Regional Earthquake-Induced Derailment Risk: Overview and Current Modeling Issues

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Overview

- Regional vs. Local Estimation
- General Framework: Seismic Risk Estimation with examples from the railroad perspective
- Spatial Variability of Ground Motion and Consequences for Regional Estimation
- Earthquake-Induced Derailment Risk

Earthquake of April 29, 1965, Seattle, Washington. The magnitude 6.5 earthquake killed 7 and caused $12.5 million property damage.
Earthquake Engineering Saves Lives!

- **San Francisco, 1989**
  « 7.1 magnitude Loma Prieta earthquake occurred on October 17, 1989. The quake was responsible for 67 deaths »
  
  - 7.1 Richter Scale
  - 67 Dead

- **Armenia, 1989**
  « With most of Armenia covered in high-rise buildings the consequences have been devastating. »
  
  - 6.9 Richter Scale
  - 25,000 Dead
RegionaL vs. Local

Traditionally, Earthquake Risk Models for railroads consider the likelihood of events on a single segment. More generally, a “point-risk assessment” would evaluate the risk of failure along a track in isolation from the other tracks.

The regional approach must assess the likelihood of multiple events triggered simultaneously by the same triggering event – an earthquake – on different segments.
Regional vs. Local

Given an earthquake scenario (magnitude $M$, source $x$) the evaluation of the probability of such multiple-event scenarios depends on the degree of spatial correlation of ground motion severity, fragility, and exposure.

- **Ground Motion** (GM) variations: wave incoherence/spatial variability of GM, soil conditions…
- **Fragility**: Structural responses (bridges, tunnels, embankments…) and level of failures
- **Exposure**: ridership, locations (rural vs. urban areas), built environment…
Seismic Risk Analysis

General framework

- **Hazard Analysis**: Ground Motion predictions
  - Earthquake rates of Occurrence $P(M, x)$
  - Hazard at site: Given a scenario-earthquake $(M, x)$, Prediction of ground motion accelerations $A = f(M, R, Soil)$

- **Vulnerability Functions**: probability of damage/failure of the structures, derailment… given different levels of Ground Motions.

- **Exposure**: number of passengers dependent on time of day, speed…

Seismic Risk = Seismic Hazard * Vulnerability * Exposure
Observation from closely-spaced seismograph arrays shows that earthquake ground accelerograms measured at different locations within the dimensions of typical structure are significantly different.
SVGM: Causes

- Wave Passage Effect: Temporal Incoherence
  - Arrival of seismic waves at different times at different stations (speed = 630km/s)

- Spatial Incoherence Effect
  - Superposition of waves from extended sources and scattered by irregularities and inhomogeneities along the path.

- Local-site effect
  - Alteration of the amplitudes and frequency content of the bedrock motion depending on the soil.

\[
\gamma_y(\omega) = \exp \left[ -\left( \frac{\alpha \omega d_{ij}}{v_s} \right)^2 \right] \cdot \exp \left[ i \frac{\omega d_i^L}{v_{app}} \right] \cdot \exp [i \theta_y(\omega)]
\]
SVGM: Causes

Coherency Function

\[ \gamma_y(\omega) = \exp\left[ -\left( \frac{\alpha \omega d_y}{\nu_s} \right)^2 \right] \exp\left[ i \frac{\omega d_y^L}{v_{app}} \right] \exp\left[ i \theta_y(\omega) \right] \]

- **Spatial incoherence**
  As \(d_{ij} \to 0\), the processes in \(i\) and \(j\) are identical (see Der Kiureghian, 1996, p. 103) \(d_{ij}=0\)

- **Temporal incoherence**
  Or “Wave passage effect”
  As \(d_{ij} \to 0\), no lag-time between processes (same arrival time) \(\tau = 0\)

- **Site Conditions**
  As \(d_{ij} \to 0\), the processes in \(i\) and \(j\) are identical (same soil...)

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Modeling of SVGM

- SVGM can be modeled as an homogenous random field with cross Spectral Density Functions

\[ S_{A_{track,t}}(\omega) = S_{A_{rock}} * g^2(t) * |H_{soil}(\omega)|^2 |H_{structure}(\omega)|^2 \]

\[ \sigma^2_{A_{track,t}} = \int_{-\infty}^{+\infty} S_{A_{track,t}}(\omega) d\omega \]
SVGM Modeling Issues

Theoretical models for $H(w)_{\text{Soil}}$

- Engineering approach – MKT modified Kanai-Tajimi

$$|H_{\text{soil}}(\omega)|^2 = \frac{1 + 4\zeta_i^2\left(\frac{\omega}{\omega_i}\right)^2}{\left[1 - \left(\frac{\omega}{\omega_i}\right)^2\right]^2 + 4\zeta_i^2\left(\frac{\omega}{\omega_i}\right)^2} * \frac{\left(\frac{\omega}{\omega_f}\right)^4}{\left[1 - \left(\frac{\omega}{\omega_f}\right)^2\right]^2 + 4\zeta_f^2\left(\frac{\omega}{\omega_f}\right)^2}$$

Ground acceleration histories can be synthetically generated from the modified Kanai-Tajimi power spectral density function.

The shortcoming of this method is that except for the site conditions, it does not integrate various factors affecting ground motion, such as Magnitude, $M$, and distance to source, $R$.

<table>
<thead>
<tr>
<th>Soil Type</th>
<th>$f_i$</th>
<th>$\zeta_i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hard rock</td>
<td>5</td>
<td>0.8</td>
</tr>
<tr>
<td>Stiff</td>
<td>3</td>
<td>0.6</td>
</tr>
<tr>
<td>Medium</td>
<td>1.5</td>
<td>0.4</td>
</tr>
<tr>
<td>Soft</td>
<td>0.5</td>
<td>0.2</td>
</tr>
</tbody>
</table>
SVGM Modeling Issues

- **Theoretical models for** $H(w)_{\text{Soil}}$

- **Physical approach** (Boore, 2003)

One of the essential characteristic of the physical approach is that it takes into account those factors affecting ground motions (source, path, and site) into unique functional form.

$$H(f, M, R)_{\text{Soil}} = CM_0 A_0(f) P_1(R, f) V_2(f) D_3(f) I(f)$$

**Source** $A_0(f)$

$$A_0(f) = \left(1 - \varepsilon \right) \left( f/f_a \right)^2 + \varepsilon \left( f/f_b \right)^2$$

**Attenuation** $P_1(R, f) = G(R) \exp(Q(R, f))$

$$G(R) = \begin{cases} 
\frac{1}{R} & R < 40 \text{km} \\
\frac{1}{40} \sqrt{\frac{40}{R}} & R > 40 \text{km}
\end{cases}$$

$$Q(R, f) = \exp\left(-\frac{\pi R}{180 f^{0.45}}\right)$$

The spectrum decays with distance due to Geometric spreading $G(R)$ and anelastic attenuation $Q(R, f)$

**Crustal Amplification** $V_2(f)$


**Near surface attenuation (kappa operator)**

$$D_3(f) = \exp(-\pi f k)$$

**Type of Ground Motion** $I(f)$

$$|I(f)|^2 = \frac{\left(f/f_{st}\right)^4}{1 + \left(f/f_{st}\right)^4 + 2\left(2\zeta_{st}^2 - 1\right)\left(f/f_{st}\right)^2}$$
SVGM Modeling Issues

Theoretical Model Structure:

\[ |H(w)|_{structure}^2 = \frac{1 + 4\xi_{st}^2 (\frac{f}{f_{structure}})^2}{\left(1 - (\frac{f}{f_{structure}})^2\right)^2 + 4\xi_{structure}^2 (\frac{f}{f_{structure}})^2} \]

Obtention of ground motion

\[ \sigma_{track,x}^2 (fst) = \int_{-\infty}^{+\infty} S_{track,x} (\omega) d\omega = \int_{-\infty}^{+\infty} |H(w)|_{soil=rock}^2 |H(w)|_{structure}^2 \]

\[ A_{max \: theo} (\omega_{st}) = c(\omega_{st}) \sqrt{\sigma_{track,x}^2} \]

\[ c(\omega_{st}) = \sqrt{2 \ln(2.8 \times \omega_{st} \times 5)} \]

The coherency function is added to the transfer functions \( H_s \).

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Seismic Risk Analysis: Derailments

- **Vulnerability:** for our study concerning railroad risks, vulnerability to derailment may be caused by different failures:
  - **Causes:**
    Given an earthquake scenario \((M, x)\), different Derailment causes are investigated. Trains may derail during the strong phase of the ground motion – derailment due to shaking - due to excessive acceleration and/or relative rail deformation. They may also derail after the motion has ended due to permanent rail deformation or failure of the soil or the supporting structure.
Earthquake-Induced Derailments

- Causes
  - Damage of the track
  - Shaking
    - Acceleration of the track
    - Acceleration due to relative displacement
  - Structure/Soil failure – bridge – embankment
Current Research

- Implement SVGM into the vulnerability analysis:
  - Calibrating the theoretical model so that it matches the actual data (empirical attenuations relationship)

- Develop a consequence model at a regional level
Questions!

Research in collaboration with

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