal with the mechanical response of a blocky system under general loading and moving boundary conditions when body movement and large deformation occur simultaneously.

In MM, minimum potential energy principle is adopted to obtain the individual matrix and the governing equation while the simplex integration (instead of numerical integration method) is used to analytically calculate the individual matrix.

The finite cover system is one of the most innovative features of the MM. There are two meshes, namely the mathematical mesh and physical mesh. The physical mesh includes the boundaries, joints, and the interfaces of different material zones. It represents the problem condition and cannot be chosen artificially. The mathematical mesh is usually a mesh of regular pattern. An illustration of the finite cover system is shown in Figure 1. In the current case, the triangular mesh is the mathematical mesh. The intersection in the mathematical mesh is called a star. Around the star, six triangles form a hexagonal mathematical cover. Overlapping the mathematical cover with the physical mesh will produce the physical cover. In Figure 1 (a), there are no joints inside the problem domain in this case, so a mathematical cover will be a physical cover. The common area of three physical covers is called a manifold element (triangle marked by gray color in Figure 1(a). The displacement field in an element can be obtained by taking the weighted average of the three individual cover functions corresponding to three physical covers. A schematic view of the weight function is plotted in Figure 2.

![Figure 1. Illustration of the finite cover system of the MM: (a) without discontinuity inside; (b) with discontinuity inside](image)

![Figure 2. Illustration of eight function for a hexagonal mathematical cover](image)

For the discontinuous problem, the MM uses path connectivity to determine whether a physical cover is connected or not [3]. A cover is connected if a continuous path can be found between any two points; otherwise, the cover is disconnected. For a path-connected cover, it is assumed that the displacement is continuous within the cover, so only a cover function is needed. However, if a cover is not path-connected, it will be divided into several sub-covers. Each sub-cover will have its own cover functions. In order to illustrate this point, an example is shown in Figure 1 (b). In this case, cover 5 and cover 6 are path-connected, while cover 9 is path-
MECHANICS

disconnected, which will be partitioned into sub-cover 9\textsubscript{1} and sub-cover 9\textsubscript{2}. The manifold element 569 marked by the gray color in Figure 1 (b) is also divided into two elements in Figure 3. The displacement field of the upper element is the weighted average of cover functions of cover 5, 6 and 9\textsubscript{1}, while the displacement field of the lower element is obtained from cover 5, 6, and 9\textsubscript{2}. By this algorithm, the discontinuity can be modeled.

MM MODELS OF DIRECT SHEAR TEST

Figure 3 (a) shows the numerical model of the direct shear test. The joint surface consists of 20 asperities. The upper half (60 cm×10 cm) specimen is smaller than the lower half (75 cm×20 cm). The lower half is fixed, while the upper half is sheared to the right by the velocity boundary applied. Compressive loading is applied to the top of the specimen to simulate the initial earth stresses. In all simulations, the normal stress loading rate and the boundary velocity are assumed to be slow enough to insure the quasi-static response. The average shear stress and the shear displacement of the upper specimen are recorded during the shearing process.

The rock material is assumed to be elastic without damage with the parameters: density = 2650 kg/m\textsuperscript{3}; Young’s Modulus = 80 GPa; Poisson’s Ratio = 0.3. The joint obeys Coulomb slip criterion with the parameters: friction angle = 30°; tensile strength = 0 MPa; cohesion = 0 MPa.

The MM mesh of the numerical model is shown in Figure 3 (b). For the MM program, the user just needs to input the physical boundaries of the model, then, the mathematical mesh, mathematical cover, physical cover and manifold element will be generated automatically. So, it is very convenient for its preprocessor and it is very suitable for our current study.

MM MODELING RESULTS AND DISCUSSIONS

The natural joint can never be uniform and homogeneous. So, the heterogeneity effect of the rock joint surface will be investigated in the current study. Firstly, the material heterogeneity is taken into account by assigning each asperity with identical geometrical parameters but different friction angles conforming to a Weibull distribution [4]. The numerical models with various heterogeneity indices and different joint inclination angles are simulated. The relationship between shear strength and heterogeneity index is shown in Figure 4. The numerical results indicate that shear strength is decreased when material heterogeneity is considered. However, its effect is limited to within 8%.

The geometrical heterogeneity is investigated by assigning
each asperity with identical friction angle but different inclination angle following a Weibull distribution [4]. Several cases with different heterogeneity index and different joint inclination angle are simulated while the results are shown in Figure 5. MM modeling results illustrate that the shear strength will be increased significantly when the geometrical heterogeneity is considered.

Figure 4. Non-dimensional shear strength vs heterogeneity index for four cases with various joint roughness

Figure 5. Non-dimensional shear strength vs. heterogeneity index for the joint with geometrical heterogeneity

CONCLUSIONS

In this paper, a numerical investigation of the mechanical behavior of initially mated artificial joints with saw-tooth shaped asperities is undertaken using manifold method (MM). Both material heterogeneity and geometrical heterogeneity are considered. Numerical results indicate that the material heterogeneity will reduce the shear strength with a very limited effect of within 8%. However, the shear strength will be increased significantly when the geometrical heterogeneity is considered.

REFERENCES

TSUNAMI HAZARD FROM THE POTENTIAL RUPTURE OF THE MANILA TRENCH

Felicia Shaw (FeliciaShaw@ntu.edu.sg)
Xiaozhen Liu (xzliu@ntu.edu.sg)
Kusnowidjaja Megawati (kusno@ntu.edu.sg)
Kerry Sieh (sieh@gps.caltech.edu)
Soon Keat Tan (ctansk@ntu.edu.sg)
Zhenhua Huang (zhhuang@ntu.edu.sg)
Tso-Chien Pan (cpan@ntu.edu.sg)

AN EARTHQUAKE RUPTURE MODEL OF THE MANILA TRENCH

The Manila Trench is a curvilinear bathymetric feature extending from southern Taiwan to Mindoro Island in the Philippines (Figure 1). With a north-south length of approximately 1000 km, and its deepest point some 5 km below sea level, it forms the surface expression of an east-dipping subduction zone which has been active over the last 20 million years.

As part of a joint project between the National Environmental Agency and the Protective Technology Research Centre, earthquake and tsunami risks from the Manila Trench have been the focus of intense study. With a possible rupture length of 1000 km, an event would be comparable in size to the 1960 $M_w$ 9.5 earthquake in Chile (Barrientos & Ward, 1990; NEIC/USGS) as well as the 2004 $M_w$ 9.15 Sumatra/Andaman event (Chlieh et al., 2007). In both cases, the ensuing tsunami caused devastation up to 8500 km from the epicentres (NEIC/USGS; Titov et al., 2005).

For our research, a 3D rupture surface was created from extant seismicity and tomography data (Bautista et al., 2001; Wu et al., 2007). This was supplemented with further data from the Global Centroid Moment Tensor Project (www.globalcmt.org). The dip of the subducting South China Sea lithosphere beneath Luzon has been constrained using earthquake locations, and the bathymetric position of the Manila Trench. The northern part of the subduction zone is inferred to dip steeply below central Taiwan, as the subduction regime undergoes a transition to collision tectonics (Shyu et al., 2007). A steeply dipping profile has similarly been inferred below the island of Mindoro, Philippines, as no significant earthquakes have been recorded immediately south of this area.

An interpolation algorithm was used to construct a mesh of best-fit accommodating these points, giving a sinuous rupture model stretching 60 km below the Earth’s surface at its deepest point (Figure 2).
Geodetic data were used to constrain the accumulation of slip over this rupture model. Using GPS measurements collected over two years (Yu et al., 1999), velocity components acting normal to the trench could be derived. These are related to slow accumulation of strain along the plate (Figure 3).

To derive the magnitude of potential slip in an event, a credible value of 40 m was taken as the maximum slip of a large megathrust earthquake, with reference to the 1960 $M_w$ 9.5 Chilean earthquake. This was then divided by the largest yearly slip rate to give the accumulation time. In the northern region of Luzon, it would require 465 years to accumulate 40 m of strain at the current convergence velocity. This time period was then used qualitatively to scale the magnitude of coseismic slip along the rest of the subduction zone. The resulting slip model is shown in Figure 4.

The model was then used as the basis for a tsunami inundation study, outlined as follows.

**TSUNAMI INUNDATION MODELLING USING COMMIT**

The Community Model Interface for Tsunami (ComMIT) is a computer tool for tsunami prediction developed by the National Oceanic and Atmospheric Administration (NOAA) of the United States. The input information of ComMIT includes bathymetry data, topography data and earthquake source information. Model run parameters, such as friction coefficient and time-step length, may be adjusted for speed and stability of the simulation.

In order to match the earthquake model constructed, 22 source panels were selected from available databases managed by NOAA and BMRC. After selecting the appropriate earthquake source locations and slip magnitudes, initial wave conditions from pre-run propagation scenarios were downloaded. The three key datasets were longitudinal velocity $u$, the lateral velocity $v$, and water depths $h_a$. An inundation simulation was then launched within ComMIT, and the spatial distribution and time history of $u$, $v$ and $h_a$ output as NetCDF files.

| Table 1 |
|-----------------|-----------------|-----------------|
| **A-grid**      | **B-grid**      | **C-grid**      |
| No. of grid points | 520 x-points (lon) by 360 y-points (lat) | 520 x-points (lon) by 360 y-points (lat) | 520 x-points (lon) by 360 y-points (lat) |
| Latitude range   | 0.8957°N - 2.3317°N | 1.0557°N - 1.7737°N | 1.1357°N - 1.4947°N |
| Longitude range   | 103.3606°E - 105.4366°E | 103.5206°E - 104.5586°E | 103.6006°E - 104.1196°E |
| Latitude spacing  | 445.28 m         | 222.64 m         | 111.32 m         |
| Maximum depth     | -63.0 m          | -44.0 m          | -199.3 m         |
| Maximum height    | 651.0 m          | 424.0 m          | 185.9 m          |
| Maximum timestep  | (CFL condition)  | 17.9 sec         | 10.7 sec         | 2.52 sec         |

*Figure 3. Plate convergence velocities from a selection of GPS stations. Values in black give trench-normal convergence in mm/yr.*

*Figure 4. Distribution of slip over the Manila Trench megathrust.*
The model set-up is summarized in Table 1 and illustrated in Figure 5.

RESULTS

Simulation of the wave propagation from the Manila Trench to Singapore takes 501 minutes to complete. This includes the time required to download initial conditions and for the actual computation. The simulation covers 37 hours of physical time.

A synthetic tide gauge reading was taken at 103.93° E, 1.21° N, indicated by a star in Figure 6. Four peaks are observed, of which the third is highest, reaching 45 cm in the Singapore Straits and doubling to ~ 80 cm in the Johor Straits (Figure 7). The result shows that many parts of Singapore coastline may be inundated, with a total area of 1 to 2 km² (Figure 8).

Future tsunami inundation modelling may allow incorporation of different friction coefficients and more detailed analysis of inundation hazard. A range of earthquake scenarios can also be constructed for assessing tsunami hazard to Singapore.

REFERENCES


INTRODUCTION

The failure assessment diagram (FAD) has now been widely accepted and used for the assessment of defects found in metallic structures. This method was originally derived from the two-criterion approach [1]. This approach states that structures can fail by either of two mechanisms, brittle fracture or plastic collapse, and these two mechanisms are connected by an interpolation curve based on the strip yield model as shown in Figure 1.

![Failure Assessment Diagram](image)

**Figure 1. Failure assessment diagram for flawed structure**

If the service point falls inside the assessment curve, the structure is considered safe, otherwise, the structure is deemed unsafe. This method enables the inspection engineers to go directly from linear elastic fracture mechanics (LEFM) calculations to elastic-plastic fracture mechanics calculations.

In BS7910 (2005) [2], the use of this method has been validated for a range of uni-planar circular hollow section (CHS) welded joints. For rectangular or square hollow section (RHS or SHS) joints, there are very few references available in the literature. A detailed validation of the FAD curves for a wide range of cracked SHS T-joints had been carried out by Lie et al. [3] recently. The range of $\beta$ ratio considered is from 0.3 to 0.8 where the failure mode is constrained in the chord face yielding. A penalty factor of 1.15 is then suggested to be applied on the plastic collapse load which is calculated by reducing the ultimate strength for the corresponding uncracked geometry. The influence of residual stresses on the plastic collapse load and the FAD curves is reported in this article.

FAILURE ASSESSMENT DIAGRAMS

In the standard BS7910 Level 2A [2] general failure assessment diagram (FAD), the assessment curve is presented as

$$K_r = \frac{K_f}{K_{mat}}$$

where $K_f$ is the fracture toughness and $K_{mat}$ is the material toughness. The assessment curve is given by

$$K_r = (1 - 0.14L_r) \left[ 0.3 + 0.7 \exp \left( -0.65L_r \right) \right]$$

where $L_r$ is the crack length normalized by the component thickness.


where

$$K_i = \frac{K_i}{K_{mat}} + \rho$$

and

$$L_i = \frac{P}{P_c}$$

(2)

where \(K_i\) is stress intensity factor, \(K_{mat}\) is fracture toughness, \(\rho\) is plasticity correction factor, \(P\) is the total applied load and \(P_c\) is the plastic collapse load of the cracked structure. When secondary stresses are present, for example, the residual stresses, the factor \(\rho\) is necessary to allow for interaction of the primary and secondary stress contributions.

As \(L_i\) increases, plasticity also increases the effective crack tip driving force. If it is considered that fracture actually occurs when the total effective crack tip driving force, namely the elastic-plastic value of crack tip driving force, reaches a critical value equivalent to the fracture toughness, then this will occur at \(\sqrt{EJ_{ep}} = K_{mat}\). Since the applied linear elastic stress intensity factor is equivalent to \(\sqrt{EJ_e}\) where \(J_e\) is the linear elastic J-integral, then Equation (2) can be rewritten as

$$K_e = \frac{K_e}{K_{mat}} + \rho = \sqrt{\frac{J_e}{J_{ep}}} + \rho$$

(3)

This equation can be used to construct the specific FAD for different geometries.

**EFFECTS OF WELDING RESIDUAL STRESSES**

The residual stresses in a welded structure are stresses caused by incompatible internal permanent strains. Welding produces large tensile residual stresses whose maximum value is almost equal to the yield strength of the materials being joined, and it is balanced by lower compressive residual stresses elsewhere in the component [4]. According to the researches by Finch & Burdekin [5], the tensile residual stress near the weld toe is close to yield stress of the material, and it is balanced by the compressive stress at the bottom as shown in Figure 2.

In the standard failure assessment procedures [2], the residual stresses can present as a secondary stress. To allow for interaction of the primary and secondary stress contributions, a plasticity correction factor, \(\rho\), is used as shown in Equation (2). To study its effects on the plastic collapse load and the failure assessment diagrams, a joint have the same dimension as specimen T3 [3] is analyzed again using ABAQUS [6] where the residual stresses are specified using INITIAL CONDITIONS routine. Different crack sizes are then introduced at the brace corner of the joint.

The load-displacement curve of this joint with a deep crack, \(a/t_o=0.8\) is illustrated in Figure 3. It can be seen that the curves with and with..ut the weld toe residual stresses are very close. It is confirmed that this self balanced stresses do not affect the static strength of the crack joint.

![Figure 3. Load-displacement curves](image)

The stress intensity factors (SIFs) under residual stress only are calculated for different crack sizes as shown in Figure 4. It can be found that the SIF for a small crack which is in the tensile residual stress region is larger. When the crack grows longer and exceeds the tensile residual stress range, the SIF becomes smaller. Although the crack extend into the original compressive region, the SIF is still positive until the crack is very deep, i.e. \(a/t_o>0.6\).

![Figure 4. SIFs under residual stresses only](image)

In the standard failure assessment procedures [2], residual stresses can present as a secondary stress. To allow for interaction of the primary and secondary stress contributions, a plasticity correction factor, \(\rho\), is used as shown in Equation (2). To study its effects on the plastic collapse load and the failure assessment diagrams, a joint have the same dimension as specimen T3 [3] is analyzed again using ABAQUS [6] where the residual stresses are specified using INITIAL CONDITIONS routine. Different crack sizes are then introduced at the brace corner of the joint.

The load-displacement curve of this joint with a deep crack, \(a/t_o=0.8\) is illustrated in Figure 3. It can be seen that the curves with and without the weld toe residual stresses are very close. It is confirmed that this self balanced stresses do not affect the static strength of the crack joint.

![Figure 2. Residual stresses distribution across the thickness](image)
DISCUSSION

To study the influence of residual stress on the FADs and validate the calculation of the correction factor, the FADs under external load only and combined external load and residual stresses are plotted in Figure 7. It can be seen from Figures 7(a) and (b) that the FADs for the joint under combined residual stresses and external load fall inside the standard FAD when \( L_r < 0.5 \). The reason for this is because of the additional plasticity effects due to interaction between residual stress and external load. If the correction factor, \( \rho \), are used together with the FE results, the FADs are close to the standard FAD, but still a little lower than the standard one. Therefore, the \( \rho \) factor calculated from BS7910 (2005) \[2\] may be underestimated for small crack which is under large tensile residual stresses.

When the crack extend to the original compressive region, the FADs for the joint under combined residual stresses and external load is very close to the FADs for the joint under external load only, and they are fall outside the standard FAD as shown in Figures 7(c) and (d). Because the SIF under the residual stresses is negative for the deep crack, \( a/t_0 = 0.8 \), the influence of the residual stresses is beneficial to the joint. In accordance with BS7910 (2005) \[2\], the influence is

Figure 5. SIFs under external loading (\( L_r = 0.65 \))

Figure 6. Correction factors under different crack size (\( L_r = 0.65 \))

Figure 7. FADs from J-integral and BS7910 (2005) \[2\] for external load and residual stresses
neglectable and $\rho$ is set to zero. The FAD for this condition is not plotted. From the above discussion, it can be seen that the influence of residual stresses on the joint with deep crack is so small that it can be neglected.

CONCLUSIONS

The influence of residual stresses on the plastic collapse load can be neglected which is consistent with relevant guidance in BS7910 (2005) [2]. For small crack which is located in the large tensile residual stresses region, the $\rho$ factor calculated from BS7910 (2005) [2] seems slightly underestimated. When the crack extends to the compressive residual stress region, the influence of residual stress on the FAD is so small that it can be neglected.

ACKNOWLEDGMENTS

The authors would like to thank Maritime Port Authority of Singapore and Maritime Research Centre at the Nanyang Technological University, Singapore, for the generous support and permission to publish the results of the completed project.

REFERENCES


HEAT CONDUCTION ANALYSIS OF NANO-TIP IN THERMAL-ASSISTED DATA STORAGE USING MOLECULAR DYNAMICS SIMULATION

Liu Xiangjun (liux0014@ntu.edu.sg)
Yang Yaowen(cywyang@ntu.edu.sg)

INTRODUCTION

Within a few years, magnetic storage technology is meeting a fundamental challenge, the well-known superparamagnetic limit. In order to propel data storage industry to continuously develop new storage technologies for large storage capacity and high data transfer rate, several attractive alternate proposals have been put forward, such as the heat-assisted magnetic recording technology and the scanning probe-based data storage technology [1,2]. In these recording technologies, the behavior of heat transfer in the nano-tips as well as between the nano-tips and the storage media during thermo-mechanical data bit formation process is a critical factor affecting the areal storage density, data bit writing/reading speed and system reliability. However, the phenomenon has yet been well understood. Molecular dynamics (MD) simulation is an ideal tool for addressing such an issue, which could provide useful information and in-depth understanding of the heat transfer phenomenon during the data writing process.

In this article, thermal properties of a nano-tip are analyzed using the nonequilibrium molecular dynamics (NEMD) simulation, which is a direct method that relies on imposing a temperature gradient and a heat flux across the system. In the NEMD simulation, the Tersoff-type $n$-body potential [3] and the Gear’s predictor-corrector integration algorithm are employed to investigate the atomic motion in the nano-tip.

MD SIMULATION

Single-crystal Si has a diamond lattice structure, characterized by strong directional bonding, low Poisson’s ratio, strong temperature-sensitive yield strength and narrow dislocations with large Peierls-Nabarro forces. The atoms of silicon touch each

heat transfer phenomenon during the data writing process.
other along the four \(\langle 111\rangle\) directions and the nearest neighbour distance is \(\sqrt{3}a_0\), where \(a_0 = 0.543\) \(\text{nm}\) is the lattice constant. In this article, a nano-tip with four-side pyramidal shape shown in Figure 1 is studied. Such a tip is convenient to construct using the anisotropic etching process technique. The tip scans over the \((100)\) planes that are parallel to the surface of the media substrate.

![Figure 1. Pyramidal structure of nano-tip](image)

The Si atoms are arranged in 10 unit cell layers of the nano-tip. The height of the nano-tip is \(10a_0 = 5.43\) nm, consisting of 10 Si (100) unit cell layers stacked upon each other. There are 7\(x\)7\(x\)7 atoms in the bottom surface of the tip, which corresponds to a contact area of approximate 5.31 nm\(^2\) (\(3\sqrt{2}a_0 \times 3\sqrt{2}a_0\)), and there are 27\(\times\)27 atoms in the top atom layer of the tip, which corresponds to a contact area of approximate 99.66 nm\(^2\) (\(13\sqrt{2}a_0 \times 13\sqrt{2}a_0\)). The total number \(f\) atoms is 11890 in the tip model.

In the NEMD simulation, the Gear’s five-value predictor-corrector algorithm is used for the numerical integration of the equations of motion of individual atoms. The step time \(t\) is set at 0.57 fs, and the nano-tip is treated with fixed boundary condition.

The Tersoff-type \(n\)-body potential is employed to describe the interactions between the silicon atoms in the nano-tip. The total Tersoff energy of the tip model is expressed in terms of the summation of atomic pair interactions, as a function of the atomic coordinates as follows:

\[
V = \frac{1}{2} \sum_{ij} W_{ij} = f_a(r_{ij})[f_a(r_{ij}) + b_r f_s(r_{ij})] \tag{1}
\]

\[
f_a(r_{ij}) = \begin{cases} 
1 & r_{ij} \leq R \\
\frac{1}{2} + \frac{1}{2} \cos \left( \frac{r_{ij} - R}{s} \right) & R \leq r_{ij} \leq S \\
0 & r_{ij} \geq S 
\end{cases} \tag{2}
\]

\[
b_r = x_g(1 + \beta r_{ij} \xi_g)^{\gamma_g} \quad \xi_g = \sum_{km,ij} f_a(r_{ij}) g(\theta_{ijk}) \tag{3}
\]

\[
g(\theta_{ijk}) = 1 + \frac{c^4}{a_0^4} - \frac{c^2}{d^2} + (h - \cos \theta_{ijk})^2 \tag{4}
\]

where \(V\) is the system potential energy; \(W_{ij}\) is the bond energy for all the atomic bonds; \(i, j, k\) label the atoms; \(r_{ij}\) is the length of the \(ij\) bond; \(b_r\) is the bond order term; \(\theta_{ijk}\) is the bond angle between the bonds \(ij\) and \(ik\); \(f_a\) represents a repulsive pair potential; \(f_s\) represents an attractive pair potential; \(f_c\) represents a smooth cutoff function to limit the range of the potential; and \(\xi_g\) counts the number of other bonds to atom \(i\) besides the \(ij\) bond. The parameters \(A, B, R, S, \lambda, \mu, \beta, n, c, d\) and \(h\) are constants which can be found in [3].

In order to investigate the thermal properties of the nano-tip, heat transformation is simulated with the NEMD and the thermal conductivity of the nano-tip is calculated based on the kinetics theory of gases and the Fourier’s law as follows.

\[
k(T) = \frac{J}{\Delta T} \tag{5}
\]

where \(k\) is the thermal conductivity; \(J (=\Delta E/2A\tau)\) is the heat flux vector defined as the amount of heat energy (\(\Delta E\)) transferred per unit time (\(\tau\)) through unit area (A) perpendicular to the direction of the flux; and \(\Delta T = \partial T/\partial z\) is the temperature gradient in the \(z\) direction along the tip height. Experimentally, \(k\) is typically obtained by measuring the temperature gradient based on a heat flux. In this simulation, it is calculated using the NEMD.

In the NEMD simulation, the system is divided into \(j\) slices along the \(z\) direction. The temperature of atoms in the slice is calculated for each iteration. The instantaneous temperature profile in each slice of the system centered at position \(z\) can be obtained by

\[
T_j(t) = \left( \sum_{i=1}^{N} m_i v_i(t) \right) / (3Nk_b) \tag{6}
\]

where \(T_j(t)\) is the temperature in the \(j\)th slice; \(m_i\) and \(v_i\) are the mass and velocity of the \(i\)th atom; \(< >\) denotes the statistical averaging over the entire simulation duration; \(N\) is the number of atoms in the \(i\)th slice and \(k_b\) is the Boltzman constant.

The current NEMD simulation consists of two stages, the energy minimization process and the constant energy process. In the former stage, the system temperature keeps constant by rescaling the velocities of atoms in the system, and the potential energy minimization process is conducted on the system by relaxing the conformation. The energy minimization is achieved if the instantaneous variations of the potential energy are less than 1 meV. After this process, the system will reach at the equilibrium status. To keep temperature constant, the velocity adjustment factor, \(\alpha\), is obtained by

\[
\alpha^2 = \frac{3nk_b \cdot T_{obj}}{\sum_{i=0}^{n} m_i \cdot v_{i,new}^2} \tag{7}
\]

\[
v_{i,new} = \alpha \cdot v_{i,old} \tag{8}
\]

where \(n\) is the total number of atoms in the system; \(T_{obj}\) is the objective constant temperature; and \(v_{i,old}\) and \(v_{i,new}\) are the velocities of the \(i\)th atom before and after rescaling, respectively.
The later stage is the constant energy process. A heat flux is imposed on the system along the $z$ direction after equilibrium. It can be realized by keeping the temperature of the hot ($T_{\text{hot}}$) and cold ($T_{\text{cold}}$) thermal reservoirs constant and setting $T_{\text{hot}} - T_{\text{cold}} = 150\text{K}$ in this simulation. The hot and cold thermal reservoirs are located at the top and bottom ends of the nano-tip, respectively. During the simulation, the kinetic energies added to the hot thermal reservoir ($\Delta \varepsilon_{\text{hot}}$) and removed from the cold thermal reservoir ($\Delta \varepsilon_{\text{cold}}$) are calculated. Thus, the heat flux can be obtained from

$$J_z = \frac{\Delta \varepsilon_{\text{hot}} + \Delta \varepsilon_{\text{cold}}}{2A(z)\cdot t} \quad (9)$$

RESULTS AND DISCUSSION

Figure 2 shows a contour plot of the temperature distribution in the nano-tip. It can be found that at the same height level (as shown in Figure 2 by dash lines), the temperature of the region near the boundary is a bit higher than that far from the boundary, which is resulted from the fixed boundary conditions. This phenomenon indicates that there exists substantial reflection of phonons and phonon boundary-scattering at the boundary.

Figure 3 shows the temperature profile of the nano-tip in the $z$ direction. Since the cross sectional areas of the tip are not constant, in order to compare with the conventional nano-structure configurations, a silicon nano-cube ($10\text{a}_0\times10\text{a}_0\times10\text{a}_0$) is also simulated with the same simulation conditions as the nano-tip. The temperature profile of the nano-cube is also shown in Figure 3. As expected, it is observed that the temperature of the nano-cube is linearly distributed. Thus, the temperature gradient is constant ($\nabla T = 1.7 \times 10^{10} \text{K} \cdot \text{m}^{-1}$ in this case) because of the constant cross sectional area. The thermal conductivity of the nano-cube can be calculated based on the Fourier’s law as $k = 2.7\text{W/mK}$. In contrast, because of the varying cross sectional area, the temperature of the nano-tip is non-linearly distributed, and the temperature gradient is therefore non-constant. The integral mean of the thermal conductivity of the nano-tip can be obtained as $K \sim 1.1\text{W/mK}$. Furthermore, it can be found that with the increase of the cross sectional area along the $z$ direction, the temperature gradient decreases, which indicates that the finite size and structural configuration effects on thermal transport diminish with the system size.

SUMMARY

The thermal properties of a nano-tip have been investigated by NEMD simulation. Obvious structural configuration and boundary condition effects on the thermal transport have been observed due to the phonon boundary-scattering and possible phonon spectrum modification. Moreover, the thermal conductivity of the nano-tip has been calculated. The results provide some insights for the future design optimization of the nano-tip structures.

REFERENCES

INTRODUCTION

Ionic polymer-metal composite (IPMC) is composed of a thin polyelectrolyte membrane and a type of noble metal chemically plated on both sides of the membrane. A hydrated IPMC strip can undergo a fast and large bending motion when a low electric potential is applied to its electrodes and generate a measurable electric potential when subjected to an imposed deformation. Although much effort has been devoted to understanding the actuation mechanism of IPMC, the mechanism has not yet been fully understood. Of all the previous research, almost all the actuation models developed are account for IPMC under static or step electric potentials. Little research has been done to model the IPMC actuation under dynamic electric potentials. In this article, a dynamic model of IPMC actuation is presented. The cation motion under dynamic electric potentials is investigated first. Analytical solution of cation motion is obtained. Based on this solution, the thicknesses of boundary layers and the bending moment are determined. An IPMC cantilever beam actuated by an alternative electric potential is calculated for illustration. Comparison with experimental data in literature is also made.

PROBLEM FORMULATION

Consider an IPMC sample with total thickness $H$, membrane thickness $h$ and length $L$, as shown in Figure 1. It is assumed that the top electrode is the cathode and the bottom electrode is the anode. The electric potentials applied at the cathode and the anode are $\Phi_1(t)$ and $\Phi_2(t)$, respectively.

\[ J^+ (z,t) = -D^+ [\frac{\partial C^+ (z,t)}{\partial z} + v^+ C^+ (z,t) E(z,t)] \frac{R}{T} \]

\[ \frac{\partial \Phi(z,t)}{\partial z} + C^-(z,t) \nu = 0 \]

where $C^+(z,t)$ is the density of cations; $D^+$ is the cation diffusivity coefficient; $v^+$ is the valence of cations; $\Phi (z,t)$ is the electric potential; $F$ is the Faraday’s constant; $R$ is the gas constant; $T$ is the temperature; and $\nu$ is the solvent velocity due to electro-osmosis. The solvent velocity $\nu$ can be determined by Darcy’s Law as

\[ \nu = \frac{D_h}{v_-} \left[ v^+ C^+ E(z,t) - \frac{\partial \Phi}{\partial z} \right] \]

where $D_h$ is the hydraulic permeability coefficient; $v^-$ and $C^-$ are the valence and density of anions, respectively; $E(z,t)$ is the electric field; and $p$ is the fluid pressure.

The time variation of cation concentration can be described by the mass conservation equation as

\[ \frac{\partial C^+(z,t)}{\partial t} = - \frac{\partial J^+ (z,t)}{\partial z} \]

Substituting Eq. (1) into Eq. (3), the following equation can be obtained, where the term due to solvent convection is dropped

\[ \frac{\partial C^-(z,t)}{\partial t} = D^- \frac{\partial^2 C^-(z,t)}{\partial z^2} + D^+ v^+ F \frac{R}{T} \]

\[ \frac{\partial C^- (z,t)}{\partial z} \frac{\partial \Phi(z,t)}{\partial z} + C^-(z,t) \frac{\partial^2 \Phi(z,t)}{\partial z^2} \]

The basic electrostatic equations associated with the problem are

\[ E(z,t) = - \frac{\partial \Phi(z,t)}{\partial z}, D = \kappa \epsilon E(z,t) \]

\[ \frac{\partial D}{\partial z} = \rho_c, \rho_c = (v^+ C^+ - v^- C^-) F \]

where $\kappa$ is the electric permittivity; $D$ is the electric displacement; and $\rho_c$ is the net charge density.

The relationship between cation concentration and electric potential can be derived from Eq. (5), which is the Poisson’s equation as
Eqs. (4) and (6) are the governing equations of the cation transportation within the IPMC membrane.

Integrating Eq. (6) with respect to $z$, the electric field due to charge concentration can be obtained as

$$
\frac{\partial \varphi(z, t)}{\partial z} = \frac{\varphi(t) - \varphi(z)}{h} + \int_{A_{1/2}}^{x} \frac{F}{\varepsilon}(v^{+}C^{+}(z, t) - v^{-}C^{-})dz
$$

Substituting Eq. (7) into Eq. (4), we can obtain

$$
\frac{\partial C^{+}(z, t)}{\partial t} = D \frac{\partial^2 C^{+}(z, t)}{\partial z^2} - \frac{v^{+}F}{RT} \frac{\partial C^{+}(z, t)}{\partial z} - \frac{v^{+}F}{\kappa_{e}RT} C^{+}(z, t)[C^{+}(z, t) - \frac{v^{-}}{v^{+}}C^{-}]
$$

where $f(t) = \frac{\varphi(t) - \varphi(z)}{h}$ and $g(C^{+}(z, t)) = \int_{A_{1/2}}^{x} \frac{hF}{\kappa_{e}}(v^{+}C^{+}(z, t) - v^{-}C^{-})dz$.

The boundary and initial conditions for the problem are

$$
\int_{A_{1/2}}^{A} \rho_{0}dz = 0
$$

$$
\varphi(h/2, t) = \varphi_{i}(t), \varphi(-h/2, t) = \varphi_{i}(t)
$$

$$
J^{+}(-h/2, t) = 0
$$

$$
\varphi_{i}(0) = 0, \varphi_{i}(0) = 0
$$

It is evident that Eq. (8) is a nonlinear partial differential equation. Due to the implicit nature of $g(C^{+}(z, t))$, analytical solution is difficult to derive. As for small ions such as Na$^{+}$ and Li$^{+}$, the electric field caused by the ions is usually much smaller than the applied electric field, it is reasonable to drop the term $g(C^{+}(z, t))$ in Eq. (8) to reduce its nonlinearity. Thus, Eq. (8) can be simplified as

$$
\frac{\partial C^{+}(z, t)}{\partial t} = D \frac{\partial^2 C^{+}(z, t)}{\partial z^2} - \frac{v^{+}F}{RT} f(t) \frac{\partial C^{+}(z, t)}{\partial z} - \frac{v^{+}F}{\kappa_{e}RT} C^{+}(z, t)[C^{+}(z, t) - \frac{v^{-}}{v^{+}}C^{-}]
$$

Assuming $z^{*} = z - \int_{z_{0}}^{z} \frac{v^{+}F}{RT} f(t)dt$ and introducing a moving coordinate where $C^{+}(z^{*}, t) = C^{+}(z, t)$ and $\zeta = \pm k z^{*} + \lambda t$, Eq. (13) can be transformed into a second order autonomous ordinary equation as

$$
k^{2}[C^{+}(\zeta)] - \frac{\lambda}{D^{+}}[C^{+}(\zeta)]
$$

$$
- \frac{(v^{+}F)^{2}}{\kappa_{e}RT} C^{+}(\zeta)[C^{+}(\zeta) - \frac{v^{-}}{v^{+}}C^{-}] = 0
$$

Letting $P(C^{+}(\zeta)) = \frac{D^{+}k^{2}}{C^{+}(\zeta)}$, Eq. (14) can be derived as the Abel equation of the second kind as

$$
P(C^{+}(\zeta))P(C^{+}(\zeta)) - P(C^{+}(\zeta))
$$

$$
- \frac{k^{2}}{\lambda^{2}} (D^{+})^{2} \left(\frac{v^{+}F}{\kappa_{e}RT}\right) C^{+}(\zeta)^{2}
$$

$$
+ \frac{k^{2}}{\lambda^{2}} (D^{+})^{2} \left(\frac{v^{+}F}{\kappa_{e}RT}\right) \frac{v^{-}}{v^{+}} C^{-} C^{+}(\zeta) = 0
$$

Setting $k = \sqrt{25a/6}$ and $\lambda = k^{2}$ where $a = (D^{+})^{2} \left(\frac{v^{+}F}{\kappa_{e}RT}\right) \frac{v^{-}}{v^{+}} C^{-}$, Eq. (15) has the following solution in parametric form as

$$
C^{+}(z, t) = \pm \tau^{1/2} g(\tau)
$$

$$
\tau = C_{i} \exp\left(-\frac{5}{3}at + \frac{\sqrt{6a}}{3} \int D^{+} \frac{v^{+}F}{RT} f(t)dt \right)
$$

where $\tau = \int \frac{d\phi}{\sqrt{(4\phi - 1)}} = C_{0}$ and $C_{0}$ is an arbitrary coefficient. The coefficients $C_{0}$ and $C_{i}$ can be determined by the boundary and initial conditions.

With the solution of cation concentration, the thickness of boundary layers can be calculated as

$$
L_{A} = \int_{A_{1/2}}^{A} Q(z, t)dz
$$

$$
L_{C} = 2 \int_{A_{1/2}}^{A} \frac{z \cdot Q(z, t)dz}{L_{A}}
$$

where $Q(z, t) = [v^{+}C^{+}(z, t) - v^{-}C^{-}] / v^{+}C^{-}$.

After determining the charge redistribution and the thicknesses of boundary layers, the bending moment can be calculated by Zhang and Yang (2007)'s bending moment expression given as

$$
M^{*} = \frac{Y_{b}h_{s}L_{s}}{6(1 + w_{r})} \left(\frac{f_{1}}{f_{m}} \exp\left(\frac{f_{1}}{\Omega}\right) - 1\right)
$$

$$
- \beta \frac{f_{c}}{f_{c1}} \left(\exp\left(\frac{f_{c}}{\Omega}\right) - 1\right)e^{(\Delta - \nu / 2)}
$$

where $Y_{b}$ is the Young's modulus of polyelectrolyte membrane of IPMC; $w_{r}$ is the initial hydration rate before application of electric potential; $\Omega$ is the angular driving frequency; $f_{m}$, $f_{c1}$.
$f_c$ and $f_{C1}$ are the coefficients associated with electrostatic stress, osmotic stress and elastic stress in membrane clusters and $\beta = L_c / L_A$.

**VIBRATION OF A CANTILEVERED IPMC BEAM**

Consider a Nafion based IPMC cantilever beam with length 30 mm and thickness 224 µm. The applied electric potential is a 1-volt sinusoidal signal with frequency of 0.25 Hz. The cation type is Na$^+$ and the solvent is water. When the electric potential is applied, the IPMC beam will vibrate at the driving frequency. The solution of transverse vibration of a cantilevered beam can be expressed as

$$w = \sum_{n=1}^{\infty} A_n X_n(x)e^{j\Omega t}$$

$$A_n = \frac{M^*}{L} \left(2 \cdot (-1)^n + k_n [-\sin(k_nL)] \right)$$

where

$$-\sinh(k_nL) + \sigma_n (\cos(k_nL) - \cosh(k_nL))] / (YI k_n^3 - \rho A \Omega^2) \right) ;$$

$$X_n(x) = [\cos(k_nx) - \cosh(k_nx)] - \sigma_n [\sin(k_nx) - \sinh(k_nx)]$$

$$\sigma_n = \frac{\cos(k_nL) + \cosh(k_nL)}{\sin(k_nL) + \sinh(k_nL)} ;$$

$k_n$ is a factor determined by the frequency equation; $Y$ and $I$ are the Young’s modulus and moment of inertia of the IPMC beam, respectively; $\rho$ is the material density; $A$ is the cross section area and $M^*_n$ is the time independent part of Eq.(19).

Figure 2 shows the deflection curves of the IPMC cantilever beam at $t=1/12f$, 1/6$f$ and 1/4$f$, where $f$ is the driving frequency. It is observed that the maximum tip displacement is 4.2% of the beam length. The experimental test conducted by Nemat-Nasser and Wu (2006) showed that the maximum tip displacement of a cantilever beam of the same dimension under the same electric potential is 3.6% of the beam length. As the experimental data of IPMC generally vary a lot from case to case, the calculation result can be viewed as acceptable.

**CONCLUSIONS**

In this article, a dynamic model of IPMC actuation has been presented. An analytical solution was obtained to describe the cation motion under applied electric potentials. Based on this solution, the thicknesses of boundary layers and bending moment expression were determined in a dynamic manner. The vibration of an IPMC cantilever beam subjected to an alternative electric potential was calculated. Comparison with experimental data showed that the result was reasonable.

**REFERENCES**


---

**FRACTURE PROPAGATION IN ROCK UNDER BLAST LOAD - A NUMERICAL INVESTIGATION**

Zhao Zhiye (czzhao@ntu.edu.sg)
Gu Jiong (gujiong@ntu.edu.sg)

**INTRODUCTION**

The drilling and blasting method has been widely used in various underground engineering applications [1]. Although the borehole pressure under the blast load has been extensively studied over the last thirty years, the mechanism by which rock is broken apart under the dynamic loads is still not fully understood, especially for rocks under a blast load with a short duration. Two approaches have been used in the
past to study the rock fracture mechanism. One approach is to directly conduct the scaled blast tests either on site or in a laboratory to provide some important guidelines for field practice, and the other approach is to employ the theoretical analysis based on the elastic wave propagation [2][3].

In recent years, the numerical approach for modeling the total fracture process has been actively developed, to extend the limitations of the laboratory/field tests and the theoretical approach. One of the numerical methods for fracture propagation simulations is the discontinuous deformation analysis (DDA) [4], which is based on the block theory and has the capability for modeling the rock mass with various discontinuities. As the blocks in the DDA are all independent with each other, and the nodal points on the interface of the blocks are assigned as double nodes, so the block boundaries can be easily modeled as potential cracks. The global block systems in the DDA do not need to be re-meshed even for large deformation during the fracture propagation, thus the DDA is an ideal method for fracture propagation analysis.

The purpose of this paper is to use the DDA to investigate on how the borehole pressure waveform affects the dynamic fracture propagation and the fracture patterns in the scaled blast test in rock sample. As rock is an inhomogeneous material and the rock fracturing can be treated as a stochastic process, the material heterogeneity effect is studied by assigning the rock tensile strength conforming to the Weibull distribution. The effect of the loading rate on the fracturing propagation is also studied.

**DDA MODEL DESCRIPTION**

The scaled blast test model consists of a blast hole in rock with a free outer boundary, as shown in Figure 1. The radii of the model and the borehole are $R_{\text{out}} = 0.4$ m and $R_{\text{in}} = 0.03$ m, respectively. Figure 2 shows the corresponding DDA model (plane strain) containing 1800 quadrangular blocks. Several measured points (denoted by small circles in Figure 2) have been set along the positive x-axis for the stress and displacement output. The DDA model parameters are as follows: rock mass density = 2650 kg/m$^3$; Poisson’s ratio = 0.3; elastic modulus $E = 60$ GPa; maximum blast hole pressure = 30 MPa; friction angle = 30°; cohesion = 66 MPa; average tensile strength = 15 MPa; analysis time interval: 0.5 us - 2.0 us; total analysis time: (2 ~ 5) times of the loading time; coefficient of uniformity $m$: 2, 5 and 20.

To generate the various applied borehole pressure waveforms, the following load history formula is used:

$$P(t) = P_b \left(e^{-\alpha t} - e^{-\beta t}\right)$$

where $P_b$ denote the maximum pressure, $\alpha$ and $\beta$ are constants which determine the rise and the decay time. Figure 3 shows the applied pressure history with maximum pressure at time $t_0$. Figure 4 shows the Weibull distribution of the tensile strength.
MATERIAL HETEROGENEITY

As a geological material, heterogeneity is the most intrinsic characteristics of rock mass. To take into account the material heterogeneity, a random variable satisfying the Weibull distribution is used to model the spatial distribution of the microscopic properties in the analysis model. Although the heterogeneity of rock is characterized by heterogeneity in both the strength and elastic modulus, in this study, the random joint property is selected as the only random microstructure to account for the heterogeneity while using a constant elastic modulus.

The two-parameter Weibull distribution can be expressed as:

\[
f(T) = \frac{m}{\mu} \left( \frac{T}{\mu} \right)^{m-1} \exp \left( -\left( \frac{T}{\mu} \right)^{m} \right)
\]

where \(\mu\) is the mean value, \(m\) is the shape parameter describing the probability distribution parameter \(T\).

In this study, the tensile strength of the rock sample is chosen to conform to the Weibull distribution. Figure 4 shows the Weibull distribution with the mean tensile strength value = 15 MPa. The shape parameter \(m\) can be considered as the heterogeneity index. A smaller \(m\) implies a more heterogeneous material and \(m=\infty\) corresponds to a homogeneous material.

NUMERICAL RESULTS AND DISCUSSIONS

General observations

To investigate the dynamic fracture process due to the applied pressure waveforms, the rise time \(t_0\) is selected as 10 us and 50 us, and \(\beta/\alpha\) are chosen as 1.5 and 30. The results of the final fracture patterns from the DDA simulations are shown in Figure 5.

In general, the formation of the fracture patterns in all cases experiences the process of crack initiation, propagation and arrest. First, the radial tensile fractures start from the vicinity of the compressive failure zone. After that, the tensile stress field causes the radial cracks to run, which is followed by stress releases around the running cracks. Finally, all the cracks arrest and the final fracture patterns are formed. Although the same maximum pressure is applied to all the models, the stress field in the rock model varied significantly with increases in the rise time. The different stress fields result in different fracture processes for each model.

Initial Loading Rate On The Fracture Processes

Figure 5 shows that the fracture patterns are strongly affected by the pressure rise time. As it can be observed in Figure 5(a) that the intense short cracks around the borehole are formed with several cracks propagate a little longer, and the fast stress release affects crack propagation and results in shorter
MECHANICS

Cracks. Figure 5(b) shows that the interval of the cracks is larger and stress released between the cracks has little effect on the growth of adjacent cracks which results in longer crack extensions. This implies that the fracture propagation is closely associated with initial pressure loading rates applied to the borehole.

**Influence of β/α**

This parameter controls the decay time of the waveforms. Under the same rise time, more energy is applied to the specimen if the decay time is longer. When the rise time is small, both the number of cracks and the length of the cracks are significantly different with different $\beta/\alpha$, as shown in Figure 5(a). When the rise time becomes longer as in Figure 5(b), there is little difference in the fracture zone, and only the crack length increases with the increase of the decay time. These findings indicate that the fracture patterns are affected to a greater extent by the rise time than the decay time. This is similar to the case of rock sample under the static borehole pressures, in which the crack extension depends on the maximum value of the applied pressure.

**Influence of the heterogeneity**

The heterogeneity of rock mass can strongly affect fracture propagations and fracture patterns. When $m$ is small, the number of cracks increases significantly and fracture patterns become very chaotic [5]. Figure 5 (b) shows that with the increase of $m$ to 20, the number of cracks and the length of cracks become more uniform and symmetrical, similar as the homogeneous material (i.e. $m=\infty$), and only the shape and position of the cracks are different.

**CONCLUSIONS**

The numerical results obtained by the DDA show that the fracture patterns are mostly affected by the rise time than the decay time. A higher loading rate increases the number of radial cracks, but the rapid stress release from adjacent cracks affects crack extension and results in shorter cracks. At a lower loading rate, few cracks initiate but propagate longer. The heterogeneity of rock mass can strongly affect fracture propagation. The number of cracks increases as the shape parameter $m$ decreases while the length of the cracks increases as the shape parameter $m$ increases.

**REFERENCES**


A COORDINATED APPROACH TO PLANNING AND SCHEDULING DECISIONS IN SUPPLY CHAINS WITH DUAL TRANSPORTATION MODES

Peeyush Mehta (pmehta@iitk.ac.in)
Rohit Bhatnagar (arbhhatnagar@ntu.edu.sg)
Teo Chee Chong (teocc@ntu.edu.sg)

INTRODUCTION

Global differences in taxes, duties, labor costs and accessibility to global markets have created incentives for firms to spread their supply chain activities globally. Firms often employ multiple-mode delivery systems for demand fulfillment in such globally disbursed supply chains. For many firms, the orders are shipped via sea transport mode which is less expensive but has a longer lead time. By the time the orders arrive, new demand information becomes available and this may necessitate placing additional orders through air transport mode, which is costly but more responsive. In practice, the decisions for sea and air shipments are usually made separately as they are regarded as approaches that serve different purposes. The decision pertaining to sea shipments seeks to fulfill the demand forecasts over the planning horizon while maximizing economies of scale in the ordering lot size. The air shipment decision, in contrast, considers the more immediate orders with an emphasis to meet the customer demand with the more up-to-date demand information.

Several studies have addressed the problem of dual transportation modes and how to coordinate decisions for dual mode supply (e.g., Moinzadeh and Schmidt 1991, Chiang and Gutierrez 1998, Chiang 2003 and Tajaras and Vlachos 2001). The dual mode problem is complex in terms of the number of problem parameters and decision variables as well as the stochastic nature of demand; hence, to achieve tractability, the existing models are developed with simplifying assumptions on lead times, transportation cost structure, frequency and sizing of shipments. Some of these assumptions include one-period lead time, instantaneous replenishment by air, fixed ordering size and placement of orders strictly at end of inventory review period. As a result, these models have found limited implementation in practice. In this research, the problem of coordinating shipment planning and scheduling decisions for both sea and air modes is addressed. A model is developed to prescribe coordination between shipment planning and scheduling decisions. In particular, an iterative solution procedure, which is tractable and is also able to capture the key aspects of the problem, is developed. Computational results suggest that significant benefits can be realized with coordination between sea and air shipment decisions using the iterative procedure.

MODEL DESCRIPTION

Sea orders are planned based upon available demand forecast over a planning horizon of \( T \) weeks. Considering a lead time for sea mode of \( L_s \) weeks, at the start of any week \( t \), the shipper needs to determine the sea shipment quantity to satisfy demand from week \( i + L_s \) to \( t + T \). In face of demand uncertainty, the shipper risks shortages and/or excessive inventories when there is a mismatch between the actual demand and the quantities shipped by sea. One common approach is to complement these sea shipments by the more responsive air shipments to minimize the inventory and shortage costs as well as to achieve the desired service levels. Without loss of generality, the lead time for air shipments is assumed to be one week. At the beginning of week \( t \), the shipper has information about the sea shipments to arrive in week \( t + 1 \) as this decision was taken at the beginning of week \( t - L_s + 1 \). It is also assumed that at the start of week \( t \), the shipper is able to observe the actual demand over week \( t \). Consequently, the shipper is able to determine the exact inventory position at the beginning of week \( t + 1 \). The other decision to be taken at the beginning of week \( t \) is to determine the air shipments required in week \( t + 1 \). To summarize, the shipper has to make the following two decisions at the beginning of week \( t \):

1. Determine quantity of sea shipments for week \( t + L_s \) to \( t + T \).
2. Determine quantity of air shipments for each day of week \( t + 1 \).

The first set of decisions is the shipment planning decisions. A mixed integer program (MIP) is developed to solve the shipment planning problem. The time unit of the planning model is one week. Over a finite planning horizon of \( T \) weeks, the decisions of the planning model at week \( t \) are to determine the amount of sea shipments from week \( t + L_s \) to \( t + T \). On a rolling horizon basis, only the decisions for week \( t + L_s \) are implemented in week \( t \); in week \( t + 1 \), new demand forecast is available and the problem is solved again. The model parameters include transportation cost structures in terms of Full Container Load (FCL) and Less than Container Load (LCL), economies of scale in ordering, densities of products, capacity restrictions of containers, fixed and variable costs for sea and air modes, inventory holding costs for both field and in-transit inventories. Shortages are assumed to be backordered and unit shortage costs are incurred for each unit.
of unfulfilled demand.

The second set of air shipment decisions is the scheduling decisions, which is considered as an operational problem. A heuristic-based model is developed that determines the quantity and schedule of air shipments at the start of week \( t \) for the demand in each day of week \( t + 1 \). The objective of the model is to minimize the inventory, shortage and air transportation costs. The heuristics captures the demand uncertainty by assuming that the forecast error for each day’s demand is normally distributed.

**SOLUTION PROCEDURE OF FEEDBACK MECHANISM**

In week \( t \), the planning decisions (sea shipments) are determined for week \( t + L_s \). The scheduling decisions (air shipments) are determined for week \( t + 1 \). The coordination between the planning and operational models is provided through a feedback policy. In the feedback policy, the operational model is solved to determine the daily scheduling of air shipments. Potential air shipments in week \( t + 1 \) are feedback to the planning model to convert the air shipment to sea shipment, thereby reducing the total transportation cost. Figure 1 provides the schematic of the feedback mechanism between the planning and operational model.

**NUMERICAL EXPERIMENT**

A numerical experiment for validating the planning and scheduling models was conducted. In this section, some of the results from the experiment are presented. The objective of the experiment is to determine the benefits of the feedback policy over the conventional no-feedback policy. In practice, it is difficult to establish the unit backorder cost. As a result, the backorder cost of a product, measured in dollars per unit per day, is considered over a wide range of values. The choice of safety stock is product-dependent and thus a wide variety of safety stock settings is considered.

Table 1 shows the results for one for the experiments conducted. It indicates the performance of the feedback policy for a product with a weekly demand of \( \sim N(70,28) \) and at a backorder-to-inventory cost ratio of 100:1, and with no safety stock. An air-to-sea cost ratio of 6:1 is used in the experiment and the planning horizon is 15 weeks. The results show an increase in the inventory costs and sea shipment costs in the feedback policy over the no-feedback policy. This is due to the larger volume of sea shipments in the feedback policy, which also leads to an increase in the inventory level. However, the larger volume of sea shipment has also caused reductions in the backorder cost and air shipments cost significantly. Hence, there is an overall decrease of 3.72% in the total costs, which is significant for firms in many industries.

The impact of the backorder cost and safety stock settings is also investigated. Figure 2 shows the percentage improvement of the feedback policy over the no-feedback policy at different backorder-to-inventory cost ratios and safety stock levels. The lower safety stock requirements create bigger needs for air orders and therefore there are more benefits in employing the feedback policy at lower safety stock settings. At higher safety stock levels, the benefits of feedback policy decrease due to the reduction in air shipments volume. At very high level of safety stock, the feedback and no-feedback policies are the same as it requires little air shipments. For the same level of safety stock, as the backorder costs increase, the
benefits also increase as there is less stock-outs with better coordination between the two modes.

Experiments were also performed by varying the model’s other parameters. For example, a sensitivity analysis is performed over the coefficient of variation of demand to understand the impact of demand variability; in another experiment, the length of planning horizon was varied to understand its impact on the performance of the feedback model. The experimental results are encouraging as they consistently show significant improvements in adopting the feedback policy.

REFERENCES


INTRODUCTION

In load-out operations, the ballast plan is generally calculated by assuming a rigid barge. The objective of the ballast plan is to maintain the deck of the barge horizontally levelled with the yard, while the load-out progresses. However, in reality, the barge is flexible and there is also foundation settlement at the yard. Excessive deflection and settlement may cause the loaded-out structure (hereafter also called the jacket) to be overstressed. Assuming a rigid barge and no yard settlement is only justified provided the deflection of the barge and the settlement of the yard are small such that they can be neglected. Without this justification, calculation done based on the assumption of a rigid barge and/or no yard settlement is not realistic and may cause damage to the jacket structure and/or the barge.

In order to represent the actual load-out operations better, a more realistic ballast calculation method which also has the prospect of reducing the effort taken is proposed. In the method, the flexibility of the barge from the outset which is different from the traditional method [1] is taken into account. The theory of beam on elastic foundations is adopted to model the load-out process. To find the optimum ballast plan, a multi-objective evolutionary algorithm (MOEA) is used. The algorithm is designed to find an optimum ballast arrangement at each load-out stage, which should minimize the deflection of the jacket and/or barge and the amount of ballast that has to be removed or shifted from the previous load-out stage to the current one. An optimum ballast plan for the whole load-out operation will be a set of optimum ballast arrangements for all the load-out stages. The simplified beam-on-elastic-foundation model and the optimization algorithm form the two cores of the proposed method.

BEAM-ON-ELASTIC-FOUNDATION MODEL

We simplify the analysis of the load-out process into an analysis of a 2-dimensional beam-on-elastic-foundation model (see Figure 1). This simplification is made possible by assuming that the geometry and the loading of the jacket and the barge are always symmetrical about the centre line dividing the port and starboard sides of the barge, and that there is only longitudinal variation of ballasts in the barge. It is assumed that the jacket is oriented with its base toward the water. We also assume that all ballast tanks have equal lengths. The analysis is static; wind, wave, current, and impact forces are neglected. Initial deformations of the barge are also neglected. However, tide variation is accounted for.

The Winkler theory of beams on elastic foundation is adopted. The differential equation for the deflection of the beam is

\[ EI \frac{d^4 y}{dx^4} = -ky + q , \]  

(1)

where \( k \) is the foundation stiffness and \( q \) is the distributed load acting upon the beam. Some part of the beam rests on the yard with foundation stiffness \( k_1 \), and the remaining part rests on water with hydrostatic stiffness \( k_2 \). We assume a trapezoidal loading due to the jacket weight, which can be separated into a uniformly distributed loading and a triangular loading.

The deflection of the beam can be obtained using the method of superposition outlined by Hetényi [2]. The beam is cut into three segments, each having different moduli of elasticity and area moments of inertia, as shown in Figure 2. Segment I is defined as the part of the jacket that rests on the yard, segment II as the part of the jacket on the barge, while segment III...
remaining part of the barge. We first find the moments and shearing forces produced at the end points of each segment, assuming an infinitely long beam. Next, the end-condition forces are applied to satisfy the required conditions at both ends of the segment, which is free at both ends. Then, the displacements and slopes at the cutting points between segments are found. Knowing the relative displacement and slope difference between the ends of the neighbouring segments, the shearing force $X$ and moment $Y$ at each of the cutting points to bring about and maintain the continuity of the beam are determined. Finally, having obtained the shearing forces and moments, the deflection of the beam at $x$ is obtained.

MULTI-OBJECTIVE EVOLUTIONARY ALGORITHM (MOEA) FOR FINDING OPTIMUM BALLAST PLAN

An optimum ballast arrangement will be one that meets the following objectives: (1) it should minimize the deflection of the jacket and/or the barge, and (2) it should also minimize the amount of ballast that has to be removed or shifted from the previous load-out stage to the current one. It should be noted, though, that a ballast arrangement which satisfies the first objective does not necessarily satisfy the latter. In other words, the objectives could be conflicting, and therefore it is likely that there are more than one optimum solution to the problem, which satisfy the objectives in a trade-off manner. When more than one objective is involved in an optimization problem like this, the task of finding the optimum solutions is known as multi-objective optimization. In our case, it is a multi-objective optimization problem (MOOP) with two objectives.

Formulation of the multi-objective optimization problem

We assume that initial ballast is already applied such that it balances the buoyancy force from the water, for a given draft. The initial ballast is calculated as follows. The minimum draft of the barge $d_{\text{min}}$ is first calculated as

$$d_{\text{min}} = \frac{w_{\text{barge}}}{k_2}, \quad (2)$$

where $w_{\text{barge}}$ is the weight of the barge. Given the draft $d$ of the barge, which has to be greater than $d_{\text{min}}$, the buoyancy of the water $F_b$ can be calculated as

$$F_b = k_2 d, \quad (3)$$

The initial ballast needed to balance the buoyancy force is therefore

$$w_{\text{in}} = F_b - w_{\text{barge}}, \quad (4)$$

and the initial ballast height is

$$h_{\text{init}} = \frac{w_{\text{in}}}{k_2}, \quad (5)$$

We use a non-dimensional value, $\alpha_i, i = 1, 2, ..., n$ (where $n$ is the total number of ballast tanks) to represent the ballast weight $w_i$ in tank $i$. $\alpha_i$ has a value from 0 to 1, and is related to $w_i$ as follows:

$$w_i = (\alpha_i)h_b - h_{\text{init}}k_2, \quad (6)$$

where $h_b$ is the height of the ballast tank. It is this $\alpha = (\alpha_1, ..., \alpha_n)$ which we seek to optimize.

The MOOP can therefore be formulated as follows:

For $0 \leq \alpha_i \leq 1$, minimize $f_i(\alpha) = y_{\text{rms}}, \quad (7)$

minimize

$$f_2(\alpha) = \begin{cases} \sum (\alpha_i' - \alpha_i) + \sum_{i=1}^{n} (\alpha_i' - \alpha_i) & \text{if } \sum \alpha_i = \sum \alpha_i' \\ \sum (\alpha_i - \alpha_i') + \sum_{i=1}^{n} (\alpha_i' - \alpha_i) & \text{if } \sum \alpha_i > \sum \alpha_i' \end{cases}, \quad (8)$$

where the first function is the root-mean-square of the deflection of the beam model. The second function is the function to calculate the amount of ballast that has to be removed or shifted from the previous stage to the current one.

The prime (’) denotes the value at the previous stage. The expression for the function is formulated assuming the ballast in one tank can be transferred to every other tank with equal speed.

To find the solution to the above MOOP, a multi-objective evolutionary algorithm (MOEA) is developed. Evolutionary
algorithm (EA) is a stochastic optimization method which processes a population of solutions throughout its iterations. This population approach is the distinctive feature of an EA and is well suited for finding a number of optimum solutions. For a comprehensive overview of MOEA the reader is referred to Deb [3].

RESULTS AND DISCUSSIONS

A load-out case study is carried out and it is assumed that there is no tide variation. The load-out process is divided into Stages 0 to 30. The incremental progress of the jacket on the barge from one stage to the next is 5 m, except for Stage 0 to 1, which is 1 m. Optimum ballast arrangements obtained for stages 21 to 30 in terms of α values are shown in Figure 3, while the deflections of the beam for the optimum ballast arrangements for stages 17 to 30 are shown in Figure 4 and Figure 5, respectively.

It is observed that the ballast arranges itself in a sinklike form to counter the jacket load at the earlier stages. As the jacket progresses, the sinklike form becomes more evident and moves to the right. Comparisons with results obtained with the assumption of a rigid barge will provide further justification for the advantage of this method. Also, with MOEA, modifying or adding objective functions can be done with ease. Interesting comparisons can be made between results obtained by minimizing the beam deflection and those by minimizing the beam curvature. It is even possible to obtain results which minimize both the beam deflection and curvature.

ACKNOWLEDGEMENTS

Research grant from Maritime and Port Authority Singapore is gratefully acknowledged. The authors would also like to thank Falconer Bryan Pte Ltd for providing an actual load-out report.
INTRODUCTION

Structural health monitoring using PZT transducers based electromechanical (EM) impedance of structures is fast emerging. The transducers are surface bonded to or embedded into the host structure and subjected to electric actuation. The actuation results in the EM admittance (EMA) signatures that serve as indicator to predict the health/integrity of the host structure (Yang et al. 2005; Annamdas and Soh 2007). However, in real-life scenarios, the structural components such as slabs, beams, and columns are constantly subjected to some forms of external loading. The EMA signature obtained for such a structure is different from the one obtained when damages are present in the structure. This study attempts to demonstrate the effect of loading on the EMA signature by experiment.

EXPERIMENTAL TEST AND RESULTS

Three different lab-sized specimens are tested with various magnitudes of external loading. For the simply supported and centre-loaded beams in this experiment, the maximum bending moment occurs at the centre of the specimen, where the PZT transducers are bonded. Figure 1 schematically illustrates the experimental setup. Table 1 lists the maximum stresses experienced by each of the specimen under different loadings.

The EMA is a function of PZT and structural properties. Especially, it is sensitive to the dynamic stiffness of the structure. The stress induced by the applied load will affect the structural dynamic stiffness and the effect will be reflected in the EM admittance signature.

Table 1. Maximum stress values in specimens

<table>
<thead>
<tr>
<th>Specimen</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Is (m^4) x 10^9</td>
<td>0.11</td>
<td>0.54</td>
<td>4.17</td>
</tr>
<tr>
<td>Load (N)</td>
<td>Maximum stress (MPa)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>46.9</td>
<td>20.8</td>
<td>3.0</td>
</tr>
<tr>
<td>100</td>
<td>93.8</td>
<td>41.7</td>
<td>6.0</td>
</tr>
<tr>
<td>150</td>
<td>140.6</td>
<td>62.5</td>
<td>9.0</td>
</tr>
<tr>
<td>200</td>
<td>187.5</td>
<td>83.3</td>
<td>12.0</td>
</tr>
</tbody>
</table>

Three aluminium beams bonded with three different PZT transducers are tested, with an increment of load 25N at the center (Figure 1). A total of nine EMA signatures are recorded.

REFERENCES

by an impedance analyzer. The trends of all these nine signatures are found to be similar. A representative signature for specimen 1 bonded with PZT A is presented in Figure 2.

In all the nine conductance (real part of EMA) signatures, it is observed that the signatures of the loaded specimens shift upwards from the base-line signature (0 N). However, the magnitude of the upward shifts does not have much correlation with the magnitude of the load applied. It is also observed that the upward shift is larger towards the higher frequency range, indicating that there is a rotation in the anti-clockwise direction of the signatures. These shifts could be attributed to the fact that the interaction between the PZT transducer and the host structure has been altered.

Other than the vertical shifts, lateral shifts of the peaks in the conductance signatures due to the increase of loading are also observed. These shifts are predominantly right-ward. Ong et al. (2002) observed the similar trend in the numerical simulation of an axially loaded beam specimen. In their simulation, the beam specimen was axially loaded such that the surface bonded with the PZT transducer experienced a tensile effect. In the present study, the bottom surface of the specimen that is bonded with the PZT transducer is also under a tensile effect (Figure 1). Therefore, the observations of this study coincide with that in Ong et al. (2002).

In the susceptance (imaginary part of EMA) plot shown in Figure 2, similar shifts to those of the conductance signatures are observed. However, the vertical shifts vary proportionately to the magnitude of the applied load, which is different from the conductance signature. Moreover, the vertical shifts are more prominent than those of the conductance signatures, especially in the high frequency range. The above observations show that the susceptance signature is probably a better indicator than the conductance signature for detecting in-situ stress in the host structure.

Figure 3 shows the susceptance signatures of PZTs installed at four different locations on specimen 1. It is evident that variations exist in the signatures due to the different stress levels at different locations. It is also evident that different stress levels in the beam specimen exhibit similar rotational shift in the susceptance signatures.

The experimental results show that in-situ stress has larger influence on the susceptance signature than the conductance signature. This indicates that susceptance is more useful for detecting in-situ stress in the structure.

CONCLUSIONS

This study focused on the effect of external loading on the EMA signature. Experimental tests were conducted using different PZTs and host structures for various magnitudes of external loading. It was observed that the influence of loading is more noticeable in the susceptance signature, indicating that the susceptance is a better indicator than the conductance for detecting the in-situ stress. This observation has relevance...
in practical applications, especially for health monitoring of stressed structural members that are likely to undergo simultaneous variation in stress and occurrence of damage.

REFERENCES


ERROR ESTIMATION FOR THIN-WALLED STRUCTURES MODELING BY 3D SOLID ELEMENTS

Lee Chi King (ccklee@ntu.edu.sg)
Xu Qiangxun (xqxun@ntu.edu.sg)

INTRODUCTION

Stress analysis of thin-walled structures (TWS) is a frequently encountered problem in structural engineering. The geometric characteristic of a TWS is that the size of the first two dimensions is one order higher than the thickness of the structure and they are often analyzed by using plate/shell finite elements (FE). However, in some applications such as the fatigue analysis of tubular structures, the use of plate/shell FE elements is inadequate for studying the stress concentrations along the joint intersections and solid 3D elements must be used. The main objective of this study is to suggest a new a posteriori error estimation procedure for TWSs using 3D elements.

THE NODAL COORDINATE SYSTEM

The problem domain is separated into two disjoint parts: the junction part $\Omega_{\text{jun}}$ and the shell part $\Omega_{\text{shell}}$ (Figure 1). In $\Omega_{\text{shell}}$, the magnitudes and variations of the surface stress along the shell surface direction are one order higher than that of the normal and shear stress. $\Omega_{\text{jun}}$ is region close to the intersections between two or more shell surfaces. The magnitudes and variations of all stress components in any direction are of the same order. A set of Nodal Coordinate Systems ($x^n, y^n, z^n$ or $x_i^n$) NCS (Figure 2) will be established at all the corner nodes of the mesh [1] for stress recovery and the error estimation.
**NORMS AND STRESS COMPONENT SEPARATION**

The FE displacement \( \mathbf{u} \) and stress \( \mathbf{\sigma} \) are inexact and the errors are defined as

\[
\mathbf{e}_u = \mathbf{u} - \hat{\mathbf{u}}, \quad \mathbf{e}_\sigma = \mathbf{\sigma} - \hat{\mathbf{\sigma}}
\]

The energy norm \( \| \mathbf{u} \|_{\Omega} \) and the error norm \( \| \mathbf{e}_u \|_{\Omega} \) for \( \Omega \) are defined as

\[
\| \mathbf{e}_u \|_{\Omega}^2 = \int_\Omega (\mathbf{e}_\sigma)^T \mathbf{D}^{-1} \mathbf{e}_\sigma \, d\Omega
\]

where \( \mathbf{D} \) is the material matrix. The relative error \( \eta_{\Omega} \) of the solution is defined as

\[
\eta_{\Omega} = \frac{\| \mathbf{e}_u \|_{\Omega}}{\| \mathbf{u} \|_{\Omega}}
\]

The total energy and error norms could be separated according to the contributions from \( \Omega_{\text{jun}} \) and \( \Omega_{\text{shell}} \):

\[
\| \mathbf{u} \|^2_{\Omega} = \| \mathbf{u} \|_{\Omega_{\text{jun}}}^2 + \| \mathbf{u} \|_{\Omega_{\text{shell}}}^2
\]

\[
\| \mathbf{e}_u \|^2_{\Omega} = \| \mathbf{e}_u \|_{\Omega_{\text{jun}}}^2 + \| \mathbf{e}_u \|_{\Omega_{\text{shell}}}^2
\]

In Eqn. 4, \( \mathbf{e}_u = \mathbf{e}_\sigma - \mathbf{\hat{\sigma}} \) with \( \mathbf{\sigma}_t \) and \( \mathbf{\hat{\sigma}} \) are the exact and the FE stress in the NCS respectively. The first integral in Eqn. 4 is computed using the global coordinate system (GCS). However, in \( \Omega_{\text{shell}} \), as some stress components will mainly vary along the surface direction, the second integral is evaluated using the NCS. The relative errors corresponding to \( \Omega_{\text{jun}} \) (\( \eta_{\Omega_{\text{jun}}} \)) and \( \Omega_{\text{shell}} \) (\( \eta_{\Omega_{\text{shell}}} \)) can be defined as

\[
\eta_{\Omega_{\text{jun}}} = \frac{\| \mathbf{e}_u \|_{\Omega_{\text{jun}}}}{\| \mathbf{u} \|_{\Omega_{\text{jun}}}}, \quad \eta_{\Omega_{\text{shell}}} = \frac{\| \mathbf{e}_u \|_{\Omega_{\text{shell}}}}{\| \mathbf{u} \|_{\Omega_{\text{shell}}}}
\]

The surface and norm components will be grouped as

\[
\begin{align*}
\text{surf } \mathbf{\sigma} &= (\mathbf{\sigma}_t, \mathbf{\sigma}_j, \mathbf{\sigma_j}, \mathbf{\gamma}_j)^T \\
\text{norm } \mathbf{\sigma} &= (\mathbf{\gamma}_\ell, \mathbf{\gamma}_\ell, \mathbf{\gamma}_j, \mathbf{\gamma_j})^T
\end{align*}
\]

such that the material matrix in the NCS, \( \mathbf{D}_i \), will be partitioned as

\[
\mathbf{D}_i = \begin{bmatrix} \text{surf } \mathbf{D}_i & 0 \\ 0 & \text{norm } \mathbf{D}_i \end{bmatrix}
\]

where \( \mathbf{u}_{\text{surf}} \) and \( \mathbf{e}_u \) could be separated into two components corresponding to the surface and normal directions such that

\[
\begin{align*}
\| \mathbf{u} \|_{\Omega_{\text{shell}}}^2 &= \| \mathbf{u}_{\text{surf}} \|_{\Omega_{\text{shell}}}^2 + \| \mathbf{u}_{\text{norm}} \|_{\Omega_{\text{shell}}}^2 \\
\| \mathbf{e}_u \|_{\Omega_{\text{shell}}}^2 &= \| \mathbf{e}_{u_{\text{surf}}} \|_{\Omega_{\text{shell}}}^2 + \| \mathbf{e}_{u_{\text{norm}}} \|_{\Omega_{\text{shell}}}^2
\end{align*}
\]

Furthermore, the surface (\( \text{surf } \eta_{\Omega_{\text{shell}}} \)) and normal (\( \text{norm } \eta_{\Omega_{\text{shell}}} \)) relative errors of \( \Omega_{\text{shell}} \) will be defined as

\[
\begin{align*}
\text{surf } \eta_{\Omega_{\text{shell}}} &= \frac{\| \mathbf{e}_{u_{\text{surf}}} \|_{\Omega_{\text{shell}}}}{\| \mathbf{u}_{\text{surf}} \|_{\Omega_{\text{shell}}}} \\
\text{norm } \eta_{\Omega_{\text{shell}}} &= \frac{\| \mathbf{e}_{u_{\text{norm}}} \|_{\Omega_{\text{shell}}}}{\| \mathbf{u}_{\text{norm}} \|_{\Omega_{\text{shell}}}}
\end{align*}
\]

**A POSTERIORI ERROR ESTIMATIONS**

The Zienkiewicz and Zhu (\( Z^2 \)) error estimator [2] is adopted for the \( a \) \( \text{posteriori} \) error estimation. A recovered stress \( \mathbf{\hat{\sigma}} \) is constructed to replace \( \mathbf{\sigma} \) in Eqn. (1) so that the estimated error in stress \( \mathbf{e}_\sigma \) is given by

\[
\mathbf{e}_\sigma = \mathbf{\sigma} - \mathbf{\hat{\sigma}}
\]

The estimated error norms for corresponding to \( \Omega, \Omega_{\text{jun}}, \Omega_{\text{shell}}, \) the surface and the normal directions are then computed as

\[
\begin{align*}
\| \mathbf{e}_\sigma \|_{\Omega}^2 &= \int_\Omega (\mathbf{e}_\sigma)^T \mathbf{D}^{-1} \mathbf{e}_\sigma + \int_\Omega (\mathbf{\hat{\sigma}})^T \mathbf{D}^{-1} \mathbf{\hat{\sigma}} \\
\| \mathbf{e}_\sigma \|_{\Omega_{\text{jun}}}^2 &= \int_\Omega (\mathbf{e}_{\sigma_{\text{jun}}})^T \mathbf{D}^{-1} \mathbf{e}_{\sigma_{\text{jun}}} + \int_\Omega (\mathbf{\hat{\sigma}})^T \mathbf{D}^{-1} \mathbf{\hat{\sigma}} \\
\| \mathbf{e}_\sigma \|_{\Omega_{\text{shell}}}^2 &= \int_\Omega (\mathbf{e}_{\sigma_{\text{shell}}})^T \mathbf{D}^{-1} \mathbf{e}_{\sigma_{\text{shell}}} + \int_\Omega (\mathbf{\hat{\sigma}})^T \mathbf{D}^{-1} \mathbf{\hat{\sigma}}
\end{align*}
\]

**STRESS RECOVERY PROCEDURE FOR TWSS**

In this study, two superconvergent patch recovery schemes, namely, the classical SPR3D scheme and the specially designed SPRN scheme will be used in \( \Omega_{\text{jun}} \) and \( \Omega_{\text{shell}} \) respectively. In both schemes, the recovery stress is constructed by first dividing the FE mesh into a number of overlapping patches, \( \Omega_J \), over each of which a continuous stress field \( \mathbf{\sigma}^+ \) is locally interpolated by a polynomial of the form

\[
\mathbf{\sigma}^+ = \mathbf{P} \mathbf{a}
\]

where \( \mathbf{P} \) is a vector of polynomial with \( m \) terms. \( \mathbf{a} \) is vector of undetermined coefficients. The value of \( \mathbf{a} \) is determined by a local least squares fit over the patch such that the functional \( \Pi_{\text{spr}}(\mathbf{a}) \) is minimized.

\[
\Pi_{\text{spr}}(\mathbf{a}) = \sum_{i=1}^{\text{NSP}} (\hat{\mathbf{\sigma}}(s_i) - \mathbf{\sigma}^+(s_i))^2 = \sum_{i=1}^{\text{NSP}} (\hat{\mathbf{\sigma}}(s_i) - \mathbf{P}(s_i))^2
\]

where NSP \( \geq m \) is the numbers of superconvergent sampling point in the patch and \( s_i \) is the coordinates of the \( i \)th sampling points. The recovery equation is given by

\[
\sum_{i=1}^{\text{NSP}} \mathbf{P}^T(s_i) \hat{\mathbf{\sigma}}(s_i) \mathbf{a} = \sum_{i=1}^{\text{NSP}} \mathbf{P}^T(s_i) \mathbf{a}
\]

After Eqn. 14 is solved, the recovered stresses will be locally
defined over $\Omega_j$ and the global recovered stress field $\tilde{\sigma}$ is obtained by simple nodal averaging. For the SPR3D scheme, $P$ contains the same polynomial terms used in the element shape functions and $s_i$ in Eqn. 14 is the global coordinate of the $i$th sample point. For the SPRN scheme used in $\Omega_{shell}$, it is preferable to express the stress components in the NCS and then separate them into surface and normal components. Hence, $s_i$ in Eqn. 14 is the coordinate of the $i$th sampling point with respect to the NCS associate with the patch assembly node. Since in $\Omega_{shell}$ the surface stress components will dominate the energy norm and their variations along the surface directions are one order higher than that in the normal ($z_n$) direction, the highest order term in $z_n$ used in $P$ is reduced form $(z_n)^2$ to $z_n$.

**NUMERICAL EXAMPLES**

Three spherical shells with an average radius of 10 and thicknesses of $t=0.5$, 1 and 2 subjected to unit uniform internal pressure were used (Figure 3). Due to symmetry, only one-eighth of the container was modelled. For each shell, three uniform meshes are created and hence totally 9 FE analyses were carried out (Figure 4). The SPR3D and the SPRN schemes were applied to obtain the recovered stress field for error estimation. The results obtained for the tested cases are summarized in Table 1. The SPRN scheme consistently outperforms the classical SPR3D scheme, even when the shell is relatively thick ($t=2$). The recovered stress fields obtained from the SPRN scheme are more accurate than those from the SPR3D scheme. The results also indicated performance improvement for SPRN scheme as the thickness of the shell is reduced.

![Figure 3. Spherical container subjected to uniform internal pressure](image)

![Figure 4. Uniform meshes used (NTD = Total numbers of DOFs)](image)

<table>
<thead>
<tr>
<th>Mesh</th>
<th>FEA</th>
<th>SPR3D</th>
<th>SPRN</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\eta_{\Omega}$</td>
<td>$\eta_{\Omega_{shell}}$</td>
<td>$\eta_{\Omega_{shell}}$</td>
<td>$\tilde{\eta}_{\Omega}$</td>
</tr>
<tr>
<td>$t=2$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>28.24</td>
<td>19.43</td>
<td>20.50</td>
</tr>
<tr>
<td>2</td>
<td>7.12</td>
<td>4.21</td>
<td>5.74</td>
</tr>
<tr>
<td>3</td>
<td>4.92</td>
<td>0.79</td>
<td>4.86</td>
</tr>
</tbody>
</table>

Table 1: Results of numerical example
Structures

Introduction

Traditionally, in structural engineering, plate and shell elements are used extensively in the analysis of thin-walled structures (TWS). With the rapid advancements in the area of error estimation and adaptivity for the finite element (FE) method, many adaptive FE refinement procedures had been developed for TWS analysis using plate and shell elements. However, due to the zero normal stress assumption of the plate and shell formulations, plate and shells elements are not suitable for the analysis of TWSs with junctions and 3D elements are deemed to be more appropriate. In this study, a new automatic adaptive refinement procedure for TWSs using 3D solid elements will be suggested. The new adaptive refinement procedure will be tested by applying it to solve a practical TWS problem.

<table>
<thead>
<tr>
<th>Mesh</th>
<th>FEA</th>
<th>SPR3D</th>
<th>SPRN</th>
<th>$\tilde{\eta}_\Omega$ (SPRN)</th>
<th>$\tilde{\eta}_\Omega$ (SPR3D)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\eta_\Omega$</td>
<td>surf $\eta_{\Omega,\text{shell}}$</td>
<td>norm $\eta_{\Omega,\text{shell}}$</td>
<td>$\tilde{\eta}_\Omega$</td>
<td>surf $\tilde{\eta}_{\text{shell}}$</td>
</tr>
<tr>
<td>$t=1$</td>
<td>1</td>
<td>21.72</td>
<td>14.13</td>
<td>16.50</td>
<td>14.95</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>4.65</td>
<td>3.41</td>
<td>3.16</td>
<td>2.71</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>1.42</td>
<td>0.74</td>
<td>1.21</td>
<td>0.35</td>
</tr>
<tr>
<td>$t=0.5$</td>
<td>1</td>
<td>16.44</td>
<td>10.43</td>
<td>12.71</td>
<td>13.11</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>3.51</td>
<td>2.44</td>
<td>2.53</td>
<td>2.07</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.79</td>
<td>0.60</td>
<td>0.53</td>
<td>0.29</td>
</tr>
</tbody>
</table>

$\tilde{\eta}_\Omega = \frac{\| u \|_B}{\| u \|_B}$ = Relative error of the recovered stress field, overall.

surf $\tilde{\eta}_{\text{shell}} = \frac{\text{surf } \| u \|_{\text{shell}}}{\text{surf } \| u \|_{\text{shell}}}$ = Relative error of the recovery stress field, surface components of $\Omega_{\text{shell}}$.

norm $\tilde{\eta}_{\text{shell}} = \frac{\text{norm } \| u \|_{\text{shell}}}{\text{norm } \| u \|_{\text{shell}}}$ = Relative error of the recovery stress field, norm components of $\Omega_{\text{shell}}$.

References


Adaptive FE analysis of thin-walled structures using 3D solid element

Lee Chi King (ccklee@ntu.edu.sg)
Xu Qiangxun (xqxun@ntu.edu.sg)
A POSTERIORI ERROR ESTIMATION

The domain of the TWS $\Omega$ is separated into the shell part $\Omega_{\text{shell}}$ and the junction part $\Omega_{\text{jun}}$ over which energy norms, error norms and relative errors are defined accordingly. For $\Omega_{\text{sub}}$, a local Nodal Coordinate System is set up such that the stress tensor will be separated into two components, namely, the surface component $\sigma_{\text{surf}}$ and the normal component $\sigma_{\text{norm}}$. The relationships among the exact $(\mathbf{u}, \sigma)$ and the FE solutions $(\mathbf{u}_h, \mathbf{\sigma}_h)$ and the errors $(\mathbf{e}_u, \mathbf{e}_\sigma)$ can be expressed as

$$\mathbf{e}_u = \mathbf{u} - \mathbf{u}_h, \quad \mathbf{e}_\sigma = \sigma - \mathbf{\sigma}_h \quad (1)$$

Since the exact stress is not known, Eqn. (1) is approximated by replacing the $\sigma$ by a more accurate recovered stress field $\mathbf{\sigma}_h$ and the estimated error norms for $\Omega_{\text{surf}}, \Omega_{\text{shell}}$ and surface and norm components in $\Omega_{\text{shell}}$ are defined as

$$\mathbf{\epsilon}_{\Omega_{\text{surf}}}^2 = \int_{\Omega_{\text{surf}}} \mathbf{\epsilon}_h \mathbf{\epsilon}_h^T d\Omega \quad (2)$$

$$\mathbf{\epsilon}_{\Omega_{\text{shell}}}^2 = \int_{\Omega_{\text{shell}}} \mathbf{\epsilon}_h \mathbf{\epsilon}_h^T d\Omega \quad (3)$$

The estimated relative errors are computed by approximating the exact energy norms by the recovered stress energy norms such that

$$\text{For } \Omega, \overline{\epsilon}_\Omega = \frac{\mathbf{\epsilon}_u}{\|\mathbf{u}\|_{\Omega}} \quad \text{for } \Omega_{\text{surf}}, \overline{\epsilon}_{\Omega_{\text{jun}}} = \frac{\mathbf{\epsilon}_u}{\|\mathbf{u}\|_{\Omega_{\text{jun}}}} \quad (4)$$

For $\Omega_{\text{shell}}$:

$$\overline{\epsilon}_{\Omega_{\text{shell}}} = \frac{\mathbf{\epsilon}_u}{\|\mathbf{u}\|_{\Omega_{\text{shell}}}} \quad (5a)$$

$$\text{surf } \overline{\epsilon}_{\Omega_{\text{shell}}} = \frac{\mathbf{\epsilon}_u}{\|\mathbf{u}\|_{\Omega_{\text{shell}}}} \text{norm } \overline{\epsilon}_{\Omega_{\text{shell}}} = \frac{\mathbf{\epsilon}_u}{\|\mathbf{u}\|_{\Omega_{\text{shell}}}} \text{ (5b)}$$

In Eqs. 5a and 5b, $\|\mathbf{u}\|_{\Omega_{\text{shell}}}$ and $\|\mathbf{u}\|_{\Omega_{\text{shell}}}$ are the energy norms computed by using the recovered stress.

THE ADAPTIVE REFINEMENT STRATEGY FOR TWSS USING 3D SOLID ELEMENTS

The objective of the adaptive refinement scheme is to seek a FE solution such that the estimated relative error $\overline{\epsilon}_\Omega$ over the $\Omega$ is less than a user prescribed target value $TAR \overline{\epsilon}_\Omega = \overline{\epsilon}_\Omega$.

$$TAR \overline{\epsilon}_\Omega \geq \overline{\epsilon}_\Omega \quad (6)$$

For TWS problems, it is possible to specify the target relative errors for different domains and stress components. Therefore, the following two conditions could also be prescribed by the user.

(i) Prescribe the target relative errors for $\Omega_{\text{surf}}, \Omega_{\text{shell}}$ and refine the mesh until

$$TAR \overline{\epsilon}_{\Omega_{\text{surf}}} \geq \overline{\epsilon}_{\Omega_{\text{surf}}}, \quad TAR \overline{\epsilon}_{\Omega_{\text{shell}}} \geq \overline{\epsilon}_{\Omega_{\text{shell}}} \quad (7a)$$

(ii) Prescribe the target relative errors for all parts and components. In this case, the following addition conditions are imposed as the termination conditions:

$$TAR \overline{\epsilon}_{\Omega_{\text{surf}}} \geq \overline{\epsilon}_{\Omega_{\text{surf}}}, \quad TAR \overline{\epsilon}_{\Omega_{\text{shell}}} \geq \overline{\epsilon}_{\Omega_{\text{shell}}} \quad (7b)$$

In order to control the refinement speed when a coarse mesh is used as an initial mesh, an immediate target relative error will be employed. During the $i$th refinement step, the immediate target relative error for the subdomain $\Omega_{\text{sub}}$, $TAR \overline{\epsilon}_{\Omega_{\text{sub}}}$, shall be computed by the following steps.

(i) Compute $\overline{\epsilon}_{\Omega_{\text{sub}}}$ for the current ($i$th) mesh.

(ii) If $\overline{\epsilon}_{\Omega_{\text{sub}}} / 2 > TAR \overline{\epsilon}_{\Omega_{\text{sub}}}$ set $TAR \overline{\epsilon}_{\Omega_{\text{sub}}} = \overline{\epsilon}_{\Omega_{\text{sub}}} / 2$, otherwise set $TAR \overline{\epsilon}_{\Omega_{\text{sub}}} = TAR \overline{\epsilon}_{\Omega_{\text{sub}}}$.

(iii) $TAR \overline{\epsilon}_{\Omega_{\text{sub}}}$ will then be used for the computation of new element sizes for the next mesh.

New element size calculation for $\Omega_{\text{jun}}$

For a 3D solid element $\Omega_j$ in $\Omega_{\text{jun}}$, existing (old) element size $h_{\Omega_j,old}$ is defined as

$$h_{\Omega_j,old} = \sqrt{\text{surf } A_{\Omega_j}} \quad (8)$$

where $\text{surf } A_{\Omega_j}$ is the mid-surface area of the element $\Omega_j$. If the mesh is optimally refined so that the total error norm is equally distributed among all the elements one could compute an allowable error norm per element $\mathbf{e}_{\Omega_j}$ such that

$$\mathbf{e}_{\Omega_j} = \frac{(\text{surf } \overline{\epsilon}_{\Omega_j})_{\Omega_j}}{\|\mathbf{u}\|_{\Omega_j}} \quad (9)$$

If the estimated error norm for the $j$th element $\Omega_j$ in $\Omega_{\text{jun}}$ is denoted as $\mathbf{e}_{\Omega_j}$, then the refinement indicator $\mathbf{\xi}_{\Omega_j}$ for this element could be defined as

$$\mathbf{\xi}_{\Omega_j} = \frac{\mathbf{e}_{\Omega_j}}{\|\mathbf{e}_{\Omega_j}\|_{\Omega_{\text{jun}}}} \quad (10)$$
Finally, $h_{\Omega_j, new}$, the new element size for $\Omega_j$ can now be computed as

$$h_{\Omega_j, new} = \frac{h_{\Omega_j, old}}{(\zeta_{\Omega_j})^{p+1.5}}$$  \hspace{1cm} (11)$$

**New element size calculation for $\Omega_{shell}$**

For a given element $\Omega_i$ in $\Omega_{shell}$, as it is expected that the thickness of the element could be much smaller than its other dimensions, two size parameters, $\text{surf} h_{\Omega_j, old}$, and $\text{norm} h_{\Omega_j, old}$ are employed to define the existing (old) element size of $\Omega_j$ in the surface and normal directions respectively. For $\text{surf} h_{\Omega_j, old}$, similar to the case for $\Omega_{p,n}$, it is defined as

$$\text{surf} h_{\Omega_j, old} = \sqrt{\text{surf} A_{\Omega_j}}$$  \hspace{1cm} (12)$$

For $\text{norm} h_{\Omega_j, old}$, it can be computed as

$$\text{norm} h_{\Omega_j, old} = \frac{t}{\text{NEL}}$$  \hspace{1cm} (13)$$

In Eqn. 13, $t$ and $\text{NEL}$ are, respectively, the thickness of the TWS and the numbers of layer of elements. After the old element sizes are known, by using a similar arguments, the allowable errors per element in the surface $\text{surf} \| e_a \|_{\Omega_{shell}}$ and norm $\text{norm} \| e_a \|_{\Omega_{shell}}$ directions can be computed as

$$\text{surf} \| e_a \|_{\Omega_{shell}} = \begin{pmatrix} \text{surf} \| e_{a_{surf}} \|_{\Omega_{shell}} \\ \text{surf} \| e_{a_{norm}} \|_{\Omega_{shell}} \end{pmatrix} \begin{pmatrix} \| u \|_{\Omega_{shell}} \\ \| t \|_{\Omega_{shell}} \end{pmatrix}^{\frac{1}{p+1.5}}$$  \hspace{1cm} (14a)$$

$$\text{norm} \| e_a \|_{\Omega_{shell}} = \begin{pmatrix} \text{norm} \| e_{a_{surf}} \|_{\Omega_{shell}} \\ \text{norm} \| e_{a_{norm}} \|_{\Omega_{shell}} \end{pmatrix} \begin{pmatrix} \| u \|_{\Omega_{shell}} \\ \| t \|_{\Omega_{shell}} \end{pmatrix}^{\frac{1}{p+1.5}}$$  \hspace{1cm} (14b)$$

Furthermore, the refinement indicators and new element sizes can now be expressed as

$$\text{surf} \zeta_{\Omega_j} = \frac{\text{surf} \| e_a \|_{\Omega_{shell}}}{\text{surf} \| e_a \|_{\Omega_j}}$$, \hspace{1cm} (15)$$

$$\text{norm} \zeta_{\Omega_j} = \frac{\text{norm} \| e_a \|_{\Omega_{shell}}}{\text{norm} \| e_a \|_{\Omega_j}}$$

$$\text{surf} h_{\Omega_j, new} = \frac{\text{surf} h_{\Omega_j, old}}{(\text{surf} \zeta_{\Omega_j})^{p+1.5}}$$  \hspace{1cm} (16a)$$

$$\text{norm} h_{\Omega_j, new} = \frac{\text{norm} h_{\Omega_j, old}}{(\text{norm} \zeta_{\Omega_j})^{p+1.5}}$$  \hspace{1cm} (16b)$$

**NUMERICAL EXAMPLE**

A CHS tubular T-joint is employed as shown in Figure 1. The joint is subjected to a uniform axial loading from the top and is fixed at both ends. Exploiting symmetry, only one quarter of the joint was modelled (Figure 2). The target relative errors specified are shown in Table 1. Note that this example contains a singular curve along the intersection of the joint along which high stress gradient occurs. The adaptive meshes used are shown in Figure 3. The convergence histories are shown in Figure 4. Due to proper refinement in different directions and parts, the adaptive refinement outperformed the uniform refinement in all means of measurement and a more accurate solution was reached by using 40% DOFs.

![Figure 1. A tubular circular hollow section (CHS) T-joint under axial loading](image)

![Figure 2. Boundary conditions applied](image)

**Table 1. Target relative errors used**

<table>
<thead>
<tr>
<th>$\text{tar} \eta_{\Omega}$</th>
<th>$\text{tar} \eta_{\Omega_{p,n}}$</th>
<th>$\text{tar} \eta_{\Omega_{shell}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>4%</td>
<td>25%</td>
<td>2%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$\text{tar} \eta_{\text{surf} \Omega_{shell}}$</th>
<th>$\text{tar} \eta_{\text{norm} \Omega_{shell}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2%</td>
<td>25%</td>
</tr>
</tbody>
</table>
Figure 3. Adaptive refinement meshes

(a) Mesh A1 (initial mesh)

(b) Mesh A2

(c) Mesh A3

(d) Mesh A4

(e) Mesh A5

(f) Zoom in view near the junction for Mesh A5

Figure 3. Adaptive refinement meshes
INTRODUCTION

Generally, the fatigue life of any tubular joint can be estimated by referring to the Stress Range – Number of Cycles (S-N) curves which depend on accurate prediction of stress concentration factor (SCF) and hot spot stress (HSS) values. To date, most studies on SCFs of tubular joints including numerical analyses and experiment tests are concentrated on simple tubular joints such as T-joints, Y-joints, gap K-joint [1,2]. For a completely overlapped K-joint, one brace called the lap brace is completely welded onto another brace called the through brace. Since the loads are transferred predominantly between the braces, the punching shear stresses on the chord wall can be reduced significantly. Because of ease of fabrication and better static strength than simple gap and partially overlapped K-joints, this type of joint is gradually being used in practice. However, the fatigue study of a completely overlapped K-joint is very limited [3]. Therefore, a full-scale completely overlapped tubular K-joint specimen had been tested in this study to investigate the stress concentration at the intersections of chord and through brace as well as through brace and lap brace. Based on the test results, SCF distributions along the weld toes of the completely overlapped K-joint specimen subjected under basic loads and stress distributions under combined loads are also presented in this study.

SPECIMEN CONFIGURATION AND DIMENSIONS

The configuration of the completely overlapped K-joint specimen is shown in Figure 1. The intersecting circumference of the brace was obtained by using a profiling technology [4] to produce smooth surfaces and to optimize the weld shapes so as in accordance with AWS (2005) specifications [5]. After welding was completed, an ultrasonic technique was used to check the welding quality so as to make sure that there is no initial defect along the weld toe. After fabrication was completed, the specimen was installed by fixing the two ends of the chord and the through brace in the testing. The external loads were applied at the end of the lap brace.


**STRAIN GAUGE LOCATIONS**

In the experimental tests, the strain gauge was used to measure the strain of the specimen near the hot spot stress region. For the joint specimen, the strain gauges were placed around the intersections on the chord, through brace and lap brace at an interval of 22.5°. Figure 2 shows the locations of the strain gauges at the two intersections. At each spot, two strain gauges were used to measure the strains perpendicular to the weld curve. The two strain gauges were placed in the range of extrapolation region specified by CIDECT (2000) specifications [6] where $L_{\text{min}}$ and $L_{\text{max}}$ used in this test are 10 mm and 20 mm respectively.

**STRESS CONCENTRATION FACTOR (SCF) AND HOT SPOT STRESS (HSS)**

The specimens were first subjected to an incremental static load on one axis, and the strains were checked against linearity and zero drift to indicate shakedown of residual stresses. After the data of the strain gauges was recorded, the hot spot strains perpendicular and parallel to the weld toe ($\varepsilon_1$ and $\varepsilon_2$ respectively) were obtained by using linear extrapolation method. To calculate the SCF values, a small element near the weld toe on the chord surface is extracted first. In the experimental tests, $\varepsilon_1 = \varepsilon_1'$ and $\varepsilon_2 = \varepsilon_2'$, then the calculation procedure of SCF can be expressed as follows:

\[
\begin{align*}
\varepsilon_1 &= \frac{1}{E} \left[ \sigma_1 - \nu (\sigma_2 + \sigma_3) \right] \\
\varepsilon_2 &= \frac{1}{E} \left[ \sigma_2 - \nu (\sigma_1 + \sigma_3) \right] \\
\sigma_3 &= 0
\end{align*}
\]

where $E$ and $\nu$ are the Young’s modulus and Poisson’s ratio respectively. From Equation (1), one can obtain

\[
\sigma_2 = \frac{E}{1 - \nu^2} (\varepsilon_2 + \nu \varepsilon_1)
\]

\[
\sigma_3 = \frac{E}{1 - \nu^2} (\varepsilon_2 + \nu \varepsilon_1) - \frac{1 + \nu}{1 - \nu^2} \varepsilon_1
\]

Figure 1. Joint details and dimensions of a completely overlapped K-joint

Figure 2. Locations of strain gauges

Intersection between chord and through brace

Intersection between through brace and lap brace
Therefore,
\[ \sigma_{HS} = \sigma_2 = \frac{1 + \nu \varepsilon_2}{1 - \nu^2} E \varepsilon_2 = c \cdot E \varepsilon_2 \] (4)
where \( c \) is a coefficient and can be expressed as
\[ c = \left( \frac{1 + \nu \varepsilon_2}{E} \right) \frac{E}{(1 - \nu^2)} \] (5)
Finally, the SCF can be obtained as follows:
\[ \text{SCF} = \frac{\sigma_n}{\sigma_n} = \frac{E \varepsilon_n}{E \varepsilon_n} = c \cdot \text{SNCF} \] (6)
where \( \sigma_n \) and \( \varepsilon_n \) are nominal stress and nominal strain respectively, while SNCF is the strain concentration factor.

**EXPERIMENTAL TESTS RESULTS**

The completely overlapped K-joint specimen was subjected under axial (AX), in-plane bending (IPB) and out-of-plane bending (OPB) in the experimental tests. The SCF distributions at the intersection between chord and through brace (CT joint) as well as through brace and lap brace (TL joint) are presented in Figures 3 to 5 for these three basic loads.

![Figure 3](image3.png)  
![Figure 4](image4.png)

From Figure 3, it can be seen that the maximum SCF of the completely overlapped K-joint specimen under AX is located at the heel on the through brace at the TL joint. For the specimen under IPB as shown in Figure 4, the maximum SCF value is also occurred along the weld toe of the TL joint, the location is near the heel of lap brace. While the loading OPB was applied, the SCF distributions of the specimen is shown in Figure 5 which illustrates that the peak SCF located at the saddles of through brace and lap brace along the TL joint, the maximum value for both braces are very similar to each other. Generally, the peak stress at the TL joint is larger than the peak stress at the CT joint. Therefore, it is very common that crack initiates along the weld of TL joint when a completely overlapped K-joint is subjected to the three basic loads.

In practice, the actual load condition of a tubular joint could be any combination of the three basic load cases. For the case
of combined loads, Gulati et al. [7] proposed an equation to determine the stress on the member of a tubular joint as follows:
\[
\sigma(\phi) = K_{AX}(\phi) f_{AX} + K_{IPB}(\phi) f_{IPB} + K_{OPB}(\phi) f_{OPB}
\]  
(7)

where \(K_{AX}(\phi)\), \(K_{IPB}(\phi)\) and \(K_{OPB}(\phi)\) are the SCF at the intersection of members for a joint under AX, IPB and OPB respectively, and \(f_{AX}\), \(f_{IPB}\) and \(f_{OPB}\) are the corresponding nominal stresses for these three basic load cases. The comparison of HSS between the test results and the values calculated from Equation (7) is shown in Figure 6, where the applied loads are AX = 100 kN, IPB = -3.5 kN and OPB = 1.5 kN respectively.

CONCLUSIONS

Experimental test of a completely overlapped K-joint was carried out in this study and SCF distributions of the specimen under three basic loads (AX, IPB and OPB) were investigated. The test results show that the intersection between through brace and lap brace of the completely overlapped K-joint is the main stress concentration area. It is clear from Figure 6 that the comparison of stresses between the tests and the superposition approach are in good agreement, showing the superposition results are slightly higher than the experimental results at the peak stress locations.

REFERENCES

INTRODUCTION

As shallow water hydrocarbon reserves continue to diminish in contrast to ever increasing global demand, recent years have seen an increasing use of floating production systems to develop deepwater sites, with water depths of 1000-3000 m being the latest frontier. A floating production system consists of three main components: the floating platform, the mooring lines and the risers, which are all compliant to forces from wind, waves and current. Dynamic response is therefore a key consideration in design, and various aspects of deepwater systems make dynamic analysis a particularly challenging task. Firstly, the moorings/risers (collectively referred to as lines) have stronger dynamic influence on the vessel at greater water depths, and a coupled analysis of the platform and the connected lines is required to ensure a reliable and cost-effective design. Secondly, there are important nonlinearities in the problem, most notably the nonlinear restoring forces provided by the mooring lines and the nonlinearity of wave forces. Thirdly, the dynamic response of the system occurs at two distinct time scales: the first order motion at the incident wave frequency (WF); and the second order low frequency (LF) motion at the platform’s natural frequencies. The WF and LF motions are also coupled due to the nonlinearities.

As a result of the complications, the current recommended practice is coupled time domain analysis, and there are several commercial packages today that employ this approach. However, the high computational cost of such an analysis makes it prohibitive for routine use. In the search for alternative approaches, the highly efficient frequency domain method is appealing, but its accuracy is not well established due to limited literature. The objective of the present work is to develop an efficient frequency domain method for coupled analysis and benchmark its accuracy against the rigorous time domain approach.

METHODOLOGY

In-house computer programs are written in MATLAB for performing the coupled dynamic analysis in the time and frequency domain. The framework used must be identical to permit a consistent comparison. The platform is modelled as a rigid body, the lines as lumped masses (see Figure 1), and the connection between the platform and the top node of a line is effected by stiff springs. A mattress of springs is used to describe the interaction of line nodes near the seabed.

The first and second order wave forces on the vessel are calculated using a diffraction analysis. The wave forces on the lines are computed using the vectorial form of Morison’s
equation. For time domain simulation of a random seastate, the wave forces are expressed as a sum over constituent seastate components obtained from a wave spectrum. For frequency domain analysis, the nonlinear drag force is linearised using the technique of stochastic linearisation. The procedure is iterative since the linearisation coefficients depend on the system response, and vice versa.

### NUMERICAL SIMULATIONS AND RESULTS

The example is a spread-moored FPSO (floating, production, storage and offloading vessel) installed in 2000 m water depth, as depicted in Figure 2. A severe seastate corresponding to a 100-year storm has been selected for the simulations. Each time domain simulation has a duration of 84 min, and the results are averaged over 10 runs to ensure that there are sufficient LF cycles. An excerpt of time history of the surge (forward) motion of the FPSO is shown in Figure 3(a) and the top tension from one of the lines is shown in Figure 3(b). The time histories are transformed to their spectral densities using fast Fourier Transform (FFT) for comparison with frequency domain results. The comparison of the spectra for surge and tension is presented in Figures 4(a) and 4(b) respectively. The standard deviation of the platform motions and line tensions are calculated from the spectra and listed in Table 1.

![Figure 2. 3D view of platform and lines](image)

![Figure 3. Time history of (a) vessel motions; (b) top tension of a line](image)

![Figure 4a. Time history of vessel motions](image)

<table>
<thead>
<tr>
<th></th>
<th>Wave Frequency</th>
<th>Low Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Time domain</td>
<td>Freq domain</td>
</tr>
<tr>
<td>Surge (m)</td>
<td>1.785</td>
<td>1.783</td>
</tr>
<tr>
<td>Sway (m)</td>
<td>1.192</td>
<td>1.191</td>
</tr>
<tr>
<td>Heave (m)</td>
<td>2.344</td>
<td>2.341</td>
</tr>
<tr>
<td>Roll (deg)</td>
<td>0.631</td>
<td>0.639</td>
</tr>
<tr>
<td>Pitch (deg)</td>
<td>1.501</td>
<td>1.500</td>
</tr>
<tr>
<td>Yaw (deg)</td>
<td>1.336</td>
<td>1.334</td>
</tr>
<tr>
<td>Top tension (kN)</td>
<td>186.3</td>
<td>180.6</td>
</tr>
<tr>
<td>Bottom tension (kN)</td>
<td>156.4</td>
<td>153.1</td>
</tr>
</tbody>
</table>
CONCLUSIONS

Numerical simulations show that the discrepancies between time and frequency domain results are within engineering expectations. Thus, a consistently formulated frequency domain approach for coupled analysis gives the accuracy and efficiency required for the design and analysis of deepwater floating structures. It is an important alternative to the more common time domain coupled analysis, due to its vastly superior computational efficiency.

REFERENCES


BACKGROUND

Since the early twentieth century safety had become an immediate major issue in both construction and shipping port industry. Both government and private sectors are spending millions of dollars to monitor the machineries and promote safety to improve the working condition. Safety of structures becomes more and more important. Crane as a common used machineries are one of the leading causes of death and injury accidents in the civil and offshore industry today. The three deaths in Singapore shipyard crane accident on April 4, 2006 remind us, it is urgent that one should pay more attention and consideration on structural safety. Below is a list of table regarding global accident caused by crane.

Crane accidents can be cased by loads and many other reasons (Figure 1). Loads include static loads, dynamic loads, wind load, and so on. Other reasons include human error, overload, structure defects, machine defects, and resulting in similar physical damage. According to accident statistics, human error

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>AccidentReports</td>
<td>231</td>
<td>287</td>
<td>269</td>
<td>171</td>
<td>161</td>
<td>184</td>
</tr>
<tr>
<td>Deaths</td>
<td>127</td>
<td>142</td>
<td>138</td>
<td>96</td>
<td>107</td>
<td>74</td>
</tr>
</tbody>
</table>

Table 1. Global Crane Accident Statistics
and overload are concerned most. All in all, crane accidents are caused by structure failure or lost of balance.

Today the industries are using traditional equipment like strain gauges with data logger and load cell to monitor the machineries, which facing limitations like the long tangled wires from gauges to the data logger and the limited distance (reach) for the sensors. Those are the major problems to most of the health monitoring system.

**OBJECTIVE**

The objectives of this project are:

1. To select the most effective wireless sensor network (WSN) for non-destructive test.
2. To build monitoring station which can monitor and deal with data from sensors for analysis.
3. To build prototype models of wireless sensors achieving data for calculation and analysis.
4. To develop two prototypes to compare the difference in efficiency of different solar cells.
5. To find and develop an efficient method to achieve data, display condition status.
6. To construct a set of WSN system, then do experiment
7. Apply this WSN technology to machineries for Civil, offshore and any other engineering application.

**PROTOTYPE DEVELOPMENT**

**Design concepts**

Solar cells are able to power up the node when they are placed under direct sunlight. But when there is no or insufficient sunlight, the solar cells can not fulfill the function as a power source to the device. Together, two AA batteries are roughly able to power the node to run for 133.68 cycles. Therefore, the concept of combining both Solar Energy and Battery Storage arise. The whole concepts begins with first the solar cells will generate enough energy to charge up the battery storage and provide enough current to power up the node while it is placed under direct sunlight. So, when there is insufficient or no sunlight, solar cells can not generate enough current to keep the node running, the battery storage will then take over and continue supply power to the node and keep it running. Figure 2 shows a schematic diagram for MICAz modification. Figure 3 demonstrates the prototype of Generation 1 and Generation 2 designs of the solar panels.

**EXPERIMENTAL TESTING**

In this experiment we are focusing in two areas:

1. The Accuracy of Data Achieved
2. The Sustainable Power Supply

The accuracy test is carried out by using the Seismic Earthquake Simulation Table which is equipped with a traditional wired accelerometer and our prototype are placed together, thus we can verify our results/data collected accuracy (Fig. 4).

An endurance test was carried out for the prototypes. The normal MICAz and the Prototypes are placed on a frame and test continuously for one week. Under the instruction of the MICAz manual if the device is powered by just two AA batteries the power will not be enough for the node to keep running for more than two days.
RESULTS

The results obtained from the wireless sensors are compared with the traditional wired data logger results. First, we compare original wireless sensor results with the wired one. The acceleration of the shaking table is set to be 0.3 g at 10 Hz which serves as a control factor of the test. After modifying the MICAz, the prototype Generation 1 can achieve agreeable results and the results from Generation 2 is even better and more accurate as the sensor in Generation 2 was lowered and kept in a shorter distance from the tested surface (Figure 5). The accuracy is focused on its quality (i.e. no junk data and all data present are valid). The reason for why the data are more closely match in low frequency test is simply due to the data retrieving rate setting done in the remote nodes, it shows that the current setting is more suitable for low frequency testing and monitoring.

As shown in Figure 6, the test started on 12\textsuperscript{th} March 2007 and all of the tested nodes are functioning until 13\textsuperscript{th} March 2007. As a normal remote node which powered by two AA batteries will not be able to have enough power to keep its function for more than two days. Therefore, as the test carry on until 14\textsuperscript{th} March 2007, the original remote node has lost its signals retrieval (The Red Line Reading) which was due to the lack of power supply, i.e. the two AA batteries has been used up. As there was continuous rain and not much sunlight exposure during the test days from 14\textsuperscript{th} March 2007 to 19\textsuperscript{th} March 2007, the solar cells may not generate enough power for the charging circuit to recharge the battery storage. Therefore, on the 4\textsuperscript{th} day, 16\textsuperscript{th} March 2007, the reading from prototype generation 1 also cut (The Green Line Reading). But prototype generation 2 (The Blue Line Reading) is able to continue to function till the end of the experiment which ended on the 19\textsuperscript{th} March 2007. It has function full seven days without any lack of power. This can prove that generation 2 is more properly designed and the increased in storage and increase in solar cells dose enhance the nodes lifespan significantly.

CONCLUSIONS

It is tested and proven the wireless sensor network can actually function as well as a traditional wired data logging sensor. The readings are accurate in terms of the quality of the data. Each sensor in sensor network takes time-stamped measurements of physical phenomena such as heat, sound, light, pressure or motion. Signal processing modules on a sensor may produce more abstract representations of the same data such as detection, classification or tracking outputs. Additionally, a sensor contains descriptions of its characteristics such as the location or type of a sensor. A sensor network database comprises all of the above data from every sensor.

There are many advantages for wireless sensor network against the wired sensors. The primary advantage is that there will not be any long tangled wire lying around, on top of that the reachable distance is also significantly improve. It is more multi-functional as compare with normal sensors, usually one single sensor board can have multi-sensing functions which normal traditional sensors usually are one sensor for one sensing function. The mobility of the sensor network system is also another advantage that normal traditional sensor system can never match with, as for wireless sensor network there is no need for the big, heavy data logger to be present and with a small mobile computer and a small remote node, the network can be formed easily.

RECOMMENDATION FOR FURTHER DEVELOPMENT

There are many possible ways to enhance this current development to improve its functionality and mobility.

The size of the modification can be further reduced. As current development in prototype generation 2, the provided solar cells are over-design to facilitate the inefficiency of solar cells.

This wireless sensor network is very open for users own personal development of applications. Individual users can
develop their own programs for different usage of such wireless sensor network.

Accessibility of the wireless sensor networks can be further enhanced by using other electronic and telecommunication means. The diagram in Figure 7 shows the true power of a wireless sensor network. The users can be notified if there is any changes or monitor the application system through PDA (Internet) or mobile phone (GSM). What the system needs to do is just link the applications to a router for internet access or a SIM card modem for GSM access, users can enjoy the true wireless freedom of the system.

![Diagram of wireless sensor network](image)

**Figure 7. Mesh Networking Diagram**

REFERENCES


MODELLING AND INVESTIGATION OF REINFORCED CONCRETE GRAVITY-LOAD-DESIGNED BEAM-COLUMN JOINTS

Paulus Irawan (cirawan@ntu.edu.sg)
Lin Xin (pg04597926@ntu.edu.sg)

INTRODUCTION

In non-seismic region, structures were usually designed based on gravity and notional horizontal loads. However, these structures sometimes will be subjected to relatively larger lateral loads due to long-distance earthquake or ground shock due to explosion. The evaluation of the behavior of these gravity-load-designed (GLD) structures under reversed cyclic lateral loads is necessary and important to ensure the safety of the occupants.

When reinforced concrete frames designed for gravity loads are subjected to lateral loads, the shear force in the joint is much larger compared with shear force in the adjacent members and bond deterioration is prone to occur in the joint. The joint may become the most vulnerable part of the RC frames. Hence, it is important to investigate the strength and deformation of GLD beam-column joint subjected to reversed cyclic lateral loads.

The bond demand in the beam-column joints under lateral loads was found larger than that under gravity loads. To transfer the force from reinforcing bars to concrete, higher bond stress in the joint occurs. If the anchorage is not sufficient, the pull-out of beam longitudinal bars at the beam-joint interface will occur and it will be the main cause of beam fixed-end rotation that can contribute significantly to the overall beam deflection.

The importance of the beam-column joint in GLD structures subjected to lateral loads to the total behavior of the structures has been realised by researchers, and some experimental
studies (Bracci et al., 1992, Aycardi et al., 1992, Li et al., 2002) have been conducted on the shear performance and poor bond condition of these beam-column joints. Analytical study based on these softened joints is very few due to the complexity of the problem.

So far, the performance of the panel under shear and other complex in-plane loads has been studied quite extensively by researchers. Sophisticated material constitutive models have been developed through experiments. Nonlinear finite element analysis programs have been developed based on these models.

Under lateral loads, more force should be transferred from reinforcement to concrete in the joint because forces on the reinforcement at the two opposite sides of the joint are in the same direction, while under gravity loads, these forces are in an opposite direction. Thus, bond stress in the joint subjected to lateral loads is much larger than bond stress in the joint subjected to gravity loads. Slip at the interface of reinforcing bars and concrete may be significant. To be able to simulate the behavior of GLD beam-column joints subjected to reversed cyclic lateral loads accurately, the bond slip between reinforcing bars and surrounding concrete should be modelled properly.

In this paper, a newly developed reinforced concrete double-panel element was used in the finite element analysis. The double-panel element consists of concrete panel and smeared reinforcement panel with bond interface between them. Each concrete and smeared reinforcement panel has eight nodes with two translation degree of freedom at each node and bond effect is modelled in the interface between the two plates as shown in Figure 1.

The main objective of this study is to model and investigate the accuracy of double-panel element in predicting the shear capacity and deformation of gravity-load-designed beam-column joints subjected to reversed cyclic lateral loads. A double-panel element was developed to model the beam-column joint with the bond slip of longitudinal bars. In the double-panel element, nonlinear behavior of concrete and smeared reinforcement panels is described, and nonlinear behavior of bond is modelled between the two panels. Cyclic constitutive laws of concrete, reinforcement and bond are applied so that this element can be used to analyze beam-column joint subjected to reversed cyclic lateral loads.

**ANALYTICAL MODEL**

**Formulation**

**Strong Form**

The equilibrium equations can be developed from the free body of concrete panel and steel bar separately as shown in Figure 2 as

\[
\frac{d\sigma_{sx}}{dx} + \frac{d\tau_{cxy}}{dy} + \frac{4}{d_{bx}} \rho_x \tau_x = 0
\]

\[
\frac{d\sigma_{sy}}{dy} + \frac{d\tau_{cxy}}{dx} + \frac{4}{d_{by}} \rho_y \tau_y = 0
\]

where \(\sigma_{sx}\) and \(\sigma_{sy}\) are the steel stresses in the x- and y-direction, \(\sigma_{cx}\) and \(\sigma_{cy}\) are the concrete normal stresses in the x- and y-directions, \(\tau_{cxy}\) is the concrete shear stress, \(\tau_x\) and \(\tau_y\) are bond stress between the reinforcing bars and concrete in x- and y-directions, \(d_{bx}\) and \(d_{by}\) are the diameter of reinforcing bar in the x- and y-directions, \(\rho_x\) and \(\rho_y\) are reinforcement ratio in x- and y-directions.

In compatibility equations, bond slip \((s_x \text{ and } s_y)\) is defined as the difference of concrete \((u_{cx} \text{ and } u_{cy})\) and reinforcement displacements \((u_{sx} \text{ and } u_{sy})\).

\[
S_x = u_{sx} - u_{cx}
\]

\[
S_y = u_{sy} - u_{cy}
\]
**Weak Form**

Equations (1) to (4) can be expressed as:

\[ \partial_t \sigma + Q_e = 0 \]  

(7)

Weighted integration form of Eq. (7) can be expressed as

\[ \int \delta u^T (x, y) (\partial_t \sigma + Q_e) d\Omega = 0 \]  

(8)

Then, the equation can be simplified as

\[ (K_{sc} - K_b)u = P \]  

(9)

**CONSTITUTIVE MODELS**

The constitutive laws include three parts: the constitutive laws for concrete, reinforcement and interface bond. The constitutive laws for concrete and reinforcement proposed by Maekawa et al (2003) based on fixed crack theory were incorporated in the analysis.

Constitutive laws on concrete consists of concrete compression model including the effect of concrete softening due to crack, tension model including the effect of tension stiffening and concrete shear model based on the contact density theory.

Constitutive law of reinforcing bars is based on the properties of the bar and the effect of bonding between bar and concrete. The average yield stress proposed by Salem and Maekawa (1999) was utilized. The post-yield stiffness, proposed by Shima et al (1987), is expressed in terms of yield stress of plain bar, average yield stress, bond properties of the bar, the strength of concrete, difference in steel ratio in two directions and the angle between the crack and bar axis.

Bond stress-slip relationship proposed by Eligehausen et al (1983) was modified by including the effect of concrete strength and diameter of reinforcement and the peak value of the model was modified as suggested by Soroushian et al (1991). The effect of steel strain observed by Maekawa and Okamura (1991) was incorporated in the bond model. At last the effect of bond deterioration due to crack (Ueda and Sato, 2002) was also taken into consideration.

**VERIFICATION**

**Detail of specimen**

Two full-scale specimens tested by Yin (2001) are used to verify the effectiveness and accuracy of the double-panel element in modeling the behavior of beam–column joints. The specimens comprises of two types of structural details denoted as C1A and C4A. The dimensions and reinforcement details for each specimen are shown in Figures 3(a) and (b).
Compressive axial load equal to 15% nominal axial capacity was applied at columns. The nominal concrete cover of the columns was 40 mm and that of the beams was 25 mm. The compressive strength of concrete $f_{c'}$ was 23.7 MPa, and the Young’s modulus of concrete $E_c$ was 26.2 GPa, while the yield strength $f_y$ of main reinforcement was 500 MPa and 510 MPa for Y32 and Y25 bars, respectively.

Testing arrangement is shown in Figure 4, where the reversed cyclic loading expressed in terms of story drift ratio and beam end deflection as shown in Figure 5 was applied at the ends of the beams. The compressive column axial load was applied at the top of the column by a hydraulic jack. A total of twelve Linear Variable Displacement Transducers (LVDT) were used to measure the total story drift at beam ends, the rigid body rotation at column ends due to the elastic deformation of the testing rig, and the plastic rotation at the beam-joint and column-joint interfaces mainly due to concrete cracking and bond loss between reinforcement and concrete. In the joint panel, the joint shear deformation was captured by installing inclinometers which had a measuring range of ±1.5 degrees. Electrical strain gauges were installed along the main reinforcing bars passing through the joint panel and at a minimum spacing of 150 mm.

In the beam-column joint and adjacent members, bond deterioration may likely to occur when the assemblage is subjected to reversed cyclic lateral loads. Then, these areas are modelled with double-panel element in the finite element analysis. Other areas are modelled with normal panel elements. Between these two elements, transitional elements are used. The finite element meshes are shown in Figure 6. Axial force is applied at top column end, and vertical displacement is applied at beam ends.

RESULTS AND DISCUSSIONS

The comparisons of analytical and experimental column shear force-story drift ratio for the two specimens are shown in Figures 7(a) and 7(b). From the figures, the analytical peak column shear forces are close to experimental results, but the post-peak envelope curves from the analysis descend faster than those from the experiment. Curves of column shear force-story drift in experimental and analytical results both give pinching shapes due to shear and bond dominated behavior. The pinching shape for the experimental results is more obvious.
Contributions of each component to the total story drift of each specimen based on the finite element analysis are shown in Figures 8(a) and 8(b). The contribution of joint shear to the total story drift keeps increasing as the story drift increases. At the total story drift of 3%, the contribution of joint shear is about 50% for these two specimens.

The effect of bond slip modelling on the shear capacity and deformation of the beam-column joints can be seen from Figures 9(a) and 9(b). It is shown that by assuming perfect bond between the reinforcing bars and surrounding concrete, the analysis will overestimate the shear capacity of the beam-column joints by 30-40%. It shows the important of modelling the bond-slip effect in the beam-column joints, especially when the bond deterioration occurs inside the beam-column joints.

CONCLUSIONS

Modelling of GLD internal beam-column joints is presented by using double-panel element to take into account the effect of bond slip between reinforcing bars and surrounding concrete. The model can simulate the behavior of GLD internal beam-column joints reasonably well when compared to the experimental results. The contribution of joint shear to the total story drift can be as high as 50% at the story drift of 3%. It is also shown that perfect bond assumption between the reinforcing bars and surrounding concrete in the joints will overestimate the shear capacity of the joints by 30-40% for the joints considered in this study.

REFERENCES


INTRODUCTION

Historical borehole information is described and presented in different ways in hardcopy site investigation reports. To analyse the voluminous data for valuable information for planning and design through 3D visualization, the hardcopy borehole data must be extracted from records containing borehole information and manually entered into a database that is specifically designed for storage, management, and retrieval of digital borehole data.

DESIGN OF BOREHOLE DATABASE SCHEME

Borehole information comes from multi-disciplinary inputs and thus the information are presented in a heterogeneous manner. The construction industry has begun to present geotechnical information in the AGS file format in recent years. The format has been accepted and implemented by a number of international government bodies and consultants and has paved the way for easy, efficient exchange of site investigation data (Kunapo et al. 2005). The AGS (2004) file format was introduced by the Association of Geotechnical and Geoenvironmental Specialists U.K. back in 1991 in its publication of “Electronic Transfer of Geotechnical Data from Ground Investigations”. The latest format version 3.1 is proposed in an addendum in May 2005.

With the objective of storing and managing data from borehole information in Singapore, we have designed a scalable borehole database based on AGS 3.1 format (Figure 1). Its scheme is based on the simplified representation of the AGS format presented by Ong et al. (2003). The database consists of 25 tables for recording the borehole data. Each table represents a group in AGS format. The tables are linked by key fields. Conceptually, these tables can be classified into three categories, namely (1) general information (2) field observations and in-situ test data and (3) laboratory tests data. Global groups contain generic information such as project information, abbreviations, units, etc. Field-related groups contain field observation and in-situ test data such as in-situ permeability test in the IPRM group, strata description in the GEOL group, etc. All the field data groups are linked directly to the HOLE group which contains information on borehole location, types, names, final depth, and so on. The

![Figure 1. Schema for the borehole database structure](image)
laboratory data groups are linked to the SAMP group which is in turn linked to the HOLE group.

THE INTERFACE FOR BOREHOLE DATABASE

To manually convert hardcopy data in existing borehole information into digital format, an easy-to-use scalable interface called Rock3D_BohManager (a plug-in in 3D Rock – an in-house 3D GIS software for geological information) has been developed using VC++ 6.0 and Microsoft Access database for data entry operation. Figure 2 illustrates the layout of the interface. The “tables” are represented by “tab” control for entering the different kinds of borehole data. Each tab contains a mini-spreadsheet for a specific type of data. For example, the data related to descriptions of project information are entered into the “PROJ” tab.

![Figure 2. Layout of the interface](image)

The interface structure in Rock3D_BohManager is easily customized by the users. The interface also provides import and export functionality in the AGS format file. In addition, it facilitates the entry of data related to the description of lithology defined for Singapore’s geology with a pick-up list in GEOL tab (Figure 3).

![Figure 3. Lithology descriptions in GEOL tab](image)

The Access MDB database that supports the Rock3D_BohManager makes use of RDBMS advantages such as entity relationships (ER), constraints, triggers, and stored procedures to automate the process of data entry and to maintain data integrity. It also enforces several rules to validate the entered data before they are submitted to the geological database for storage.

A SAMPLE OF THE JURONG ISLAND BOREHOLE DATABASE

Rock3D_BohManager was used by us to enter data from two projects in Jurong Island to create a borehole database. The geotechnical data is sourced from information in the investigation records of 29 boreholes - ranging from horizontal, vertical to inclined boreholes. All entered data have been efficiently stored in the Access MDB database; thus allowing us to access and visualize the data readily by using 3D Rock. A sample of 3D visualization of entered data from the Jurong Island projects in 3D Rock is shown in Figure 4. In this manner, geospatial data can also be checked for correctness.

![Figure 4. The 3D visualization of Jurong Island Borehole Database in 3D Rock](image)

CONCLUSIONS

This paper presents the design of a borehole database based on AGS format. Rock3D_BohManager, a data entry interface, is developed for manual entry of borehole data to the Access database. The structure of the database and the layout of the interface are optimized during entry of data from borehole information obtained from the Jurong Island projects and the retrieval of the data in 3D Rock for 3D visualization.

REFERENCES

APPLICATION OF 3D GIS IN ROCK CAVERN

Zhong Zheng (zhongzheng@ntu.edu.sg)
Tor Yam Khoon (cyktor@ntu.edu.sg)

INTRODUCTION

In Singapore, many strategic underground facilities and infrastructures for various military and non-military applications have been developed in recent years. Government organizations and the private construction industry have gathered large amounts of subsurface information during planning, designing and construction stages. Three-dimensional Geographic Information System (3D GIS) is considered a sophisticated 3D digital information system platform for the underground space. The system application can be used to reconstruct 3D models of rock caverns.

3DRock, a 3D GIS, developed with the VC++ programming language, enables the integration, visualization, and analyses of 3D models of rock caverns.

ARCHITECTURE OF 3DROCK

3DROck consists of three parts – the graphic user interface, modules and the database (Figure 1). It contains four basic functional modules – the spatial analysis module, 3D display module, information query module, and the data transfer module. Various modules for other professional demands can also be integrated into 3DROck.

Interactive roaming in virtual caverns and pre-defined path navigation are the primary functions of the system. Basic operations such as pan, scale, and rotation are also featured enhancing the interaction of the system. In addition, 3DROck provides capability for multi-level query of spatial and non-spatial information during the process of dynamic interaction. This feature facilitates easier realization of rock cavern structure. Finally, 3DROck can establish the virtual environment of rock cavern, break through the limitation of professional field by providing flexible Application Program Interface (API), and meet the requirements for archiving structures of rock caverns and conserving historical documents.

SCENE MODELLING AND VISUALIZATION

Geological stratum modelling by multi-DEM algorithm gives rise to a nicer-looking surface and enables an individual surface to be turned on or off and edited. Figure 2 shows the primary result of geological modeling combined with the 3D CAD models of rock cavern.

Figure 1. Architecture of the 3DROck system

Figure 2. Integration of underground cavern infrastructure and geological information
A 3D CAD model has become a more important data source for 3D GIS due to the technical predominance of CAD in graphic process and real-3D modelling. An accurate and complex scene model is made up of a huge number of triangles such as a mesh generated from the point cloud obtained from terrestrial laser scanning (Figure 3), but it is difficult for even the most advanced graphics computers to display the scene at smooth frame rates. Level of Details (LOD) algorithm is used to reduce the complexity of the scene through decreasing the quantity of triangles and vertexes.

A modelling approach on discrete LOD is chosen for this system. Used for the mesh are these four discrete LODs:

(a) **Special Level** (SL) is only used in the representation of the structure model. It is the finest model as it contains the whole structure and all its textures. It thus supports indoor interaction and querying the attributes of single components.

(b) **High Level** (HL) expresses the appearance of a structure (as the SL does) through using model and texture.

(c) **Middle Level** (ML) is created on the basis of HL through manually reducing the quantity of an object’s triangles and vertexes as well as modifying the sizes of textures.

(d) **Low Level** (LL) is the simplest model in all of the LODs. It only represents the simplest models of a structure by textures.

**INTEGRATED DATABASE MANAGEMENT**

It is important to establish an appropriate spatial index in order to accelerate calling and invoking 3D vector model data for a metadata scene (Li, 2003). Spatial index is regarded as a sort of spatial data structure and the spatial objects not related to a given spatial operation are excluded from the more efficient operation. LOD-R-tree is perfectly suitable for organizing and managing large amount of 3D data. It is designed to organize 3D data in this system. As shown in Figure 4, the mesh of tunnel in the scene are subdivided into top Triangular Irregular Networks (TIN), floor TIN, and side TIN parts according to the different detailed representation for establishing LOD-R-tree index. Each part can be further divided into several TINs which are made up of many triangles. The approach of disassembling models not only satisfies the requirement of establishing the spatial index as LOD-R-tree, but the approach also serves the purpose of 3D space partitioning. Moreover, the 3D data organized in LOD-R-tree contributes to smooth real-time rendering of photorealistic images so that it meets the requirements of multi-scale spatial query and spatial analysis by integrated applications of database management techniques.

An independently developed 3D model Database Management Engine (DBME) which is based on the integration of Oracle 9i database and file management system (FMS) is adopted by us for the system. Oracle 9i database provides an open management mechanism for spatial data through an interface designed to manage and manipulate spatial data, and it has the full capacity of RDBMS (relational database management system), so that storing, calling, and analyzing of spatial data are faster and more efficient than before. Tables created within the Oracle 9i database can be assembled to store model components including information about nodes, elements, and calculations at a given time step. On the other hand, it is well known that FMS has some characteristics such as flexibility, speed, generality, and high independency. FMS adapts to the management of isolated files such as audio and video files. Therefore, the ideal combination of Oracle 9i and FMS allows for efficient management and rendering of the data within the 3D GIS visualization environment.

**CONCLUSIONS**

This paper presents the implementation of a 3D GIS for rock caverns which is capable of storing, accessing, and visualizing effectively all 3D geological data through an integrated database. It is eminently suited for archiving the accurate 3D documentation of rock caverns. A modelling approach integrating LOD and CAD is also presented.

**REFERENCES**

A STUDY OF DRIVER COMPLIANCE TO SIGNALLING DURING LANE CHANGING

Lum Kit Meng (ckmlum@ntu.edu.sg)

BACKGROUND

Driving is a highly complex task that requires continual integration of perception, cognition and motor response. Among the various subtasks, lane changing is the one that incorporates many of the critical aspects of driving, such as controlling the vehicle at the lower level, monitoring of the current traffic situation and making decision on when to perform lane changing. It is also reported that this decision-making process is further influenced by other behavioural and environmental factors. Besides, signalling also plays an important part as it gives advanced information and warns other road users of the driver’s intention. In many countries, there are traffic laws and regulations that specifically ensure that drivers switch on their signals before changing lane. Despite the vast attention given to the general nature of driving and law enforcement, there is a lack of research interest on lane changing. It is therefore the intent of this study to evaluate the various factors influencing driver compliance, especially signalling during lane changing.

RESULTS AND DISCUSSIONS

The video recordings which captured the traffic characteristics and signalling of drivers prior to lane changing at a number of selected arterial roads were reduced and the data assembled. Based on the assembled data, the effects of various pertinent variables on signalling prior to lane changing were analysed and discussed as follows:

Types of Vehicle Driven

From Figure 1, it is apparent that car drivers had the lowest proportion who would switch on the signals before changing lane. Only 648 out of 1,829 car drivers (or 35%) had switched on their signals while changing lane. Car drivers were observed to make lane changes with fewer difficulties and much swifter. Perhaps due to these inherent advantages over other vehicles, car drivers were less reluctant to switch on their signals and constituted the highest proportion. The next group with the large proportion of drivers not switching on their signals was taxi drivers. This is expected as taxi drivers are more attentive in looking for commuters and less diligent in switching on their signals. Bus and heavy goods vehicle drivers observed the rules somewhat better, which could be due to their vehicle sizes and slowness in changing lane. Lastly, a Chi-Squared test indicated that there was a statistically significant relationship between signalling for lane changing and vehicle types driven (p-value = 0.001).

Effects of Vehicles Tailgating

The results in Figure 2 demonstrate the driver’s responsiveness and awareness when their vehicles were being tailgated by a following vehicle. Fifty-eight percent of drivers would switch on their signals when they were aware of vehicles tailgating them. It is also noted that 713 out of 1,233 drivers would choose to switch on their signals when they were followed closely by other vehicles. Interestingly, the same percentage (58%) of vehicles out of the 1,893 changed lanes without signalling when it was observed that no vehicle was tailgating them. A Chi-Squared test indicated that there was a statistically significant relationship between signalling for lane changing and vehicle types driven (p-value < 0.01). This finding also demonstrated the drivers’ consciousness and fear of being hit by a closely-followed vehicle. This behaviour is particularly noticeable when drivers slowed down their vehicles while approaching the right-turning exclusive lane to execute their turns.
TRANSPORTATION

Purpose of Lane Changing

Figure 3 shows a consistent trend of vehicles not switching on the signals regardless of their purposes in changing lane, that is, 1,893 out of a total 3,126 drivers not switching on their signals. One distinct exception was found when vehicles were turning at junctions. These drivers were seen to be more readily switching on their signals while approaching the turning lanes. In such cases, some drivers would even make multiple-lane changing to get to their desired lane. It could also be due to the necessity of lane changing manoeuvres, where drivers had indicated their turn signals more promptly as compared to other situations. Repositioning in queues had the least number of vehicles switching on their signals. These drivers were seen to drive forward at clawing speed when they observed that there was a shorter queue in the adjacent lane. It could partly be due to the bigger gap in the adjacent lane and slower speed that had resulted in drivers not switching on their signals. Lastly, a Chi-Squared test indicated that there was a statistically significant relationship between signalling for lane changing and reasons for changing lane (p-value < 0.010).

CONCLUDING REMARKS

Within the context of the experimental design, the findings generally indicated that slightly more than half of the vehicle drivers surveyed along arterial roads had performed signalling prior to lane changing. Worst still, only one in three car drivers did so. This is totally unacceptable and a poor driving culture at large. As stated in the Road Traffic Act of Singapore, it is mandatory to signal your vehicle prior to changing lane. Signalling is to forewarn other road users of his intention, and safety could thus be enhanced. Without doing so, it demonstrates a lack of safety consciousness on the part of drivers.

STUDYING DRIVERS’ PARKING DECISIONS USING A DYNAMIC PARKING SIMULATOR

Tan Yan Weng (cywtan@ntu.edu.sg)
William Young (Bill.Young@eng.monash.edu.sg)

INTRODUCTION

The provision of off-street, multi-storey parking systems is an important means of achieving better use of road space for the movement of vehicles, especially in areas where land supply is limited and land values are at a premium. While the problems associated with parking are not new, the parking landscape has changed in recent years. One change is that urban developments are increasingly mixed use; they contain different land uses offering a diverse range of goods and services. Integrated developments with combinations of office, shopping, entertainment and residential uses are not uncommon in many cities. Another change is the emergence of Advanced Parking Management Systems (APMS) that can potentially improve traffic flow by providing drivers with real-time information on parking space availability and helping them to make more informed choices. This paper presents the development of a PC-based dynamic parking simulator that is being used to study drivers’ parking decisions in multi-storey car parks of urban developments.

THE EPSILON SIMULATOR

The EPSILON (Evaluation of Parking Systems using m[icro]simulation on a Local r[oad] N[etwork]) simulator is integrated with a discrete event, microsimulation model. The microsimulation model that interfaces with the simulator treats traffic and parking by considering the movement of individual vehicles over small time increments through the application of car-following, lane-changing, give-way and parking procedures (Figure 1). The main advantage of the simulator approach is the ability to control experiments and to repeat them as often as desired, providing a potentially rich source
of inexpensive data. It also offers a safe method of measuring parking behaviour, which is otherwise very difficult and hazardous to collect in the real world. Further, by mounting the simulator on a portable notebook PC, experiments can be conducted outside the confines of the laboratory and on a wider, sample of the driving population. Subjects taking part in the simulator experiments become part of the simulation as they exert control over one vehicle in the simulated world (Figure 2). While ‘driving’ in the simulator, subjects can interact dynamically with other vehicles. Other vehicles can also interact with the subject-controlled vehicle, and as a result of these interactions, influence traffic and parking conditions.

MODEL CALIBRATION AND APPLICATION

Proper representation of model parameters is important as it reflects the driving environment and influences the vehicle movement. Drivers travelling in enclosed spaces have been found to be significantly constrained by geometric characteristics. The following equation, calibrated from 8 multi-storey car park sites, is applied to estimate the mean circulation speed (in km/h) of vehicles within a multi-storey car park:

\[
V_c = 7.597 + 0.212LL + 1.759\text{VTYPE} \quad (R^2=0.87) \tag{1}
\]

where \( LL \) is link length and \( \text{VTYPE} \) is a dummy variable (\( \text{VTYPE} = 1 \) if vehicle is a car, zero otherwise).

Packing and unparking manoeuvres can impede the movement of through vehicles in circulation and affect the dynamic capacity of the car park. Observational surveys were conducted to measure the parking/unparking times of a random sample of vehicles at three multi-storey car parks in the Singapore CBD. The use of the log-normal distribution provided a good fit to the observed values using the KS test at 5% level of significance. As such, the model randomly assigns a time required to make each manoeuvre, computed by sampling from the log-normal distribution.

The model was applied to The Heeren Shopping Centre car park to test the ability of the procedures to simulate movement and parking. This shopping centre is located within the Singapore CBD and contains a good mix of offices, retail shops and restaurants. The car park is underground with three parking decks (levels B2, B3 and B4; level B2 is the first basement level upon entry). Each parking level measures around 70 m by 56 m in area. The coded network comprises 47 nodes, 56 road links, 6 walk links and 165 spaces. Over 100 objects were added to represent building columns, walls and external structures.

Traffic and parking conditions in the car park were simulated over a 16-hour period (06:00 to 22:00). The first hour was treated as the ‘warm-up period’ using short parking durations; output from this hour was excluded in the analysis. The second hour was used to ensure that the initial accumulation was similar to the actual value. Inputs for the O-D matrix, trip purpose and vehicle type proportions, and parking duration were obtained from on-site surveys conducted on a typical Saturday. Parking strategies were randomly assigned to drivers based on the following split:

(i) 20% of drivers minimise their perceived drive time;
(ii) 40% minimise their perceived walk time; and
(iii) 40% minimise their combined perceived drive and walk times. The model was run five times with different random seed numbers and the results were averaged over five runs.

Figure 3 compares the observed hourly parking accumulation (i.e. spaces occupied) at the three parking levels recorded from the parking patrol survey with those predicted by the model. It can be seen that most points lie reasonably close to the line of perfect agreement. The results are encouraging given that the data on trip purpose and parking duration were rather sparse and not available for certain intervals as a result of survey constraints; duration values from other intervals were applied where data were unavailable. These partly contributed to the differences between the observed and modelled results.

CONCLUSIONS

This article presents the development of a PC-based dynamic parking simulator that forms part of an on-going research to study drivers’ parking decisions in multi-storey car parks. The simulator provides an economical, safe and efficient means of data capture through controlled experiments. It attempts to re-create the travel experience of driving along the accessway, queuing at the entry/exit gate (if necessary), searching for a parking space, manoeuvring to the space and walking to the final destination. An important feature of the simulator is that it interfaces with a microsimulation model so that the traffic and parking conditions are the consequences of the interactions between the subject-controlled vehicle and other vehicles in the simulation.
PERFORMANCE CHARACTERISTICS OF HOT-MIX ASPHALT WITH RECYCLED CONCRETE PIPE PRODUCTION RESIDUE

Tan Peng Hoe (ta0001oe@ntu.edu.sg)
Wong Yiik Diew (cydwong@ntu.edu.sg)

INTRODUCTION

Despite the aggressive promotion of waste minimisation and recycling programmes initiated by National Environment Agency (NEA), recycling rate of waste alkaline materials (WAM) such as concrete pipe production residue (CPPR) and cement kiln dust (CKD) is not high [1]. Some WAM continues to be disposed of at Pulau Semakau Landfill without any further reuse or reclamation. Coupled with the “producer pay” principle adopted by Singapore government to reduce waste by charging fee based on the disposal tonnage, disposal of WAM at landfill is increasingly becoming less favourable. A possible solution to this problem is incorporating WAM as partial replacement material of mineral granite in hot-mix asphalt (HMA).

On the other hand, the escalating urban redevelopment activities as presented in the Concept Plan 2001 [2] and booming growth in Singapore’s construction industry have posed a shortage in the supply of granite aggregate. Thus, the use of WAM in HMA can reduce the exploitation of granite aggregate as well as solving the WAM disposal problem while ensuring sustainable construction. So far, research into the recycling of WAM in asphalt industry, such as those conducted by Taha et al. [3], has focused more on the use of CKD as a substituting component in HMA [4]. There is yet much data available on the utilisation of CPPR as a constituent material of HMA. Thus, this study shall focus on feasibility of using CPPR as a potential constituent material of HMA.

MATERIALS AND EXPERIMENTAL METHODS

Materials

The asphalt binder of penetration grade 60/70 used in this study was kindly supplied by Shell Bitumen Singapore. The granite aggregates in various sizes were from Indonesia. The CPPR was derived from tailings in the pipe-spinning process, and was collected in its slurry state from Bilcon Industries Pte Ltd. The CPPR was air-dried for a week which produced a substantial quantity of fines through simple hand crushing and machine grinding. Only CPPR particles below 75µm (fines) was used in this study as the substituting component in HMA.
TRANSPORTATION

X-ray Diffraction (XRD) Analysis

The chemical-crystallographic composition of CPPR was studied using Powder X-ray Diffraction (XRD) analysis. XRD is a versatile, non-destructive technique for examining chemical-crystallographic structure of solids with application of Bragg’s law of diffraction. The XRD test on the CPPR sample was performed using a Bruker AXS D8 Advanced X-ray diffractometer with setting of 5°-80° two theta range and 2°/s step size. Knowing the chemical-crystallographic composition of CPPR shall provide a more fundamental understanding of its contribution towards the performance of HMA.

Specimen Preparation and Testing

Marshall specimens were prepared with 6% CPPR fines substitution of granite fines (size below 75 µm) with size distributions conforming to the Land Transport Authority (LTA) W3B Mix Specification. The Marshall method, developed by the U.S. Corp of Engineers, is currently the most widely used method in determining optimum binder content of HMA. The Marshall Test was conducted in accordance with ASTM 1994 D1559-89 method [5].

Two series of W3B-CPPR hybrid Marshall specimens were manufactured, the first series at varying binder contents to determine the optimum binder content, and the second series at the optimum binder content to investigate the creep and resilient modulus characteristics. The results for W3B-CPPR hybrid mixes were then compared with those determined from conventional W3B HMA mix.

The dynamic creep test was used to study creep characteristics by applying a repetitive compressive loading to simulate traffic loading [6,7]. The specimens were warmed to 50 ºC for two hours to simulate the high operating ambient temperature under Singapore environment. The Materials Testing Apparatus (MATTA) manufactured by IPC Ltd. Australia was used in both dynamic creep and modulus tests.

The resilient modulus ($M_r$) test is a non-destructive test that can be used to investigate the stiffness of the specimens as well as to generate input (load spreading capacity) for pavement design or pavement evaluation and analysis. The 5-pulse indirect tensile test specified by Australian Standard (AS 2891.13.1-1995) was performed to determine the resilient modulus [8].

RESULTS AND DISCUSSION

Physical Characteristics of Concrete Pipe Production Residue (CPPR)

CPPR is a fine powder upon air-drying and is off-white to fawn or light brown in colour. It has a specific gravity of 1.67, lower than the granite fines with specific gravity of 2.54, thereby resulting in a lower aggregate blend density of 2.465 g/cm³ compared to all-granite blend density of 2.59 g/cm³.

XRD Analysis

Figure 1 reveals that the CPPR sample consisted mainly of quartz 78-2315 ($\text{SiO}_2$), portlandite 44-1481 ($\text{Ca(OH)}_2$) and calcite 05-0586 ($\text{CaCO}_3$).

Marshall Mix Design

Stability, flow, air voids in total mix (VTM), voids in mineral aggregate (VMA) and voids filled with binder (VFB) are the five determining parameters of optimum binder content. The binder content of the W3B-CPPR hybrid mix at 5.25% was found to satisfy all the mix design criteria stipulated by LTA, and 5.25% was thus adopted as the optimum binder content. This optimum binder also lies within the 4.5-5.5% range for conventional W3B mix.

Dynamic Creep Test

The dynamic creep test results which can serve as a means of evaluating the rutting potential of HMA are shown in Figures 2 and 3. Generally, high creep-resistant HMA will achieve higher pulse counts (or number of load applications) at a specified micro-strain $\varepsilon_n$ (or permanent deformation). Five W3B-CPPR specimens were fabricated for testing purpose with three specimens tested shortly after fabrication, and the remaining two specimens tested after being aged for two months. The pulse counts for each specimen are tabulated in Table 1.
TRANSPORTATION

From the test results shown in Table 1 and plotted in Figures 2 and 3, the un-aged W3B-CPPR specimens had relatively lower pulse counts at the minimum slope point and at 10,000 \( fn \) than conventional all-granite W3B specimens but the pulse counts at 30,000 \( fn \) were comparable. This implies that substituting granite fines with CPPR can produce comparable creep resistance (and rutting) in the HMA.

The two W3B-CPPR specimens that were aged for two months (W3B-CPPR4 and W3B-CPPR5) had comparatively higher average pulse counts. The higher creep resistance may be due, in part, to solidification of CPPR fines inside the HMA during the aging process thereby producing a stiffer interlocking matrix. Another contributing factor would be the slightly lower VTM in both specimens given that better creep resistance can be expected for densely compacted mix. The specific reasons for the better creep performance in the aged W3B-CPPR specimens are therefore not definitive, and further investigation such as scanning electron microscope (SEM) analysis is recommended.

### Resilient Modulus Test

The resilient modulus test measures the stiffness of the material and gives a rough estimation of mixes’ response to moving wheel loads. The 5-pulse indirect tensile test on W3B and W3B-CPPR specimens are shown in Table 2. Both the conventional W3B mix and the hybrid mix incorporating 6% CPPR gave comparable modulus values. This shows that partial replacement of granite fines with CPPR does not

### Table 1. Dynamic creep test results

<table>
<thead>
<tr>
<th>Type of mix</th>
<th>VTM (%)</th>
<th>Pulse counts at min. slope</th>
<th>Pulse counts at 10,000 ( fn )</th>
<th>Pulse counts at 30,000 ( fn )</th>
</tr>
</thead>
<tbody>
<tr>
<td>W3B (5.0% binder)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C1</td>
<td>3.10</td>
<td>1032</td>
<td>1709</td>
<td>4184</td>
</tr>
<tr>
<td>C2</td>
<td>3.24</td>
<td>1752</td>
<td>1332</td>
<td>5221</td>
</tr>
<tr>
<td>C3</td>
<td>2.95</td>
<td>2275</td>
<td>3570</td>
<td>6919</td>
</tr>
<tr>
<td>Average</td>
<td>3.09</td>
<td>1678</td>
<td>2204</td>
<td>5442</td>
</tr>
<tr>
<td>W3B-CPPR (5.25% binder)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CPPR1</td>
<td>3.22</td>
<td>1288</td>
<td>1719</td>
<td>6219</td>
</tr>
<tr>
<td>CPPR2</td>
<td>3.25</td>
<td>928</td>
<td>1513</td>
<td>4656</td>
</tr>
<tr>
<td>CPPR3</td>
<td>3.25</td>
<td>1296</td>
<td>1043</td>
<td>4553</td>
</tr>
<tr>
<td>Average</td>
<td>3.24</td>
<td>1171</td>
<td>1425</td>
<td>5142</td>
</tr>
<tr>
<td>W3B-CPPR (Aged for 2 months; 5.25% binder)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CPPR4</td>
<td>2.45</td>
<td>5504</td>
<td>4172</td>
<td>17601</td>
</tr>
<tr>
<td>CPPR5</td>
<td>2.81</td>
<td>3472</td>
<td>3425</td>
<td>11469</td>
</tr>
<tr>
<td>Average</td>
<td>2.63</td>
<td>4488</td>
<td>3799</td>
<td>14535</td>
</tr>
</tbody>
</table>

### Table 2. Resilient modulus results

<table>
<thead>
<tr>
<th>Type of Mix</th>
<th>Specimen</th>
<th>VTM %</th>
<th>Resilient Modulus (MPa)</th>
<th>Average Resilient Modulus</th>
</tr>
</thead>
<tbody>
<tr>
<td>W3B</td>
<td>1</td>
<td>3.10</td>
<td>3376</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>3.24</td>
<td>2834</td>
<td>3108</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>2.95</td>
<td>3113</td>
<td></td>
</tr>
<tr>
<td>W3B-CPPR</td>
<td>2</td>
<td>3.22</td>
<td>2772</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>3.25</td>
<td>2973</td>
<td>3035</td>
</tr>
</tbody>
</table>

Figure 2. Creep profile of conventional W3B HMA

Figure 3. Creep Profile of W3B-CPPR HMA
compromise the resilient modulus property in the HMA.

**CONCLUSIONS**

XRD analysis revealed that CPPR consisted of mainly quartz 78-2315 (SiO$_2$), portlandite 44-1481 (Ca(OH)$_2$) and calcite 05-0586 (CaCO$_3$). The HMA incorporating 6% CPPR fines (W3B-CPPR) hybrid mixes with optimum binder content of 5.25% satisfied all LTA Marshall design criteria. The creep and resilient modulus characteristics of hybrid mix were comparable with conventional W3B mix, suggesting the feasibility of CPPR as a replacement material for granite in local HMA application. Future work shall entail additional investigations into the performance of aged W3B-CPPR hybrid mix, and wheel tracking test to study rutting performance.

**REFERENCES**


INTRODUCTION

Breakwaters that are in the form of vertical slotted barriers allow the exchange of seawaters between harbors and open seas, especially the water exchange forced by tidal currents and the wind-driven currents. The gaps in the slotted walls may also allow fish to pass through, reducing the adverse impact of traditional breakwaters on the ecosystem inside harbors. A brief review on the wave interaction with double slotted barriers can be found in reference [1]. The construction cost for this type of breakwaters can be lower than the traditional rubble mound breakwaters in relatively deep waters. For example, slotted breakwaters can be ideal candidates in the protection of very large floating structures (VLFS) such as near-shore large floating airports that might extend offshore to a considerable water depth. Understanding the wave scattering by slotted barriers in the presence of a steady current is important to the economical design of this type of breakwaters. Reported here are a series of experiments for the cases where steady currents are opposing incident water waves.

EXPERIMENTAL SET-UP

The experiments were conducted in a wave-current flume. The glass-walled wave flume is 15.0m in total length, 0.3m in width and 0.5m in depth. A pump-pipe system provided a re-circulating current $U$ that was opposing the incident waves generated by a wave generator. Double slotted barriers, made of rectangular aluminum bars, were placed about 3m away from a wave absorber. The thickness of each bar was $b = 0.006m$, and the width was $w = 0.02m$. The porosity of each slotted barrier was 0.2. In the experiments, the distance between the two slotted barriers (chamber width $B$) could be adjusted from 0.1m to 0.8m. The still water depth was fixed at $h = 0.2m$ in the experiments. The experimental set-up is shown in Figure 1.

RESULTS AND DISCUSSIONS

The effects of wave length $L$ (or wave frequency) on the wave reflection and transmission coefficients are shown in Figure 2 and Figure 3, respectively, where the theory for $U = 0$ is reported in [2]. The wave period was fixed at $T = 1.1s$. Two steady currents were studied.

Without current, there is an obvious variation of the reflection coefficient with relative wave length $B/L$. The minimum reflection coefficient occurs at about $B/L = 0.25$; while the maximum reflection coefficient occurs at $B/L = 0.5$. For waves on weak opposing currents, the reflection coefficient varies with $B/L$ in a way similar to that without current, except that the reflection coefficients in the presence of the opposing current are slightly greater than those without current.

Experiments also showed that the opposing current can significantly reduce the transmission coefficient. Thus the design of slotted breakwaters based on the study for pure waves is conservative. The reduction in the transmission coefficient is due to the current-enhanced wave energy loss. With and without currents, the variation of the transmission coefficients with the relative wave length $B/L$ is not significant. This feature has important implication for the design of the slotted breakwaters; as far as the transmission coefficient is concerned, the slotted barrier can be designed with any reasonable chamber width.

As the opposing current does not significantly alter the reflect coefficient, the steady current does not worsen the sourcing due to the reflected waves. Since the steady current can remarkably reduce the transmission coefficient, it is possible to design slotted barriers with increased gaps without significantly increasing the transmission coefficients when the effects of the current are taken into consideration.
WATER RESOURCES

CONCLUSIONS

1. Steady opposing currents can significantly increase the wave-energy loss induced by double slotted barriers and remarkably reduce the wave transmission through the barriers.

2. It is suggested that coastal currents should be taken into consideration for an economical design of slotted breakwaters.

REFERENCES


INTRODUCTION

Aquatic vegetation affects turbulence properties and momentum transfer in open-channel flows and thus the fate and transport of sediments and contaminants [1]. The existing studies of vegetated flows show that the early 1D model is not suitable for detailing the relevant mechanisms of turbulence and momentum transfer. The structure of vegetated open channel flows depends on several factors including flow depth and flexibility and arrangement of vegetation [3][4][5]. However, their effects have not been adequately investigated. This study attempted to experimentally investigate properties of vegetated open channel flows with different vegetation sizes and densities.

METHODOLOGY

Experiments were conducted with an array of rigid rods placed on a flume bottom to simulate vegetation. Both the arrangement of rods and the flow depth varied as a steady flow was generated in the flume as sketched in Figure 1. The data collected were further processed to examine the flow pattern and effects of several relevant factors.

Four test configurations, AS60, BS60, BS30 and CS30, were prepared. Here A, B and C denote the rod diameter, 3 mm, 6.8 mm and 8.2 mm, respectively, S represents the triangular rod arrangement on the channel bottom, and the number indicates the smallest rod-rod distance in mm. All the rods used measured 100 mm in height, while the flow depth varied from 90 to 200 mm, thus simulating both emerged and submerged vegetations.

PIV MEASUREMENTS OF VEGETATED OPEN CHANNEL FLOWS

Liu Xiaozhen (xzliu@ntu.edu.sg)
Cheng Nian Sheng (cnscheng@ntu.edu.sg)
Wang Zhiqian (zqwang@ntu.edu.sg)
Tan Soon Keat (ctansk@ntu.edu.sg)

Figure 1. Experimental Set up

Figure 3. Variation of transmission coefficient with relative wave length B/L
RESULTS AND DISCUSSION

Altogether 48 cases were investigated but only some results are presented because the others show similar information. Here, we use the longitudinally-averaged velocity, $U_x$, the laterally-averaged velocity, $U_z$, and the plane-averaged velocity, $U_{xz}$, to characterize flows in the presence of various vegetation conditions.

Figures 2 and 3 show the longitudinally-averaged and laterally-averaged velocity profiles for Case AS60, respectively. The flow depth was 180 mm while the vegetation height was 100 mm. It is noted that the transverse variation of $U_x$ is significant within the vegetation, in comparison to the longitudinal variation of $U_z$.

Shown in Figure 4 is a comparison of plane-averaged velocity profiles for Case AS60. The velocity is scaled by $U_b$, the average velocity near the channel bottom, which is not influenced by the flow above the vegetation and also the bottom friction. The flow depth varies from 90 to 200 mm. Two zones can be generally identified within the vegetation [3]. The flow velocity appears uniform in the lower part, which is referred to as “longitudinal exchange zone”. The velocity increases, because of the above-vegetation effect, in the upper part called “vertical exchange zone”. Above the vegetation, the velocity is affected by the flow depth. Similar phenomena can also be observed in Figures 5, 6 and 7.

Furthermore, by comparing Case AS60 with Case BS60 and Case BS30 with Case CS30, we also notice that the mean velocity profile is also influenced by the rod diameter.
The effect of vegetation density can be observed by comparing Figure 5 for Case BS60 with Figure 6 for Case BS30. However, it seems that such effects are independent of the rod diameter, as illustrated by the similar variations shown in Figures 4 and 5 and also those in Figures 6 and 7.

CONCLUSIONS

In the presence of vegetation, the average velocity varies more significantly in the transverse direction than in longitudinal direction. Within the vegetation, two exchange zones exist, one being characterized by constant near-bed velocity and the other being strongly influenced by the above-vegetation flow. The rod diameter and vegetation density play different roles in the plane-averaged velocity profiles above the vegetation.

REFERENCES


EFFECT OF CHANNEL SHAPE ON TIME OF TRAVEL IN CHANNEL

Tommy Wong Sai Wai (cswwong@ntu.edu.sg)

INTRODUCTION

For a catchment comprising a network of open channels and overland planes, the time of travel in the channels have profound effects on the runoff characteristics of the catchment. For channels with a long time of travel, the catchment concerned will have a long time of concentration. For this catchment, the design rainfall intensity derived from...
the rainfall intensity-duration-frequency curves will be small. Hence, the catchment outflow will also be small. Conversely, for channels with a short time of travel, the catchment outflow will be large. Intuitively, the shape of the channels must have an effect on the time of travel. Hence, the channel shape can be used as a means to manage the runoff from a catchment. In this article, based on the kinematic wave theory, the effect of channel shape on the time of travel is compared for seven channel shapes. The channels are subject to a uniform lateral inflow and a constant upstream inflow. The seven channel shapes are (a) square, (b) wide rectangular, (c) deep rectangular, (d) triangular, (e) vertical curb, (f) parabolic, and (g) circular, as shown in Figure 1.

\[ t_{ts} = \text{time of travel in a square channel.} \]

\[ t_{tw} = \text{time of travel in a wide rectangular channel,} \]

\[ \mu_e = \text{dimensionless flow depth ratio which relates the normal flow depth, } y_e, \text{ at the end of the channel at equilibrium to } W, \text{ as follows:} \]

\[ \lambda = \text{dimensionless inflow ratio which relates the upstream inflow, } Q_u, \text{ to the lateral inflow, } q, \text{ as follows:} \]

\[ L = \text{length of channel.} \]

\[ t_{td} = \text{time of travel in a deep rectangular channel.} \]

\[ t_{tt} = \text{time of travel in a triangular channel, and } z = \text{reciprocal of the side slope of the channel.} \]

\[ t_{tv} = \text{time of travel in a vertical curb channel.} \]

\[ t_{tp} = \text{time of travel in a parabolic channel.} \]

Figure 1. Channels of seven shapes: (a) square \((y = W)\); (b) wide rectangular \((y << W)\); (c) deep rectangular \((y >> W)\); (d) triangular; (e) vertical curb; (f) parabolic; (g) circular

TIME OF TRAVEL RATIOS

In order to compare the time of travel for the seven channel shapes on a unified basis, the square channel has been chosen as a constant. In the comparison, the channels are subject to the same lateral inflow and the upstream inflow, and except for the channel shape and size, all the other channel properties are also the same. Dividing the time of travel formula of the seven channel shapes by the time of travel formula of the square channel give the following time of travel ratios:

(1) The time of travel ratio for the square channel, \( t_{ts} / t_u \), is:

\[ t_{ts} = 1 \]

(2) The time of travel ratio for the wide rectangular channel, \( t_{tw} / t_u \), is:

\[ t_{tw} = 0.577 \left[ \frac{(1+2\mu_e^2)}{\mu_e} \right]^{1/20} \frac{(\lambda+1)^{3/4} - \lambda^{3/4}}{(\lambda+1)^{1/4} - \lambda^{1/4}} \]

(3) The time of travel ratio for the deep rectangular channel, \( t_{td} / t_u \), is:

\[ t_{td} = 0.917 \left[ \frac{1}{(1+2\mu_e^2)} \right]^{1/2} \left[ \frac{1}{\lambda+1} \right]^{1/4} \left[ \frac{1}{(\lambda+1)^{1/4} - \lambda^{1/4}} \right] \]

(4) The time of travel ratio for the triangular channel, \( t_{tt} / t_u \), is:

\[ t_{tt} = 0.816 \left( \frac{1+z^2}{z} \right)^{1/4} \]

(5) The time of travel ratio for the vertical curb channel, \( t_{tv} / t_u \), is:

\[ t_{tv} = 0.685 \left[ \frac{1+\sqrt{1+z^2}}{z} \right]^{1/4} \]

(6) The time of travel ratio for the parabolic channel, \( t_{tp} / t_u \), is:

\[ t_{tp} = 0.883 \left[ \frac{\mu_e \sqrt{(1+\mu_e)}}{\mu_e} \right]^{1/2} \left( \frac{1+\lambda}{1+\lambda} \right)^{1/2} \left( \frac{(1+\lambda)^{1/4} - \lambda^{1/4}}{(1+\lambda)^{1/4} - \lambda^{1/4}} \right) \]

where \( t_{ts} \) = time of travel in a square channel.

where \( t_{tw} \) = time of travel in a wide rectangular channel,

where \( \mu_e \) = dimensionless flow depth ratio which relates the normal flow depth, \( y_e \), at the end of the channel at equilibrium to \( W \), as follows:

where \( \lambda \) = dimensionless inflow ratio which relates the upstream inflow, \( Q_u \), to the lateral inflow, \( q \), as follows:

where \( L \) = length of channel.

where \( t_{td} \) = time of travel in a deep rectangular channel.

where \( t_{tt} \) = time of travel in a triangular channel, and \( z \) = reciprocal of the side slope of the channel.

where \( t_{tv} \) = time of travel in a vertical curb channel.

where \( t_{tp} \) = time of travel in a parabolic channel.
The time of travel for the circular channel, $t_c / t_s$, is:

$$
t_c = \frac{0.946 \left( \left( \frac{\lambda + 1}{\lambda} \right)^{1/4} - \lambda^{1/4} \right)}{t_s}
$$

(9)

where $t_c$ = time of travel in a circular channel.

**EFFECT OF SEVEN CHANNEL SHAPES ON TIME OF TRAVEL**

Derived from Eqs. (1), (2), and (5)-(9), Figure 2 shows the $t_c / t_s$, $t_w / t_s$, $t_d / t_s$, $t_t / t_s$, $t_v / t_s$, and $t_p / t_s$ curves, for $\lambda = 0-2$. For the triangular and vertical curb channels, three values of $z$ are selected. They are $z = 0.2$, 1, and 5 representing channels with steep, medium and mild side slope, respectively. For the rectangular and parabolic channels, three values of $\mu_e$ are selected. They are $\mu_e = 0.1$, 1 and 10 representing channels with small, medium and large flow depth, respectively.

In practice, except for the most upstream reach, all channels have upstream inflow. Hence for the channels with upstream inflow, the ones that produce longest time of travel are the deep rectangular ($\mu_e = 10$) and the vertical curb with steep side slope ($z = 0.2$). Hence, the use of these channels produce smaller catchment outflow. The channel that produce shortest time of travel is the parabolic channel with large flow depth ($\mu_e = 10$). Hence, the use of this channel produces larger catchment outflow. For the remaining channel shapes, they produce medium times of travel. They are the triangular, the parabolic with small and medium flow depths ($\mu_e = 0.1$ and 1), the circular, the square, and the wide rectangular ($\mu_e = 0.1$).

**CONCLUSIONS**

By means of the derived formulae, the effect of channel shape on the time of travel for seven channel shapes have been compared on a unified basis. The comparison shows that for channels with upstream inflow, the channels that produce the longest time of travel are the deep rectangular, and the vertical curb with steep side slope. Hence, the use of these channels produce smaller catchment outflow. The channel that produces the shortest time of travel is the parabolic channel with large flow depth. Hence, the use of this channel produces larger catchment outflow.

Figure 2. Effect of seven channel shapes on time of travel
WATER RESOURCES

EFFECT OF GRID TURBULENCE ON PARTICLE SETTLING

Zhou Qi (zhou0044@ntu.edu.sg)
Cheng Nian Sheng (cnscheng@ntu.edu.sg)

INTRODUCTION
The suspension of solid particles in turbulent flows is involved in applications in geophysical fluid mechanics and also many industrial processes. Understanding of the particle behavior that could be described by hydrodynamic parameters is essential for the modeling and design of the industrial processes. When the fluid phase is at rest or in laminar motion, plenty of experimental results are available for many scenarios; however in the presence of turbulence, the particle settling behavior might be significantly different from that in the still water, depending on turbulence and particle characteristics. The experimental data and reliable correlation for the turbulence effect is not abundant in literature, probably due to the considerable experimental difficulties.

Recent efforts that are related to this paper have been demonstrated in several studies. For example, Brucato et al. measured the settling velocity exhibited by a cloud of particles in a Couette-Taylor flow field by means of residence time technique [1]. Their results showed that particle drag is either unaffected or increased by free stream turbulence, depending on particle size and turbulence intensity. Friedman and Katz studied the rise rate of droplets in the presence of isotropic turbulent flow generated by rotating grids by exploring the turbulence effect in terms of Stokes number, turbulence intensity and droplet Reynolds number [2]. It was showed that the mean rise rate of light droplets can be enhanced by turbulence. As illustrated in these two studies, the current understanding is inconclusive of how turbulence would modify the settling/rising rates of solid particles or fluid droplets.

The experimental work presented in this paper was conducted using an alternative experimental technique, where the turbulent flow was first artificially generated by placing an oscillating grid in a water tank and the settling behavior of the particle affected by turbulence is then analyzed with the images recorded with a video camera. A sketch of the experimental setup is given in Figure 1. In comparison with turbulence observed in boundary layers and open channel flows, the turbulence generated by the oscillating grid is theoretically simpler, which is characterized by its zero-mean flow velocity and two-dimensional homogeneity [3], [4].

EXPERIMENTAL SETUP
Figure 1 shows a schematic representation of the turbulence-generating system used in this study. The water tank was made of glass and had dimensions of 50 x 50 cm in the cross section and 100 cm in height. The tank was supported by a platform with an adjustable height. A grid made of square bars of 1 x 1 cm had a mesh size of 5 cm, giving a solidity of 36%. The grid was hung vertically 30 cm above the bottom of the tank by four steel bars of 0.5-cm diameter, which were connected to a speed-controlled motor. The water level was maintained at 98 cm from the bottom of the tank.

![Figure 1. Experimental setup](image)

The settling processes of particles were captured using a Digital Video Camcorder, with a resolution of 1420 x 1140 pixels. The video captured was transferred to a computer in the AVI format with a frequency of 25 frames per second for further analysis. The position and time data were derived from the digital video using video-motion analysis software Video Point 2.0. The six particles tested were spherical grains made of baked clay material (see Table 1). The grains were paint-coated to make their surface waterproof. The density of the grains so prepared was slightly higher than that of water. Each grain was tested repeatedly at least for 8 times to avoid errors that may arise if using different particles even with similar characteristics such as size and density.

RESULTS AND DISCUSSION
Plotted in Figure 2 are the vertical distributions of the ratio of the settling velocity affected by turbulence, \( w_t \), to that measured in still water, \( w_s \). The figure shows that the velocity...
ratio reduces with an increase in the distance from the mid-plane of the grid and is generally larger than unity for all cases, which indicates that the particles settled faster than in the turbulent flow. By noting that the turbulence decays if the distance from the grid mid-plane is increased, the settling velocity enhanced by the turbulence could be closely related to the turbulence intensity. For each grain, which was tested at two oscillating frequencies, i.e. $f = 2$ and $3$ Hz, larger velocity ratios can be observed for higher oscillation frequency, but with an exception, occurring at $d = 9.30$ mm, probably due to its largest grain size. It is also worth mentioning that the data scatter significantly for the case of $d = 6.04$ mm, which may be caused by its smallest settling velocity in still water (see Table 1).

The experimental results presented in Figure 2 can be further analyzed with dimensional considerations. For quantifying the turbulence generated by the oscillating grid, here we use an analytical solution derived from the $k - \varepsilon$ turbulence model [4]. The solution gives the dimensionless turbulent kinetic

<table>
<thead>
<tr>
<th>Particle diameter $d$ (mm)</th>
<th>Settling velocity in still water $w_s$ (m/s)</th>
<th>$\frac{w_t}{w_s}$</th>
<th>Average settling velocity affected by turbulence $w_t$ (m/s)</th>
<th>Water temperature ($^\circ$C)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>$f = 2$ Hz</td>
<td>$f = 3$ Hz</td>
</tr>
<tr>
<td>4.17</td>
<td>0.0667</td>
<td>295</td>
<td>0.0969</td>
<td>0.1084</td>
</tr>
<tr>
<td>5.08</td>
<td>0.0546</td>
<td>294</td>
<td>0.0677</td>
<td>0.0811</td>
</tr>
<tr>
<td>6.04</td>
<td>0.0217</td>
<td>140</td>
<td>0.0474</td>
<td>0.0558</td>
</tr>
<tr>
<td>6.71</td>
<td>0.0410</td>
<td>294</td>
<td>0.0550</td>
<td>0.0640</td>
</tr>
<tr>
<td>8.05</td>
<td>0.0378</td>
<td>325</td>
<td>0.0545</td>
<td>0.0577</td>
</tr>
<tr>
<td>9.30</td>
<td>0.0372</td>
<td>368</td>
<td>0.0586</td>
<td>0.0560</td>
</tr>
</tbody>
</table>

Table 1. Properties of grains tested

Figure 2. Distributions of $w_t/w_s$. The data points denoted by ‘Δ’ were measured at $f = 2$ Hz and those denoted by ‘x’ measured at $f = 3$ Hz.
energy and dissipation rate expressed respectively as,
\[ \tilde{k} = (1 + \tilde{z} / 1.82)^{-5} \]
\[ \tilde{\varepsilon} = (1 + \tilde{z} / 1.82)^{-0.85} \]
The dimensionless quantities are defined as
\[ \tilde{k} = k / k_0 \]
\[ \tilde{\varepsilon} = \varepsilon / \varepsilon_0 \]
\[ \tilde{z} = z / (k_0^{1.5} \varepsilon_0^{-1}) \]
(2)
The values of \( k_0 \) and \( \varepsilon_0 \) are evaluated with the oscillating frequency and grid properties. Furthermore, it is assumed that the particle settling could be more relevant to the scalings applied to the dissipation subrange, which are associated with Kolmogoroff scale eddies, than the scalings of the larger, energetic eddies. Therefore, the time scale is taken as
\[ T_\eta = \sqrt{v / \varepsilon} \]
(3)
And the velocity scale is defined as
\[ U_\eta = (\varepsilon v)^{1/4} \]
(4)
On the other hand, it is noted that the characteristic particle time or the particle relaxation time, \( T_p \), is related to \( w_t \) as
\[ T_p = \rho w_t / \left[ g(\rho - \rho_f) \right] \]
which characterizes the time scale of the momentum of the fluid to be transferred to the particle in the two-phase system [5]. Here the particle density was evaluated from \( w_t \) using the standard drag coefficient curve for spheres. In Figure 3, the measurement of \( w_t \) being scaled with \( U_\eta \) is plotted against \( T_p / T_\eta \) for \( f = 2 \) Hz. A very similar relation also exists for \( f = 3 \) Hz. Figure 3 shows that \( w_t / U_\eta \) decreases significantly with increasing \( T_p / T_\eta \), and the variation is also subject to the grain size to certain extent. However, as a first approximation, the relation shown in Figure 3 can be simply represented by
\[ \frac{w_t}{U_\eta} = 35 \left( \frac{T_\eta}{T_p} \right) \]
(6)

CONCLUSIONS
In this study, turbulence was artificially generated within a confined water tank. The particle settling behavior was then observed and analyzed. The results demonstrated that the settling velocity could be enhanced significantly by turbulence. The analysis is also conducted using the scalings that are related to the dissipation subrange rather than the large energetic eddies. The turbulence-affected settling velocity, when scaled by the Kolmogoroff velocity scale, is shown to be dependent on the ratio of the particle relaxation time to the Kolmogoroff time scale. It should be mentioned that the experiments were conducted only for limited Reynolds numbers, i.e. \( w_s d / \nu = 140-368 \), and local convective effects were not considered.

REFERENCES
SOIL IMPROVEMENT FOR SUSTAINABLE ENVIRONMENT

Principal Investigator: Harianto Rahardjo

Soil improvement for stability of trees is important for maintaining the sustainability of the “garden city” environment in Singapore. Trees have been part of urban environment and provide numerous advantages to human life. However, uprooted trees can be dangerous since they may cause damages to property (e.g., houses and vehicles) and infrastructures and may also cause injury or loss of life.

The engineering properties of soil as a medium for tree growth also play an important role in tree stability. Finer-gained soils, such as top soil, have commonly been used for tree growing media. However, several cases of tree failures associated with low soil strength have occurred in Singapore. In order to enhance the soil strength for tree stability, the top soil was mixed with granite chip at different percentages.

Results of the laboratory tests showed that the hydraulic properties and shear strength of the top soils changed with the addition of granite chips. The air-entry value, $\psi_a$, residual matric suction, $\psi_r$, and residual volumetric water content, $\Theta_r$, of the soil mixtures decreased with the increase in the granite chip content. Beyond the air-entry value of the granite chip, the shape of SWCCs of the soil mixture of 80% granite chip and 20% top soil and the soil mixture of 50% granite chip and 50% top soil were controlled by the shape of SWCC of the top soil. The effective angle of internal friction, $\Phi^*$, of the soil mixture increased by 25% (i.e., from $33^\circ$ to $44^\circ$) with an addition of 50% granite chip and increased by 31% (i.e., from $33^\circ$ to $48^\circ$) with an addition of 80% granite chip. The angle indicating the rate of increase in shear strength relative to the increase in matric suction, $\Phi^*$, of the soil mixtures decreased with the increase in granite chip content.

Field study showed that soil suctions developed near the ground surface fluctuated following the weather conditions and soil suctions decreased with depth. Assessment on the tree growth performance showed that the uncompacted top soil and in-situ soil at IMM site were the most suitable media for tree growth. The trees planted in the soil mixtures of 80% granite chip and 20% top soil and the soil mixture of 50% granite chip and 50% top soil have also shown quite good growth performance based on visual observation and results of tree girth and shoot length measurements.

Theoretical modeling indicated that wind force required causing tree instability increased with the increase in the granite chip content. The wind force at failure due to shear failure of soil ($F_{sw}$) is the lowest, while the wind force at failure due to tensile failure of soil-root system ($F_{sw\text{root}}$) is the highest. In other words, the soil-root system will most likely fail due to the shear failure of soil.
Twenty steel column specimens were subjected to elevated temperatures. One loading test was carried out at ambient temperature to determine the working load to be applied to the other specimens in the same series for elevated temperature tests. The variable parameters were slenderness ratio and axial restraint ratio. The experimental measurements are presented and compared with predictions from numerical simulations using FEMFAN-3D, a program developed by NTU. It is concluded that buckling temperature decreases as slenderness ratio increases, under a fixed restraint ratio. Applying increased axial restraint to the columns has a negative effect of reducing the buckling temperatures.

Eleven composite column tests were conducted under elevated temperature conditions. The composite columns were categorised into three series with different variable parameters, namely overall cross-sectional size, load ratio and axial restraint ratio. Results show that the fire resistance of composite column improves with an increase in overall cross-sectional size. An increase in load ratio or axial restraint ratio will lead to a reduction in its fire resistance. Test results are compared with FEMFAN-3D predictions for verifying the accuracy of the program.

Column behaviour under elevated temperatures and predictions and limitations of the numerical program FEMFAN are discussed in the report.

THE USE OF FLOW CYTOMETRY FOR PATHOGEN DETECTION

Principal Investigator: Karina Gin
Report No: CEE/2007/176

Outbreaks of waterborne diseases are usually caused by pathogenic bacteria and viruses, most of which are difficult to detect and quantify in water supplies and natural aquatic environments. The conventional practice is to enumerate indicator microorganisms as proxies for pathogens associated with faecal contamination. In the past, the commonly used indicators include total coliforms, faecal coliforms (FC) and faecal streptococci (FS). In recent years, the determination of specific indicator bacteria, such as Escherichia coli (FC) and Enterococci (FS), is slowly replacing these measurements, depending on the applications of the water (Mugglestone et al., 2001). In either case, the methods used typically entail plate incubations over a period of at least 24 hours and enumeration of colonies by microscopy. The disadvantages of such methods are the long analysis time involved and the non-culturability of some target bacteria. In addition, recent studies have shown that even in the absence of indicator bacteria, pathogenic viruses may still be present in water supplies (Grabow et al., 2001). These difficulties point to an urgent need to develop faster, more accurate methodologies for detecting target microbes.

While many methods are available, the challenge lies in finding a suitable method which gives rapid results and good specificity. Recent advances in molecular techniques have opened up new possibilities in the area of rapid identification of target microbes. PCR is a relatively fast method for detecting specific microbes; however, it has limitations when it comes to quantifying actual cell concentrations in water samples. In recent years, flow cytometry has made a significant impact on research concerning the environmental monitoring of pathogenic and non-pathogenic microbial populations. The advantage of flow cytometry lies in its rapid analysis of cells in terms of cell counts, fluorescence and light scattering properties. For example, millions of cells can be analyzed within minutes, compared to plate incubations, which may require many hours or even days.

Further discrimination can be made based on the auto-fluorescence properties of naturally occurring cellular substances such as pigments and aromatic amino acids. For non-autofluorescing cells, fluorescence in-situ hybridisation (FISH) with labelled rRNA-targeted oligonucleotide probes coupled with flow cytometry offers one possibility for the rapid detection and quantification of specific microbes, such as E. coli (Aman and Ludwig, 2000, Pernthaler et al., 2001). However, some of the problems encountered with rRNA probes include low cellular ribosome content, inaccessibility of the probe target sites and the impermeability of cell walls, leading to poor fluorescence and hence, detection (Fuchs et al., 2001). Our recent study using in situ PCR (ISPCR) to amplify gene sequences within a cell, while simultaneously incorporating fluorochromes, also shows promise for the rapid detection and enumeration of target microbes (Gin et al., 2002).

Alternatively, target specificity can be achieved using monoclonal antibodies (MABS) conjugated with one or more fluorochromes, such as in the cases of Cryptosporidia and Giardia detection (Vesey et al., 1994, Ferrari et al., 2000) and virus-infected cells (Abad et al., 1998). More recently, the availability of highly fluorescent nucleic acid specific dyes have even enabled the detection and quantification of individual virus particles (Brussaard et al., 1999, Li and Dickie, 2001). By coupling these specific fluorescent probes with flow cytometry, thousands of cells can be analysed within minutes. This saves considerable time from conventional plate incubation techniques, an important factor to consider when dealing with potential disease outbreaks.

While these methods hold promise, the applications of some of these techniques using environmental samples have yet to be realised. Complications are likely to arise from the presence of dissolved ions, detritus, phytoplankton and other microorganisms, while from the perspective of methodology, hybridisation and flow cytometric protocols have to be optimised so that rapid and accurate analysis can be carried out. In this study, we focus on the detection of bacteria spores. Currently, antibody based probes can be used to detect pathogenic spores but problems arise due to non-specificity of the probes. To overcome this, we propose to develop molecular based probes which are more specific to target bacteria spores. However, spores are generally more resistant and the challenge would be to develop and optimise procedures to allow good penetration of the probes into the cells. In addition, target cells may be present at very low
concentrations and hence, there is a need to incorporate a method of concentrating large volumes of water into the flow cytometry protocol. These are the main issues to be tackled in this research project, with the overall target to develop protocols for the rapid detection and enumeration of bacterial spores.

**DESIGN OF ADVANCED MATERIAL FOR BLAST PROTECTION OF CIVIL STRUCTURES**

**Principal Investigator:** Ma Guowei  
**Report No:** CEE/2007/177

A mesoscale numerical model is firstly developed to investigate the deformation mode and the dynamic compressive strength of cellular materials. The loading rate effect on the nominal stresses at the impact side and the stationary side of a cellular material sample are discussed. Previous experimental studies on the dynamic behavior of cellular materials are reviewed and analyzed with the mesoscale numerical model. The resistance of the cellular material against blast loading is also studied at the mesoscale. The blast resisting capacity of the cellular material is analytically predicted based on a shock wave theory. A double-layer foam cladding is then proposed to fulfill different structural protection purposes. The energy absorption capacity of the double-layer foam cladding under blast load is analytically derived based on the shock wave theory. Good agreement is found between the analytical and numerical results.

To consider the stiffness of the protected structure, an analytical Load-Cladding- Structure (LCS) model is further developed. Two non-dimensional parameters are introduced to describe the relations between the foam cladding and the protected structure. Based on the LCS model, the maximum allowable blast load for the structure with the protection of a particular foam cladding can be predicted. It is seen that the maximum deflection of the protected structure subjected to a certain explosive load varies with the two non-dimensional parameters of the foam cladding. The foam cladding can be appropriately designed to achieve structural retrofit against blast loads. Two structural models with sacrificial foam claddings are numerically simulated using LS-DYNA. The numerical results conform to the conclusion based on the LCS model that the foam cladding should be designed appropriately with reference to the potential blast load and the protected structure. The present LCS model can be conveniently used for the design and evaluation of foam claddings to retrofit military and civil structures.

Tests on the dynamic properties of aluminum foams have also been conducted. The results show that the material is suitable to be used for sacrificial cladding design.

**ABSTRACT OF PhD THESES**

**MEASUREMENT AND MODELLING OF GROUND RESPONSE DUE TO DYNAMIC LOADING**

**Candidate:** S Anand  
**Report No:** CEE/PhD/2007/131

The need for research in measurement and modelling of ground motion in Singapore soils stems from the uncertainty of applying existing guidelines and formulations such as TM5-855-1 (1986) to provide predictions of free-field stresses and motions in Singapore soils. Shock wave propagation through soil due to a buried explosive loading is a complex function of the dynamic soil properties, explosion products, and geometry of the explosion. However, there is limited research on shock wave propagation in Singapore soils. The research is undertaken in stages, starting with site characterisation to obtain the dynamic properties of Singapore soils and field explosion testing to calibrate a numerical model. Parametric analyses were also performed and new relationships were derived for prediction of free-field stresses and motions in Singapore soils. The proposed equations are dimensionless and are more versatile than equations found in TM5-855-1 (1986). These equations are suggested for use in Singapore soils.

**CHARACTERIZATION OF SMART PZT TRANSDUCER AND ADMITTANCE SIGNATURES USING PZT-STRUCTURE INTERACTION MODELS FOR STRUCTURAL HEALTH MONITORING**

**Candidate:** Annamdas Venu Gopal Madhav  
**Report No:** CEE/PhD/2007/132

Structural health monitoring (SHM) and security monitoring (SM) are two important challenges for the modern world in recent time. The monitoring of existing aero, civil and mechanical (ACM) structures has become a regular feature due to natural calamities or continuous usage of structures causing wear and tear or terror attacks. The last few years have witnessed rapid development in the areas of non-destructive evaluation (NDE) by the emergence of the electromechanical impedance (EMI) technique. This technique employs piezoelectric-ceramic (PZT) transducers for the prediction of structural response known as electromechanical (EM) admittance. Surface bonded PZT transducers have seen more prominent applications in the recent past in SHM. However, this research developed surface bonded and embedded PZT-structure interaction models. Most of the existing EMI models
are single PZT based interaction models, which has limited area of sensing. These models cannot be applicable for SHM of huge structures, where multiple PZT transducers need to be installing at critical locations of the structure. Thus, the present research developed such multiple PZT-based interaction models. Furthermore PZT material properties are easily influenced by external factors such as the atmosphere and the presence of electric and magnetic fields. Hence, this research made a step by step analysis to understand the PZT properties prior to their usage in the interaction models. Thus, this research presented the characterization of the PZT properties. Last but not least, this research also studied the influencing factors of EM admittance using the developed interaction models; to characterize the EM admittance signature.

**BUCKLING BEHAVIOUR OF STEEL AND COMPOSITE BEAMS AT ELEVATED TEMPERATURES**

**Candidate:** Ronny Budi Dharma  
**Report No:** CEE/PhD/2007/133

The objective of this research was to study the buckling behaviour of steel and composite beams at elevated temperatures. Both global buckling in the form of lateral torsional buckling and local buckling were studied. The first part of the study focused on the lateral torsional buckling behaviour of bare steel beams with an aim to develop design approaches for laterally unrestrained steel beams at elevated temperature. The second part focused on the local buckling behaviour which limits the ductility of beams. Both bare steel beams and composite deck slab with re-entrant steel decking were considered for the second part to investigate the ductility issue related to inelastic behaviour in the hogging moment regions under fire conditions and to propose the model of the moment-rotational relationships.

Numerical analysis using MSC.MARC Mentat and published test results were used to study the lateral torsional buckling of steel beams at elevated temperatures. Subsequently, a general approach, different from the current approach, called an alternative approach was suggested. Besides, a simple analytical approach, based on Rankine principle, was applied to estimate the lateral torsional buckling failure of steel beams in fire. Both proposals were shown to provide a good correlation with the numerical and test results.

The investigation of the local buckling behaviour at elevated temperatures comprised of both experimental and numerical investigation. The experimental investigation consisted of two series of tests, namely, investigation on steel beams as the first series and investigation on composite beams as the second series. The numerical investigation involved fairly extensive parametric studies using the numerical model which had been validated with test results. Finally, the analytical models for the moment-rotational relationships under fire conditions were proposed.

**DEVELOPMENT OF ADVANCED BIOFILTRATION PROCESS FOR HYDROGEN SULFIDE CONTROL**

**Candidate:** Duan Huiqi  
**Report No:** CEE/PhD/2007/134

Odor emission is a severe problem common to most wastewater treatment operations and particularly significant at urban treatment plants. Economical advantages coupled with environmental benefits make the process of odor biofiltration an attractive option, compared to the current chemical scrubber and activated carbon techniques. However, there still exist inefficiencies pertaining to the media used in biofiltration processes, such as the need for adequate residence time, limited life-time, and pore blockage of the media, which at present, render the technology economically unattractive. This study aims to develop a novel active medium, termed as biological activated carbon (BAC), through bacteria immobilization on activated carbon, a supporting medium with generally high specific surface area. It is expected that BAC could provide improved performance in removal of the major odorous pollutants such as hydrogen sulphide (H$_2$S) from the sewage air, by achieving an optimum balance and combination of the media adsorption capacity with the biodegradation of H$_2$S through the bacteria immobilized on the BAC.

The feasibility of developing BAC as a packing medium for H$_2$S removal was preliminary evaluated in lab-scale biofilters. A mix culture of sulfide oxidizing bacteria dominated by Acidithiobacillus Thiooxidans acclimated from activated sludge was used as bacterial seeds and biofilm was mostly developed through culturing the bacteria in the presence of carbon pellets in mineral media. A rapid startup (a few days) was observed and the maximum elimination capacity of the BAC reached 181 gH$_2$S·m$^{-3}$·h$^{-1}$ at 94% removal efficiency (RE). If inlet concentration was within 30 ppmv, over 99% of H$_2$S removal was achieved at a gas retention time (GRT) as low as 2s. The bacteria in the acidic biofilter demonstrated a capacity for H$_2$S removal in a broad pH range (pH 1–7).

Experimental evidences show that spent carbon (H$_2$S saturated carbon) could be re-used to develop BAC in a biofilter, thus providing some sense on the potential re-use or bio-regeneration of spent carbon.

To overcome the limitations found in the biofilter based on BAC, a horizontal, cross-flow biotrickling filter was designed to treat H$_2$S. It was found to be able to work efficiently from the first day of operation. The maximum elimination capacity (EC) of the system is 113 gH$_2$S·m$^{-3}$·h$^{-1}$ at RE of 96%. If inlet concentration was kept at around 20 ppmv, H$_2$S removal of over 99% was achieved at a GRT of 3 s. The pH of the system should be maintained above 1 to avoid inhibition of microbial growth. Bacterial population in the recirculation sump should be controlled within the range of 10$^9$–10$^{10}$ cfu·mL$^{-1}$ for optimal performance while avoiding clogging. High system buffer effect was evident because of the high carbon adsorption ability. Pressure drop test showed that the BAC bed had a much higher pressure drop than that of a conventional packing material in a chemical scrubber. Fortunately, the horizontal
design alleviated this problem to some extent.

The mechanism of H\textsubscript{2}S elimination on BAC was investigated following the horizontal biotrickling filter (HBTF) operation. A series of BAC samples were taken from the inlet to outlet of the HBTF to examine the different effects of adsorption and biodegradation on H\textsubscript{2}S removal. A correlation between the available surface area and pore volume with the extent of microbial immobilization and H\textsubscript{2}S uptake is evidenced. Scanning electron microscopy (SEM) photographs show the direct carbon structure and biofilm coated on the surface of the carbon pellets. Fourier transform infrared (FTIR) spectra, differential thermogravimetric (DTG) curves and carbon-hydrogen-nitrogen-sulfur (CHNS) results indicate less diversity of H\textsubscript{2}S oxidation products on BAC than those previously observed on exhausted carbon from H\textsubscript{2}S adsorption only. The predominant oxidation product on BAC was sulfuric acid and the biofilm was believed to enhance the oxidation of H\textsubscript{2}S on carbon surface. A mathematical modeling of the kinetics behavior of this HBTF was also developed in this work to achieve a better understanding to the key phenomena occurring in the process.

The combined effect of adsorption and biodegradation on activated carbon surface was studied with regards to the distribution of H\textsubscript{2}S oxidation products. Four parallel lab-scale biofiltration columns were operated for 120 h to investigate in-depth the mechanisms involved in treating H\textsubscript{2}S using BAC. Removal efficiency of the virgin (non-bacterial) activated carbon (VAC) bed dropped quickly to 30% within the first 8h, and eventually to 0% on saturation. Biofilter columns with the BAC, however, stay about 27% RE throughout their operation though the performance did fluctuate. The various S species in both aqueous and solid phases were determined using inductively coupled plasma optical emission spectrometry (ICP-OES), ion chromatography (IC), x-ray fluorescence (XRF) and carbon-hydrogen-nitrogen-sulfur (CHNS) element analyzer, respectively. It was found that sulfate sulfur percentage to total sulfur in the BAC system was twice that in the VAC system.

The findings of this research demonstrated that the combination of biodegradation and adsorption on BAC is capable of removing H\textsubscript{2}S for a substantial period of time. A biotrickling filter using this new BAC is a viable biotechnology for the efficient removal of H\textsubscript{2}S, the predominant odorous compound in sewage air. Studies on the mechanisms and modeling enable a better understanding to the biofiltration process applied in H\textsubscript{2}S removal using BAC.

Halogenated organic compounds (HOCs) are widely detected contaminants in polluted surface water and groundwater. Zero-valent Fe (ZVI) technology is a promising treatment method to deal with the HOCs. Due to some drawbacks of the ZVI technology, nano-scale bimetallic particles system has been developed in recent years. Although many studies on reductive dehalogenation of HOCs have been conducted over the last two decades, the mechanism involved remains rather elusive.

The main objectives of this study are to examine the kinetics, pathways and mechanisms of reductive dehalogenation reactions of chlorinated and brominated methanes with the nano-scale bimetallic particles. Both kinetic and mechanistic examinations are considered in establishing the major and minor transformation pathways. Meanwhile, the influences of pH, surfactant, natural organic matter, and nitrate on the dehalogenation kinetics were also investigated because these factors have direct impact on practical application of ZVI technology in treating polluted groundwater and wastewater.

Nano-scale Fe, Ni/Fe and Pd/Fe particles were synthesized by the wet chemical reduction method with sodium borohydride as the reductant. The nano-scale Ni/Fe and Pd/Fe particles were synthesized through co-reduction and post-coating method, respectively. The theoretical ratio of Ni to Fe in the synthesized nano-scale Ni/Fe particles was 1:4, while the Pd contents in the palladized Fe were 0.2% and 1% (w/w). The particle sizes were smaller than 100 nm, as observed with transmission electron microscope (TEM). The BET surface areas of the nano-scale particles were over one order higher than that of the commercial micro-scale Fe particles.

Batch reduction experiments were conducted to investigate reductive dehalogenation of the halogenated methanes with the two different types of the nano-scale bimetallic particles as well as with the nano-scale Fe and the commercial micro-scale Fe. The reductions of the target compounds were confirmed to follow pseudo-first order kinetics. The specific reduction rate constant for the transformation of carbon tetrachloride (CTC) with the Ni/Fe particles was 9.22×10\textsuperscript{-2} l h\textsuperscript{-1} m\textsuperscript{-2}, which was 13.2 times higher than that with the commercial micro-scale Fe particles. The specific reduction rate of CTC with the 0.2% Pd/Fe particles was 1.61×10\textsuperscript{-1} l h\textsuperscript{-1} m\textsuperscript{-2}, which was even higher than that with the Ni/Fe particles. As the Pd content increased from 0.2% to 1%, it could further accelerate the reduction rate of the halogenated methanes for up to five times of the rate with the 0.2% Pd/Fe. Sodium borohydride was used to regenerate the aged nano-scale particles. The reactivities of the regenerated particles could be partially recovered to their fresh state.

The reduction of the halogenated methanes to end products could follow both parallel and sequential pathways. The main non-halogenated end product was found to be methane. However, the amount of methane produced was related to the type of zero-valent metals used. Based on the simulated reductive dehalogenation kinetics, CTC was found to reduce mainly through the hydrogenolysis pathway to chloroform (CF) with the nano-scale Ni/Fe or 0.2% Pd/Fe particles. On the other hand, the prominent reduction pathway of CF with

KINETIC AND MECHANISTIC EXAMINATION OF ABIOTIC REDUCTIVE TRANSFORMATION OF HALOGENATED METHANES WITH BIMETALLIC NANO-SCALE IRON PARTICLES

Candidate: Feng Jing
Report No: CEE/PhD/2007/135
the nano-scale bimetallic particles was through elimination to methane and other hydrocarbons. Dichloromethane (DCM) was usually persistent in the presence of the nano-scale bimetallic particles. In general, brominated methanes were more readily reduced than their chlorinated counterparts. The reductions of carbon tetrabromide (CTB) and bromoform (BF) were both mainly through the hydrogenolysis pathway. However, complete debromination of dibromomethane (DBM) to methane was the more favorable pathway compared to hydrogenolysis.

Linear free energy relationships (LFERs) were also established for the dehalogenation reactions of halogenated methanes. Based on the single-parameter LFERs, it was proposed that the first electron transfer process was the rate limiting step for both hydrogenolysis and elimination processes in the dehalogenation of brominated methanes. Based on the statistic analysis, two-parameter regression relationships were also established for the kinetics prediction for the dehalogenation reactions with the nano-scale Fe or Pd/Fe particles.

The existence of phosphate base buffer solution has inhibition effect on the dechlorination reaction. The inhibition effect of three anthropogenic surfactants on the dechlorination reaction followed the order: dodecyl pyridinium chloride (DPC) (cationic) > sodium dodecyl sulphate (SDS) (anionic) > nonylphenol ethoxylate (NPE) (nonionic). Therefore, NPE was the most suitable surfactant for in-situ groundwater remediation and ex-situ soil wash process, if the recovered water is to be treated with nano-scale Fe particles. The appearance of higher nitrite concentration (> 2mM) could passivate the Fe surface and stall the dechlorination reaction. The regeneration of the aged nano-scale particles with sodium borohydride could only partial recover their original reactivity.

**STRUCTURAL DAMAGE DETECTION AND DIAGNOSIS USING TIME-DOMAIN DATA**

**Candidate:** Gao Feng  
**Report No:** CEE/PhD/2007/136

This study aims to develop general methodologies and implementation schemes to enhance the robustness of the time domain methods for damage diagnosis and extend the ability to the assessment of damage severity. Major contributions of this study include 1) the development of a novel time-series analysis method, which requires only acceleration response signals from the structure, for detection of the occurrence and location of damage; 2) extension of the above method to noise-contaminated vibration signals, with a novel scheme incorporating Kalman filter to establish the virtual Input-Output signal pairs that essentially represent the underlying physical system; and 3) formulation of a residual generator technique, based on geometric concept for disturbances decoupling problem (DDP), for detecting and locating the damage using acceleration measurements instead of displacements. The method also enables quantitative estimation of the severity of damage in individual elements of a complicated system. Numerical examples and experimental case studies are given to demonstrate the implementation and effectiveness of the proposed approaches.

**DEVELOPMENT OF A ROCK MASS CHARACTERISTICS MODEL FOR TBM PENETRATION RATE PREDICTION**

**Candidate:** Gong Qiuming  
**Report No:** CEE/PhD/2007/137

The objectives of this research are to study rock mass fragmentation mechanism induced by TBM cutters, and to develop a TBM penetration rate prediction model. The rock breakage process under TBM rolling cutters was simulated by using Universal Distinct Element Code (UDEC). The main rock mass properties, which influence rock mass breakage process and hence the penetration rate, include rock compressive strength, rock brittleness index, joint spacing and joint orientation. The in situ shield friction and penetration tests were performed to analyze the rock mass breakage mechanism at various thrust levels. A specific rock mass boreability index was proposed to express the rock mass boreability. Extensive site data collection and laboratory tests were conducted to obtain rock mass properties, TBM performance data and machine parameters. A database was then established. A rock mass characteristic (RMC) model for the TBM penetration rate was obtained through a nonlinear statistical analysis. Then, parametric studies were carried out to investigate the effect of rock mass properties on penetration rate based on the new model. The results were analyzed and compared with the numerical simulation results. The results are in good agreement with each other.

**HYBRID SUBMERGED MEMBRANE SYSTEM WITH SORPTION MEDIA IN SUSPENSION**

**Candidate:** Jia Yue  
**Report No:** CEE/PhD/2007/138

The performance of the hybrid powdered activated carbon (PAC)-submerged membrane system for trace organics treatment from water was studied through both experimental studies and mathematical simulations.

The PAC adsorption process optimization was studied by investigating the effects of PAC particle size, continuous/ intermittent air bubbling at different bubbling rates and additional factors introduced by air bubbling on the adsorption efficiency through single solute batch adsorption tests on atrazine removal.

The adsorption kinetics coefficients $k_f$ (liquid film) and $D_s$ (surface diffusion) were quantified through both a simple approach of film mass transfer and the complex homogeneous surface diffusion model (HSDM) respectively based on the
single solute batch test data. Mathematical models have been developed to describe PAC adsorption in both a bubbling mixed single-stage continuous process and a two-stage countercurrent PAC-submerged hollow fiber membrane system under batch and continuous dosing of PAC. The developed models were verified and then used to predict the product water quality at different operation conditions such as different air bubbling rates, carbon dosages and water fluxes.

Finally, a preliminary study of novel in-situ regeneration method for saturated PACs in a hybrid submerged membrane system using photocatalytic oxidation (TiO₂) was made and confirmed experimentally.

**FATIGUE BEHAVIOUR OF SQUARE-TO-SQUARE HOLLOW SECTION T-JOINTS WITH CORNER CRACKS**

*Candidate: Ji Hongli  
Report No: CEE/PhD/2007/139*

In this study, fatigue tests are carried out on four SHHS T-joints. Static tests are first carried out to investigate the Stress Concentration Factor (SCF) and Hot Spot Stress (HSS) distributions along the intersection of chord and brace. Alternating Current Potential Drop (ACPD) technique is then employed to monitor the crack growth and crack shape development when the joints are subjected to cyclic loads. The experimental data are recorded and the fatigue performance of the four T-joints is investigated. The crack growth curves, rates at the deepest point and the crack length are presented. Crack surfaces and crack shapes are investigated thoroughly by using a clay modelling technique after the fatigue tests are completed. Based on the information obtained from the fatigue tests, a geometrical mesh model is proposed. The crack surface is represented as an unsymmetrical 3D curved surface with deepest point located at the corner of the brace-chord intersection and the crack shape (front) is modeled as a piecewise unsymmetrical bi-elliptical curve. Subsequently, a mesh generator for SHHS T-joints with corner surface crack is developed. The validity of the proposed geometrical model and the reliability of the proposed mesh generation scheme are confirmed by comparing the numerical results against the fatigue test results. The validated modeling technique is then used to conduct finite element analysis (FEA) on the crack profiles, weld size and contact problems in SHHS T-joints. Based on the FEA results, a general equation to represent the crack surface is proposed. Finally, a life prediction procedure for part-through crack (PTC) is introduced. This procedure is illustrated by using the four test specimens and its validity is confirmed by the test results.

**FLOW DISTRIBUTIONS AND SCOURING AROUND ABUTMENTS IN TWO-STAGE CHANNELS**

*Candidate: Joko Nugroho  
Report No: CEE/PhD/2007/140*

The objectives of the present research are to study the flow distribution and scouring around abutment terminated at the floodplain of a two-stage channel under clear water scour condition. Flowfield observations and scouring experiments were done to achieve the objectives.

Three types of scour hole geometry were observed in this study, i.e. the inverted cone type, edge-truncated inverted cone type and the extended upstream edge-truncated inverted cone type.

Near the abutment tip, in the flat bed condition, the velocities at the lower depth were higher than those of the upper part due to the effect of the flow diversion and the associated downflow and a bed shear stress amplification was observed. After the scour hole formed, the velocity vectors around the abutment showed less deflection compared to that of the flat bed condition and an anticlockwise vortex was formed at the section adjacent to the abutment.

A relationship, which involves bulk parameters related to the flow, sediment and abutment properties, linking the flow depth ratio to the approach flow on the floodplain is proposed and used in the formulation of a semiempirical equation for the equilibrium scour depth.

Results on the effect of separating the flow interaction between floodplain and main channel showed that the flow velocity in the floodplain was lower in the non-interacting case compared to that of interacting condition. The effect of the length of the separated reach at the upstream of the abutment was insignificant to the flow distribution and scouring process.

**STRATEGIC ANALYSIS OF LARGE LOCAL CONSTRUCTION COMPANIES IN CHINA**

*Candidate: Kang Jian  
Report No: CEE/PhD/2007/141*

Competition among construction companies in China are getting more and more intense in an attempt to secure a larger market share. Unfortunately, many of them fail and suffer from low profitability. With an objective to improve the situation, this research aims to build a conceptual model to help large construction enterprises in China develop sound corporate strategy and strive for better performance in the long-run. The conceptual model integrates two main streams of strategic management theories – the Industrial Organization (IO) theories and the Resource-Based View (RBV), as well as other proposed models that had been developed for the international construction context. The critical variables in the conceptual model and their relationships are identified through environmental analysis and a series of case studies, which consist of 12 large Chinese construction companies. The model is further verified and refined through statistical analyses of survey results, which has a sample size of 85 valid responses.
POTENTIAL USE OF RESIDUAL SOIL AND GEOSYNTHETIC MATERIAL IN CAPILLARY BARRIER SYSTEM

Candidate: Henry Krisdani
Report No: CEE/PhD/2007/143

Rainfall-induced slope failures frequently occur in residual soil slopes in tropical regions. Previous research works indicated that the main cause of slope failure in residual soil slopes is rainfall infiltration. One of the possible preventive measures for the rainfall-induced slope failures is the use of a soil cover, such as capillary barrier system, to minimize water infiltration into the slope. A capillary barrier is a soil cover consisting of a fine-grained soil layer overlying a coarse-grained soil layer. In this study, the use of a local residual soil as the fine-grained layer in a capillary barrier system was investigated. In addition, the use of a geosynthetic material as the coarse-grained layer in a capillary barrier system was also studied. Laboratory model and numerical analyses were carried out to study the performance of capillary barrier system under infiltration and evaporation processes. The results indicated that the geosynthetic material used in this study performed satisfactorily as a coarse-grained layer. The residual soil is not recommended to be used as a fine-grained layer due to its slow rate of water storage recovery and significant shrinkage characteristics.

SCALED BOUNDARY FINITE ELEMENT METHOD FOR FLUID-STRUCTURE INTERACTION

Candidate: Li Shangming
Report No: CEE/PhD/2007/143

Fluid-structure-interaction (FSI) occurs whenever relative motion between a structure and a fluid media occurs. Over the last three decades or four, a wealth of numerical computational methods have been developed to address the FSI problems, including both bounded and unbounded fluid domains. Amongst those available numerical computational methods, the most popular ones are the traditional finite element method (FEM) and the boundary element method (BEM). This study presents the first attempt to extend the boundary finite element method (BFEM) for FSI problems.

In this study, the BFEM is enhanced and extended for modeling the bounded/unbounded acoustic fluid media, while the FEM is employed to model the structure. To enable the BFEM to be employed in FSI problems, a relationship between fluid velocity and fluid pressure corresponding to scattered waves needs to be developed. The author developed that new relationship based on the BFEM and acoustic approximations. By combining the fluid velocity-to-pressure relationship, a FEM/BFEM coupling procedure is developed. Its performances are investigated through 2-dimensional FSI problems. Satisfactory results are obtained. The results demonstrate that the BFEM is very efficient in modeling both unbounded and bounded acoustic fluid. However, the solution of the BFEM for bounded acoustic fluid was found sensitive to the dissipation coefficient when applying the numerical Newmark time-integration scheme.

In addition, a modified BFEM formulation is developed for solving problems related to infinite beams on visco-elastic-typed fluid foundations. The formulation is validated by checking against benchmark results.

BIOFILTRATION OF HYDROGEN SULPHIDE AND TOLUENE USING A NOVEL BIOLOGICAL ACTIVATED CARBON BIOTRICKLING FILTER

Candidate: Liang Juan
Report No: CEE/PhD/2007/144

Granular activated carbon with microorganisms on its surface formed a novel packing medium termed as biological activated carbon (BAC). This Study conducted to test potential improvements to current biofiltration processes by investigating the use of the novel support medium for mixture gases removal. Experiments were firstly conducted to evaluate the BAC capacity in a bench biofilter. BAC presented a better performance than GAC as a pure gas pollutant adsorbent. The application of BAC for treatment of gas mixer was evaluated in three experimental biofilters - a neutral pH single-stage biofilter, a low pH single-stage biofilter and a two-stage biofilter, to evaluate the capacity for both H₂S and VOCs. Results demonstrated that BAC biofilters obtained high removal efficiencies for both H₂S and VOCs. The two-stage biofilter performance was the best among the three biofilters tested because degrading microorganisms grew in different environments and the two-stage bioreactor allowed for separate media beds of different microorganisms. The removal mechanisms of the BAC were investigated after the biofilter operation. The BAC system combining adsorption and bioregeneration has the following advantages: faster development of the biomass; resistance to shock loading; stable and good performance; allowing the treatment of hydrophobic biodegradable gases.

INTERNATIONAL STRATEGIC MANAGEMENT OF CHINESE CONSTRUCTION FIRMS

Candidate: Liu Guozhi
Report No: CEE/PhD/2007/145

With the rapid increase in China’s construction demand and the liberalization of the construction market after its entry into WTO, foreign contractors are presented with tremendous opportunities to participate in construction activities in China. Concurrently, Chinese construction firms (CCFs) are also actively involved in international construction projects. Such developments pose both opportunities and threats for CCFs. How can CCFs effectively compete with their international
competitors? Strengthening their international strategic management (ISM) hence becomes a top priority and challenge. The aim of this research is to provide new insights on the ISM of CCFs.

This research aims to build a conceptual model to examine the major sources of CCFs’ international competitiveness. Fundamental strategy theories and related Chinese research were systematically reviewed. The conceptual model was formulated based mainly on the industrial organisation economics view and the resource-based view. It incorporated variables of firm-specific resources/capabilities, generic competitive strategies, market entry strategies, and the international performance of CCFs. These variables and their relationships were identified through extensive literature review and ascertained through environmental analysis.

Based on the conceptual model, 22 hypotheses were developed. These hypotheses were tested through a questionnaire survey with 92 senior managers of large CCFs. The conceptual model was revised based on the hypothesis results. The revised model revealed a difference in the significance of the identified firm specific resources/capabilities and strategies. Key findings indicated that three strategies – cost leadership, differentiation and sophisticated contracting, strongly influence the international performance of CCFs. Three firm-specific resources/capabilities – financial capability, project management capability and reputation, were found to be strongly contributing to firm strategy and performance.

APPLICATION OF REAL OPTION IN RISK EVALUATION AND MANAGEMENT OF PPP/PFI PROJECTS

Candidate: Liu Jicai
Report No: CEE/PhD/2007/146

Public-Private Partnership / Private Finance Initiative (PPP/PFI) has been a widely applied scheme to deliver large-scale infrastructure systems. A privately financed infrastructure project is inherently risky. When the values of flexible measures to counteract such risks are overlooked, the value of a project may be understated. Real option assumes that managers can take advantage of upsides and avoid obvious pitfalls during the development of a project. In this research, the primary objective is to study how real option can be applied to infrastructure projects with risks and uncertainties. The case study method is used to achieve the research objectives based on the data collected. These case studies can be classified into short and major cases. The analyses of short cases identify embedded options in each project, based on which preliminary strategies incorporating the real option concept are designed. The analyses of major cases demonstrated the application of real option evaluation methodology to infrastructure projects. Ultimately, the findings in this research lead to a new risk management framework that incorporates the real option concept. This framework should be useful for structuring a more equitable risk and value sharing arrangement among project stakeholders.

EFFECTS OF LOW FREQUENCY ULTRASOUND PRETREATMENT ON ANAEROBIC DIGESTION OF SLUDGE

Candidate: Mao Tao Hong
Report No: CEE/PhD/2007/147

This study examines the effects of sonication treatment on sludge characteristics using sonication generated at low frequency of 20 kHz. The influences of sonication pretreatment of sludge on the subsequent anaerobic digestion were investigated by using batch cultures and upflow anaerobic sludge blanket (VASB) digesters. Comparing with the control VASB digester, the TCOD removal improved by 1-17%, 1-31% and 1-32% in the digesters fed with sludge sonicated sludge at densities of 0.18W/mL, 0.33W/mL and 0.52W/mL, respectively. The improved organics removal efficiency corresponded with significant increase in biogas production by 45-175%, 140-220% and 86-220% in the respective digesters, as well as an overall increase in methane composition by 2-17%.

The experimental study indicated that sonication pretreatment of sludge could bring about several benefits in treatment plant operation. These include captical cost saving out of smaller unit digester, operating cost savings in downstream sludge treatment and disposal, and increase in energy yield derived from improved biogas production.

THERMAL BEHAVIOUR OF HARDENED CEMENT PASTE ON HEAT AND MASS TRANSFER

Candidate: Jeffrey Ng Leng Ping
Report No: CEE/PhD/2007/148

Fire is known to cause spalling in concrete structures. Structural integrity of the building will be affected as the reinforcement steels will be weakened when exposed to heat directly in the absence of concrete cover. Fire resistance of concrete structural elements are often predicted based on the assumption that spalling does not occur. This assumption is often not satisfied in real fire test. Researches show that spalling is more susceptible in high strength concrete, blended concrete and concrete of low water/cement ratio. Such quantifications are not always valid. The fundamental cause of spalling is still not addressed. Hence, this research uses the microstructure of hardened cement paste as the foundation for analysing the occurrence of spalling. Material models relating non-evaporable moisture loss and porosity subjected to elevated temperature were developed as they were identified as parameters that influence significantly on gas pressure build up in cementitious material. The development of material models eliminates uncertainty in material behaviour of various mix designs when analysing occurrence of spalling. Experimental data on mass loss and volume of pores measurements performed on specimens of different water/cement ratio (including pozzolana) and degree of hydration...
subjected to different temperatures were used to develop the material models that are applicable to hardened cement paste, cement mortar and concrete. An analytical model on heat and mass transfer based on microstructure model was also developed to solve temperature, mass of vapour and gas pressure distributions within heated cementitious material. A key improvement in the proposed model from existing models is the ability to model two plateaus in temperature-time domain corresponding to the evaporation of evaporable (100°C) and non-evaporable moisture (530°C) which was observed in experiments. The advantage of having the ability to model the plateaus would enable a more accurate analysis of thermal stresses and structural responses of cementitious material. Results of the simulation were validated with experimental data on temperature distribution in hardened cement paste of different moisture content and rate of heating. Results of the parametric analysis show that the proposed model is able to address the problem of spalling better than using indirect parameters such as compressive strength, water/cement ratio, blended hardened cement paste.

SHEAR BEHAVIOUR OF STEEL MEMBERS AND BEAM-TO-COLUMN JOINTS UNDER ELEVATED TEMPERATURES

Candidate: Qian Zhen Hai
Report No: CEE/PhD/2007/149

The objective of current research is to investigate the possibility of using “Component-Based” method to predict steel joint behaviour at elevated temperatures. In this study, beam web shear component of joint has first been simplified into an equivalent girder web panel subjected to shear force. Five series of beams have been tested at both ambient and elevated temperatures, without thermal restraints. In addition, three more series of specimens have been tested subjected to thermal restraints at higher temperatures. All plate girders tested at elevated temperatures exhibit web buckling failure mode, similar to ambient temperature tests. Mechanical model for shear component in present work has been improved from plate theory. In addition, simple analytical procedures have been developed to obtain a clear description for deflection behaviour of shear component. Detailed finite element simulations have also been conducted, to investigate both single web and overall beam behaviour. Apart from structural component analyses, six steel beam-to-column joints have been tested as “Cruciform” assemblies, which consisted of three cruciform specimens tested at 700°C with three restrained levels, and another three specimens tested at three isothermal temperatures, without thermal restraints. Detailed finite element simulations have also been conducted with good agreements with test results. With utilization of “Component-Based” method, a simple analytical model has been established with incorporation of shear component in beam web. Moment-rotation results obtained from this analytical model show acceptable agreements compared with test results. Thus, proposed mechanical model is able to predict behaviour for extended end-plate joint at elevated temperatures.

DESIGN AND PERFORMANCE OF STONE MASTIC ASPHALT IN SINGAPORE CONDITIONS

Candidate: Qiu Yunfeng
Report No: CEE/PhD/2007/150

The objective of the research is to provide a methodology of quantifying coarse aggregate stone-to-stone contact in SMA with different aggregate packing to yield high rutting resistance; thus, developing a new mix design procedure and leading to an improved SMA mixture design and performance. The concepts that utilised aggregate interlock and aggregate packing were proposed to develop coarse aggregate stone-to-stone contact. A total of thirty-seven mixtures were tested for developing and analysing coarse aggregate stone-to-stone contact in SMA mixtures. Each mixture composed of different combinations of the aggregate gradation through a rational approach to the selection of relative amounts of coarse and fine aggregates and asphalt binder. Laboratory performance tests were conducted to characterise the volumetric properties, resilient modulus, resistance to permanent deformation, and rut susceptibility of these mixtures. A two dimensional dynamic finite element procedure was developed in order to expand the experimental results to other aggregate type and maximum aggregate size to investigate their coarse aggregate stone-to-stone contact.

The results in this study improved the SMA mixture design and production by providing a method to characterise coarse aggregate stone-to-stone contact in SMA mixtures through the fundamental principles of particle packing.

STUDY ON GROUNDWATER RECHARGE CHARACTERISTICS AT RECLAIMED LAND SITE

Candidate: Stephen Tan Boon Kean
Report No: CEE/PhD/2007/151

A thorough understanding of rainfall recharge processes and their influencing factors is essential for management of groundwater systems. This research investigates the rainfall recharge characteristics at an unconfined sandy aquifer, the Changi reclaimed land, which is situated at the eastern coast of Singapore. Based on results from time series and spectral analyses, a theory based on stress transfer velocity was established to provide logical explanations for the rainfall-recharge relationship, the observed stress-filtering and recharge rate characteristics at the unconfined sandy aquifer. From deterministic modeling results, a theory was developed and validated to provide physical explanations for the observations, based on the residence time of the percolated rainwater within the vadose zone. The ‘residence time’ theory developed provides physical proofs to the ‘stress transfer velocity’ theory. New approaches were also developed and applied for estimating the specific yield and saturated hydraulic conductivity of the unconfined aquifer. The values
obtained were found to agree well with field and laboratory measurements and the typical ranges from the literature. As soil evaporation is the major rainfall recharge loss at the study site, an extensive study was carried out to investigate the major open water evaporation mechanism at the study area. Radiation-based and artificial neural network (ANN) models were developed for modeling the hourly and daily open water evaporation rates at the study area. They were found to be capable of yielding reliable evaporation estimates.

Three series of soil column tests under the processes of continuous evaporation/infiltration were carried out for sands and Singapore residual soil to further validate the modified model. It was found that the matric suction changes mainly in the top 10 to 15 cm of the soil columns. The pressure head and temperature profiles obtained in the soil column tests were in good agreement with the experimental data, thus verifying the suitability and adequacy of the modified model in modeling evaporation and infiltration processes in unsaturated soils.

FUZZY MULTIPLE CRITERIA DECISION SYSTEM FOR CONTRACTOR SELECTION

Candidate: Dharmendra Singh
Report No: CEE/PhD/2007/152

This research aims at developing a fuzzy multiple criteria decision system for contractor selection that is well-structured in approach and robust in analysis, in order to assist construction clients in making complex decisions regarding contractor selection in a systematic, realistic and productive way. A financial evaluation model is also developed to assess the changes in the financial health of candidate contractors during the contractor selection process.

Based on the knowledge acquired through literature review and the questionnaire survey, a computer-interactive contractor selection system is developed using Visual Basic and Microsoft Excel. The system employs the fuzzy set theory to deal with the uncertainty and vagueness surrounding the subjective nature of the decision-making and multiple attribute decision method to handle the simultaneous consideration of multiple criteria and multiple decision-makers. Using actual contractor selection cases, the applicability and flexibility of the system are ascertained by testing its validity in terms of user friendliness, functionality, usefulness and sensitivity range. The system predictions show a high level of accuracy and a reasonable representation of the actual cases results.

NONLINEAR FINITE ELEMENT ANALYSIS FOR REINFORCED CONCRETE FLAT PLATE FLOORS

Candidate: Wang Wenyuan
Report No: CEE/PhD/2007/154

A three dimensional finite element model has been developed for nonlinear analysis of reinforced concrete flat plate structures. A 3-D hypo-elastic orthotropic material model based on equivalent uniaxial strain concept for modeling the material properties of uncracked concrete and cracked reinforced concrete was proposed. The material properties of the multidirectional-cracked reinforced concrete are represented by the material properties of the intact concrete and a number of uniaxially cracked concrete with their coupling solids. Cracking effects due to multiple non-orthogonal cracks are traced in each uniaxially cracked concrete. A new layering scheme for shear correction was formulated directly in shell element formulations. The proposed material model has been proved to be capable of simulating the material properties of cracked reinforced concrete with good accuracy. The developed finite element model was proved to be an effective and efficient numerical tool for simulating the nonlinear behavior of RC flat plate structures.

INSIGHTS INTO MECHANISM OF AEROBIC GRANULATION IN SEQUENCING BATCH REACTOR

Candidate: Wang Zhiwu
Report No: CEE/PhD/2007/155

Abstract: Aerobic granulation is a novel environmental biotechnology recently developed for treating a wide spectrum of wastewater. Although extensive research effort has been dedicated to the development of aerobic granules in sequencing batch reactor (SBR), the mechanism responsible for aerobic granulation still remains unclear. Thus, this study attempted to address a basic question of what are the potential driving forces of aerobic granulation in SBR.

In the first phase of study, four SBRs were operated at different volume exchange ratios of 20 to 80%. Results showed that a rapid aerobic granulation could be achieved in the SBR run at the high volume exchange ratio, and the characteristics of mature aerobic granules in terms of mean size, SVI, granule
Consequently, it seems that a large fraction of EPS produced higher than that of those non-readily biodegradable EPS. EPS was 5 times lower than that of acetate, but 50 times aerobic granules under starvation condition. Kinetic analysis 50% of EPS produced by aerobic granules would be readily studied in the last phase of study. Results showed that about The biodegradability of EPS produced by aerobic granules was present in the granule shell would play a protective role core. It is a reasonable consideration that the insoluble EPS, whereas its core part was filled with soluble and readily biodegradable EPS. Meanwhile, the shell of aerobic granule exhibited a high hydrophobicity as compared to the granule core. It is a reasonable consideration that the insoluble EPS present in the granule shell would play a protective role with respect to the structure stability and integrity of aerobic granule.

In the third phase of study, the roles of EPS and hydrophobicity in maintaining the structure and stability of aerobic granule were investigated. It was found that aerobic granule had a heterogeneous structure, i.e. an outer shell with high biomass density and an inner core having a low biomass density. Results further showed the outer shell of aerobic granule was composed of poorly soluble and non-easily biodegradable EPS, whereas its core part was filled with soluble and readily biodegradable EPS. Meanwhile, the shell of aerobic granule exhibited a high hydrophobicity as compared to the granule core. It is a reasonable consideration that the insoluble EPS loadings, substrate compositions and SRTs on EPS production, a long period to investigate the effect of different substrate loadings, substrate compositions and SRTs on EPS production, bacterial community structure and membrane fouling tendency. Further, membrane fouling mechanisms caused by EPS was investigated by comparing the contributions of dissolved solids and suspended solids to membrane fouling in MBRs. DGGE technique and bacterial isolation were employed to study the functions of the strains isolated from the MBR. Membrane fouling mechanism of pure culture was analyzed by studying cell characteristics.

In order to interpret the roles of various driving forces of aerobic granulation in SBR, a unified selection pressure theory was thus developed in this study. This theory shows that all driving forces of aerobic granules that have been identified so far (e.g. settling time, volume exchange ratio and discharge time) can be unified into one single parameter i.e. minimum settling velocity of bioparticles. It was further demonstrated that aerobic granulation in SBR would be mainly determined by the magnitude of the minimum settling velocity applied, e.g. successful aerobic granulation would be achieved at a minimum settling velocity no smaller than 8 m h⁻¹. The proposed selection pressure theory indeed can provide a useful guideline for upscaling, manipulating and optimizing aerobic granular sludge SBR.

In the second phase of study, four SBRs were run at respective discharge time of 5, 10, 15 and 20 min in order to look into the effect of discharge time on aerobic granulation. It was shown that discharge time would be a key parameter influencing aerobic granulation in SBR. A prolonged discharge time would result in a failure of aerobic granulation even though both settling time and volume exchange ratio were controlled properly. It appeared that a relatively long discharge time of 20 min could unfavour aerobic granulation, e.g. a reduced cell surface hydrophobicity and EPS production were observed.

In the third phase of study, the roles of EPS and hydrophobicity could serve as the energy reservoir for aerobic granules which can be used under starvation condition.

Keywords: aerobic granulation, selection pressure, volume exchange ratio, discharge time, EPS, hydrophobicity, biodegradability

**ENHANCED MEMBRANE BIOREACTOR (MBR) OPERATION BY OPTIMISATION OF BACTERIAL POPULATION**

*Candidate: Wu Bing*

*Report No: CEE/PhD/2007/156*

This research program aimed to identify the conditions in a MBR that would help to reduce membrane fouling. An alternative objective was to identify specialized biomass which were membrane friendly under typical MBR operating conditions. Dynamic EPS characteristics in a MBR were studied under periodic and sequential changes of operating parameters. Then parallel MBR systems were operated for a long period to investigate the effect of different substrate loadings, substrate compositions and SRTs on EPS production, bacterial community structure and membrane fouling tendency. Further, membrane fouling mechanisms caused by EPS was investigated by comparing the contributions of dissolved solids and suspended solids to membrane fouling in MBRs. DGGE technique and bacterial isolation were employed to study the functions of the strains isolated from the MBR. Membrane fouling mechanism of pure culture was analyzed by studying cell characteristics.

**MODELLING DRIVER RESPONSE UNDER ROAD PRICING**

*Candidate: Xie Litian*

*Report No: CEE/PhD/2007/157*

Transportation planners and researchers have for many years been interested in the performance of the Singapore Electronic Road Pricing (ERP) system as a method of relieving congestion. The ERP system is constantly evolving, which calls for explicit models to predict the effects of its changes. Responding to such a need, this study proposes a practical modelling methodology for estimating and forecasting the short-term impacts of ERP introduction and rate adjustment on peak period traffic volumes. For practical purpose, it is proposed to use traffic volume data and transaction data automatically collected by the ERP system in the model calibration and application. Corresponding to the new issues of modelling based on traffic volume and ERP transaction data, several novel approaches are proposed. Separate models are developed for different categories of motorists. The proposed methodology was tested on several roads in Singapore. The results show that this methodology can be applied to a peak period road pricing system with time-variable rates.
BEHAVIOUR OF REINFORCED EMBANKMENTS ON SOFT GROUND AND RELIABILITY ANALYSIS

Candidate: Xu Bo
Report No: CEE/PhD/2007/158

Stability analysis of slopes or embankments is greatly affected by uncertainty of soil properties. The current design practice is based on the factor of safety which cannot directly reflect the input uncertainty. Probabilistic stability analysis is a rational way to incorporate uncertainty in the design procedure. Unfortunately, most geotechnical engineers are reluctant to adopt probabilistic techniques. The objective of this study is to provide a practical approach to integrate probabilistic analysis in the stability evaluation of reinforced embankments on soft ground.

Behaviour studies of the unreinforced and reinforced embankment on soft ground are first carried out by finite element method. The effects of reinforcement on ground surface settlement, lateral displacement, excess pore water pressure and the development of plastic zone in the soft soil foundation are investigated. The conventional limit equilibrium method of slices and finite element method are used to calculate the factor of safety for the embankments. The results from different stability analysis methods are compared.

The effects of different optimization procedures on the location of critical circular or noncircular slip surface for reinforced embankments on soft ground are also investigated based on the extended Spencer’s method. The optimization procedures include the grid search method, the simplex method, the genetic algorithm method, BFGS method and pattern search method.

Uncertainties of the critical reinforcement strain are studied by direct Monte Carlo simulation based on finite element method through the proposed procedure based on the response surface method. Two different approaches, the direct autocorrelation approach and the variance reduction approach, are considered to model the spatial variability of soil properties.

The effects of undrained shear strength, critical reinforcement strain, reinforcement modulus, Bjerrum’s vane correction factor, unit weight of the embankment fills, friction angle of the embankment fill, spatial variability of undrained shear strength in the foundation and reinforcement force distribution on the reliability of the reinforced embankment on soft ground are investigated in detail via the first-order reliability method (FORM).

In the last part of this study, a simplified reliability analysis approach is proposed for the embankment on soft ground based on the response surface method. The reliability index is calculated by the ellipsoid method based on first-order reliability method (FORM). The response surface is formed progressively. After obtaining the design point and the trust region parameter, the importance sampling technique is adopted to calculate the failure probability. Only a few calculations are required. It is more efficient than the direct Monte Carlo simulation, which may need a large number of calculations. The sensitivity of the input parameters to the reliability of the embankment can be assessed via the Spearman rank correlation coefficients based on the direct Monte Carlo simulation for the response surface obtained.

BEHAVIOURAL STUDY OF COMPLETELY OVERLAPPED TUBULAR JOINTS UNDER MONOTONIC AND CYCLIC AXIAL LOADING

Candidate: Yang Ye
Report No: CEE/PhD/2007/159

The completely overlapped tubular joint configuration shows better static strength and energy dissipation than simple gap joints. However, the structural behaviour of the joint are still not well understood and the design of such joint configuration is not covered in the existing offshore recommendations. In the current study, the behaviour of the completely overlapped tubular joint under monotonic and cyclic loading is experimentally and numerically investigated. The failure mechanism and the ultimate strength of the joint are the two main areas of study. A set of parametric equations is proposed for predicting the ultimate capacity of the joint under lap brace axial compression. The effect of geometrical parameters and load characteristics on the cyclic behaviour of the joints is investigated. It is recommended that the dissipative zone of the completely overlapped tubular joint under cyclic loading should be designed at the short segment of the through brace joining the chord.

BIODEGRADATION OF P-NITROPHENOL BY AEROBIC GRANULES IN A SEQUENCING BATCH REACTOR

Candidate: Yi Shan
Report No: CEE/PhD/2007/160

This research study aims to deploy aerobic granulation in a sequencing batch reactor (SBR) for biodegradation of p-nitrophenol (PNP) in contaminated wastewaters. This study also seeks to identify and characterize the indigenous PNP-degrading populations in the aerobic granules for understanding the underlying mechanisms involved in PNP biodegradation by aerobic granules in the SBR.

Aerobic granules to treat PNP-contaminated wastewaters were successfully developed in a SBR. The characterization of the granules indicated the privilege of using the aerobic granulation SBR for the biodegradation of toxic and challenging compounds as PNP. The investigation on two indigenous PNP-degrading populations, Burkholderia sp. strain PNP-01 and consortium PNP-04 revealed that broad PNP biodegradation mechanisms were employed by aerobic
granules, which was probably one of the major reasons for the stability and high efficiency of the PNP biodegradation by aerobic granules in the SBR.

ANALYSIS OF METALLIC CELLULAR MATERIALS FOR BLAST MITIGATION

Candidate: Ye Ziqing  
Report No: CEE/PhD/2007/161

A mesoscale numerical model is developed to investigate the dynamic behavior of cellular materials under impacts and blast loads. A double-layer foam cladding is then proposed to fulfill different structural protection purposes. The blast resistant capacity of the double-layer foam cladding is analytically derived. Good agreement is found between the analytical and numerical results. To consider the stiffness of the protected structure, an analytical Load-Cladding-Structure (LCS) model is further developed. Two non-dimensional parameters are introduced to describe the relations between the foam cladding and the protected structure. Knowing any two of the three components of the LCS model, the third one can be determined or predicted. Two structural models with sacrificial foam claddings are then simulated using LS-DYNA. The numerical results conform to the conclusion based on the LCS model that the foam cladding should be designed appropriately with reference to the potential blast load and the protected structure.

SUBMERGED HOLLOW FIBER MEMBRANES: HYDRODYNAMIC AND FOULING STUDY

Candidate: Adrian Yeo Piah Song  
Report No: CEE/PhD/2007/162

Hollow fiber membranes have the advantage of the highest surface area to volume ratio of any type of membrane configuration. This thesis examines the interaction between the filtration performance and the bubble-induced hydrodynamics around submerged hollow fibers as well as physical characteristics such as fiber looseness and aerator configuration. Two non-invasive methods, Particle Image Velocimetry and Phase Contrast X-Ray MicroImaging (XMI) were used to characterize shear stresses, fiber movement and fouling. It was found that it was possible to provide the same level of performance with significantly less air flow by using smaller bubbles as opposed to larger ones. The standard deviations of the shear stress, and the acceleration of the fiber showed the best correlation with the performance for the tight fibers and loose fibers respectively. XMI was shown to be very useful for observing bubble formation and fouling within the membrane.

INTEGRATED PLANNING AND SCHEDULING FOR PRECAST CONCRETE PRODUCTION

Candidate: Zhai Xiaofeng  
Report No: CEE/PhD/2007/163

Planning and scheduling play an important role in precast production management. In practice, however, this work is primarily carried out on a rule-of-thumb basis. An integrated planning and scheduling model, IPSMPP, is proposed in this research for make-to-order precast production using a comprehensive casting organization. IPSMPP captures distinctive features of precast production and covers both aggregate planning at the tactical level and detailed scheduling at the operational level. Five modules at the two levels are designed for different planning purposes. A Simulation-GA based approach is proposed to solve specific problems in every module. Specialized priority rules and bidirectional simulations are further formulated in order to improve the schedule performance. Based on the model and its inner workings, a prototype system is developed. The validity of IPSMPP is finally demonstrated in two example tests by comparison of the results from the prototype system and other traditional approaches.

BIODEGRADATION OF TERT-BUTYL ALCOHOL (TBA), AND TREATMENT OF TBA CONTAMINATED WASTEWATER BY AEROBIC GRANULES

Candidate: Zhuang Weiqin  
Report No: CEE/PhD/2007/164

The focus of this study is the biodegradation of tert-butyl alcohol (TBA) and the complete biological removal of TBA from contaminated water using aerobic granulation system. Aerobic granulation is a novel biological wastewater treatment technology which has several benefits as compared to the conventional activated sludge systems. Aerobic granules are dense and compact microbial aggregates with good settling capabilities, good bioactivity, larger biomass retention, and good resistance to chemical toxicity. TBA was chosen as a model compound in this study because of its high recalcitrance and inhibitory characteristics. The aims of this study were to evaluate the utility of the sequencing batch reactor (SBR) to acclimated microorganisms towards biological removal of TBA, to cultivate TBA-degrading aerobic granules in SBR using TBA as sole carbon and energy source, to isolate and characterize TBA-degrading pure microbial cultures, and to elucidate a TBA degradation mechanism of aerobic granules archived via microbial interaction.
Publications of academic staff in journals and conference proceedings during the period from 1 July 2006 to June 2007. Authors who are not members of the School are marked by *.


Lam, J.S.L., 2006. Managing Container Shipping Supply. Proceedings of the International Association of Maritime Economists Annual Conference, Melbourne, 12-14 July. (Received Best Paper Award)


structured TiO₂ microsphere – A new approach in removing natural organic matter. Proceedings of the 4th IWA Leading-Edge Conference & Exhibition on Water & Wastewater Technologies, Singapore, 4-7 June.


Ng, W.J., 2006. Industrial Wastewater Treatment. Imperial College Pr


Proceedings of the 1st International Conference: From Invention and Development to product; From Research Institutes to the Water Industry, Ben-Gurion University of the Negev, Sed Boqer Campus, Israel, 28-30 November.


PUBLICATIONS


Yuan Weifeng and Tan, K.H., 2007. Analytical inelastic buckling loads of restrained steel columns under longitudinal


### IN FOCUS

#### ACHIEVEMENTS AND COMMENDATIONS

##### RESEARCH CENTRES

- Environmental Engineering Research Centre (EERC)
- Maritime Research Centre (MRC)
- Protective Technology Research Centre (PTRC)

##### RESEARCH PROJECTS

##### CONSTRUCTION MANAGEMENT

- Carbon finance and impact on feasibility of infrastructure project - ZaHung Hydro Power Project, Vietnam
- Simulated annealing algorithm for optimizing multi-project linear scheduling with multiple resource constraint
- Automatic 3D modeling development and application for hydraulic construction
- Computer-aided visualization for rescue in indoor environments

##### CONSTRUCTION TECHNOLOGIES

- Utilization of waste materials in manufacturing of Self-Compacting Concrete
- Numerical study of moisture gradient in drying of concrete

##### ENVIRONMENTAL

- Removal of endocrine disrupting contaminants using molecularly imprinted polymers
- Multiscale characterization of reverse osmosis and nanofiltration membranes and implications for fouling mitigation
- Layered Double Hydroxides (LDHs) for oxyanions removal from water
- Removal of antibiotics by GAC adsorption
- The recovery of phosphate on water reclamation plant using microbial reduction of iron ore
- Effect of protein on biohydrogen production from starch of food waste
- Enhancement of food waste digestion in the hybrid anaerobic solid-liquid system

##### GEOTECHNICS

- Static Compaction of Bentonite
- Effects of hydraulic properties on slope stability in residual soil

##### MECHANICS

- Simulation on rock mass deformation by using manifold method
- Tsunami hazard from the potential rupture of the manila trench
- Influence of residual stresses on the failure assessment diagrams of a cracked square hollow sections T-joint
- Heat conduction analysis of nano-tip in thermal-assisted data storage using molecular dynamics simulation
- Dynamic behavior of ionic polymer-metal composites
- Fracture propagation of rock under blast - A Numerical Investigation

##### MARITIME STUDIES

- A coordinated approach to planning and scheduling decisions in supply chains with dual transportation modes

##### STRUCTURES

- Ballast plan optimization in load-out operations with consideration of barge flexibility
- Effect of loading on PZT electromechanical admittance signature
- Error estimation for thin-walled structures modeling by 3D solid elements
- Adaptive FE analysis of thin-walled structures using 3D solid elements
- Strain and stress concentration of a completely overlapped tubular K-joint
- Efficient dynamic analysis of deepwater floating production systems
- Structural health monitoring using wireless sensor network
- Modelling and investigation of reinforced concrete gravity-load-designed beam-column joints

##### SPATIAL INFORMATION

- The design of a database for boreholes in 3D GIS.
- Application of 3D GIS in rock cavern

##### TRANSPORTATION

- A study of driver compliance to signalling during lane changing
- Studying drivers’ parking decisions using a dynamic parking simulator
- Performance characteristics of hot-mix asphalt with recycled concrete pipe production residue

##### WATER RESOURCES

- Effects of currents on double slotted wave barriers
- PIV measurements of vegetated open channel flows
- Effect of channel shape on time of travel in channel
- Effect of grid turbulence on particle settling

##### RESEARCH PROJECTS

- Abstracts of Research Reports
- Abstracts of PhD Theses

##### PUBLICATIONS

### CONTENTS

- Influence of residual stresses on the failure assessment diagrams of a cracked square hollow sections T-joint
- Heat conduction analysis of nano-tip in thermal-assisted data storage using molecular dynamics simulation
- Dynamic behavior of ionic polymer-metal composites
- Fracture propagation of rock under blast - A Numerical Investigation
- A coordinated approach to planning and scheduling decisions in supply chains with dual transportation modes
- Ballast plan optimization in load-out operations with consideration of barge flexibility
- Effect of loading on PZT electromechanical admittance signature
- Error estimation for thin-walled structures modeling by 3D solid elements
- Adaptive FE analysis of thin-walled structures using 3D solid elements
- Strain and stress concentration of a completely overlapped tubular K-joint
- Efficient dynamic analysis of deepwater floating production systems
- Structural health monitoring using wireless sensor network
- Modelling and investigation of reinforced concrete gravity-load-designed beam-column joints
- The design of a database for boreholes in 3D GIS.
- Application of 3D GIS in rock cavern
- A study of driver compliance to signalling during lane changing
- Studying drivers’ parking decisions using a dynamic parking simulator
- Performance characteristics of hot-mix asphalt with recycled concrete pipe production residue
- Effects of currents on double slotted wave barriers
- PIV measurements of vegetated open channel flows
- Effect of channel shape on time of travel in channel
- Effect of grid turbulence on particle settling
- Abstracts of Research Reports
- Abstracts of PhD Theses

### ADDITIONAL COPIES AND ENQUIRIES

For general enquiries about this publication and request for additional copies, please write to:

Chair  
School of Civil and Environmental Engineering  
Nanyang Technological University  
50 Nanyang Avenue  
Singapore 639798  
Tel: 65-67905264  
Fax: 65-67910676  
Email: D-CEE@ntu.edu.sg