Geotechnical aspects in Earthquake Engineering

Dr. Adil Zekaria (AAiT)

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Outline

- Introduction
- Seismic response of soils
- Influence of Local Soils (Site Effects)
- Liquefaction of Soils
- Damage of structures due to liquefaction
- Soil-Structure Interaction
- Soil Models for dynamic analysis

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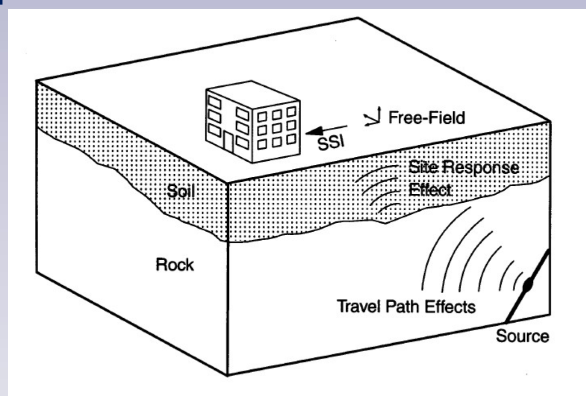
Introduction

- Schematics on the context of Seismic Response a Structure



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Introduction

- **Source effect**: earthquake magnitude, rupture mechanism and distance from earthquake
- **Travel path effect**: Attenuation of seismic waves as they travel from source to site through bedrock
- **Site effect**: frequency dependent amplification and attenuation of seismic waves propagating through soils towards surface.
- **SSI**: accounts for the effect of foundation flexibility on the structural response and the effect of structure in modifying Free Field Motion.

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Seismic response of Soils

- Soil behavior under dynamic loading depends upon many factors, including:
  - the nature of the soil;
  - the environment of the soil (static stress state and water content); and
  - the nature of the dynamic loading (strain magnitude, strain rate, and number of cycles of loading).

Some soils increase in strength under rapid cyclic loading, while others such as saturated sands or sensitive clays may lose strength with vibration.

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Seismic response of Soils

- The behavior of soils under cyclic loading plays a crucial role in determining the extent and distribution of ground displacements, which in turn are directly related to the potential for causing earthquake damage.
- One of the key dynamic parameter for soils is *damping*, two fundamentally different damping phenomena are associated with soils, namely
  - material damping and
  - radiation damping

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Seismic response of Soils

- **Material damping (internal damping):** in a soil occurs when any vibration wave passes through the soil. It can be thought of as a measure of the loss of vibration energy resulting primarily from hysteresis in the soil.

  (*where hysteresis is the nonlinear force displacement response of a material under cyclic reversible loading condition*.)

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Seismic response of Soils

- ***Radiation damping (geometric damping) :*** is a measure of the energy loss from the structure through radiation of waves away from the footing, i.e. it is a purely geometrical effect.

  Both the material and radiation damping are very difficult to be measured in the field.

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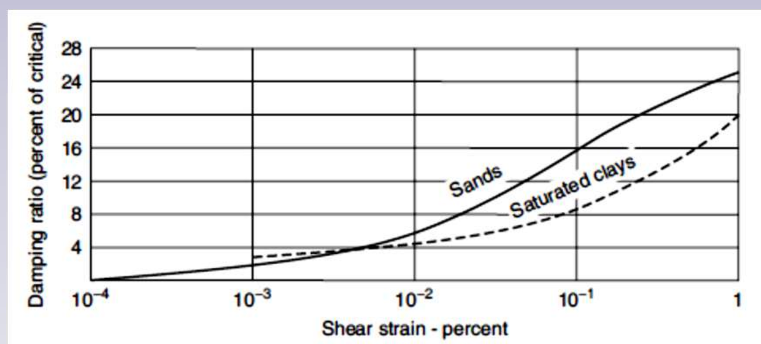
Seismic response of Soils

- Some material damping values are therefore given in the Figure which represent average values of laboratory test results on sands and saturated clays. (Seed et al 1970)



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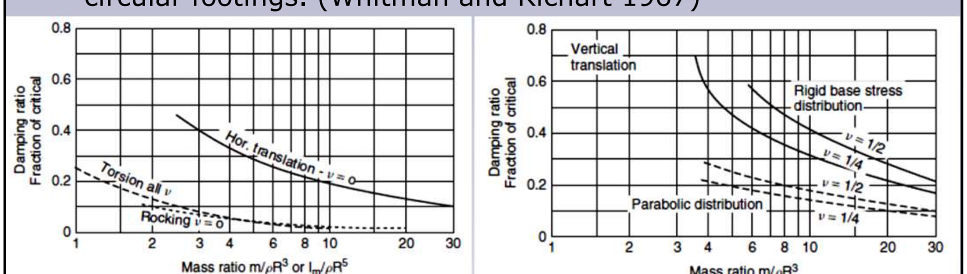
Seismic response of Soils

- The theory for the elastic half-space has been used to provide estimates for the magnitude of radiation damping of circular footings. (Whitman and Richart 1967)



Where m is the mass of foundation block plus machinery, *R* is the radius (or equivalent radius) of the soil contact area at the foundation base, *ρ* is the mass density of the soil and *v* is Poisson’s ratio for the soil

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Influence local Soils

- **Local soil condition** surrounding the structure and shaking intensity during earthquake may **affect the stability of structure**.
- Large scale tilting of well built houses in the Nigatta earthquake of 1964 focused the attention of the professionals on problems of soil dynamics: Requiring a careful attention by Engineers.

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Influence local Soils

- There is a great variety of possible geological and local soil conditions at construction sites, which give rise to a variety of responses in earthquakes
  - modification of bedrock excitation during transmission through the overlying soils (amplification or attenuation);
  - topographical effects;
  - settlement of dry sands;
  - liquefaction of saturated cohesionless soils.

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Influence local Soils

- The methods of analyzing these responses vary in complexity, from simple empirical criteria to highly sophisticated analytical techniques. Regardless of the resources available, it should be borne in mind that knowledge of the real dynamical characteristics of the underlying soils is always incomplete, and the sophistication of the analyses used should not exceed the quality of the available data.

Influence local Soils

- Effect of soil on bedrock excitation
  - The presence of soil overlying bedrock modifies the excitation in a complex manner, with conflicting effects dependent on dynamic characteristics of the soil layers and the strength of the excitation
  - In many earthquakes, the degree of damage to structures situated on soils has been reported as worse than that occurring on adjacent bedrock sites. Measured on the subjective intensity scales, the intensity may increase by 1 or 2 units (or occasionally more) compared with bedrock, depending on the soil type. Such measures of soil effects are very crude, but give a broad indication of the effect of soil layers when amplification, or sometimes attenuation, occurs.

Influence local Soils

- Effect of soil on bedrock excitation
  - The modifications to the incoming bedrock motions are dependent on several factors, notably:
    - amplitude of shaking;
    - frequency of vibration;
    - properties of soil (modulus and damping);
    - geometry, depth and stratification of the soils;
    - water level (liquefaction).
  - It follows from the above that it is essential to understand the dynamical properties of soils as it highly affect the structures and in order to predict their response.

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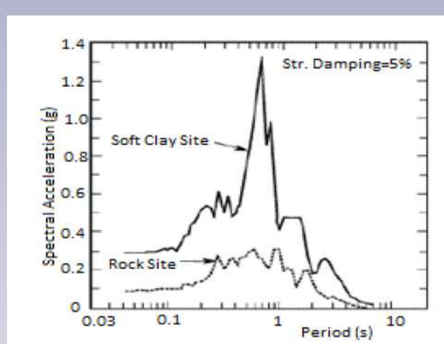
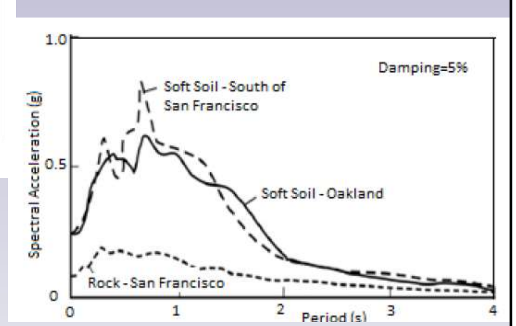
Site Effects





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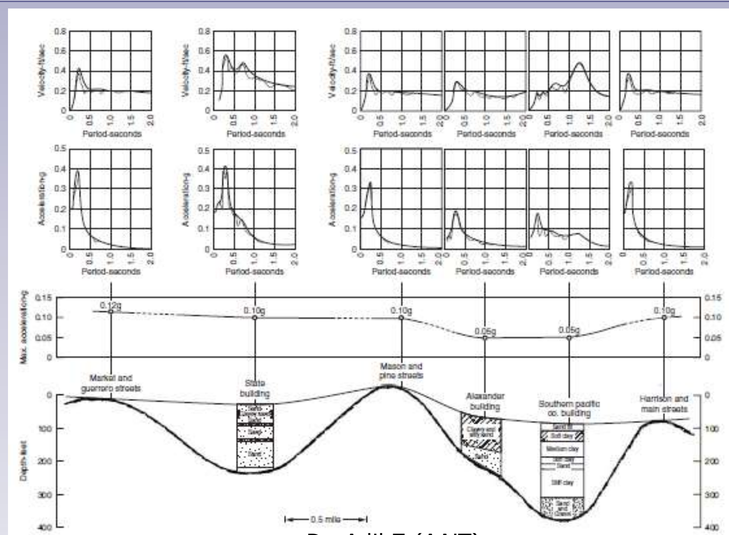
Site approximately same distance from the epicenter – San Francisco EQ 1967



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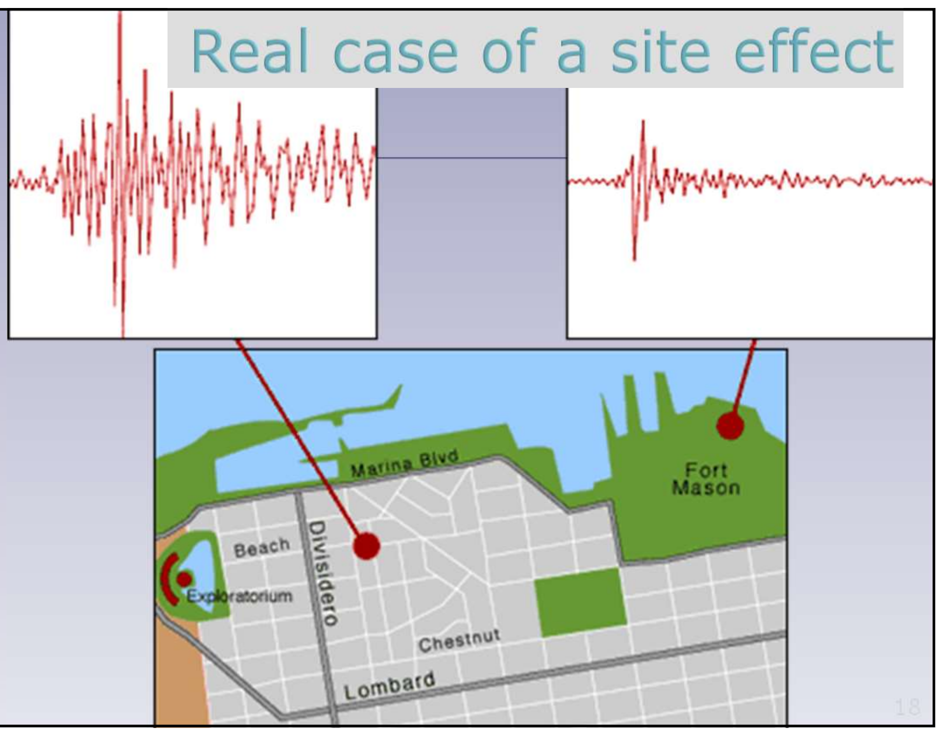
Real case of a site effect



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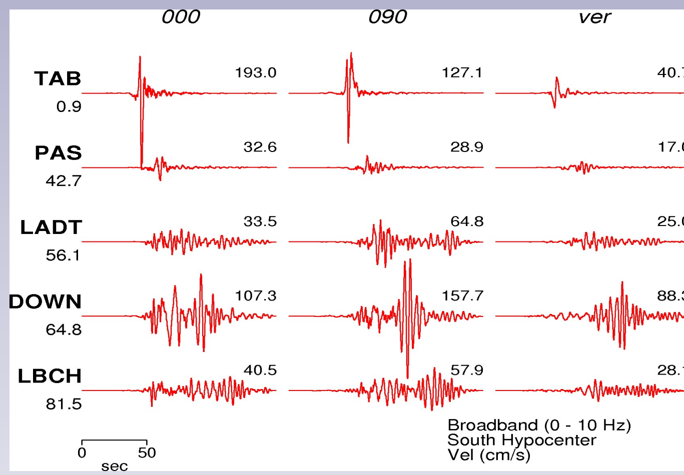
Real case of a site effect

- Velocity records for M7.8 San-Andreas event (2008)



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Extreme case: Soil Liquefaction

- Liquefaction: compaction of water-saturated soil during intense shaking allows water to flow upward and the soil loses its shear strength and flows, becoming liquefied into a kind of quicksand
  - Liquefaction strikes soft, sandy water-saturated soils
    - Usually low-lying and flat
  - Buildings may tilt or sink into liquefied sediments; tanks may float

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General liquefaction criteria

- Historical criteria
  - What liquified last time?
- Geological criteria
  - What soil is similar to soils that liquified last time
- Compositional criteria
  - See next slide
- State criteria
  - Relative density, pre-stress

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Liquifaction criteria

- Fraction finer than 0.005 mm <15%
- Liquid Limit, LL <35%
  - "Liquid limit" - water content above which material acts as a liquid
- Natural water content > 90%
- LL Liquidity Index <0.75

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Liquefaction of Soils

- Liquefaction of Soil
  - Soils behave like a liquid. How and why?
  - To understand the above phenomenon: Some understanding of basics required
    - Total stress,
    - Pore water pressure
    - Effective stress

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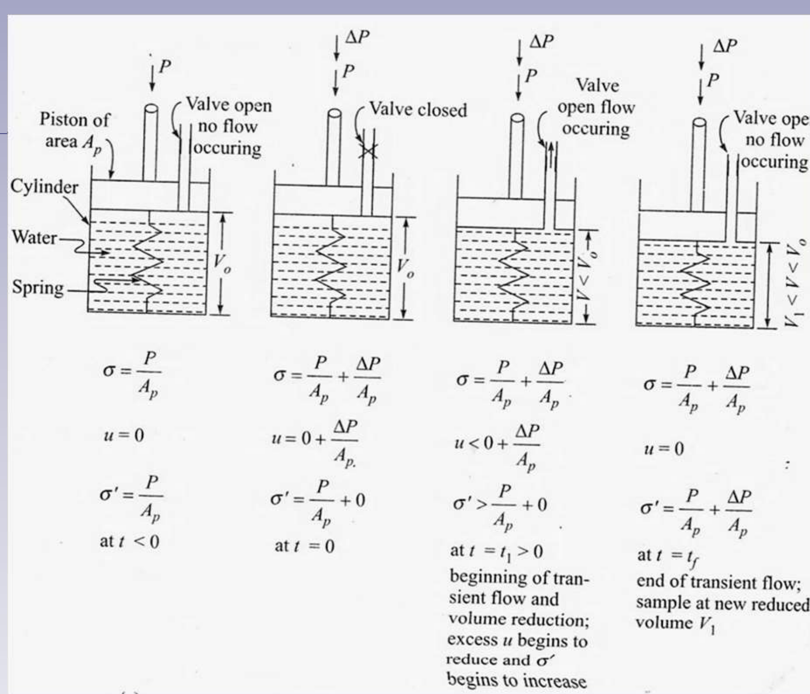

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Liquefaction of Soils

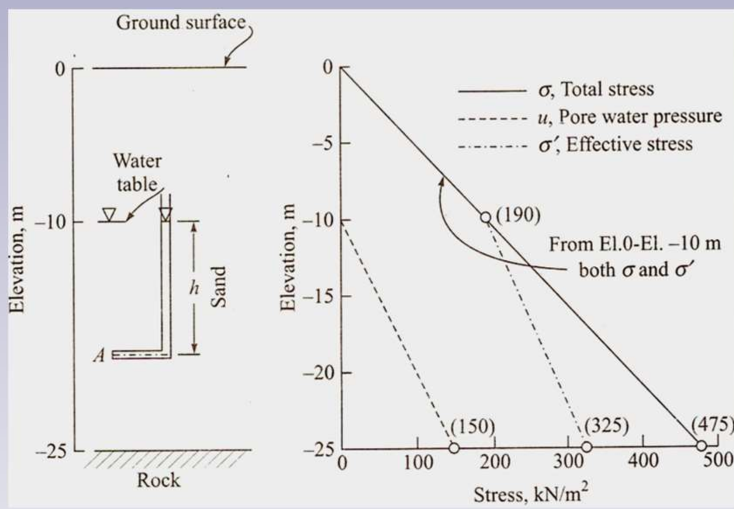

Figure 1

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Liquefaction of Soils

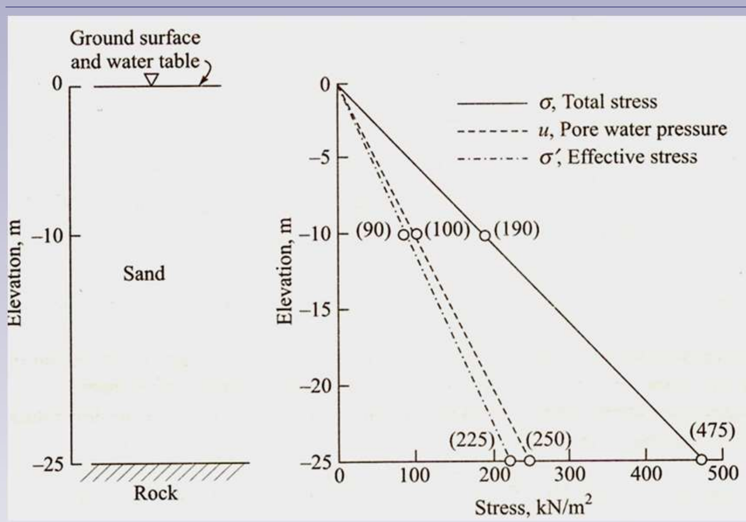

Figure 2

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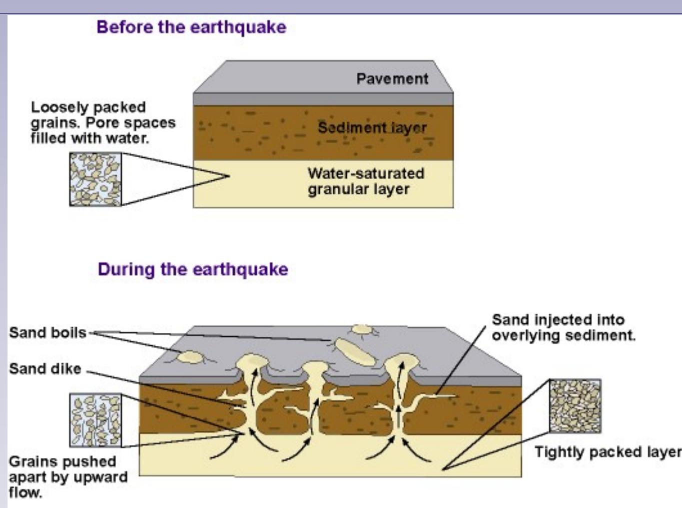
Liquefaction of Soils

Case	Total Pressure	Pore Pressure	Effective Pressure
Figure- 1	475	150	325
Figure- 2	475	250	225

- Saturated sand when subjected to ground vibration, it tends to compact and decrease in volume ; if drainage is unable to occur, the tendency to decrease in volume results in an increase in pore water pressure and when this becomes equal to the overburden pressure effective stress becomes equal to zero, sand looses its strength completely and it develops a liquefied state.

Liquefaction of Soils



EARTHQUAKE-INDUCED LIQUEFACTION

The Damage of Embankment Structures due to liquefaction

Collapsed Embankment

Tokachi-Oki EQ, 2003 M=8.3

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The Damage of Port Structures due to liquefaction

Trace of Sand Boiling

Tokachi-Oki EQ, 2003 M=8.3

Settlement behind Quay Wall

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The Damage of Port Structures due to liquefaction

Hyogo Port, Kobe , Japan

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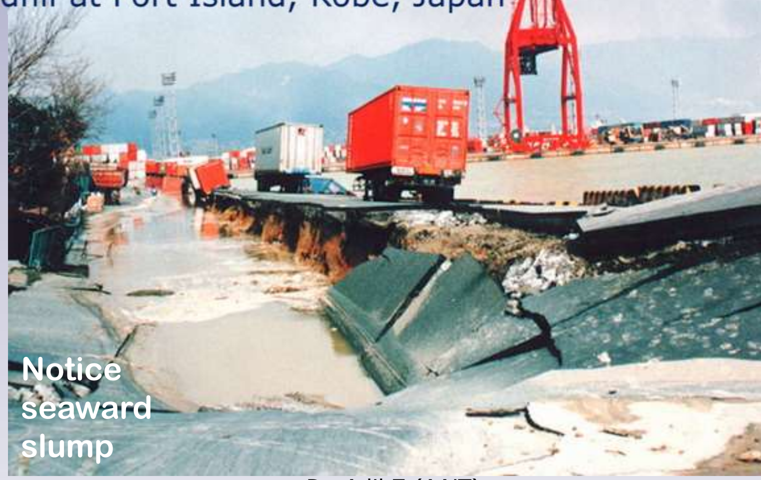
The Damage of Port Structures due to liquefaction

Landfill at Port Island, Kobe, Japan



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The Damage of Buildings due to liquefaction

Caracas EQ 1967, M=6.6

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The Damage of Buildings due to liquefaction

Nigatta EQ 1964 M=7.5

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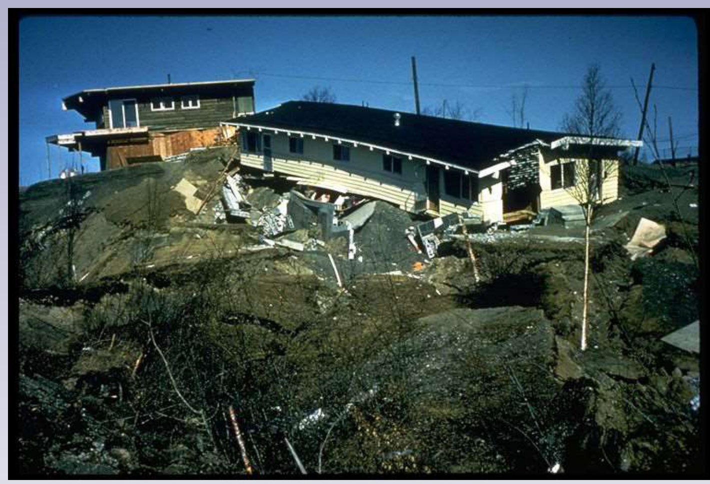
The Damage of Buildings due to liquefaction



Alaska EQ 1964 M=9.2

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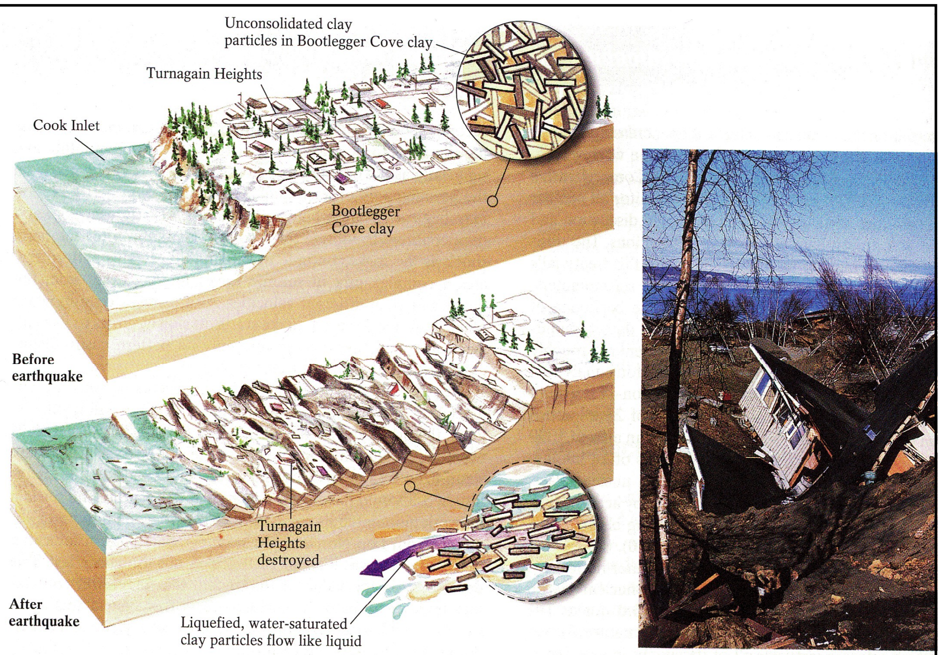
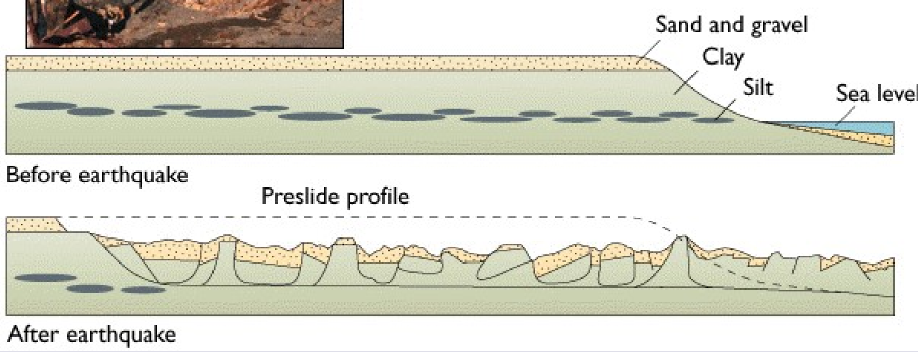


Figure 10-10 Liquefaction occurs when the grains in a layer of wet, fine-grained sediment are shaken during an earthquake. In 1964, the clay layer beneath the entire Turnagain Heights area of Anchorage, Alaska, liquefied, producing a chaotic landscape of jumbled homes and asphalt blocks

Cross-sections of the bluffs at Turnagain Heights before and after 1964 Alaska quake



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The Damage of Buildings due to liquefaction

Kocaeli EQ 1999 M=7.2

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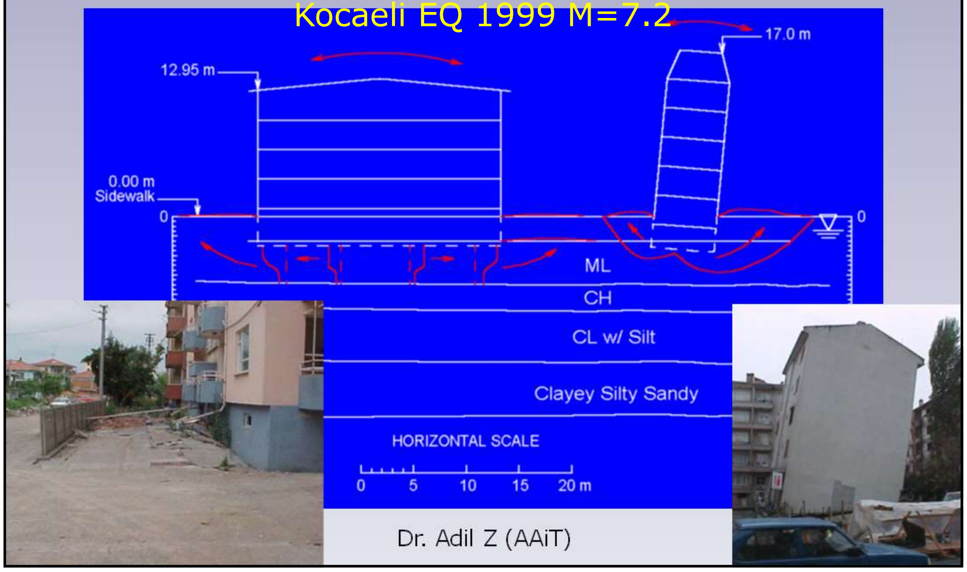
The Damage of Buildings due to liquefaction



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Geological factors that influence the degree of liquefaction

- Depositional environment or type of sediment
  - alluvial deposits are typically porous “loose” sands and silts
- Age
  - young alluvial deposits are typically more porous (higher susceptibility)
  - older deposits become more compacted and cemented (lower susceptibility)
- Ground shaking magnitude
  - Ground shaking is amplified in soft, unconsolidated sediments

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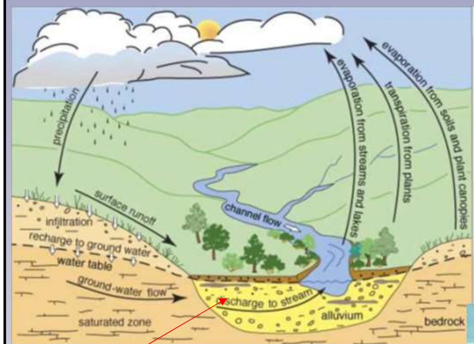

Copper river, Alaska

alluvium–unconsolidated, loose, sediments deposited by a river

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Soil Effects

- Stronger shaking on
  - Soft soil, Landfill
  - Waterside sites
- Seismic waves grow in amplitude when they pass from rock into less rigid material such as soil
  - Soils behave like jelly in a bowl, which shakes much more than the plate

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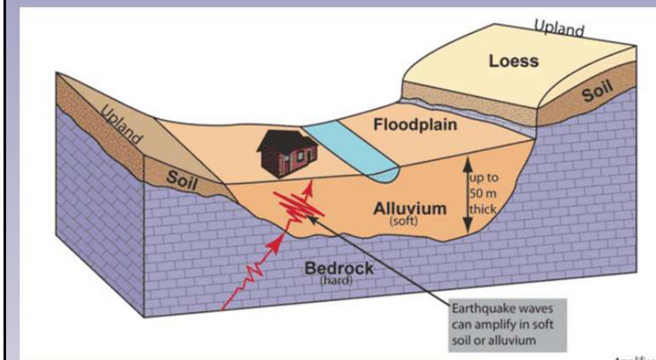

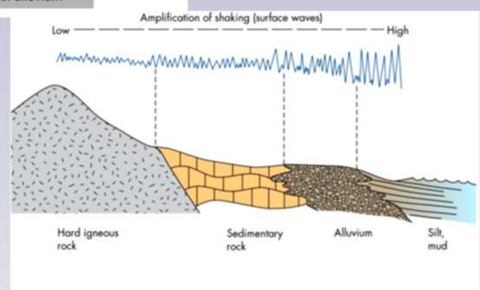

Ground shaking is amplified in soft, unconsolidated sediments

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Liquefaction of Soils

- Building that collapsed during Caracas EQ (1967), Nigatta EQ (1964), Alaska EQ (1964) and Izmit EQ (1999) earthquakes due to liquefaction of the subsurface with little or no damage to the structure itself, where **liquefaction** is a process in which the soil loses shear strength and *approaches the state of a liquid* due to a transient *accumulation of excess pore pressures*.

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Liquefaction of Soils

- Counter measures against liquefaction
  - Modifying the mechanical properties of soil - densification
    - Compaction by vibro-floatation
    - Blast densification
    - Dynamic compaction by dropping heavy weight (for uncontrolled fills)
  - Modifying the chemical properties of soil - grouting
    - Stabilization of soils
    - Jet grouting or Compaction grouting
    - Application of reinforced earth (vibrostone columns)
  - Modifying the flow of water
    - Filtration (improve drainage)
    - Lowering of ground water table
    - Mitigation of lateral flow by providing baffle walls

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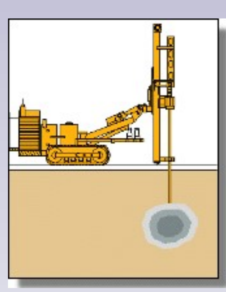
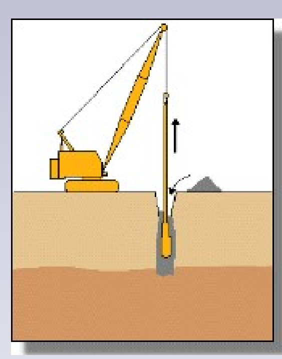
Liquefaction of Soils

- Counter measures against liquefaction





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Liquefaction of Soils

- Counter measures against liquefaction

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Soil-Structure Interaction

- Most of the civil engineering structures involve some type of structural element with direct contact with ground. When the external forces, such as earth quake act on these systems, neither the structural displacements nor the ground displacements, are independent of each other.
- The process in which the response of the soil influences the motion of the structure and the motion of the structure influences the response of the soil is termed as **soil-structure interaction (SSI)**

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Soil-Structure Interaction

- It has been common practice to ignore the SSI effects by simply treating structures as if rigidly based regardless of the soil condition, because of the difficulties (cost, complexity & validity) involved in making the dynamic analytical model of soil system.
- However, intensive study in recent years has produced considerable advances in of knowledge of SSI effects and advanced analytical techniques also become available.

Soil-Structure Interaction

- The response of a structure during an earthquake depends on:
  - characteristics of the ground motion,
  - the surrounding soil, and
  - the structure itself.

  This interaction between the structure and the soil is named soil-structure interaction (SSI).

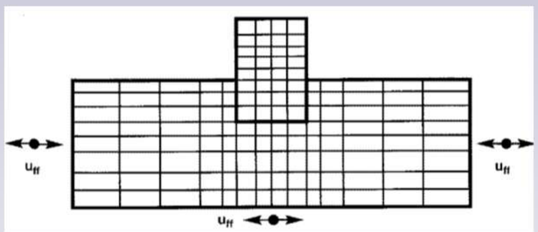
Soil-Structure Interaction

- <u>General Methodologies of SSI analysis</u>

  1. Direct (Single Step) method

  ✓ entire soil foundation – structure system is modeled and analyzed in a single step

  ✓ Appropriate for non linear analysis (accounting geometric and material non linearity)



$$[M]\{\ddot{U}\} + [K^*]\{U\} = -[M]\{\ddot{U}_{ff}(t)\}$$

U_{ff} = free field acc.

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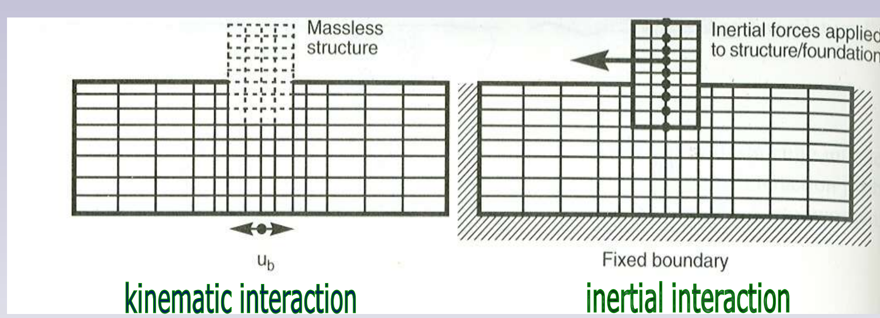
Soil-Structure Interaction

2. Multi- Step method

✓ Uses the principle of superposition

✓ Limited to the analysis of linear systems



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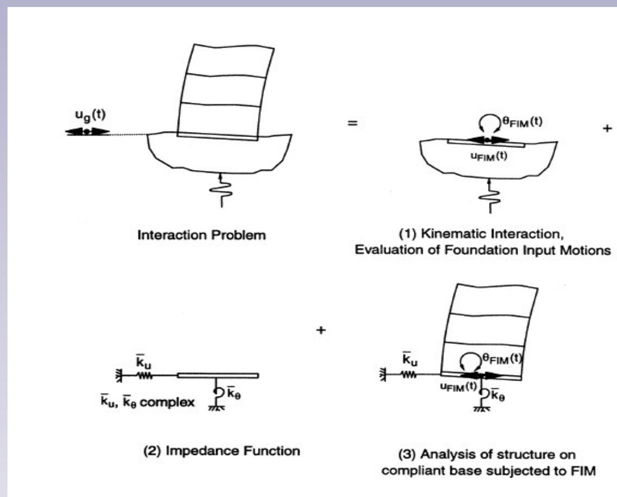
Soil-Structure Interaction



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Soil-Structure Interaction

Soil structure interaction(SSI): is defined as the *interdependent responses relationship* between a structure and its supporting soil.

The behavior of the structure is *dependent* on the nature of the supporting soil and similarly the behavior of the stratum is *modified* by the presence of the structure.

Soil-structure interaction broadly can be divided into two phenomena:

a) kinematic interaction and

b) inertial interaction.

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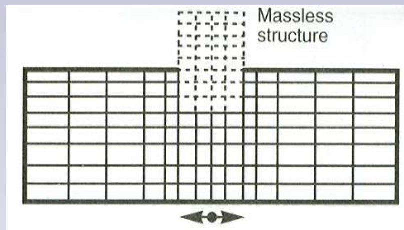
Soil-Structure Interaction

- Earthquake ground motion causes soil displacement known as free-field motion. However, the foundation embedded into the soil will not follow the free field motion. This *inability of the foundation to match the free field motion* causes the ***kinematic interaction*.**



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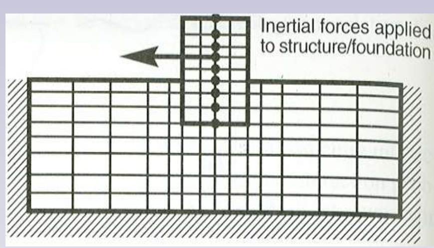
Soil-Structure Interaction

- On the other hand, the mass of the super-structure *transmits the inertial force to the soil* causing *further deformation* in the soil, which is termed as ***inertial interaction.***



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Soil-Structure Interaction

- **Neglecting SSI is reasonable** *for light structures in relatively stiff soil* such as low rise buildings and simple rigid retaining walls.
- **The effect of SSI, however, becomes significant** for heavy structures resting on relatively soft soils
  - For example: nuclear power plants, high-rise buildings and elevated-highways on soft soil

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Soil-Structure Interaction

- Perhaps the leading question to be answered about soil–structure interaction is: '*For what soil conditions will the rigid base assumption lead to significant errors in the response calculations?*' Veletsos and Meek (1974) have suggested that consideration of soil–structure interaction is only warranted for values of the ratio $\frac{v_s}{fh} < 20$

→framed buildings when Vs ≤ 600m/s, or

→for shear wall buildings when Vs ≤ 900m/s

where v_s is the *shear-wave velocity* in the soil half-space, f is the *fixed-base frequency* of the single-degree-of-freedom structure, and h is its *height*.

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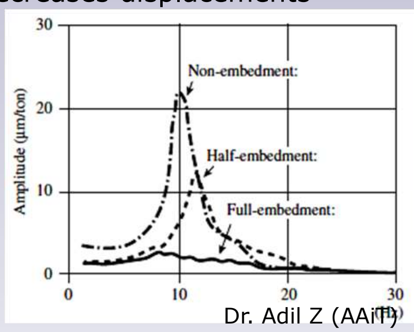
Soil-Structure Interaction

- **Effect of embedment**
  - Increasing embedment depth
    - Increases static stiffness
    - Decreases period of vibration
    - Decreases displacements



Soil Models for Dynamic Analysis

- There are five different categories of models of varying complexity for the representation of soil behavior.
- The best model is the one that includes the effects of the following parameters and may be accounted for *depending on the sensitiveness* of the structure

Soil Models for Dynamic Analysis

- The parameters are:
  - Soil stiffness
  - Material damping
  - Radiation damping allowing for strain dependence (non linearity)
  - Variation of properties in 3D
  - Embedment of the structure in the soil.

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Soil Models for Dynamic Analysis

- The five categories of varying complexity

  (1) equivalent-static springs and viscous damping model;

  (2) Shear beam model;

  (3) Elastic or visco-elastic half-space model;

  (4) Finite elements model;

  (5) Hybrid model of (3) and (4).

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Soil Models for Dynamic Analysis

(1) **Equivalent-static springs and viscous damping model**

- Springs & dashpots located at the base of the structure
- The *simplest method* of modeling the soil
- Uses *springs, located at the base of the structure*, to represent the appropriate selection of horizontal, vertical, and torsional stiffness of the soil
- ***Foundation spring stiffness,*** is determined by using the zero-frequency (static) stiffness derived from elastic half-space theory as given in the next table,

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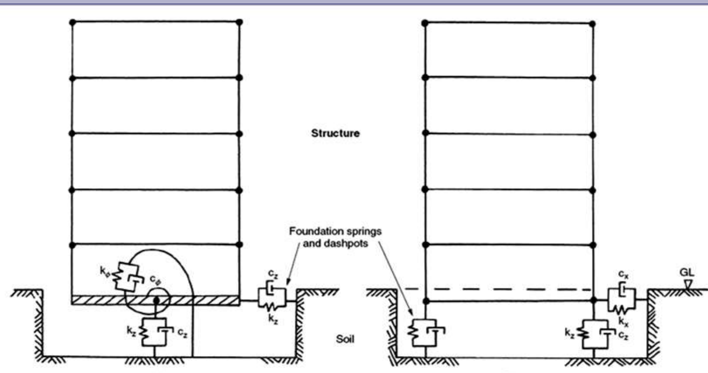
Soil Models for Dynamic Analysis



Elementary soil-structure analytical models representing soil properties

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Soil Models for Dynamic Analysis

Discrete foundation properties for rigid plate on elastic half-space

Motion	Circular footings			Rectangular footings
	Spring stiffness k	Viscous damper*	Added mass*	Spring stiffness k
Vertical	$\frac{4GR}{1-v}$	$1.79\sqrt{k\rho R^3}$	$1.5\rho R^3$	$\frac{G}{1-v}\beta_z\sqrt{BL}$
Horizontal	$\frac{8GR}{2-v}$	$1.08\sqrt{k\rho R^3}$	$0.28\rho R^3$	$2G(1+v)\beta_x\sqrt{BL}$
Rocking	$\frac{8GR^3}{3(1-v)}$	$0.47\sqrt{k\rho R^5}$	$0.49\rho R^5$	$\frac{G\beta\phi BL^2}{1-v}$
Torsion	$\frac{16GR^3}{3}$	$1.11\sqrt{k\rho R^5}$	$0.7\rho R^5$	†

G= shear modulus; R= radius of footing; ν= Poisson's ratio; ρ= mass density; B,L= Plan dimension; β= coefficients

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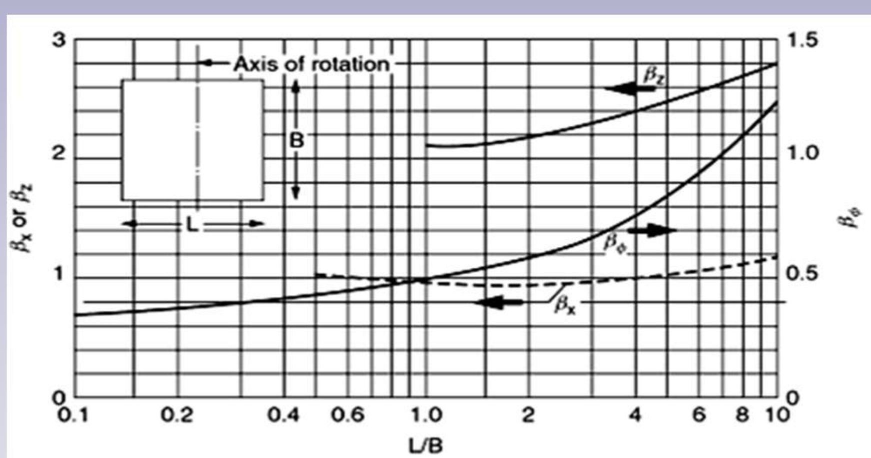
Soil Models for Dynamic Analysis



Coefficients for rectangular footing

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Soil Models for Dynamic Analysis

(2) Shear beam model:

- used to model the soil layers overlying bedrock although difficulties arise in choosing appropriate stiffness and damping values for the soil;
- using continua or lumped masses and springs distributed vertically through the soil profile**;**
- non-linearity may be allowed for by using iterative linear analyses, or by non-linear foundation springs.

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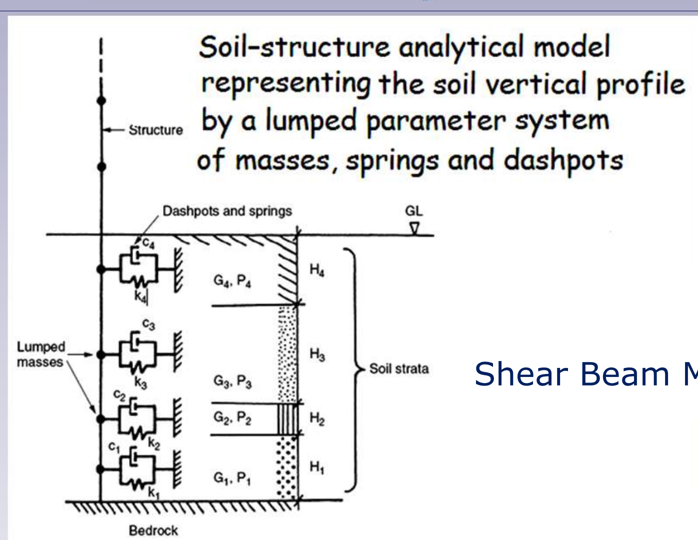
Soil Models for Dynamic Analysis



Shear Beam Model

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Soil Models for Dynamic Analysis

(3) Elastic or visco-elastic half-space model;

- Radiation damping can be modeled better as frequency dependent
- Non linear behavior can not be explicitly modeled
- Effect of soil layer may be included
- Effect of embedment are not directly treated (may be considered by increasing foundation stiffness)

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Soil Models for Dynamic Analysis

(4) Finite elements model;

- Most comprehensive
- Permits radiation damping & three dimensionality change of soil stiffness both vertically & horizontally
- *Embedment of footing is easily dealt with*
- Non linearity can also be modeled with non linear FEM (very expensive)
- Alternatively non linearity can be modeled as repetitive linear model with adjustment of modulus & damping as function of strain level

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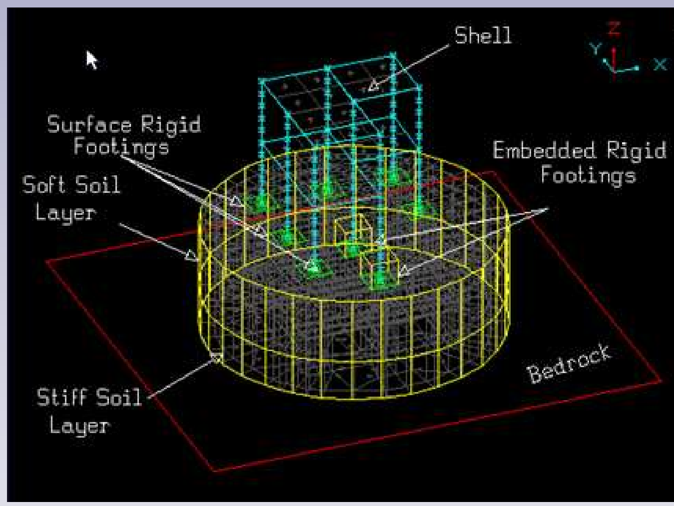
Soil Models for Dynamic Analysis



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Soil Models for Dynamic Analysis

(5) Hybrid model

half space model and finite element model

Combines the two methods by taking the advantage of the desirable features,

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Soil-Structure Interaction Effects

- In general, soil-structure interaction will cause the **natural frequency** of a soil structure system to be **lower** than the natural frequency of the structure itself, **because** periods of vibration of a structure increase with decreasing stiffness of the subsoil.
- Radiation damping will generally cause the total damping of a soil structure system to **be greater than** that of the structure itself.
- Because of these effects, *soil structure interaction tends to reduce the demands on the structure.*

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Soil-Structure Interaction Effects

- Rigorous numerical analyses have shown that increase in natural period of structure due to SSI is **not** always beneficial
  - **Soft soil sediments** can significantly elongate the period of seismic waves and the increase in natural period of structure may lead to the **resonance** with the long period ground vibration
  - The **ductility demand** can significantly increase with the increase in the natural period of the structure due to SSI effect
  - The permanent deformation and failure of soil may further aggravate the seismic response of the structure.

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Summary: Hazards of various geological foundations

- Soft soils
  - stronger shaking, settlement
- Wet soils
  - liquefaction potential, land sliding potential
- Cliffs and ridges
  - stronger shaking, land sliding potential

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That is all for now

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