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CERTIFICATION COURSE

EARTHQUAKE RESISTANT DESIGN OF FOUNDATIONS

Lecture 35: Ground Response Analysis (GRA)

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ERD of Foundations - Modules

1. Introduction
2. Shallow Foundations
3. Pile Foundations
4. Well Foundations
5. SSI for Deep Foundations
6. Miscellaneous

Module - 5

SSI for Deep Foundations



Module - 5: Chapters

1. Introduction to Soil-Structure Interaction
2. Effects of Soil-Structure Interaction
3. SGM and Wave Propagation
4. Dispersion & Attenuation of Waves, Damping
5. Ground Response Analysis (GRA)
6. Soil-Pile Interaction

Chapter-5: Ground Response Analysis (GRA)

1. **One-dimensional GRA**
2. **Two-dimensional GRA**
3. **Boundary Conditions**

Ground Response Analysis

- One of the most important and commonly encountered problems in geotechnical earthquake engineering is the evaluation of ground response.
- *Ground response analyses* are used to predict ground surface motions for development of design response spectra, to evaluate dynamic stresses and strains for evaluation of liquefaction hazards, and to determine the earthquake-induced forces that can lead to instability of earth and earth-retaining structures.

Ground Response Analysis

Under ideal conditions, a complete ground response analysis would model the rupture mechanism at the source of an earthquake, the propagation of stress waves through the earth to the top of bedrock beneath a particular site, and would then determine how the ground surface motion is influenced by the soils that lie above the bedrock. In reality, the mechanism of fault rupture is so complicated and the nature of energy transmission between the source and the site so uncertain that this approach is not practical for common engineering applications.

Ground Response Analysis

- In practice, empirical methods based on the characteristics of recorded earthquakes are used to develop predictive relationships, which are often used in conjunction with a seismic hazard analysis to predict bedrock motion characteristics at the site.
- The problem of ground response analysis is one of determining the response of the soil deposit to the motion of the bedrock immediately beneath it.
- Despite the fact that seismic waves may travel through tens of kilometers of rock and often less than 100m of soil, the soil plays a very important role in determining the characteristics of the ground surface motion.

Ground Response Analysis

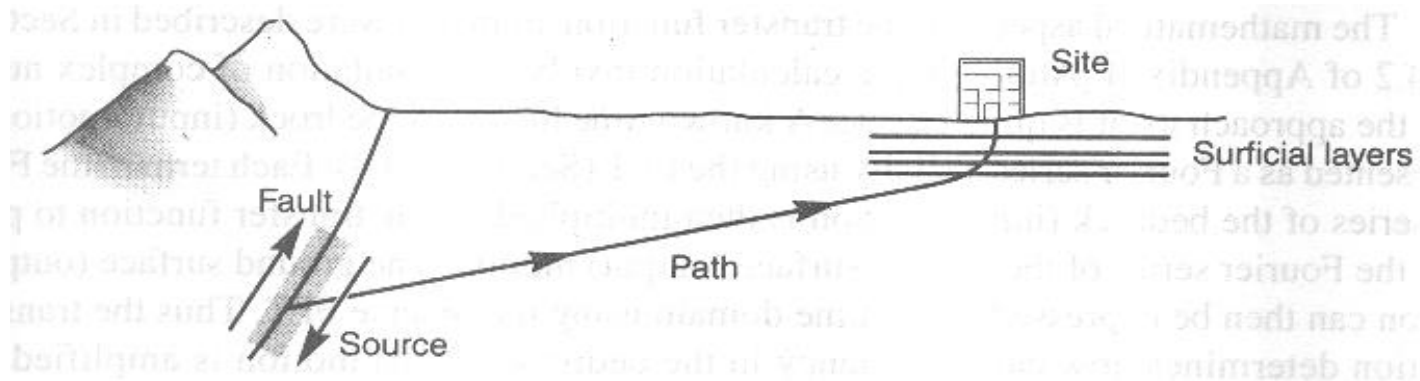
- The influence of local soil conditions on the nature of earthquake damage has been recognized for many years. Earlier seismologists and, recently, geotechnical earthquake engineers have worked toward the development of quantitative methods for predicting the *influence of local soil conditions on strong ground motion*.
- Over the years, a number of techniques have been developed for ground response analysis. The techniques are often grouped according to the dimensionality of the problems that can be addressed.

1-D Ground Response Analysis

- When a fault ruptures below the earth's surface, body waves travel away from the source in all directions. As they reach boundaries between different geologic materials, they are reflected and refracted.
- Since the wave propagation velocities of shallower materials are generally lower than the materials beneath them, inclined rays that strike horizontal layer boundaries are usually reflected to a more vertical direction.
- By the time the rays reach the ground surface, multiple refractions have often bent them to a nearly vertical direction.

1-D Ground Response Analysis

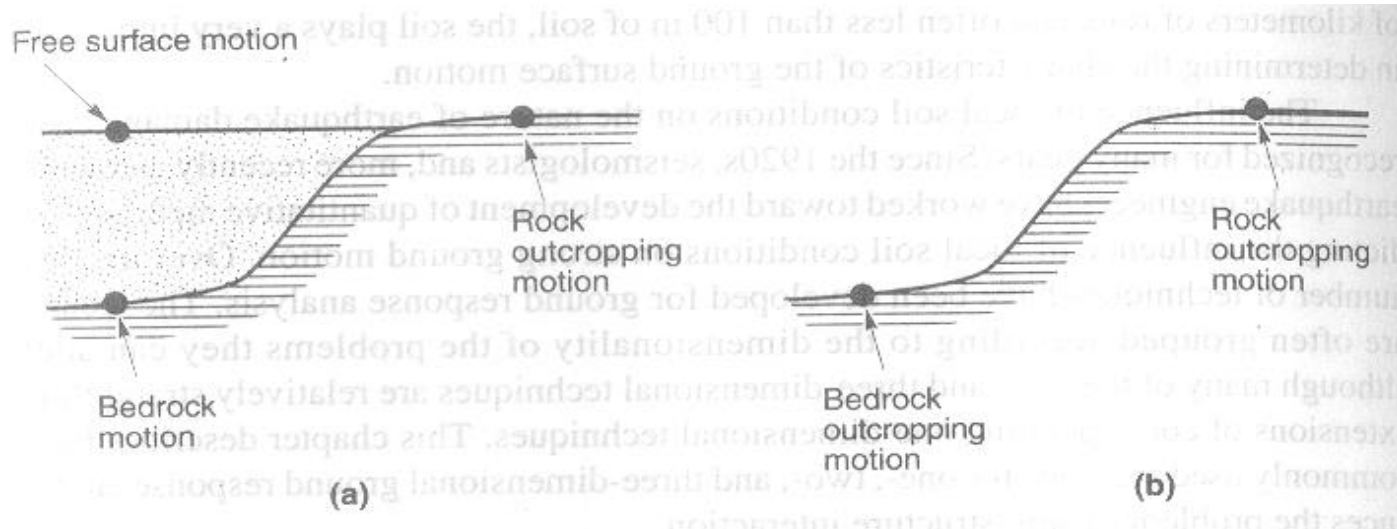
1-D ground response analyses are based on the assumption that all boundaries are horizontal and that the response of a soil deposit is predominantly caused by SH-waves propagating vertically from the underlying bedrock.



Refraction process producing nearly vertical wave propagation near ground surface

1-D Ground Response Analysis

1. **Free surface motion:** The motion at the surface of a soil deposit
2. **Bedrock motion:** The motion at the base of the soil deposit (top of bedrock)
3. **Rock outcropping motion:** The motion at a location where bedrock is exposed at the ground surface.
4. **Bedrock outcropping motion:** The motion at the top of bedrock, If the soil deposit was not present.



1-D Analysis: Linear Approach

- The transfer functions can be used to compute the response of single-degree-of-freedom systems. For the ground response problem, transfer functions can be used to express various response parameters, such as displacement, velocity, acceleration, shear stress, and shear strain, to an input motion parameter such as bedrock acceleration.
- Because it relies on the principle of superposition, **this approach is limited to the analysis of linear systems**. Nonlinear behavior can be approximated, using an iterative procedure with equivalent linear soil properties (e.g. **SHAKE**).

Uniform Undamped Soil on Rigid Rock

A uniform layer of isotropic, linear elastic soil overlying rigid bedrock



Linear elastic soil deposit of thickness H underlain by rigid bedrock

Uniform Undamped Soil on Rigid Rock

Harmonic horizontal motion of the bedrock will produce vertically propagating shear waves in the overlying soil. The resulting horizontal displacement can be expressed, using the principal of wave propagation as:

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

where ω is the circular frequency of ground shaking, k the wave number ($= \omega/v_s$) and A and B the amplitudes of waves traveling in the $-z$ (upward) and $+z$ (downward) directions, respectively. **At the free surface ($z = 0$), the shear stress, must vanish, this boundary condition yields that the unknown coefficients $A=B$.**

Uniform Undamped Soil on Rigid Rock

Ratio of displacements at the free surface and that at the bedrock is found which leads to transfer function:

$$F_1(\omega) = \frac{u_{\max}(0, t)}{u_{\max}(H, t)} = \frac{2Ae^{i\omega t}}{2A \cos(kH) e^{i\omega t}} = \frac{1}{\cos(kH)} = \frac{1}{\cos(\omega H / v_s)}$$

The modulus of the transfer function is the amplification factor

$$|F_1(\omega)| = \frac{1}{|\cos(\omega H / v_s)|}$$

which indicates that **the surface displacement is always at least as large as the bedrock displacement and, at certain frequencies, is much larger.**

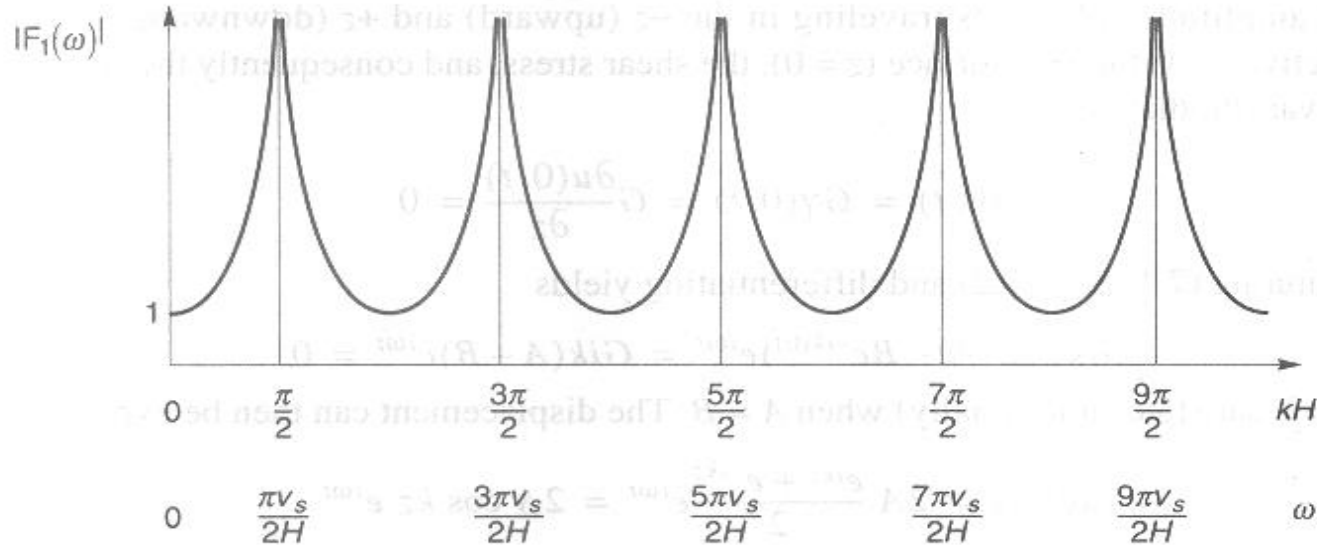
Uniform Undamped Soil on Rigid Rock

Thus $|F_1(\omega)|$ is the ratio of the free surface motion amplitude to the bedrock motion amplitude (or, since the bedrock is rigid in this case, the bedrock outcropping motion).

As $\omega H/v_s$ approaches $\pi/2 + n\pi$, the denominator of above equation approaches zero, which implies that infinite amplification, or *resonance*, will occur.

This simple model illustrates that the response of a soil deposit is highly dependent upon *the frequency of the base motion*, and that the frequencies at which strong amplification occurs depend on the *geometry (thickness) and material properties (s-wave velocity)* of the soil layer.

Uniform Undamped Soil on Rigid Rock



Variation of steady-state response of undamped linear elastic layer with frequency

Uniform Damped Soil on Rigid Rock

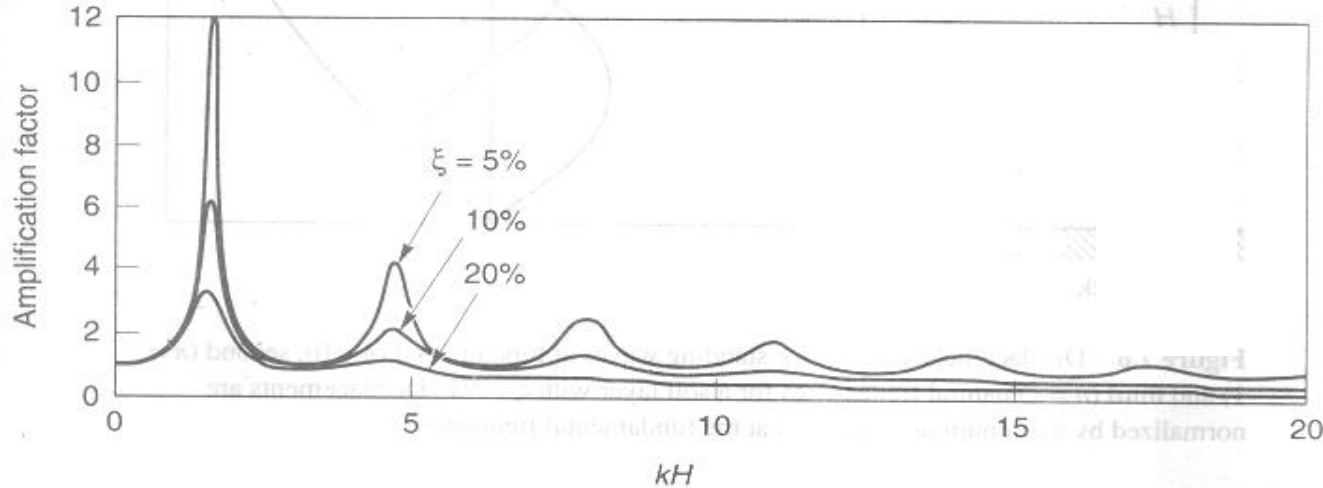
- The type of unbounded amplification predicted by the previous analysis is not practical as no dissipation of energy or damping in soil was assumed.
- Since damping is present in all materials, more realistic results can be obtained by repeating the analysis with damping. Assuming the soil to have the shearing characteristics of a Kelvin-Voigt solid, and writing the wave equation and solution of that is given by:

$$|F_2(\omega)| = \frac{1}{\sqrt{\cos^2(kH) + (\xi kH)^2}} = \frac{1}{\sqrt{\cos^2(\omega H / v_s) + (\xi \omega H / v_s)^2}}$$

Uniform Damped Soil on Rigid Rock

- For small damping ratio, above Eq. indicates that amplification of a damped soil layer also varies with frequency.
- The amplification will reach a local maximum whenever $kH = \pi/2 + n\pi$, but will never reach a value of infinity. Since (for $\xi > 0$) the denominator will always be greater than zero. The frequencies that correspond to the local maxima are the natural frequencies of the soil deposit.
- The variation of amplification factor with frequency is shown for different level of damping in next slide. Comparing the Figs for undamped and damped cases shows that damping affects the response at high frequencies more than at lower frequencies.

Uniform Damped Soil on Rigid Rock



Influence of frequency on steady-state response of damped linear elastic layer. The n^{th} natural frequency of the soil deposit is given by

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

Uniform Damped Soil on Rigid Rock

The greatest amplification factor occurs approximately at the lowest natural frequency, also known as the fundamental frequency:

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

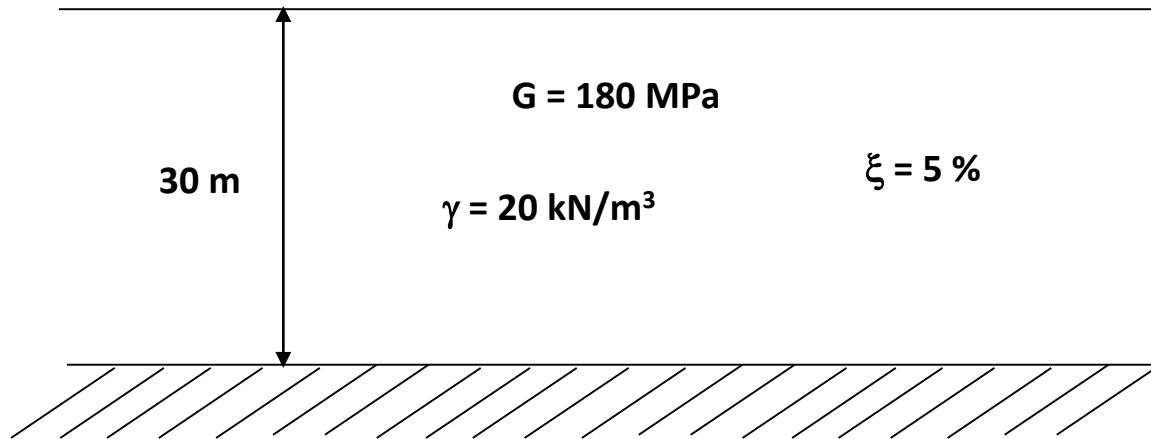
The period of vibration corresponding to the fundamental frequency is called the characteristic site period:

$$T_s = \frac{2\pi}{\omega_0} = \frac{4H}{V_s}$$

The characteristic site period, which depends only on the H and V_s , provides a very useful indication of the period of vibration at which the most significant amplification can be expected.

Numerical Example

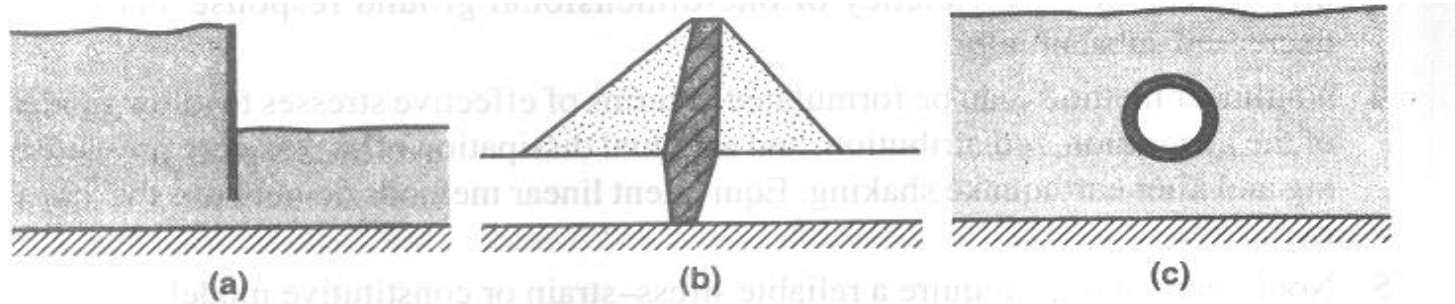
A soil stratum on a rigid bedrock is subjected to harmonic excitations. Find the first (fundamental) and second natural undamped frequencies of the stratum in Hz. Determine transfer functions at first two natural frequencies.



2-D Dynamic Analysis

- The methods of 1-D ground response analysis are useful for level or gently sloping sites with parallel material boundaries. Such conditions are not uncommon and one-dimensional analyses are widely used in geotechnical earthquake engineering practice.
- For many other problems of interest, however, the assumptions of 1-D wave propagation are not acceptable. Sloping or irregular ground surfaces, the presence of heavy structures or stiff, embedded structures, or walls and tunnels all require two-dimensional or possibly even three-dimensional analysis.

2-D Dynamic Analysis



Examples of common problems typically analyzed by 2-D plane strain dynamic response analyses: (a) Cantilever retaining wall; (b) Earth dam; (c) Tunnel

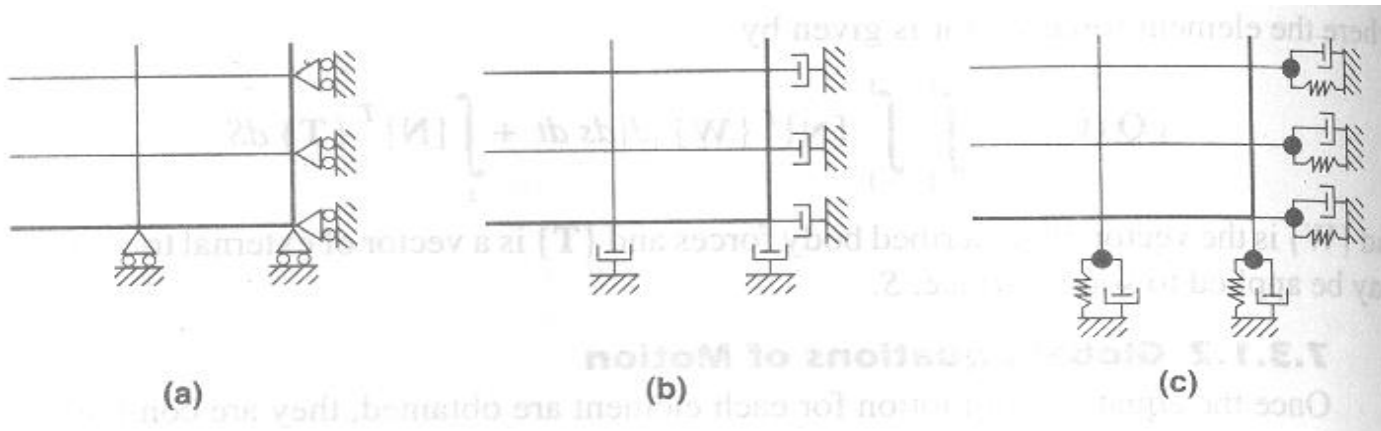
Boundary Conditions

- For computational efficiency it is desirable to **minimize the number of elements in a finite-element analysis.**
- Since the maximum dimensions of the elements are generally controlled by the wave propagation velocity and frequency range of interest, minimizing the number of elements usually becomes a matter of **minimizing the size of the discretized region.**
- As the size of the discretized region decreases, the influence of boundary conditions becomes more significant.

Boundary Conditions

- For many dynamic response and soil-structure interaction problems, rigid or near-rigid boundaries such as bedrock are located at considerable distances, particularly in the horizontal direction, from the region of interest.
- As a result, wave energy that travels away from the region of interest may effectively be permanently removed from that region.
- In a dynamic finite-element analysis, it is important to simulate this type of radiation damping behavior. The most commonly used boundaries for finite-element analyses can be divided into three groups.

Boundary Conditions



Three-types of finite-element mesh boundaries:

- (a) Elementary boundary in which zero displacements are specified;**
- (b) Local boundary consisting of viscous dashpots;**
- (c) Lumped-parameter consistent boundary consisting of springs, dashpots and masses**

References:

1. Kramer S.L. (1996). Geotechnical Earthquake Engineering, Prentice Hall, Upper Saddle River, NJ, USA

Thank You

