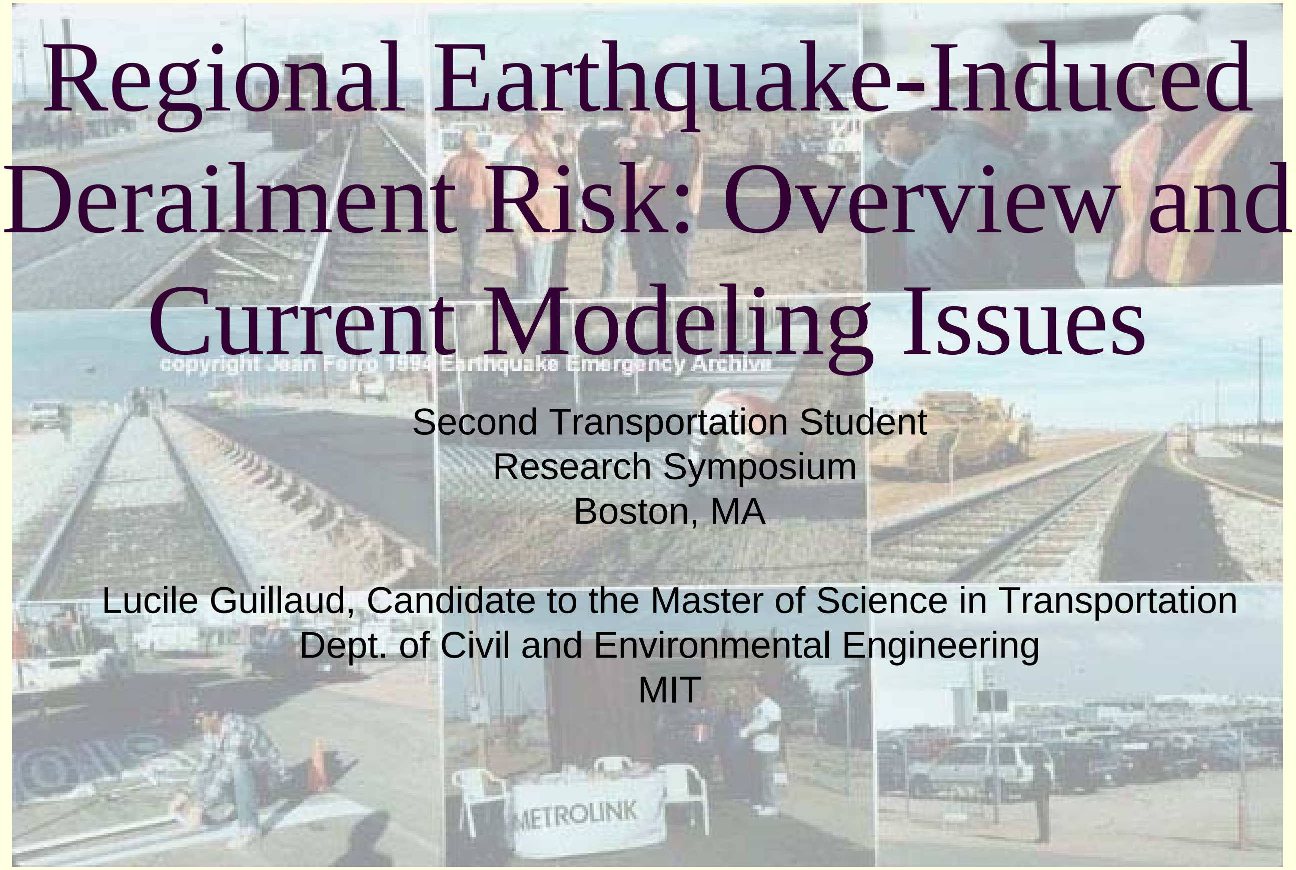
Turkey, on August 17, 1999



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.

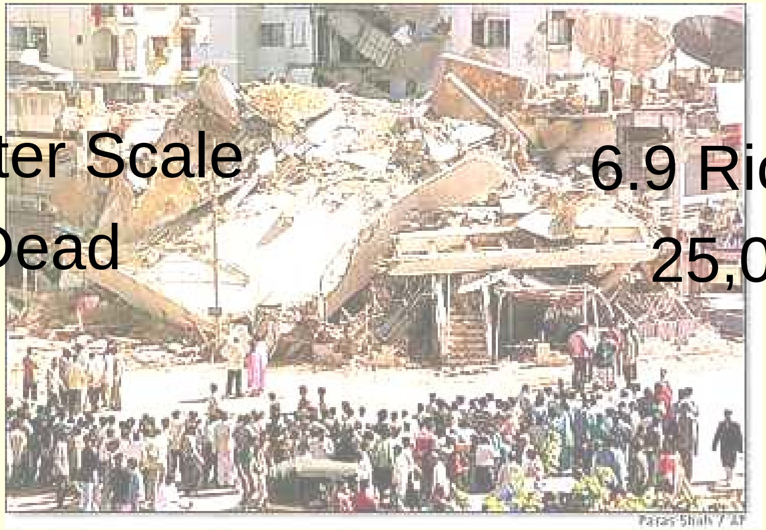
Earthquake Engineering Saves Lives!

- San Francisco, 1989

« *7.1 magnitude Loma Prieta earthquake occurred on October 17, 1989. The quake was responsible for 67 deaths»*

- Armenia, 1989

« *With most of Armenia covered in high-rise buildings the consequences have been devastating. »*



7.1 Richter Scale

67 Dead

6.9 Richter Scale

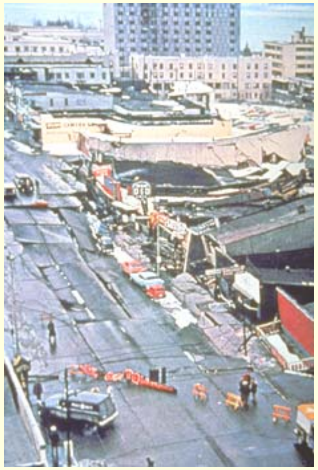
25,000 Dead

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 <u>multiple events</u> triggered <u>simultaneously</u> by <u>the same triggering event – an earthquake -</u> on different segments.

Regional vs. Local

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



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

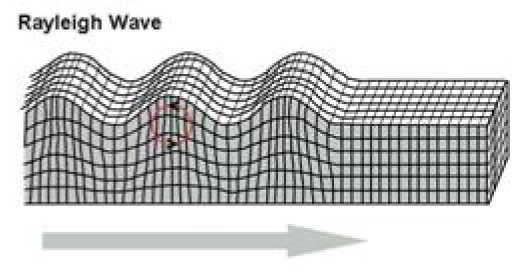
Seismic Risk Analysis

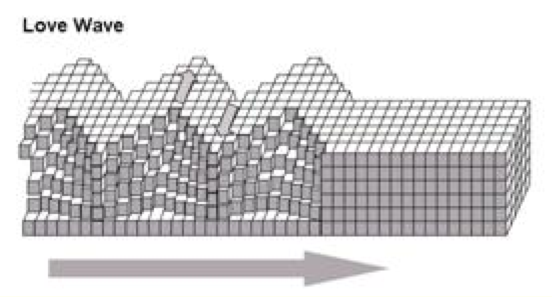
- General framework
  - Hazard Analysis: Ground Motion predictions
    - Earthquake rates of Occurrence P(M, x)
    - Hazard at site: Given a scenario-earthquake (M, x), Prediction of ground motion accelerations A = f(M, R, Soil)
  - Vulnerability Functions: probability of damage/failure of the structures, derailment… given differents levels of Ground Motions.
  - Exposure: number of passengers dependent on time of day, speed…

Seismic Risk = Seismic Hazard * Vulnerability * Exposure

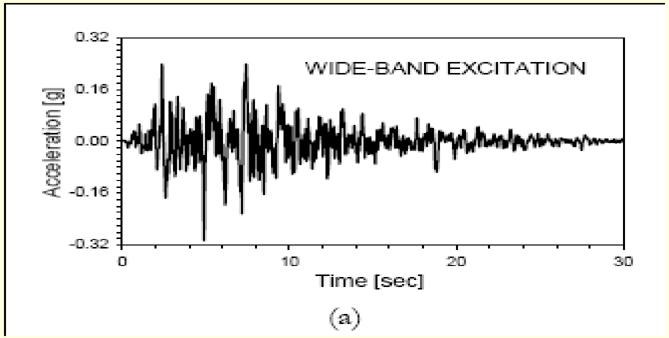
Seismic Risk Analysis: SVGM

- Hazard Analysis: Spatial Variability of Ground Motion





Observation from closely-spaced seismograph arrays shows that earthquake ground accelerograms measured at different locations within the dimensions of typical structure are significantly different.



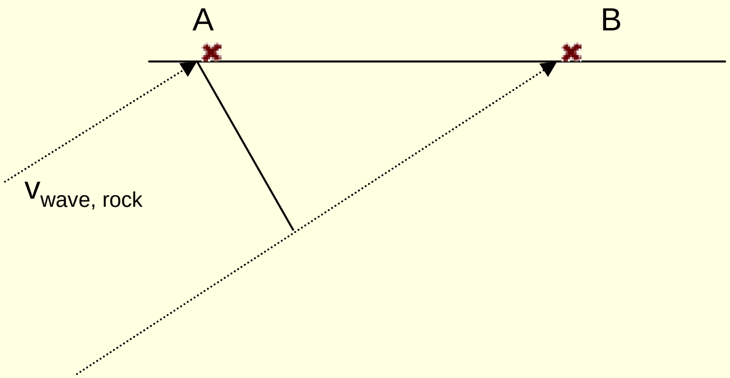
SVGM: Causes

- 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.

$$\gamma_{ij}(\omega) = \exp\left[-\left(\frac{\alpha\omega d_{ij}}{v_s}\right)^2\right]\cdot\exp\left[i\,\frac{\omega d_{ij}^{L}}{v_{app}}\right]\cdot\exp\left[i\theta_{ij}(\omega)\right]$$

SVGM: Causes

Coherency Function



$$\gamma_{ij}(\omega) = \exp\left[-\left(\frac{\alpha\omega d_{ij}}{v_s}\right)^2\right] \cdot \exp\left[i\frac{\omega d_{ij}^L}{v_{app}}\right] \cdot \exp\left[i\theta_{ij}(\omega)\right]$$

<u>Spatial incoherence</u>
As $d_{ij} \rightarrow 0$, the processes in i and j are identical (see Der Kiureghian, 1996, p. 103) $d_{ij}=0$

<u>Temporal incoherence</u>
Or "<u>Wave passage effect</u>"
As $d_{ij} \rightarrow 0$, no lag-time between processes (same arrival time) $\tau = 0$

<u>Site Conditions</u>
As $d_{ij} \rightarrow 0$, the processes in i and j are identical (same soil…)

Modeling of SVGM

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

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

$$\sigma^2_{A_{track,t}} = \int_{-\infty}^{+\infty} S_{A_{track,t}}(\omega)\, d\omega$$

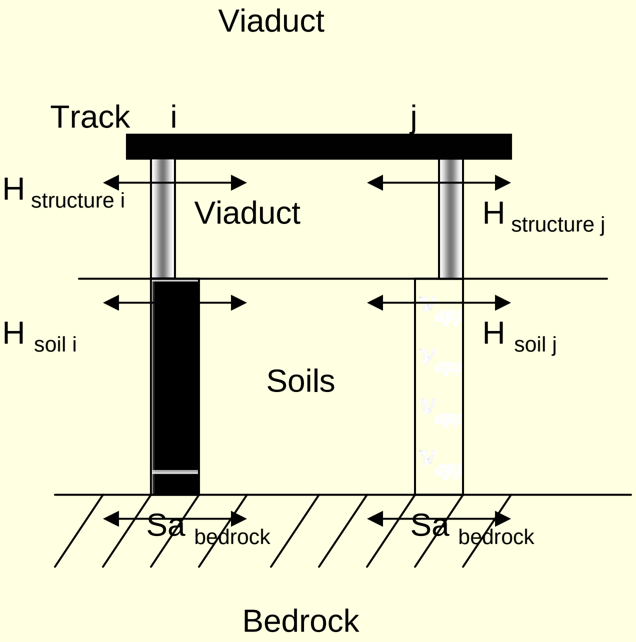


Figure 1.b

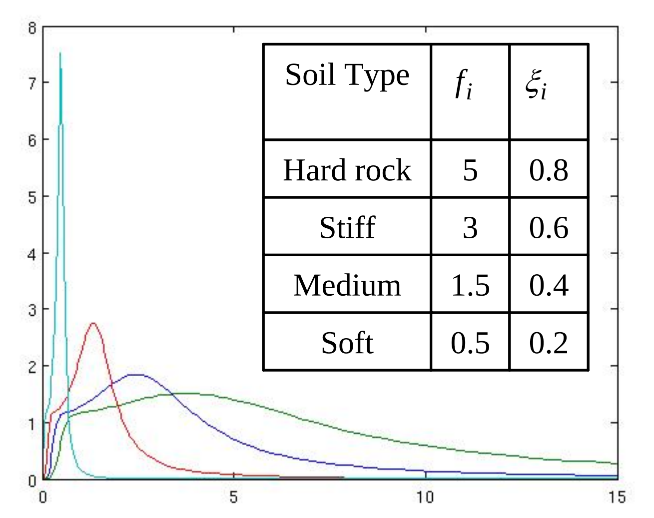
SVGM Modeling Issues

- Theoretical models for H(w)Soil
  - Enginering approach – MKT *modified Kanai-Tajimi*

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

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.



Soil Type	f_i	ξ_i
Hard rock	5	0.8
Stiff	3	0.6
Medium	1.5	0.4
Soft	0.5	0.2

SVGM Modeling Issues

- Theoretical models for H(w)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.

$$\boxed{\left|H(f,M,R)_{soil}\right| = CM_0\ A_0(f)\,P_1(R,f)\,V_2(f)\,D_3(f)\ \ I(f)}$$

Source $A_0(f)$

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

Attenuation

$$P_1(R,f) = G(R) * Q(R,f)$$

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

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

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

Crustal Amplification $V_2(f)$

cf Boore and Joyner, 1997.

Near surface attenuation (kappa operator)

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

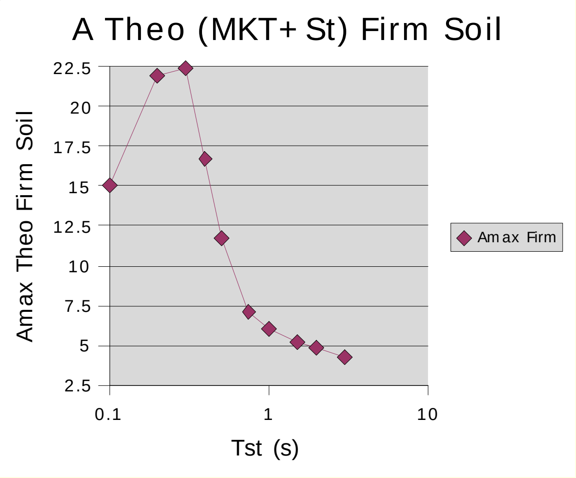
Type of Ground Motion $I(f)$

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

SVGM Modeling Issues

- Theoretical Model Structure:

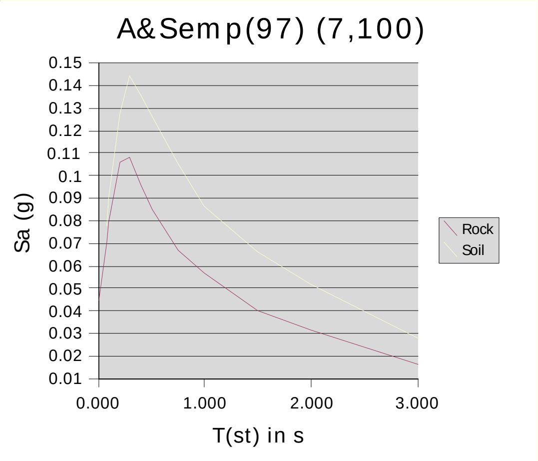
$$|H(w)|^2_{structure} = \frac{1+4\xi_{st}^2\left(f/f_{structure}\right)^2}{\left(1-\left(f/f_{structure}\right)^2\right)^2 + 4\xi_{structure}^2\left(f/f_{structure}\right)^2}$$



- Obtention of ground motion

$$\sigma^2_{A_{track,t}}(fst) = \int_{-\infty}^{+\infty} S_{A_{track,t}}(\omega)d\omega = \int_{-\infty}^{+\infty}|H(w)|^2_{soil=rock}|H(w)|^2_{structure}$$

$$A_{\max\ theo}(\omega_{st}) = c(\omega_{st}) * \sqrt{\sigma^2_{A_{track,t}}} \qquad c(\omega_{st}) = \sqrt{2\ln(2.8*\omega_{st}*5)}$$



The coherency function is added to the transfer functions Hs.

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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