URBAN SEISMIC HAZARD MAPPING USING GEOPHYSICAL TECHNIQUES

Jim Hunter
Geological Survey of Canada
VSP: DOWNHOLE SHEAR WAVE MEASUREMENTS
(in cased boreholes)

Well-locking 3-component geophones
Surface Reflection/Refraction Site Analyses and MASW
Landstreamer Array with Vibratory Source

Shear wave reflection profiling. Notre-Dame Est, Montreal

MiniVib Source in radial orientation

two 24 ch 3-comp land streamers
Fraser River Delta, British Columbia
Shear Wave Velocity Site Locations
Ground Resonance

Equally important as Vs30 mapping – should be used together for site interpretation

Rule of Thumb

13 stories = 0.1 s x 13 stories = 1.3 s structure period

If fundamental site period of the ground also ~1.3s, then increased resonance of structure could occur
Zonation of Ottawa, Ontario

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Carleton University (CSRN)

Dr. Jim Hunter, GSC
Dr. Andre Pugin, GSC
Dr. Susan Pullan, GSC
EXTENT OF CHAMPLAIN SEA SEDIMENTS

- soft sediments up to 130 m thick
- low Vs overlying high Vs glacial sediments and rock
NBCC High Seismic Hazard Areas of Eastern Canada (Sa = 0.2 seconds)
Simplified Surficial Geology

Water
Deglacial/postglacial sediments (soft soil - 65%)
Glacial sediments (dense soil - 15%)
Bedrock (hard rock - 20%)
City of Ottawa
Overburden Thickness Map
Data sources – 685 surface geophysics sites
10 geophysical boreholes
25 line-km of Landstreamer
Data sources – 21,000 water wells and engineering boreholes
Ottawa NEHRP Zonation Map based on $V_{s30}$ measurements
Ottawa Fundamental Site Periods based on soil thicknesses and Vs velocities
Variation of $\text{Sa}(0.2)$ values for NEHRP C across the City of Ottawa for the “design” earthquake
Variation of Sa(0.2) values for the “design” earthquake after accounting for differing NEHRP zones across the City of Ottawa
Applications of the maps

Office of Emergency Management:

- maps help to predict areas of City where the greatest shaking may occur
- maps will be used during upcoming review of the City’s comprehensive vulnerability analysis
- maps will be used in prioritizing City’s response for the affected neighbourhoods during a significant earthquake event
- City will be seeking NRCan’s advice about:
  • Conducting a hazard assessment using the maps
  • Public education of earthquake hazards
Applications of the maps

Planning and Infrastructure Department:

- **Building Code Services:**
  - maps are used on a daily basis as part of screening process for assessment of potential developments
  - information for out-of-town developers on the variability of soil conditions in the Ottawa area
  - Map information may lead to the stipulation of increased level of geotechnical analysis for building permit approval
Future applications

- **Quantitative risk analysis**
  - Microzonation maps add a critical framework layer that represents the variability of the seismic hazard

- **Emergency management exercises**
  - Ottawa seismic site categories map being incorporated into SHAKEMAP by CHIS for improved earthquake modeling

- **Planning city growth**
  - High-level tool for siting critical infrastructure (can avoid terrains prone to greater shaking)
The End!

Thank you for your attention!

Jim Hunter
Hazard Mapping is the Framework for Risk Assessment
Urban Seismic Hazard Mapping

Shear Wave Velocities of Soils and Rock are Key Measurements in the Hazard Framework

(shear wave velocities to be defined shortly)
Urban Seismic Hazard Mapping

Thick **Soft Soils**
Having Low Shear Wave Velocities
Are Associated With
Increased Shaking and Damage
Q: IS SOFT SOIL A PROBLEM IN HIGH HAZARD ZONES IN CANADA?

A: Yes
Q: IF SO, WHERE ARE THESE ZONES? (with respect to population density)
Q: HAS THERE BEEN PREVIOUS EVIDENCE OF MAJOR EARTHQUAKE DAMAGE? (close to population centers today)

A: East – Charlevoix QC, 1663 AD M7.0, 
    Lefevre Ont 7050 ybp M 6.5-7.0, 
    Bourget Ont 4550 ybp M6.0-6.5 

West – several large events in the geological record, 
    the last major event on the west coast was 1700 AD, M8-9
EARTHQUAKE BODY WAVES

P WAVE

Direction of Propagation

Particle Motion

S WAVE

Direction of Propagation

Particle Motion
EARTHQUAKE SURFACE WAVES

RAYLEIGH WAVE

LOVE WAVE

Direction of Propagation

Particle Motion
Example Seismic Record of a Local Earthquake
The epicentre was north of Ottawa and Montreal

West Quebec Seismic Zone
L’Annonciation M3.3  2009-11-02 03:16:44
Lat 46.12 Lon 74.73 Distance: 96.7 km NE

RAYLEIGH & LOVE WAVES
S-WAVE
P-WAVE

ORLEANS SEISMOGRAPHS
(1.6 km apart)
- STN ORHO - 90 m soil
- STN ORIO - bedrock

TIME from Start of Earthquake (seconds)
What happens to earthquake waves in soft soils to cause the concern?

- The seismic waves slow down passing through soils.
- The wavelengths get shorter, but have the same energy per wavelength, hence,
- The amplitude of shaking increases.
Impedance Contrast Amplification

- Soft soil
- Stiff soil
- Bedrock
- Bedrock
Impedance Contrast Amplification
Resonance Amplification Added

Diagram showing the effects of resonance amplification in soil layers:
- Soft soil
- Stiff soil
- Bedrock

The diagram illustrates how vibrations in soft soil can be amplified when reaching the bedrock.
Basin Effects: focussing, defocussing

Mexico City, 1985 after Rial et al., 1992
Combined soft soil effects

Greater shaking
Longer shaking

Soft soil
Stiff soil
Bedrock
Bedrock

Natural Resources Canada
Ressources naturelles Canada
Canada
Canadian Urban Seismic Risk

- Vancouver
- Québec
- Toronto
- Victoria
- Ottawa/Hull
- Other municipalities
<table>
<thead>
<tr>
<th>Site Class</th>
<th>Soil profile name</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Hard rock (e.g., granite)</td>
</tr>
<tr>
<td>B</td>
<td>Rock (e.g., limestone)</td>
</tr>
<tr>
<td>C</td>
<td>Very dense soil or soft rock (e.g., till or shale)</td>
</tr>
<tr>
<td>D</td>
<td>Stiff soil (e.g., gravel)</td>
</tr>
<tr>
<td>E</td>
<td>Soft Soil (e.g., marine clay)</td>
</tr>
<tr>
<td>F</td>
<td>Others</td>
</tr>
</tbody>
</table>
### NBCC seismic site categories (NEHRP)

<table>
<thead>
<tr>
<th>Site Class</th>
<th>Soil profile name</th>
<th>Defined based on geotechnical properties of the upper 30 m</th>
<th>Soil average shear wave velocity, $V_s$ (m/s)</th>
<th>Standard penetration resistance, $N_{60}$ (blow counts)</th>
<th>Soil undrained shear strength, $S_u$ (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Hard rock (e.g., granite)</td>
<td>na</td>
<td>$V_s &gt; 1500$</td>
<td>na</td>
<td>na</td>
</tr>
<tr>
<td>B</td>
<td>Rock (e.g., limestone)</td>
<td>na</td>
<td>$760 &lt; V_s &lt; 1500$</td>
<td>na</td>
<td>na</td>
</tr>
<tr>
<td>C</td>
<td>Very dense soil or soft rock (e.g., till or shale)</td>
<td>$360 &lt; V_s &lt; 760$</td>
<td>$N_{60} &gt; 50$</td>
<td>na</td>
<td>$S_u &gt; 100$</td>
</tr>
<tr>
<td>D</td>
<td>Stiff soil (e.g., gravel)</td>
<td>$180 &lt; V_s &lt; 360$</td>
<td>$15 &lt; N_{60} &lt; 50$</td>
<td>na</td>
<td>$50 &lt; S_u &lt; 100$</td>
</tr>
<tr>
<td>E</td>
<td>Soft Soil (e.g., marine clay)</td>
<td>$V_s &lt; 180$</td>
<td>$N_{60} &lt; 15$</td>
<td>na</td>
<td>$S_u &lt; 50$</td>
</tr>
<tr>
<td>F</td>
<td>Others</td>
<td>Site specific evaluation required</td>
<td></td>
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<td></td>
</tr>
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NEHRP Zone Mapping

### 2005 NBCC

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</tr>
<tr>
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<td>Rock (e.g., limestone)</td>
<td>( 760 &lt; V_s &lt; 1500 )</td>
<td>na</td>
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<tr>
<td>C</td>
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<td>( 360 &lt; V_s &lt; 760 )</td>
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Soil average shear wave velocity, \( V_s \) (m/s)  
Standard penetration resistance, \( N_{60} \)  
Soil undrained shear strength, \( S_u \) (kPa)
Ground Accelerations for NEHRP Zone C for the “1 in 2500” year event
NBCC Amplification Factors
Look-up tables

Table 2. Values of $F_s$ as a Function of Site Class and $T=0.2\ s$ Spectral Acceleration.

<table>
<thead>
<tr>
<th>Site Class</th>
<th>$Sa(0.2) \leq 0.25$</th>
<th>$Sa(0.2) = 0.50$</th>
<th>$Sa(0.2) = 0.75$</th>
<th>$Sa(0.2) = 1.00$</th>
<th>$Sa(0.2) = 1.25$</th>
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<tbody>
<tr>
<td>A</td>
<td>0.7</td>
<td>0.7</td>
<td>0.8</td>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td>B</td>
<td>0.8</td>
<td>0.8</td>
<td>0.9</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>C</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>D</td>
<td>1.3</td>
<td>1.2</td>
<td>1.1</td>
<td>1.1</td>
<td>1.0</td>
</tr>
<tr>
<td>E</td>
<td>2.1</td>
<td>1.4</td>
<td>1.1</td>
<td>0.9</td>
<td>0.9</td>
</tr>
<tr>
<td>F</td>
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<td></td>
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<td></td>
<td></td>
</tr>
</tbody>
</table>

Credit for better sites
Ottawa

Non-Linear effects on soft soils
Deamplification

Table 3. Values of $F_s$ as a Function of Site Class and $T=1.0\ s$ Spectral Acceleration.

<table>
<thead>
<tr>
<th>Site Class</th>
<th>$Sa(1.0) &lt; 0.1$</th>
<th>$Sa(1.0) = 0.2$</th>
<th>$Sa(1.0) = 0.3$</th>
<th>$Sa(1.0) = 0.4$</th>
<th>$Sa(1.0) &gt; 0.5$</th>
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</thead>
<tbody>
<tr>
<td>A</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.6</td>
<td>0.6</td>
</tr>
<tr>
<td>B</td>
<td>0.6</td>
<td>0.7</td>
<td>0.7</td>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td>C</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>D</td>
<td>1.4</td>
<td>1.3</td>
<td>1.2</td>
<td>1.1</td>
<td>1.1</td>
</tr>
<tr>
<td>E</td>
<td>2.1</td>
<td>2.0</td>
<td>1.9</td>
<td>1.7</td>
<td>1.7</td>
</tr>
<tr>
<td>F</td>
<td></td>
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</tr>
</tbody>
</table>

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Non-Linear effects on soft soils
Less amplification

AMPLIFICATION FACTORS TO NEHRP ZONE C (FIRM GROUND) FOR CANADIAN SITES
Shear Wave Measurement Techniques

- Seismic Cone Penetrometer (SCPT)
- Downhole Seismic Profile (VSP)
- Surface Refraction/Reflection Site Analyses
- Seismic Landstreamer profiling
- Multi-channel Analysis of Surface Waves (MASW)
SEISMIC CONE PENETROMETER - SCPT
(Conetec Investigations Ltd)