Structural vibration: overview, modelling and evaluation

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2. Structural response to destructive dynamic actions
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   3.1 Overview of ground-borne vibrations
   3.2 Assessment methodologies and criteria
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   3.4 Mitigation
4. Concluding remarks
1. Introduction

2. Structural response to destructive dynamic actions
Structural vibration applications in civil engineering

- **Destructive dynamic effects**
  - Earthquake, blast …
  - Strong wind – high rise buildings and bridges

- **Vibration related serviceability, occupants comfort**
  - Large-span, light structures: wind, large crowds
  - Buildings structures: traffic; construction; blasting

- **Vibration based structural health monitoring and damage detection**
Introduction
Introduction

Air blast (shock wave)

“Total blast load” on structure

Shock strike causing localized damage

Stress wave in earth causing ground vibration

Detonation

Alfred P. Murrah Building, Oklahoma
April 19, 1995, ~2000kg TNT truck bomb
168 fatalities, >500 injuries.

Khobar, Dhahran, Saudi Arabia
Dhahran, Saudi Arabia
November 1996 (~9000kg@**m)
London Millennium Bridge opened June 2000
Introduction

- **Dynamic characteristics of loading**
- **Dynamic properties of the structure**

- **Air blast (shock wave)**
- **Shock strike causing localized damage**
- **"Total blast load" on structure**
- **Stress wave in earth causing ground vibration**

- **Direction of Propagation**
- **Particle Motion**

- **P WAVE**
- **S WAVE**
- **RAYLEIGH WAVE**

- **Animation L. Braile**

- **Graphs showing x-dir, y-dir, z-dir, t (s), f (Hz)**

- **f (Hz) values:** 100, 200

- **t (ms) values:** 1, 10
Introduction

- Dynamic characteristics of the load
- Dynamic properties of the structure

\[ f_1 \sim 1\text{Hz} \]
\[ f_3 \sim 3\text{Hz} \]
\[ f_n \sim 20\text{Hz} \]

Animation B. Rozsasi
The natural modes are inherent with any structure.

A particular mode may be excited in a real world situation as well, is you really want to ......
Introduction

Dynamic properties of 1) loading + 2) structure
= dynamic response
Classification

- Increasing freq.
- Reducing duration

- SDOF
- MDOF
- Lumped mass (Frame)
- FE etc
- Mesoscale

Global

Local ... subscale

Mesoscale ...
SDOF Model

SDOF – simple and yet instructive:
1) Global response; global force (base shear)
2) Global displacement

Suitable for fundamental mode dominant response
(regular, low to medium rise structures)

(Note: Special SDOF for localised response possible!)

Downside: no spatial info; no higher modes effect
Example: Generating probabilistic demand (displacement spectra using SDOF)

FUNDAMENTAL PERIOD
in seconds

height is the main determinant

equipment ~ buildings ~ 10-20 story ~ 40 story ~ Citicorp

0.05 " 0.1 " 0.5 " 1.0-2.0 " 7.0

ACCELERATION (g)

TIME (sec.)

ACCELERATION (g)

T (1/f)
MDOF Model

Lumped mass stick or frame

Capable of modelling higher mode participation; distribution of deformation (inter-storey drift).
MDOF Model

✓ Recent studies: MDOF for PBD

a) “storey capacity factors” for distribution of drifts – in connection to disp spectrum

b) Damage based MDOF evaluation - in connection to damaged based spectrum
**FE / other techniques**

a) Low dynamic (seismic) but with complex systems (frame + wall + solid core etc)

b) Intermediate (e.g. ground shock); Local + Global

c) High impulsive loading, dominant stress wave effects, drastic spatial and time variation, and spalling / fragmentation – numerical simulation
**FE / other techniques**

**Recent studies:**
Timoshenko beam + lumped mass model

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**Equivalent mass/spring for global horizontal mode participation**

- a) Column-mass-spring model (Horizontal loading)

**Colum with distributed mass and stiffness $\rho, EI, GA$**

**Equivalent mass/spring for global vertical mode participation**

- b) Beam-mass-spring model (Vertical loading)

**Beam with distributed mass and stiffness $\rho, EI, L$**

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20
Elastic solutions

(Lu and Gong 2007)
Nonlinear solutions

- Direct shear (Sliding)
- Diagonal shear
- Bending

Shear Force (kN) vs. Shear Strain

Shear Force (kN) vs. Shear Strain

Moment (kNm) vs. Curvature

Resistance vs. Displ.

Failure index

PGV=1.56m/s
PGV=3.12
PGV=3.90

Shear slip
Shear strain
Curvature

Principal ground motion frequency

10Hz
100Hz
200Hz

(Gong and Lu 2007)
3. Ground borne vibrations and building effects
3.1 Overview of ground-borne vibrations

**Common sources of ground-borne vibration**

- trains,
- buses on rough roads,
- construction activities such as blasting, pile driving and operation heavy earth-moving equipment.

**Effects:**

- feelable movement of building floors,
- rattling of windows, shaking of items on shelves or hanging on walls, and rumbling sound.
- In extreme cases the vibration can cause damage to building:

Annoyance from vibration often occurs when the vibration exceeds the threshold of **perception by 10 decibels or less** which is about an order of magnitude below the **damage threshold for normal buildings.**
Typical ground motions - characteristics

typical earthquake
ground motions;

Main pulse short
duration; dominant freq.
typical 3-component time records and power spectral density induced by in-depth blasting

(No. of passenger cars: 8; train speed: 125 km/h; recorded at 13 m apart from sleeper.)

(Kim and Lee, 1999)
typical 3-component time records and power spectral density induced by friction pile driving
**Specific to road traffic:**

Three basic types of dynamic tire forces acting on the pavement surface simultaneously:

1. Impact forces of the individual parts of the tire tread.

2. Impact forces linked to the unsuspended mass of the vehicle: axles, wheels, and tires. At highway speeds: 10 to 15 Hz, this frequency is related to the frequency of the tire bounce (also called axle hop).

3. Impact forces linked to the fundamental frequency of trucks. At highway speeds, typically 1 - 2 Hz.
Examples of road traffic induced ground vibrations ...
Vibration waves excite foundation & propagate throughout the remainder of building.

Max. vibration amplitude often at resonant frequencies of various components of the building.

Very complex paths;
- Very complex transmission mechanisms;
- Precise modelling difficult;
- Theoretical analysis
- Empirical measurements

Vibration of transit structure / road surface excites adjacent ground: vibration waves

Energy generated from contact interaction and moving load (local dynamic stress field)

Propagation of vibration waves through soil/rock strata

Soil Vibration Propagation Path
- Structural Vibration
- Radiated Sound

Soil Layer 1

Soil Layer 2

Bedrock

(Background drawing after FTA 2006)
Ground-borne vibration transmission

- **Source**
  - Surface Condition
  - Vehicle Parameters
  - Vehicle Speed

- **Transmission Path**
  - Distance
  - Soil/Ground Absorption
  - Ground Topography

- **Receiver**
  - Building Parameters
  - Receiver Location
Propagation of ground-borne vibrations

The **Rayleigh waves** are the most important form for the propagation of traffic induced vibration.
3.2 Assessment methodologies and criteria
Descriptors and general criteria

- **Vibratory motions:** displacement is easier to understand, but is rarely used:
  a) transducers use velocity/acceleration;
  b) more importantly, the response of humans, buildings (service/cosmatic damage) and equipment is more accurately described using **velocity or acceleration**.

- **Amplitude Descriptors:**
  - PPV
  - rms (velocity);
  - Decibel (V-db)
• Example of velocity in absolute units (in/s here; SI: m/s)
• Running RMS over 1s
• **Decibel (V-db)**

Like sound pressure, ground borne vibration from feelable to annoying / structural damaging varies by orders of magnitudes, so it make sense to compare magnitude by (common) logarithmic scale

\[
L_V = 20 \times \log_{10} \left( \frac{V}{V_{ref}} \right)
\]

So 20db = 10 (times ref value)

40db = 100 (times)

60db = 1000 (times)

+20db: increase by 10 times

-20db: decrease by 10 times (to 10%)
\[
Lv = 20 \times \log_{10}\left(\frac{V}{V_{\text{ref}}}\right)
\]

\(V_{\text{ref}}\): USA \(1 \times 10^{-6}\) in/s,

EU, Aus etc: \(5 \times 10^{-8}\) m/s

Making \(Lv_{\text{USA}} \approx Lv_{\text{other}} + 6\) db.
<table>
<thead>
<tr>
<th>Human/Structural Response</th>
<th>Velocity Level*</th>
<th>Typical Sources (50 ft from source)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Threshold, minor cosmetic damage</td>
<td>100</td>
<td>Blasting from construction projects</td>
</tr>
<tr>
<td>fragile buildings</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Difficulty with tasks such as reading a VDT screen</td>
<td>90</td>
<td>Bulldozers and other heavy tracked construction equipment</td>
</tr>
<tr>
<td>Residential annoyance, infrequent events (e.g. commuter rail)</td>
<td>80</td>
<td>Commuter rail, upper range</td>
</tr>
<tr>
<td>Residential annoyance, frequent events (e.g. rapid transit)</td>
<td>70</td>
<td>Rapid transit, upper range</td>
</tr>
<tr>
<td>Limit for vibration sensitive equipment. Approx. threshold for human perception of vibration</td>
<td>60</td>
<td>Commuter rail, typical</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>Bus or truck over bump</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Rapid transit, typical</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Bus or truck, typical</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Typical background vibration</td>
</tr>
</tbody>
</table>

*RMS Vibration Velocity Level in VdB relative to 10^-6 inches/second

Note: US V-db

FTA 2006
<table>
<thead>
<tr>
<th>Vib. Velocity Level</th>
<th>Noise Level</th>
<th>Human Response</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Low Freq1</td>
<td>Mid Freq2</td>
</tr>
<tr>
<td>65 VdB</td>
<td>25 dBA</td>
<td>40 dBA</td>
</tr>
<tr>
<td></td>
<td>~0.05mm/s</td>
<td></td>
</tr>
<tr>
<td>75 VdB</td>
<td>35 dBA</td>
<td>50 dBA</td>
</tr>
<tr>
<td></td>
<td>~0.15mm/s</td>
<td></td>
</tr>
<tr>
<td>85 VdB</td>
<td>45 dBA</td>
<td>60 dBA</td>
</tr>
<tr>
<td></td>
<td>~0.5mm/s</td>
<td></td>
</tr>
</tbody>
</table>

Notes:
1. Approximate noise level when vibration spectrum peak is near 30 Hz.
2. Approximate noise level when vibration spectrum peak is near 60 Hz.
Response to transit-induced vibration
### Table 1. Effects of Vibration on People and Buildings according to TRRL

<table>
<thead>
<tr>
<th>PPV&lt;sup&gt;a&lt;/sup&gt; (mm/s)</th>
<th>Human Reaction</th>
<th>Effect on Buildings&lt;sup&gt;c&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 – 0.15</td>
<td>Imperceptible</td>
<td>Unlikely to cause damage of any type</td>
</tr>
<tr>
<td>0.15 – 0.3&lt;sup&gt;b&lt;/sup&gt;</td>
<td>Threshold of perception</td>
<td>Unlikely to cause damage of any type</td>
</tr>
<tr>
<td>2.0</td>
<td>Vibrations perceptible</td>
<td>Recommended upper level to which ruins and ancient monuments should be subjected</td>
</tr>
<tr>
<td>2.5</td>
<td>Continuous exposure to vibrations begins to annoy&lt;sup&gt;d&lt;/sup&gt;</td>
<td>Virtually no risk of “architectural” damage to normal buildings</td>
</tr>
<tr>
<td>5</td>
<td>Vibrations annoying to people in buildings</td>
<td>Threshold for risk of “architectural” damage in houses with plastered walls and ceilings</td>
</tr>
<tr>
<td>10 - 15</td>
<td>Continuous vibrations unpleasant and unacceptable</td>
<td>Would cause “architectural” and possibly minor structural damage</td>
</tr>
</tbody>
</table>

<sup>a</sup> Peak Particle Velocity

<sup>b</sup> Indicates a significant increase in PPV

<sup>c</sup> Reference: UK Transport Res Lab

<sup>d</sup> Indicates a transition to more significant annoyance
Building damage

Transient vibration guide values for cosmetic damage:
Line 1 RC; Line 2: unreinforced

(BS 7385-2)
FACTORS THAT INFLUENCE GROUND-BORNE VIBRATION AND NOISE

Vibration source:
The physical parameters of the transit facility / road surface conditions

Vibration paths; the geology,

Vibration receiver: the building

<table>
<thead>
<tr>
<th>Soil Type</th>
<th>Vibration levels are generally higher in stiff clay-type soils than in loose sandy soils.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rock Layers</td>
<td>Vibration levels are usually high near at-grade track when the depth to bedrock is 30 feet or less. Subways founded in rock will result in lower vibration amplitudes close to the subway. Because of efficient propagation, the vibration level does not attenuate as rapidly in rock as it does in soil.</td>
</tr>
<tr>
<td>Soil Layering</td>
<td>Soil layering will have a substantial, but unpredictable, effect on the vibration levels since each stratum can have significantly different dynamic characteristics.</td>
</tr>
<tr>
<td>Depth to Water Table</td>
<td>The presence of the water table may have a significant effect on ground-borne vibration, but a definite relationship has not been established.</td>
</tr>
</tbody>
</table>
FACTORS THAT INFLUENCE GROUND-BORNE VIBRATION AND NOISE

Vibration source:
The physical parameters of the transit facility / road surface conditions

Vibration paths; the geology,

Vibration receiver: the building

<table>
<thead>
<tr>
<th>Foundation Type</th>
<th>The general rule-of-thumb is that the heavier the building foundation, the greater the coupling loss as the vibration propagates from the ground into the building.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Building Construction</td>
<td>Since ground-borne vibration and noise are almost always evaluated in terms of indoor receivers, the propagation of the vibration through the building must be considered. Each building has different characteristics relative to structureborne vibration, although the general rule-of-thumb is the more massive the building, the lower the levels of ground-borne vibration.</td>
</tr>
<tr>
<td>Acoustical Absorption</td>
<td>The amount of acoustical absorption in the receiver room affects the levels of ground-borne noise.</td>
</tr>
</tbody>
</table>
Practical assessment procedure

Because ground-borne vibration, especially traffic-induced, is generally a random process, it is normally not effective to perform a time domain analysis.

Instead, frequency domain analysis is common (not when nonlinearities are involved though).

General form:

\[ Y(\omega) = H(\omega)X(\omega) \]

In log-db scale:

\[ \lg Y(\omega) = \lg X(\omega) + \lg H(\omega) \]

\[ \text{db}_Y = \text{db}_X + \text{db}_H \]
A typical flow chart

\[ L_v = L_F + TM_{\text{line}} + C_{\text{build}} \]

\[ L_A = L_v + K_{\text{rad}} + K_{A-\text{wt}} \]

(FTA 2006)
**Major Steps in Detailed Analysis (engineering approach)**

1. Develop estimates of the **force density**. Can be based on previous measurements or a special test program. Adjustments for factors such as traffic speed, road surfaces, track support system, and vehicle suspension.

2. Measure the **point-source transfer mobility** at representative sites. The transfer mobility is a function of both frequency and distance from the source. (Mobility: velocity; inertiance: acceleration, displacement: receptance.

3. Use numerical integration to estimate a **line-source transfer mobility** from the point-source transfer mobilities.

4. Combine force density and line-source transfer mobility to project **ground-surface vibration**.

5. Add adjustment factors to estimate the **building response** to the ground-surface vibration and to estimate the A-weighted sound level inside buildings.

More detailed discussion follows ......
Typical force density for rail transit vehicle, 40mph
Example of point source transfer mobility

Example of line source transfer mobility
From Foundation to receiver room: very complex

Detailed evaluation: numerical procedures such as the FEM

Empirical method: Adding adjustments to the 1/3-octave band spectrum of the projected ground-surface vibration:

- **Building response or coupling loss:** due to the presence of the building foundation.

- **Transmission through the building:** Amplitude typically decreases as the vibration energy propagates through the building (resonance see below). Normal assumption is that vibration attenuates by 1 to 2 dB for each floor.

- **Floor resonances:** Amplification effect.
  - A typical wood-frame residential structure, $f_{1n} = 15 ~20$Hz
  - RC slab floors: $f_{1n} = 20~30$ Hz.
  - Amplification gain of $\sim 6$ dB (about doubling in amplitude) should be used in the frequency range of the fundamental resonance.
Foundation response for various types of buildings
Obtaining transfer mobility

Test Configuration for Measuring Transfer Mobility

Point mobility:

Line transfer mobility: measurement using a line of impact
Analysis of transfer mobility
Deriving Force Density

Force Density is not a quantity that can be measured directly; it must be inferred from measurements of transfer mobility and traffic vibration at the same site.

For deriving force density, the best results are achieved by deriving line-source transfer mobility from a line of impacts. The force density for each 1/3 octave band is then simply:

\[ L_F = L_v - TM_{\text{line}} \]

where LF is the force density, Lv is measured train ground-borne vibration, and TMline is the line-source transfer mobility.
3.3 Detailed analysis and modelling
3.3 Detailed analysis and modelling

- More accurate description of source excitation; stochastic/random vibration;
- Wave propagation from source to site (transfer function development)
- Soil-foundation/building interaction: coupled model (transmissibility from soil to building foundation)
- Building responses; with sufficient details and possibly incorporation of non-structural components
- (reduced model – not reduced accuracy – using b-col. analogy class of model) e.g. with the model by Lu & Gong 2007
Schematic Illustration
(Main ingredients)

- Structural model – as detailed as needed
- Non-structural elements may also need be incorporated
- Soil interface model (freq dependent spring + dashpot)
- Ground vibration input (time history)
(Newland 1991)
A fully-coupled 3D FE model (1,336,592 nodes)
(Ju 2008)
3.4 Mitigation
3.4 Mitigation

... Best measure = improved maintenance procedures: problems with lack of road / track maintenance ~20 dB. No practical control measures will provide >15~20 dB attenuation.

Typical seven categories of measures:

(1) maintenance procedures,
(2) location and design of special trackwork, road improvement,
(3) vehicle modifications – not always possible,
(4) changes in the road / track support system,
3.4 Mitigation

... Best measure = improved maintenance procedures: problems with lack of road / track maintenance ~20 dB. No practical control measures will provide >15~20 dB attenuation.

Typical seven categories of measures:

(5) **building modifications**, e.g. vibration isolation of buildings with elastomer pads
The floor upon which the vibration-sensitive equipment is located could be stiffened and isolated from the remainder of building.

(6) adjustments to the vibration transmission path, e.g. using tranches, and

(7) operational changes – speed limit etc.
Modify & “block” ground vibration transmission paths

Vibration reduction at Ledsgard, using lime-column (as embankment enhancement and as barrier)

3rd generation of gas cushion system

(Massarsch, 2004)
Isolation barrier / trench shall have a depth corresponding to the Rayleigh wave length of the disturbance.

\[ \beta \tau = \left( \frac{BT}{\lambda^2} \right) \]

\[ \lambda = \frac{c}{f} \]
Building isolation

Base isolation in more challenging situations
Wellington Hospital, London (Grootenhuis 1999). To limit the internal noise and vibration due to the moving traffic, the building is base-isolated on rubber bearings.
Other transmission loss mechanisms

- Flexible column
- Resilient pad at position $h$ (metres) above ground level

“Resilient pad”

Solid line = rigid column on bearing pad; unrealistic for flexible column
Flexible column
Displacement response at position $z$ (metres) above ground level
Resilient pad at position $h$ (metres) above ground level
Pile sub-structure

(a) Vibration above the pad
(b) Vibration below the pad
(c) Power spectra above the pad
(d) Power spectra below the pad
(e) Transmissibility curves
(f) Coherence between signals

(Newland 1991)
Concluding remarks

Isolation of buildings from ground vibration: other general considerations

- Passive and active control measures from seismic control could be considered
- Ground borne vibration has very different frequency characteristic; relatively broad band and higher frequencies: affects effectiveness of control measures
- Floor vibration is of key concerns (global structural vibration less a problem): affects choice of control measures
- Vibration transmission from foundation through columns/walls and spread out: mechanisms to boost transmissibility loss along paths desirable
- Good understanding of phenomena / principles essential