Micro Seismic Hazard Analysis

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Overview

- Site effects
  - Soft ground effect
  - Topographic effect
- Liquefaction

- Methods for estimating site effects:
  - Soft ground effects:
    - Numerical methods: 1D response analysis (Shake)
    - Experimental/Emperical methods: HVSR method
  - Topographic effect:
    - Only qualititative methods
- Methods for estimating liquefaction:
    - Determine liquefaction potential
    - “Simplified procedure” by Seed and Idriss

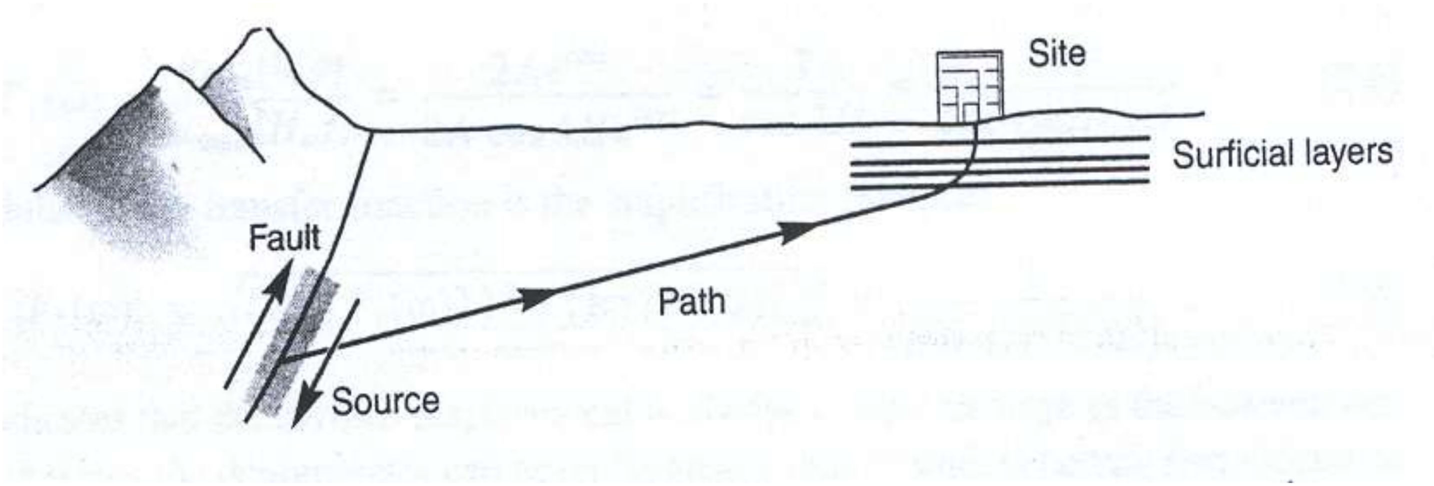
Basic physical concepts and definitions

- What are site effects?
  - Effect of the local geology on the the characteristics of the seismic wave
- Local geology:
  - "Soft" sediments (overlying bedrock)
  - Surface topography

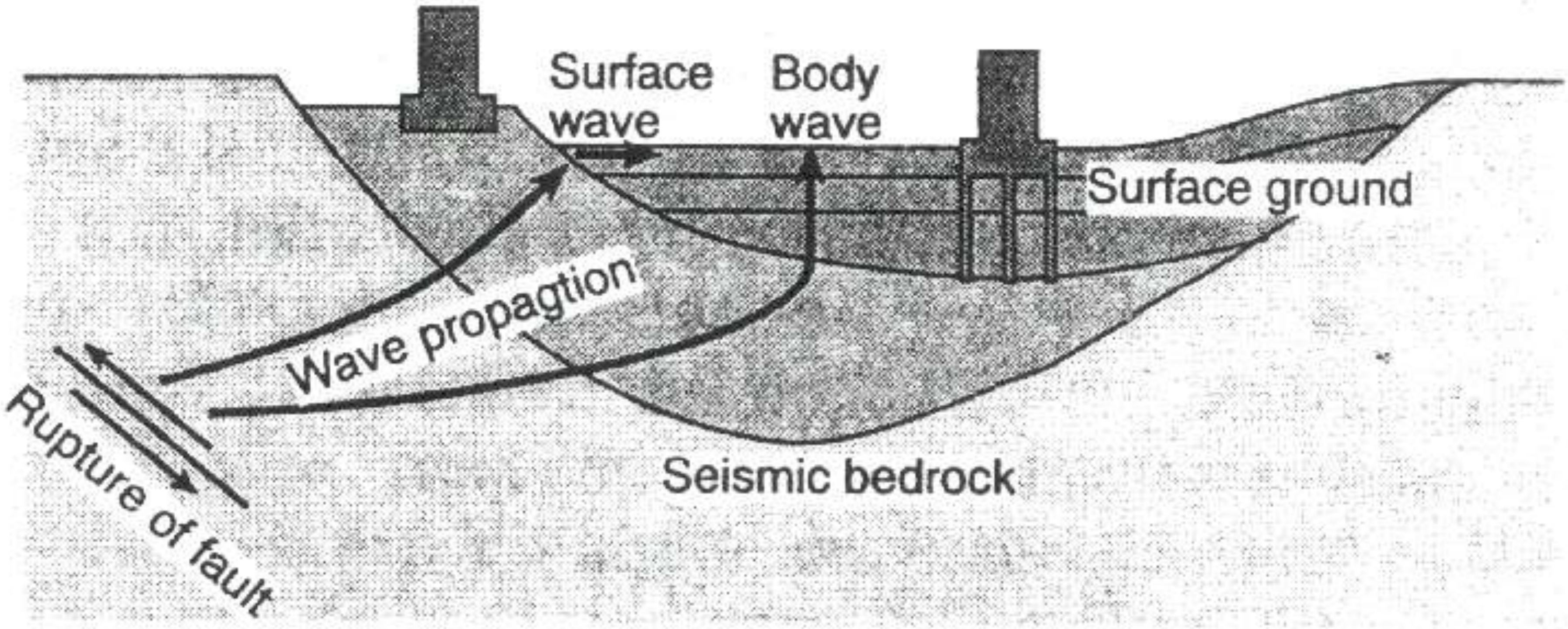
- The local geology can modify the characteristics of the incoming seismic wave, resulting in an amplification or de-amplification

Basic physical concepts and definitions (1)

- Earthquake signal arriving at the site affected by:
  - Source activation (fault rupture)
  - Propagation path (attenuation of the signal)
  - Effect of local geology ((de-)amplification)



Basic physical concepts and definitions (2)



Site effects due to low stiffness surface soil layers - Soft ground effect (1)

- Influence of impedance and damping
  - Seismic impedance (resistance to motion): $I = \rho \cdot Vs \cdot \cos\theta$
    - ρ: density (kg/m^3 or kN/m^3)
    - Vs: (horizontal) shear wave velocity (m/s)
      measure of stiffness of the soil
    - Θ: angle of incidence of the seismic wave
  - Near the surface: $\theta \approx 0$:
    $I = \rho \cdot Vs$

Site effects due to low stiffness surface soil layers - Soft ground effect (2)

- Differences in impedance are important:
- If impedance becomes smaller:
  - Resistance to motion decreases
  - Law of preservation of energy: Amplitude increases -> amplification
  - However, much of the increased energy is absorbed due to the damping of the soft soil

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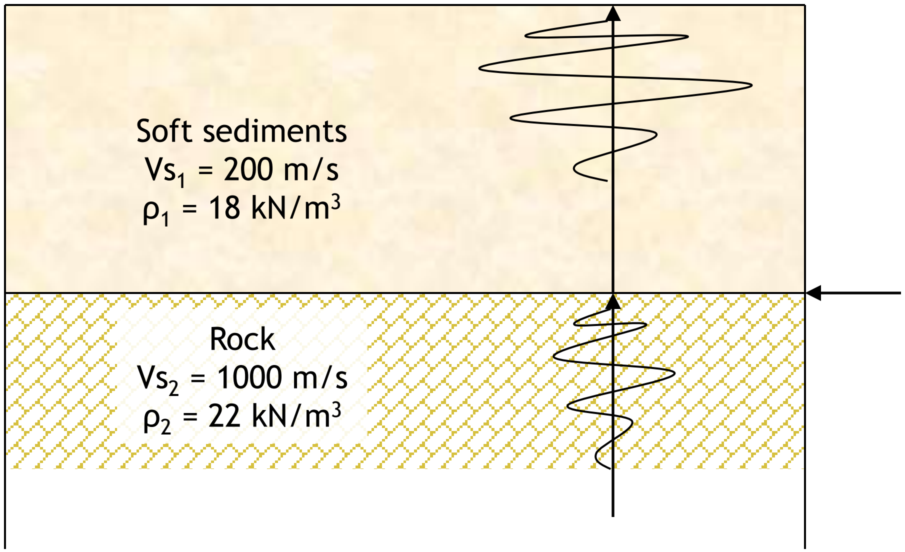
Site effects due to low stiffness surface soil layers - Soft ground effect (3)

- Impedance contrast:

$$C = \rho_2 \cdot Vs_2 \;/\; \rho_1 \cdot Vs_1$$



$$C = 22 \cdot 1000 \;/\; 18 \cdot 200$$

$$C = 6.1$$

Site effects due to low stiffness surface soil layers - Soft ground effect

- In the Earth, changes in impedance occur primarily in the vertical direction.
  - horizontal sedimentary strata near the surface
  - increase in pressure and temperature with depth
- Large impedance contrast between soft soil overlying bedrock cause also strong reflections:
  - Seismic waves become "trapped" within the soil layers overlying the bedrock
  - Trapped waves start interfering with each other, which may result in resonance (at the natural or fundamental frequency of the the soil)

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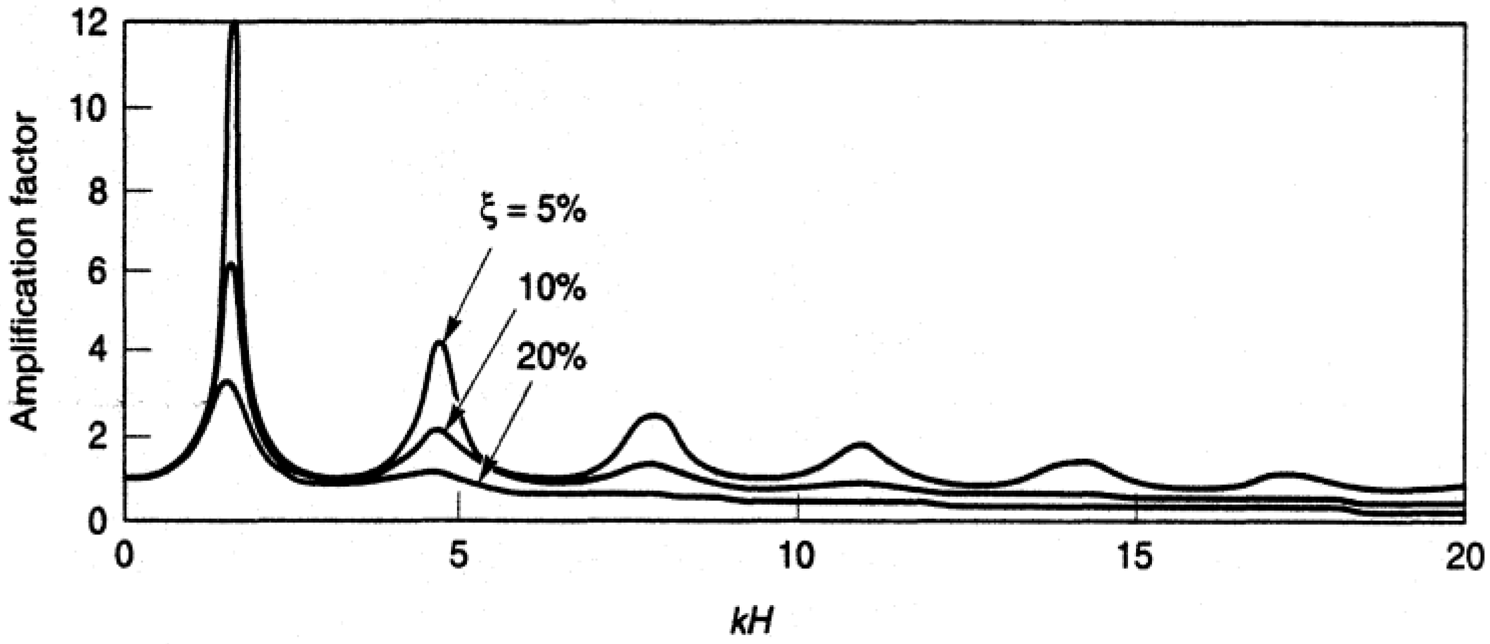
Frequency and amplification of a single layer uniform damped soil

- Variation of amplification with frequency (for different levels of damping)
- Damping affects the response at high frequencies more than at low frequencies



Fundamental frequency and characteristic site period

- *N*-th natural frequency of the soil deposit:

$$\omega_n \approx \frac{V_s}{H}\left(\frac{\pi}{2} + n\pi\right) \quad n = 0,1,2,\ldots,\infty$$

- The greatest amplification factor will occur at the lowest natural frequency: <u>fundamental frequency</u>

$$\omega_0 = \frac{\pi V_s}{2H}$$

Characteristic site period

- The period of vibration corresponding to the fundamental frequency is called the characteristic site period

$$T_S = \frac{2\pi}{\omega_0} = \frac{4H}{V_S}$$

- The characteristic site period, which only depends on the soil thickness and shear wave velocity of the soil, provides a very useful indication of the period of vibration at which the most significant amplification can be expected

Amplification at the fundamental frequency

$$A_0 = \frac{2}{\frac{1}{C} + 0.5 \cdot \pi \cdot \xi_1}$$

- A_0 = amplification at the fundamental resonant frequency
- C = impedance contrast
- ξ_1 = material damping of the sediments

Natural frequency of buildings

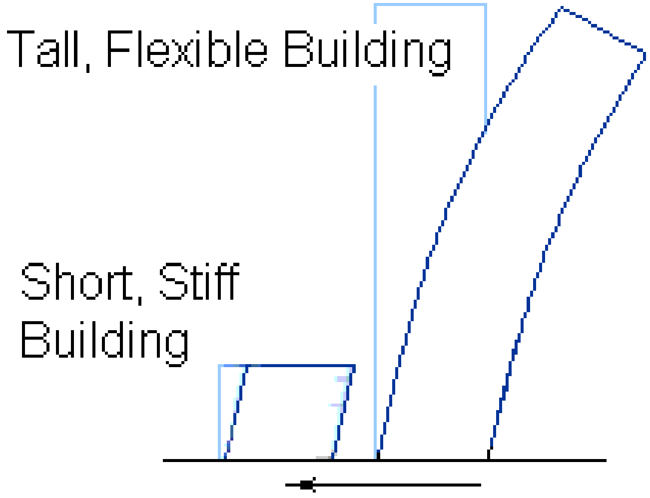
- All objects or structures have a natural tendency to vibrate
- The rate at which it wants to vibrate is its fundamental period (natural frequency)

$$f_n = \frac{1}{2\pi}\sqrt{\frac{K}{M}}$$

K= Stiffness
M = Mass

Natural frequency of buildings

- Buildings tend to have lower natural frequencies when they are:
  - Either heavier (more mass)
  - Or more flexible (that is less stiff).
- One of the main things that affect the stiffness of a building is its height.
  - Taller buildings tend to be more flexible, so they tend to have lower natural frequencies compared to shorter buildings.



Examples of natural frequencies of buildings

Type of object or structure	Natural frequency (Hz)
One-story buildings	10
3-4 story buildings	2
Tall buildings	0.5 – 1.0
High-rise buildings	0.17

Rule-of-thumb:
$F_n = 10/n$

F_n = Natural Frequency
n = number of storeys

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(Partial) Resonance

- Buildings have a high probability to achieve (partial) resonance, when:
  - The natural frequency of the ground motion coincides with the natural frequency of the structure
- Resonance will cause:
  - Increase in swing of the structure
  - Given sufficient duration, amplification of ground motion can result in damage or destruction

Vertical standing waves

- Vertical traveling waves will generate standing waves with discrete frequencies
  - If the depth range of interference is large, the frequency will be low.
  - If the depth range of interference is small the frequency will be higher.

Inelastic attenuation

- Earthquakes: seismic waves with broad range of frequencies
- Inelastic behaviour of rocks cause high frequencies to be damped out
- The farther a seismic wave travels, the less high frequencies it contains: anelastic attenuation

Summarising: building resonance and seismic hazard (1)

- Response of a building to shaking at its base:
  - Design and construction
  - Most important: height of the building

Building resonance and seismic hazard (2)

- Height determines resonance frequency:
  - Low buildings: high resonance frequencies (large wavelengths)
  - Tall buildings: low resonance frequencies (short wavelengths)
- In terms of seismic hazard:
  - Low-rise buildings are susceptible to damage from high-frequency seismic waves from relatively near earthquakes and/or shallow depth
  - High-rise buildings are at risk due to low-frequency seismic waves, which may have originated at much greater distance and/or large depth

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Soft ground effect - summary

- Soft soil overlying bedrock almost always amplify ground shaking
- Given specific ground conditions and sufficient duration of the quake, resonance can occur, resulting in even larger amplifications
- If a structure has a natural frequency similar to the characteristic site period of the soil, very large damage or total collapse may occur

Soft ground effect - example

- 19 Sept. 1985 Michoacan earthquake, Mexico City (M 8.0, MMI IX)
  - Epicenter far away from city (> 100 km)
  - PGA's at rock level 0.04 g - but amplification due to soft ground: 5 x
  - Greatest damage in Lake Zone: 40-50 m of soft clay (lake deposits)
  - Characteristic site period (1.9-2.8 s) similar to natural period of vibration of 5-20 storey buildings
  - Most damaged buildings 8-18 storeys

Michoacan earthquake

Collapsed 21-Story Office Building. Buildings such as the one standing in the background met building code requirements

The 44-floor Torre Latinoamericana office building in the background on the right, remained almost totally undamaged.

Methods to estimate (1D) soft ground effects

- Theoretical (numerical and analytical) methods
  - A-priori knowledge of:
    - Subsurface geometry and geotechnical characteristics
    - Expected earthquake signal: design earthquake
  - E.g.: Shake 1D numerical
- Experimental-Emperical
  - A-priori knowledge of geology not needed
  - E.g.: HVSR, SSR (comparison of spectral ratios of seismograms of large event or microtremors)

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How do we carry out a ground response analysis study? (1)

1. Seismic macro hazard analysis: use a 'design earthquake' that represents the expected ground motion
   - Most probable frequency characteristics and recurrence interval using probabilistic approach
   - Often, just use the available nearest historic seismic record which caused lots of damage using deterministic approach
   - Or, create synthetic seismogram from other location through transfrom using Green's functions

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How do we carry out a ground response analysis study? (2)

2. Quantification of the expected ground motion
   - Determining the response of the soil deposit to the motion of the bedrock beneath it, for a specific location or area

How do we quantify the expected ground motion?

- Determining the manner in which the seismic signal is propagating through the subsurface
- Propagation is particularly affected by the subsurface geology
- Large amplification of the signal occurs mostly in areas where layers of low seismic velocity overlies material with high seismic velocity

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What do we use to quantify the expected ground motion?

- Using peak ground acceleration
  - Acceleration and force are in direct proportion
  - Peak acceleration often correspond to high frequencies, which are out of range of the natural frequencies of most structures
- Response spectra analysis
  - Current standard method for ground response analysis
  - Maximum ground response (amplification) for different frequencies

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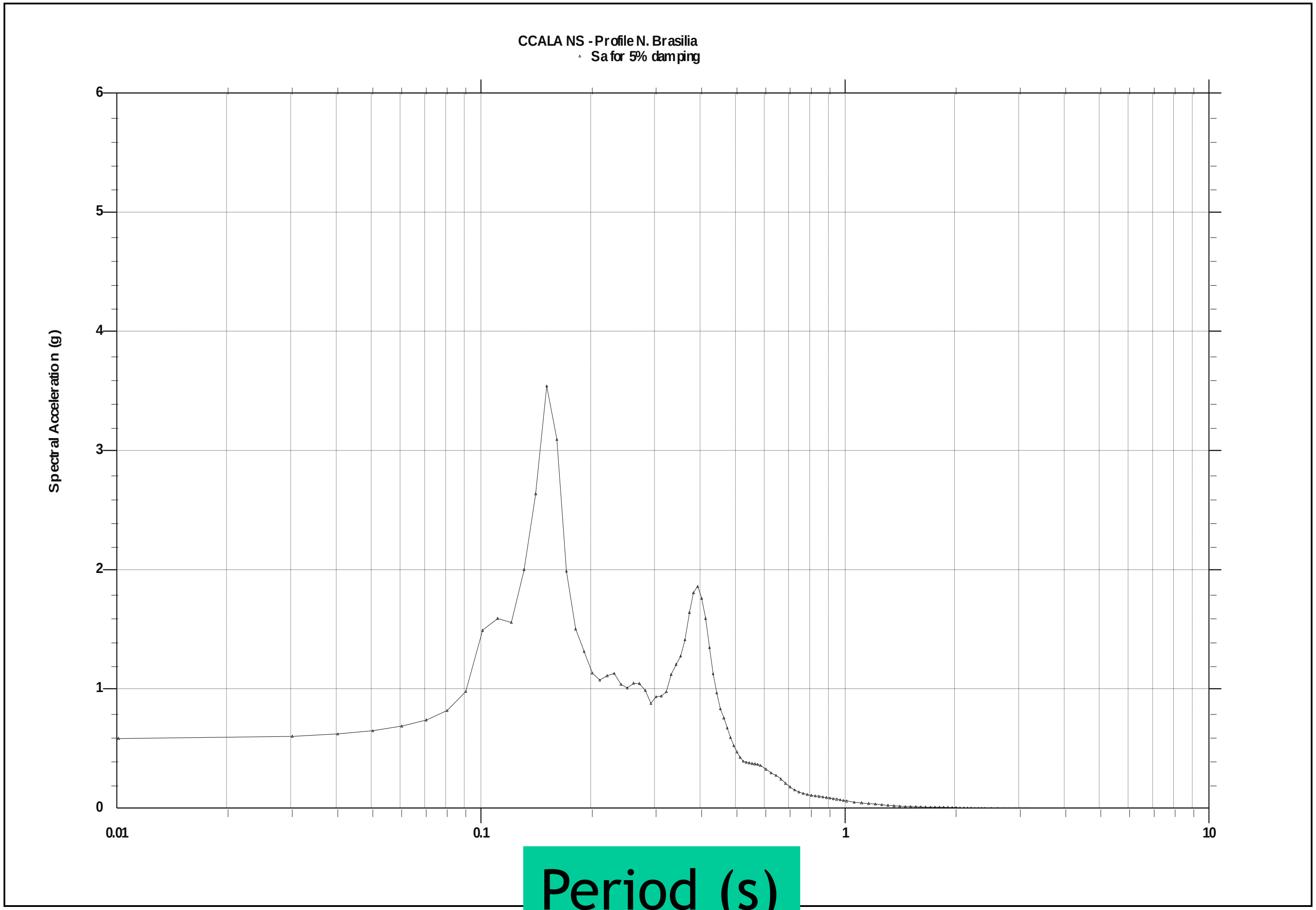
Example of response spectrum



Spectral acceleration (g)

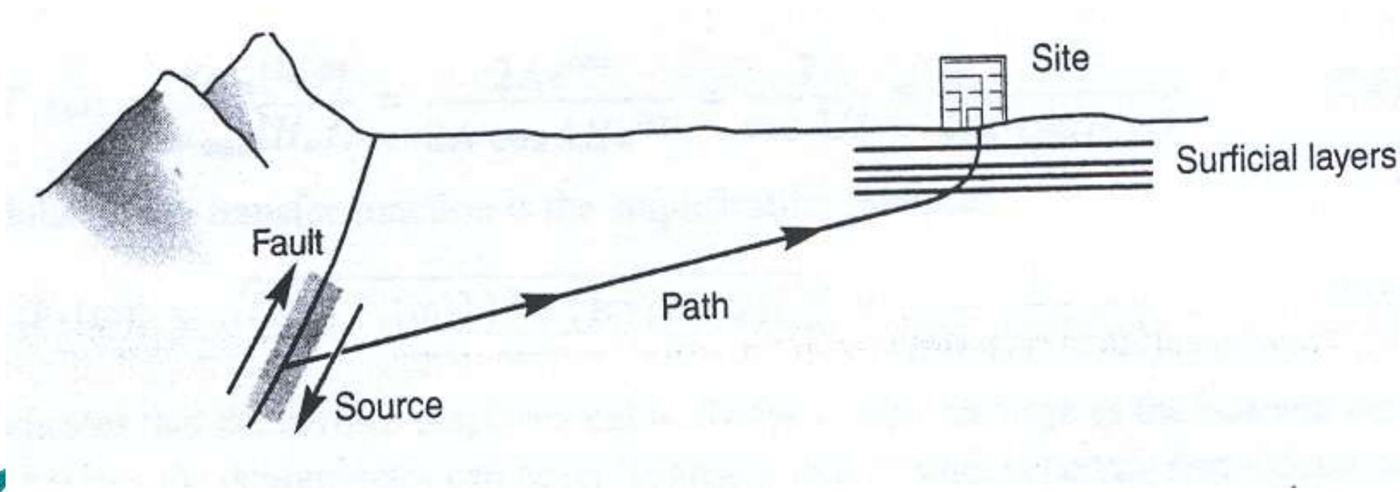
Period (s)

SHAKE

- The equivalent linear approach to 1D ground response analysis of layered sites has been coded into a widely used computer program SHAKE (1972)
- Other programs, based on same approach:
  - Shake91
  - ShakeEdit/Shake2000
  - ProShake/EduShake

1D ground response analysis Assumptions (1)

- Inclined seismic rays are reflected to a near-vertical direction, because of decrease in velocities of surface deposits



1D ground response analysis Assumptions (2)

- All boundaries are horizontal
- Response of the soil deposit is caused by Shear waves propagating vertically from the underlying bedrock
- Soil and bedrock are assumed to extend infinitely in the horizontal direction (half-sphere)

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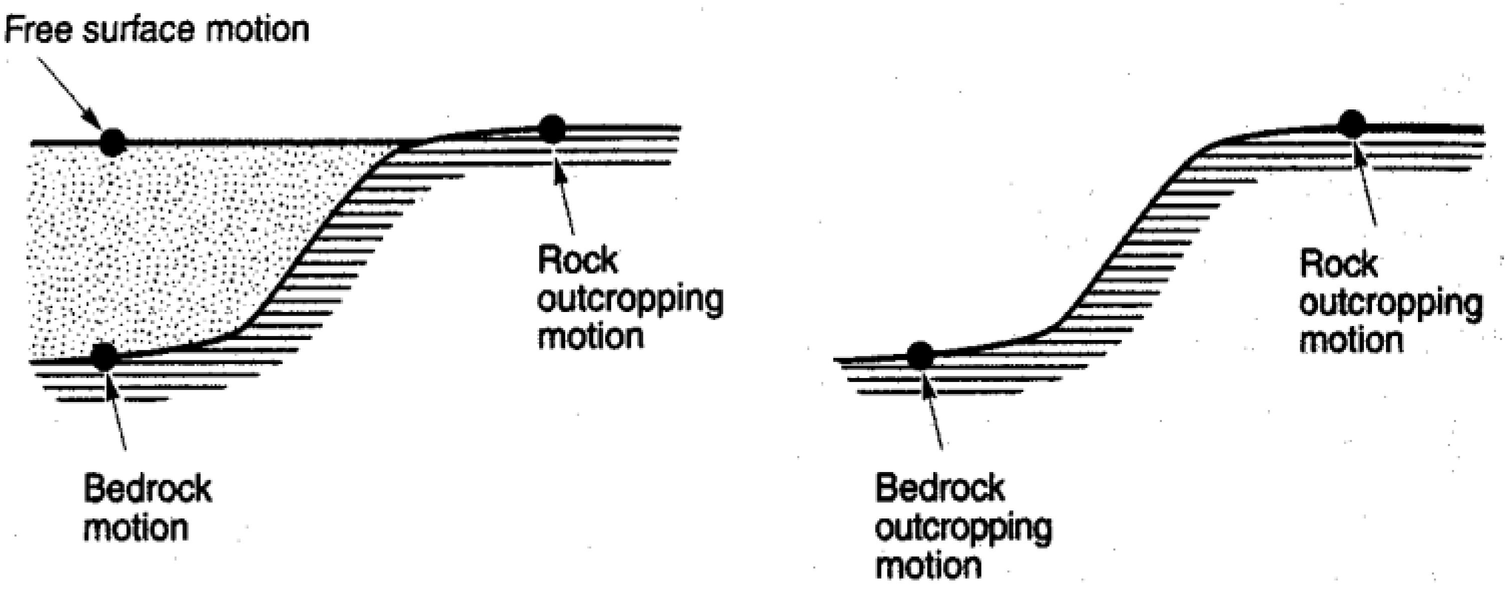
Definitions used in the ground response model



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Transfer Function as technique for 1D ground response analysis

1. Time history of bedrock (input) motion in the frequency domain represented as a Fourier Series using Fourier transform
2. Define the Transfer Function
3. Each term in the Fourier series is multiplied by the Transfer Function
4. The surface (output) motion is then expressed in the time domain using the inverse Fourier transform

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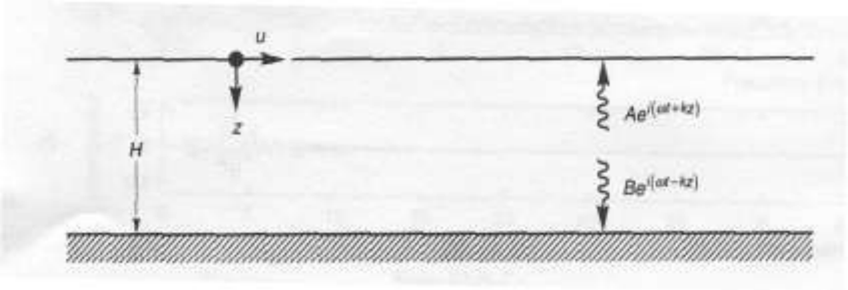
Define the transfer function (1)

- Solution to the wave equation for a uniform single soil layer (simplest case):



$$u(z,t) = Ae^{i(\omega t + kz)} + Be^{i(\omega t - kz)}$$

$$\text{k} = \text{wave number} = \frac{2\pi}{\lambda} = \frac{\omega}{V_s}$$

$$\text{A} = \text{Amplitude of shear wave in upward direction}$$

$$\text{B} = \text{Amplitude of shear wave in downward direction}$$

Define the transfer function (2)

- For uniform undamped soil:

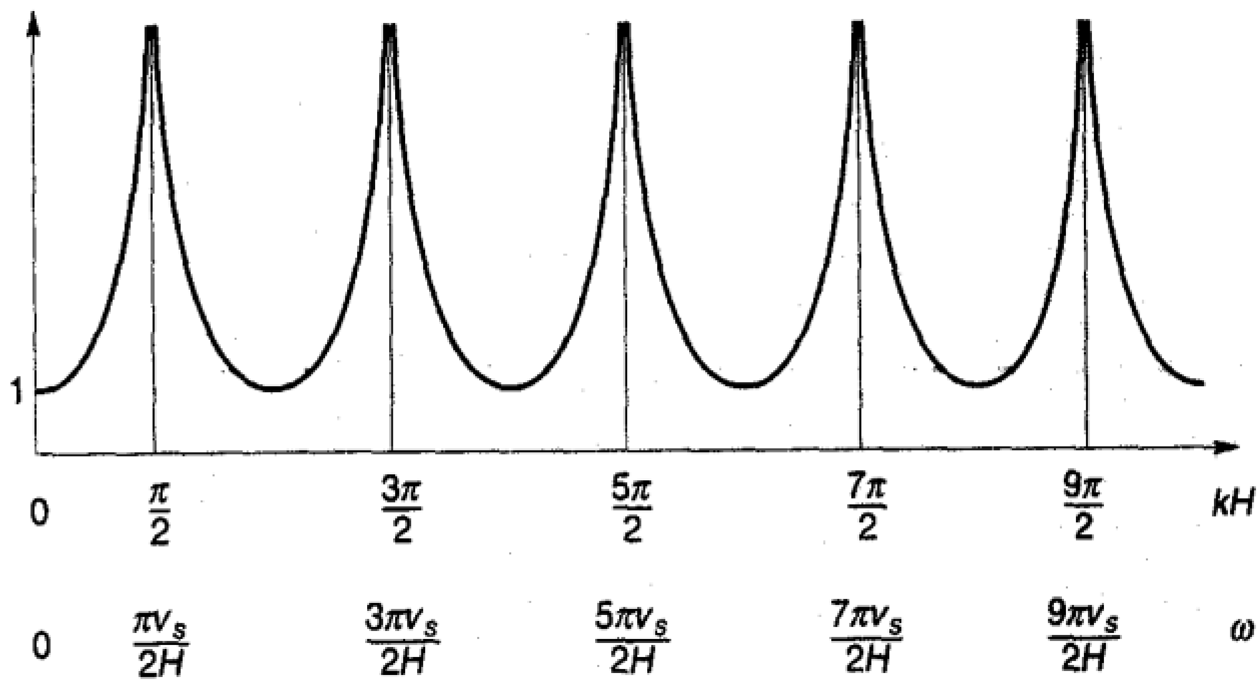
$$F(\omega) = \frac{u_{\max}(0,t)}{u_{\max}(H,t)} = \frac{1}{\cos kH} = \frac{1}{\cos(\omega H / V_s)}$$

$$|F(\omega)| = \frac{1}{|\cos(\omega H / V_s)|} \text{(amplification function)}$$

$$\omega H / V_s = \frac{\pi}{2} + n\pi \Rightarrow |F| \to \infty \text{ (resonance)}$$

Transfer function for one-layer uniform undamped soil

- Variation of amplification with frequency (for different levels of damping)



Effect of transfer function on Amplitude spectrum

Surface level →

↑

Transfer function

↑

Base level ←
(Bedrock)

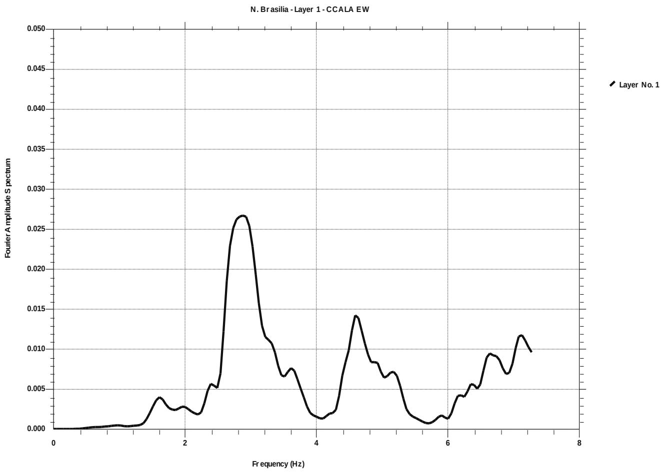


Figure 1. Fourier amplitude spectrum for CCALA signal - EW component, surface level.

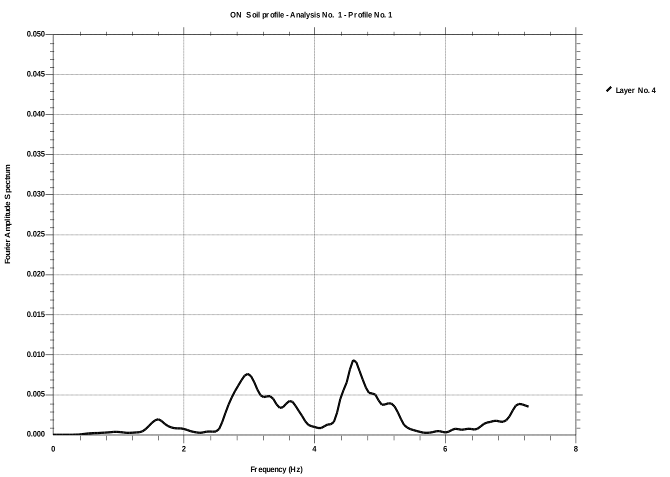


Figure 2. Fourier amplitude spectrum for CCALA signal- EW component,, base level.

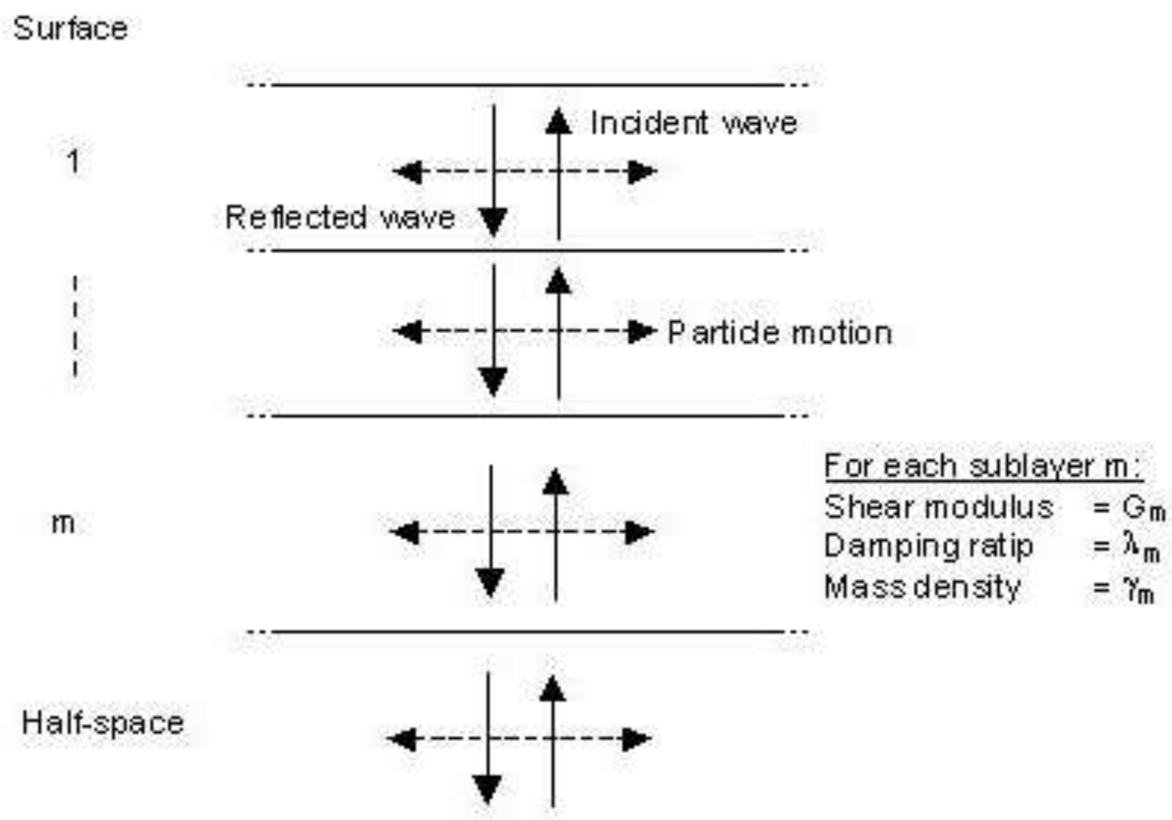
Approach to simulate the non-linear behaviour of soils

- Complex transfer function only valid for linear behaviour of soils
- Linear approach must be modified to account for the non-linear behaviour of soils

Procedure to account for non-linearity

- Linear approach assumes constant:
  - Shear strength (G)
  - Damping (ξ)
- Non-linear behaviour of soils is well known
- The problem reduces to determining the equivalent values consistent with the level of strain induced in each layer
- This is achieved using an iterative procedure on the basis of reference (laboratory) test data
  - Modulus reduction curves
  - Damping curves

General, simplified profile as assumed by the SHAKE program

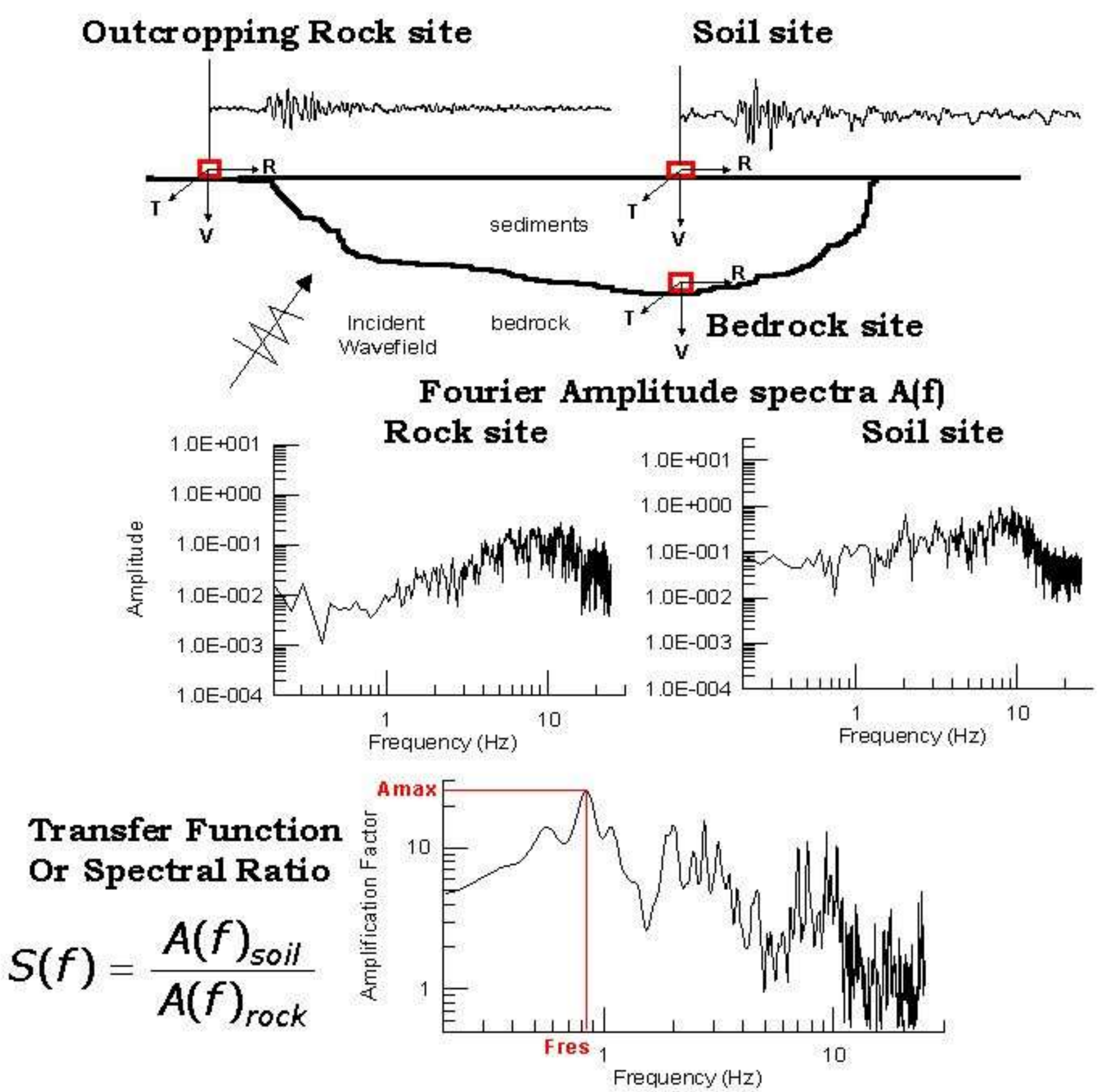


Experimental-Emperical

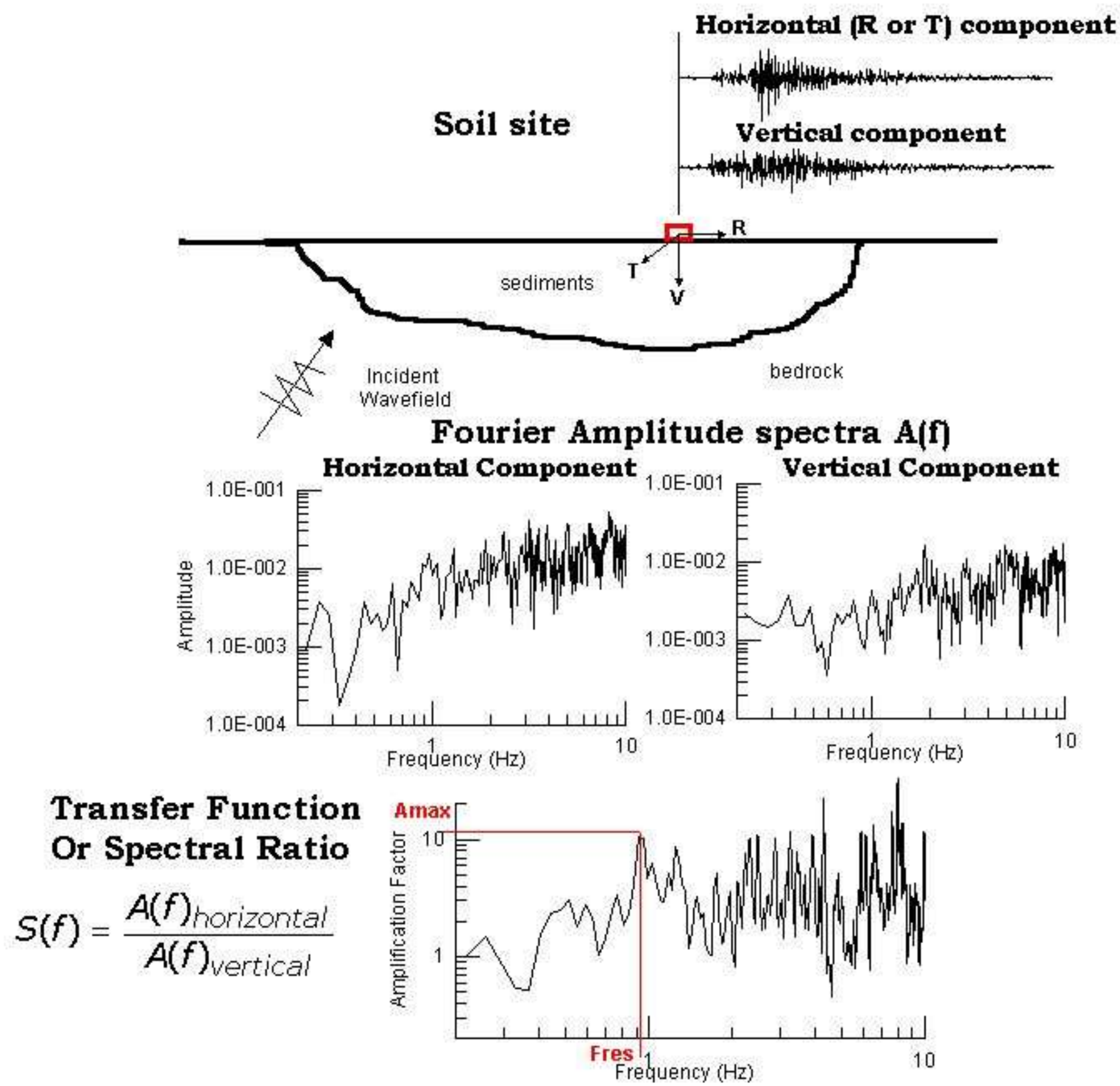
- Standard Spectral Ratio Technique (SSR)
  - Depend on reference site (in rock)
- Horizontal to Vertical Spectral Ratio Technique (HVSR)
  - No reference site needed

- Analysis of site effects using seismic records in the frequency domain

Standard Spectral Ratio Technique (SSR)



Horizontal to Vertical Spectral Ratio Technique (HVSR)



Nakamura's or H/V method (1)

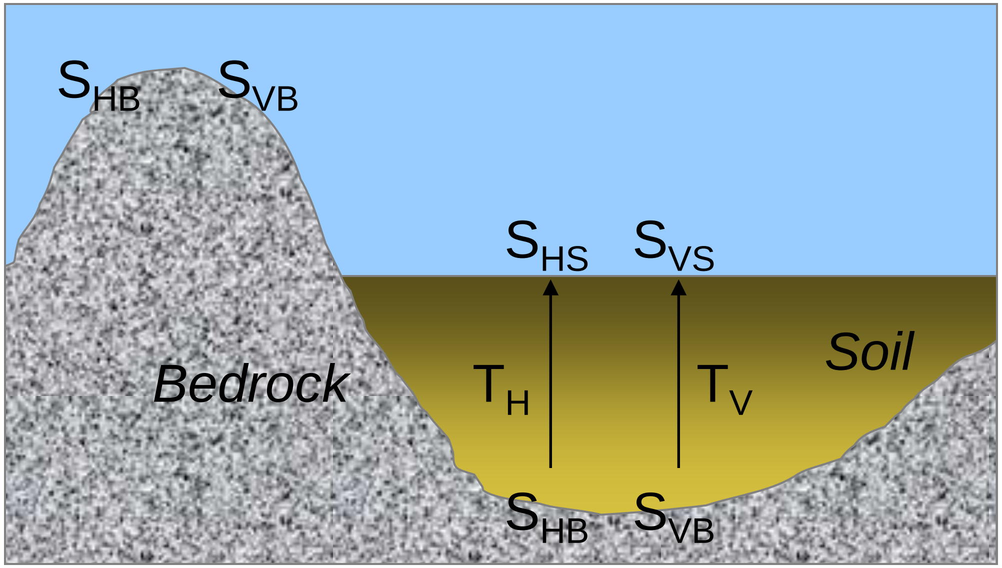
- Summary:
  - Dividing the Horizontal Response spectrum (H) by the Vertical Response spectrum (V) yield a uniform curve in the frequency domain for different seismic events
  - Assumption: since different seismic event yield the same H/V curve, it is possible to determine this using microtremors
  - H/V curve show a peak in amplification at the fundamental frequency of the subsurface – that is when the resonance occurs
  - By setting up a dense seismic network measuring those microtremors it is possible to carry out a microzonation without intensive borehole surveys

Nakumura’s or H/V method (2)

- Establish empirical transfer functions T_H and T_V on the basis of the horizontal and vertical microtremor measurements on soil surface and at bedrock level:

$$T_H = \frac{S_{HS}}{S_{HB}}$$

$$T_V = \frac{S_{VS}}{S_{VB}}$$



Nakumura's or H/V method (3)

- Modified site effect function:

$$T_{Site} = \frac{T_H}{T_V} = \frac{S_{HS} \cdot S_{VB}}{S_{HB} \cdot S_{VS}}$$

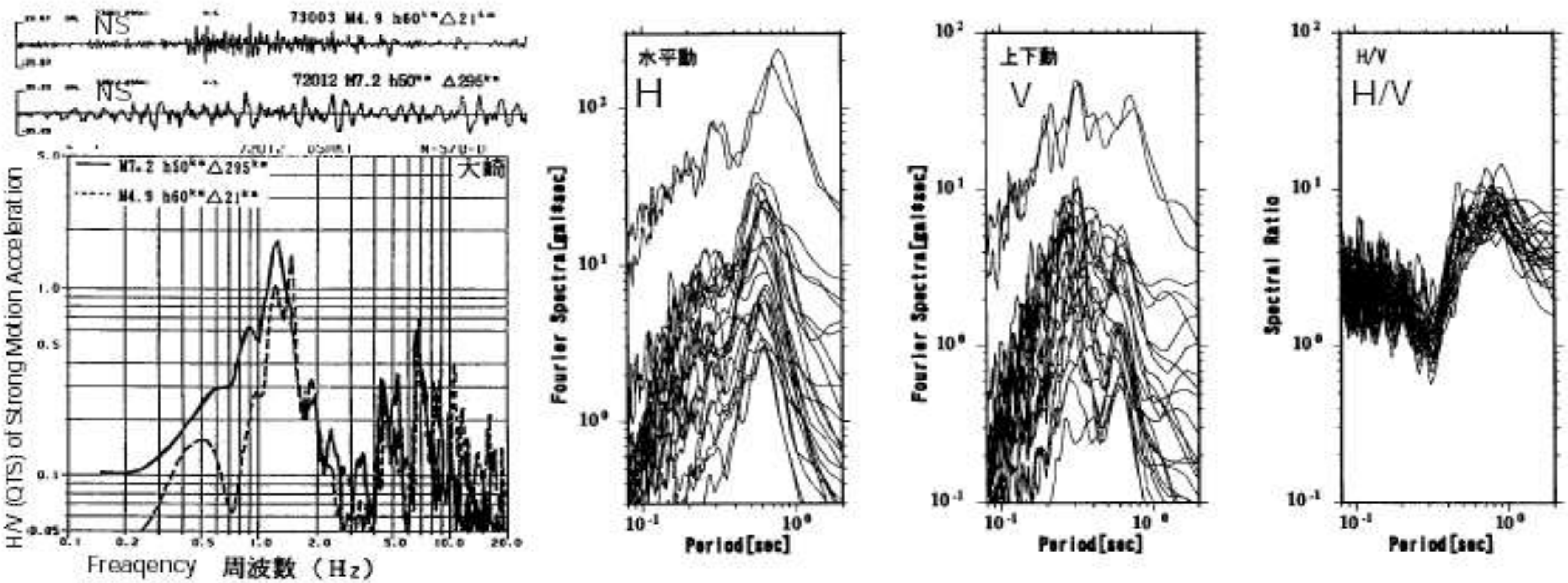
- Many observations show that:

$$\frac{S_{VB}}{S_{HB}} = 1 \qquad \Rightarrow T_{Site} = \frac{S_{HS}}{S_{VS}}$$

- T_{site} shows a peak in the amplification at the fundamental frequency of the site

Nakumura's or H/V method (4)

- T_{site} or H/V curve shows the same peak irrespective of type of seismic event at F_0



(a) Osaki (Nakamura et. al., 1989)

(b) Miyazaki (Okuma et. al. , 1999)

Figure 11. H/V of strong ground motion for different earthquakes recorded at the same station.

Nakumura's or H/V method (5)

- If F_0 and A_0 are known from the H/V curves and the seismic velocity of the bedrock (V_B) is also known, bedrock level or soil thickness (H) can be calculated:

$$F_0 = \frac{V_S}{4 \cdot H}$$

$$A_0 = \frac{V_B}{V_S}$$

$$\Rightarrow H = \frac{V_B}{4 \cdot A_0 \cdot F_0}$$

Site effects due to surface topography

- General observation: buildings located on hill tops or close to steep slopes suffer more intensive damage than those located at the base
  - Amplification is larger for the horizontal than for the vertical
  - The steeper the slope, the higher the amplification
  - Maximum effect if the wavelengths are comparable to the horizontal dimension of the topographic feature
  - Absolute value of amplification ratio very difficult to quantify due to complex reflections within the geometry

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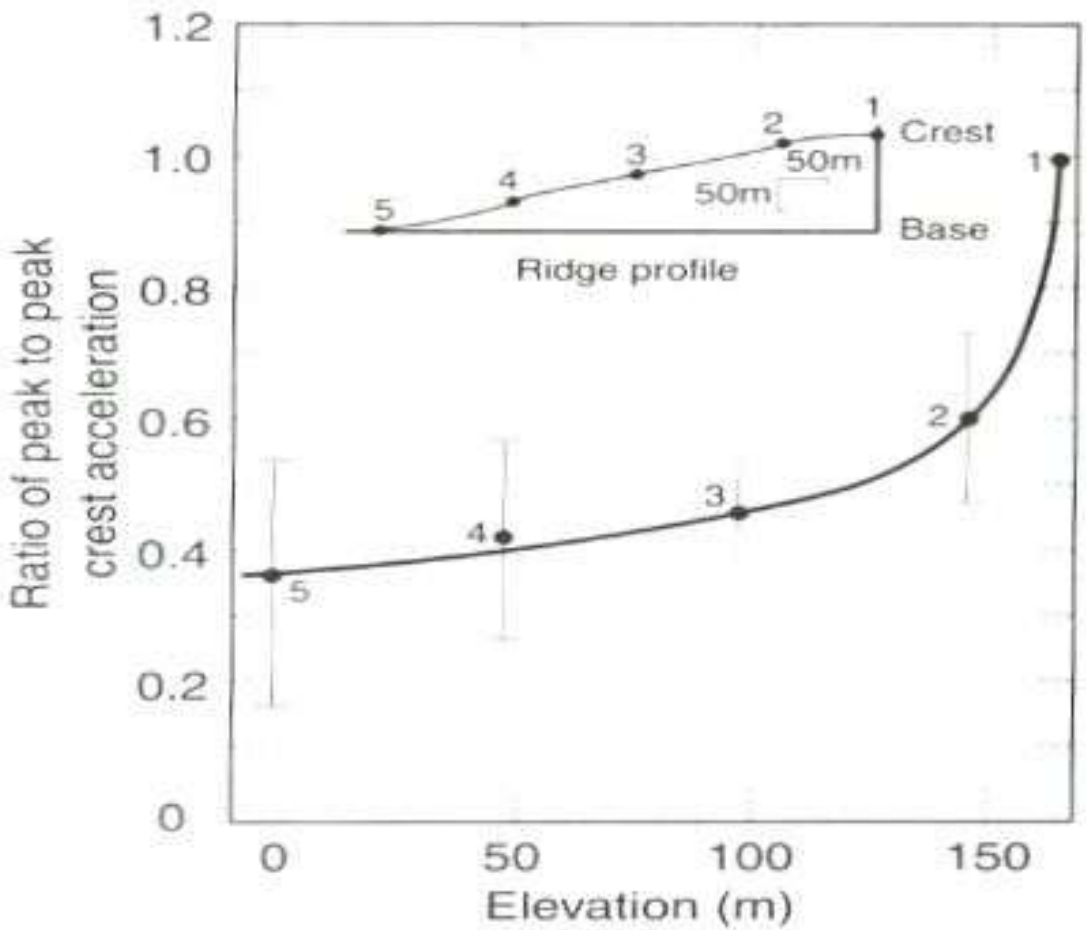
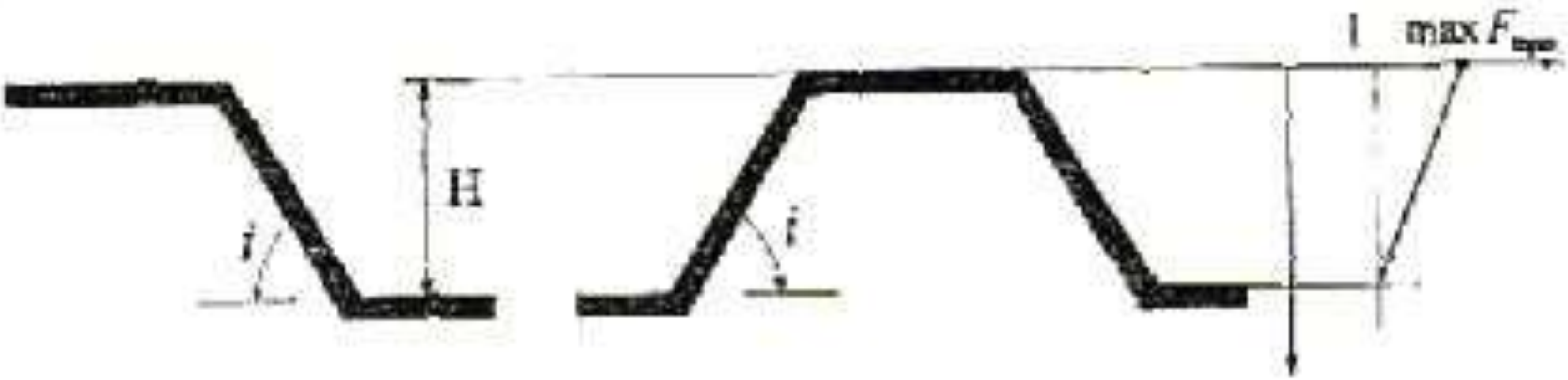
Site effects due to surface topography

- Recorded normalised peak accelerations



Site effects due to surface topography

- European Seismic code (EC8-2000)



$$\max F_{topo.} \geq \begin{cases} 1.4, & i > 30^\circ \\ 1.2, & 15^\circ < i < 30^\circ \\ 1, & H < 30\text{m} \ \text{or} \ i < 15^\circ \end{cases}$$

Liquefaction

Liquefaction - general (1)

- Typically occurs in saturated, loose sand with a high groundwater table
- During an earthquake, the shear waves in the loose sand causes it to compact, creating increased pore water pressure (undrained loading):
  - Upward flow of water: sand boils
  - Turns sand layer (temporarily) into a liquefied state - liquefaction

Liquefaction - general (2)

- Commonly observed in low-lying areas or adjacent to lakes, rivers, coastlines
- Effects:
  - Settlement
  - Bearing capacity failure of foundation
  - Lateral movements of slopes
- In practice:
  - Structures sink or fall over
  - Buried tanks may float to the surface

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Liquefaction - governing factors (1)

1. Earthquake intensity and duration (basically a high magnitude)
   - Threshold values: a_{max} > 0.10 g; M_L > 5
2. Groundwater table
   - Unsaturated soil above gw table will NOT liquefy
3. Soil type: non-plastic cohesionless soil
   - Fine-medium SAND, or
   - SAND containing low plasticity fines (SILT)

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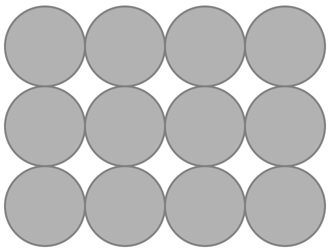
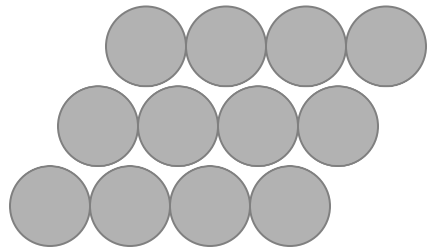
Liquefaction - governing factors (2)

4. Soil relative density (D_r)

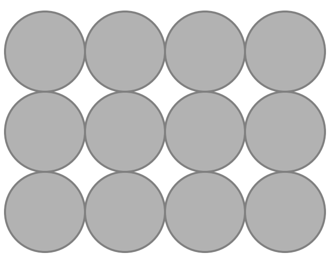


Loosely packed

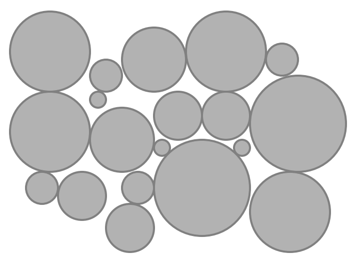


Densely packed

5. Grain size distribution



Poorly graded
(Well sorted)



Well graded
(Poorly sorted)

Liquefaction - governing factors (3)

6. Placement conditions
   - Hydrologic fills (placed under water)
   - Natural soil deposits formed in
     - Lacustrine (Lake)
     - Alluvial (River)
     - Marine (Sea) environments
7. Drainage conditions
   - Example: if a gravel layers is on top of the liquefiable layer, the excess pore pressure can easily dissipate

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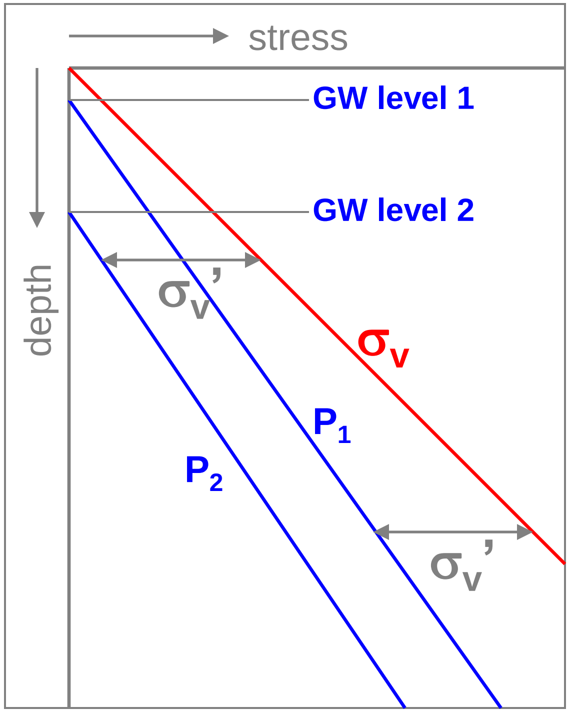
Liquefaction - governing factors (4)

8. Effective stress conditions
   - If the vertical effective stress (σ_v') becomes high, liquefaction potential becomes lower:
     - Low groundwater table
     - At larger depth (> 15 m.)



Liquefaction - governing factors (5)

9. Particle shape
   - Rounded particles tend to densify more easily than angular particles
10. Age, cementation
    - The longer a soil deposit is, the longer it has been able to undergo compaction and possibly cementation, decreasing liquefaction potential
11. History
    - Soils already undergone liquefaction, will not easily liquefy again
    - Pre-loaded sediments (erosion, ice-sheet) will no easily liquefy

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Liquefaction – governing factors *summary*

- Site conditions:
  - Site that is close to epicenter or location of fault rupture (macro hazard zone)
  - Soil that has a groundwater table close to the surface
- Soil type:
  - Loose SAND that is well-sorted and rounded, recently deposited without cementation and no prior loading or seismic shaking

Methods to estimate liquefaction potential

- Most commonly used liquefaction analysis:
  - "Simplified Procedure" by Seed & Idriss
  - Using SPT (Standard Penetration Test) data
- Procedure:

1. Check appropriate soil type (see before)
2. Check whether soil below groundwater table (from borehole)
3. Determine Cyclic Stress Ratio (CSR):
   1. Effective stress in soil: thickness, unit weight, GW level
   2. Earthquake characteristics
4. Determine Cyclic Resistance Ratio (CRR)
   1. Based on SPT data (N-value)
5. Calculate Factor of Safety: FoS = CRR/CSR