Dynamic Soil Properties and their Methods of Determination

Dr. Arindam Dey
Associate Professor
Department of Civil Engineering
Geotechnical Engineering Division
IIT Guwahati

Presentation Schedule

- Introduction to dynamic properties of soils
  - Why we should be interested?
  - What are the dynamic properties?
  - What are the factors influencing dynamic properties?
- Evaluation of dynamic properties of soils
  - What are the various categories of tests available?
  - What are the various types of high strain field tests?
  - What are the various types of low strain laboratory element tests?
  - What are the various types of high strain laboratory element tests?
- Cyclic triaxial test
  - The apparatus and its components
  - Dynamic properties of Brahmaputra sand and Red Soil
  - Liquefaction Criteria for Brahmaputra Sand
- Summary and Takeaway
Introduction to Dynamic Soil Properties

Soil is a three-phase material

- Interaction of phases under applied static/cyclic load
  - Low strain and deformations/displacements
  - Soil mass shaking under wave propagation effect
  - Large strain and deformations/displacements
  - Flow of soil mass during landslides or liquefaction

[Diagram of soil phases: Solid, Liquid, Air]
Dynamic Properties of Soil

- Necessity to investigate dynamic soil properties
  - *Ground response analyses*
  - *Liquefaction evaluation studies*
  - *Seismic design of various structures*
  - *Seismic requalification*

- What are dynamic soil properties?
  - *Influences the soil behavior under dynamic loading*
    - Strain-dependent Shear modulus
    - Strain-dependent Damping ratio
    - Liquefaction parameters

- Strain-dependent shear modulus
  - *Modulus of rigidity*
    - Shear stiffness of material and its decay

- Strain-dependent damping ratio
  - *Rate of decay of oscillation of seismic wave*
    - Dissipation of seismic energy

- Liquefaction parameters
  - *Cyclic Stress Ratio (CSR) and excess Pore-water Pressure Ratio ($r_u$)*
    - Liquefaction phenomenon
      - Reduction in shear strength of soil under undrained shearing
      - Increase in pore pressure and a consequent reduction in effective stress
Strain-dependent Shear Modulus

- Hysteresis loop and Backbone curve
  - *Effect of cyclic shear strain amplitude on shear modulus*
    - Backbone/Skeleton curve: Line joining the peak shear stress at each cycle of shear strain corresponding to the cyclic strain amplitude of each cycle
      - Characteristics of the backbone curve
        - Initially linear, First yield, Strain hardening, Ultimate Strength, Ductile Limit, Strength loss, Residual strength and Complete failure
      - Secant shear modulus: Line joining the origin and various points of the backbone curve

  ![Backbone curve diagram](image)

Modulus Reduction Curve

- Secant shear modulus and Backbone curve
  - *Varies with cyclic shear strain amplitude*
    - Low strain amplitude
      - $G_{sec}$ is high
      - $G_{sec}$ reduces with the increase in the strain amplitude
  - *Slope at the origin of backbone curve*
    - Largest value of $G_{sec}$
      - Referred as Maximum Shear Modulus ($G_{max}$)
  - *Modulus ratio ($G_{sec}/G_{max}$)*
    - $G_{sec}/G_{max} = 1$ at $\gamma_c = 0$
    - Modulus ratio decreases at higher cyclic shear strain amplitudes
    - Modulus reduction curve → Describes the degradation of shear modulus with the increase in the cyclic shear strain amplitude

![Modulus reduction curve diagram](image)
Liquefaction

- Liquefaction
  - *Phenomenon at which shear strength decreases*
    - Effective stress ($\sigma'$) = total stress ($\sigma$) - pore pressure ($u$)
- Types of Liquefaction
  - Based on soil nature and shear stress condition
    - Flow liquefaction or flow failure
      - Soil becomes weak and flow like water
      - More pertaining to the cohesionless soils
      - Both excess PWP and axial deformation reaches their threshold
    - Cyclic mobility or strain softening
      - Soil becomes soft but does not exhibit significant deformation
      - More pertaining to the cohesive soils
      - Axial deformation may not reach the threshold even when the excess PWP has reached its threshold

Manifestation of Liquefaction

- NIIGAATA
- BHUJ
- ALASKA
- KANDLA
- KOBE
Manifestation of Liquefaction

- Seed and Lee (1966)

\[ \tau_{\text{cyc}} = 0.65 \tau_{\text{max}} \]

\[ \tau_{\text{max}} = \frac{a_{\text{max}}}{g} \sigma_v r_d \]

- Earthquake-induced loading expressed in terms of cyclic shear stresses
- Compared with the liquefaction resistance of the soil
- Cyclic shear stress: \( \tau_{\text{cyc}} = 0.65 \tau_{\text{max}} \)
- \( \tau_{\text{max}} = \frac{a_{\text{max}}}{g} \sigma_v r_d \)
- \( a_{\text{max}} \) = peak acceleration of seismic wave (in g)
- \( \sigma_v \) = total vertical stress
- \( r_d \) = stress reduction factor

Evaluation of Liquefaction Potential

- Cyclic Stress Approach (Seed and Idriss, 1971)

\[ \gamma_{\text{cyc}} = 0.65 \frac{a_{\text{max}}}{g} \frac{\sigma_v r_d}{\sigma_y \gamma_{\text{cyc}}} \]

- Earthquake-induced loading is expressed in terms of cyclic strain
- Cyclic strain: \( \gamma_{\text{cyc}} = 0.65 \frac{a_{\text{max}}}{g} \frac{\sigma_v r_d}{\sigma_y \gamma_{\text{cyc}}} \)
Factors influencing Dynamic Properties

- From the literature it has been observed that the dynamic properties of soils significantly influenced by many factors like:
  - Soil type
  - Plasticity index
  - Cyclic strain amplitude
  - Relative density
  - Frequency of loading cycle
  - Effective confining pressure
  - Overconsolidation ratio
  - Number of loading cycles

Factors influencing Liquefaction Potential

- Liquefaction potential affected by many factors:
  - Cyclic stress ratio
  - Initial shear stress condition
  - Shear strain amplitude
  - Relative density
  - Fine content
  - Plasticity index
Dynamic Properties of Soil

- Strain-dependent shear modulus and damping ratio
- Cyclic stress ratio and Number of cycles for liquefaction

Different Strain Levels of Dynamic Loading

- Low strain range (< 0.001 % or 10^{-3} %)
  - Elastic theory applicable
  - Do not generate nonlinear stress conditions
  - Wave propagation problems
  - Foundation of machines

- High Strain range (> 0.01 %)
  - Dynamic behaviour is non-linear
  - Permanent deformations (plastic)
  - Significant volume change

- Intermediate strain levels (~10^{-2} %)
  - Response starts beginning non-linear
Tests to Evaluate Dynamic Soil Properties

Field Tests

**Low strain tests** (<0.001%)  
Source produces a pulse of waves, whose times of arrival are measured by receivers

- Seismic Reflection Test (SRT)
- Seismic Refraction Survey (SRS)
- Cross-Hole Test (CHT)
- Down-/Up-hole Test (DHT/UHT)
- Suspension Logging Test (SLT)
- Seismic Cone Penetration Test (SCPT)
- Steady-State-Vibration Test
- Cyclic Plate Load Test (CPLT)
- Spectral Analysis of Surface Waves (SASW) Test
- Multichannel Analysis of Surface Waves (MASW) Test

**High strain tests** (>0.001%)  
Various other mechanisms of creating disturbance

- Seismic Cone Penetration Test (SCPT)
- Standard Penetration Test (SPT)
- Dilatometer Test (DMT)
- Pressuremeter Test (PMT)
- Block vibration test
- Cyclic Plate Load Test (CPLT)
Laboratory Tests

Element Tests

Low strain tests ($< 0.001\%$)
- Resonant Column Test
- Ultrasonic Pulse Test
- Piezoelectric Bender Element Test

High strain tests ($> 0.001\%$)
- Cyclic Simple Shear Test
- Cyclic Torsion Test
- Cyclic Triaxial Test

Model Tests

- Shake Table Test
- Tilt Table Test
- Centrifuge Test

Selection of type of equipment or method depends on
- Range of strain of interest
- Problem to be analyzed at hand

High Strain Field Tests
Standard Penetration Test (SPT)

- Characterization of in-situ soil shear strength
  - Standard Penetration Test (SPT) – Soils with granular composition
  - Several correlations between N-value and Vs: Imai and Tonouchi (1977)

\[ V_s = \sqrt{G_l \rho} \]

\[ V_s = 91A^{0.337} \]

Seismic Cone Penetration Test (CPT)

- Characterization of in-situ cyclic shear strength of soil
  - In-situ Cone Penetration Test (CPT) – Soils having fine contents
    - Skin friction, End bearing resistance and pore-water pressure
Vane Shear (VST)

- Characterization of in-situ soil shear strength
  - Soils with significantly low undrained shear strength
    - Field Vane Shear Test

Dilatometer and Pressuremometer Tests (DMT and PMT)

- Characterization of in-situ soil strength
  - **Dilatometer**: Steel blade having a thin, circular expandable membrane mounted on one face
  - **Pressuremeter**: Cylindrical probe having a flexible membrane with guard cells at both ends
  - Pushed into the ground and the membrane is expanded using air
  - Soil parameters
    - $c_u$, $K_o$, OCR, $c_v$, $k$, soil stiffness

<table>
<thead>
<tr>
<th>Material Index</th>
<th>$I_o = \frac{(p_1 - p_u)}{(p_u - u_s)}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dilatometer Modulus</td>
<td>$E_D = 34.7(p_1 - p_u)$</td>
</tr>
<tr>
<td>Horizontal Stress Index</td>
<td>$K_o = \frac{(p_1 - u_s)}{\alpha_o}$</td>
</tr>
</tbody>
</table>

- $I_o < 0.6$, clay
- $0.6 < I_o < 1.8$, silts
- $I_o > 1.8$, sands
Block Vibration Test

- Block Vibration Test (IS 5249: 1992)
  - Estimate the dynamic properties
    - Coefficient of elastic compression ($C_u$)
    - Young’s modulus ($E$)
    - Damping Ratio ($\xi$)
  \[ A_z = \frac{a_z (\text{mm/s}^2)}{4\pi^2 f^2} \]

Dynamic Parameters of Foundation Soil

- Coefficient of elastic compression of soil
  \[ f_{nz} = \text{Natural frequency (Hz)} \]
  \[ m = \text{Mass of the block, exciter and motor (kg.sec}^2/\text{m}) \]
  \[ A = \text{Contact area of the block with the soil (m}^2) \]
  \[ C_u = \frac{4\pi^2 f_{nz}^2 m}{A} \]

- Coefficient of elastic compression for actual foundation
  \[ A_1 = \text{Area of the foundation} \]
  \[ C_{u1} = C_u \sqrt{\frac{A}{A_1}}, \quad A_1 \leq 10 \text{ m}^2 \]
  \[ C_{u1} = C_u - 10, \quad A_1 > 10 \text{ m}^2 \]

- Damping coefficient of soil
  \[ \xi = \frac{f_2 - f_1}{2f_{nz}} \]
Dynamic Parameters of Foundation Soil

- Modulus of elasticity of soil
  - $C_s = \text{Coefficient depending on } L/B \text{ ratio}$
  - $B, L = \text{Width and Length of the block}$
  - $\mu = \text{Poisson’s ratio of soil}$

$$C_u = \frac{E}{(1-\mu^2)} \times \frac{C_s}{\sqrt{BL}}$$

$C_s$ (Barkan, 1962)

<table>
<thead>
<tr>
<th>L/B</th>
<th>$C_s$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>1.06</td>
</tr>
<tr>
<td>1.5</td>
<td>1.07</td>
</tr>
<tr>
<td>2.0</td>
<td>1.09</td>
</tr>
<tr>
<td>3.0</td>
<td>1.13</td>
</tr>
<tr>
<td>5.0</td>
<td>1.22</td>
</tr>
<tr>
<td>10.0</td>
<td>1.41</td>
</tr>
</tbody>
</table>

Poisson’s ratio

<table>
<thead>
<tr>
<th>Types of Soil</th>
<th>Poisson’s ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clay</td>
<td>0.5</td>
</tr>
<tr>
<td>Sand</td>
<td>0.30 to 0.35</td>
</tr>
<tr>
<td>Rock</td>
<td>0.15 to 0.25</td>
</tr>
</tbody>
</table>

Horizontal Block Resonance Test

- Oscillator direction and Transducers position are changed

$A_s = \frac{a_s (\text{mm/s}^2)}{4\pi^2 f^2}$

$C_r = \frac{8\pi^2 r f_{jy}^2}{(A_0 + I_0) \pm \sqrt{(A_0 + I_0)^2 - 4rA_0I_0}}$

$r = \frac{M_m}{M_{m0}} \quad I_0 = 3.46I / M_{m0}$
Low-Strain Laboratory Element Tests

Determination of $G_{\text{max}}$

Resonant Column Test

• Typical characteristics
   Solid / hollow cylindrical specimen
   Subjected to harmonic torsional or axial loading
    • Electromagnetic loading system
    • Frequency / amplitude controlled
    • Random noise / impulse loading

Excited at the bottom and the response is picked up at the top (velocity or acceleration)
Free-Free

Driving force is applied on the top & response pickup is also placed on the top
Fixed-Free
Resonant Column test

• Basic principle
  ❖ Excite one end of a confined cylindrical soil specimen by means of torsional or longitudinal excitation

• Measurements
  ❖ Resonance frequency and Amplitude of vibration
  ❖ Estimate the fundamental mode resonance frequency

• Based on resonating frequency
  ❖ Determine wave propagation velocities and strain amplitudes using the theory of elasticity from the measured values
    • $V_c$ or $V_s$ depending on longitudinal or torsional excitation
  ❖ Evaluate the dynamic moduli and damping ratio

Free-Free Conditions

• Source and receiver at the other ends of the sample
• Longitudinal excitation
  ❖ Longitudinal wave velocity
    \[ v_c = \frac{\omega_n L}{\pi} = \frac{2\pi f_n L}{\pi} = 2 f_n L \]
  ❖ Dynamic low-strain elastic modulus
    \[ E = 4 f_n^2 \rho L^2 \]
• Torsional excitation
  ❖ Shear wave velocity
    \[ v_s = \frac{\omega_n L}{n\pi} = 2 f_n L = \sqrt{\frac{G}{\rho}} \]
  ❖ Dynamic low-strain elastic modulus
    \[ G = 4 f_n^2 \rho L^2 \]
• Poisson’s ratio
  \[ \mu = \frac{E}{2G} - 1 \]
**Fixed-Free Conditions**

- Source and receiver at the same end of the sample

- **Longitudinal excitation**
  
  - Wave velocity at modal vibrations
    
    \[
    \frac{W_s}{W_m} = \frac{AL\gamma}{mg} = \alpha \tan \alpha
    \]

    - \( A \) \rightarrow Cross-sectional area of the sample
    - \( L \) \rightarrow Length of the sample
    - \( \gamma \) \rightarrow Unit weight of soil
    - \( m \) \rightarrow Mass of the attachments on the top of the specimen

  - Longitudinal wave velocity
    
    \[
    v_c = \frac{2\pi f_n L}{\alpha}
    \]

  - **Dynamic low-strain elastic modulus**
    
    \[
    E = \rho v_c^2 = \rho \left( \frac{2\pi f_n L}{\alpha} \right)^2 = 39.48 \frac{\rho f_n^2 L^2}{\alpha^2}
    \]

- **Shear wave velocity**
  
  \[
  v_s = \frac{2\pi f_n L}{\alpha}
  \]

- **Dynamic low-strain shear modulus**
  
  \[
  G = \rho v_s^2 = 39.48 \frac{\rho f_n^2 L^2}{\alpha^2}
  \]
Bender Element Test

- Bender elements
  - Bonded piezo-electric materials
    - The element bends due to contrasting expansion and contraction due to passage of voltage (transmitter)
    - Similarly, a lateral deflection of the bender element produces voltage (receiver)

Ultrasonic Pulse Test

- Shear modulus
  \[ G = \rho v_s^2 = \rho \frac{L^2}{t_{pk} - pk} \]
High-Strain Laboratory Element Tests

Cyclic Triaxial Test

- Salient features
  - **Test device consists of the standard triaxial testing equipment extended with a cyclic axial loading unit**
    - Cell pressure can also be applied cyclically
    - Isotropic or anisotropic initial stress conditions
    - Determination of strain-dependent shear modulus and damping ratio
    - Determination of liquefaction potential and liquefaction parameters

- Code:
  - ASTM D3999 (2011)
  - ASTM D5311 (2011)
  - BS 1377-8 (1990)
Cyclic Simple Shear Test

- **Salient features**
  - A short cylindrical specimen is restrained against lateral expansion.
    - By applying cyclic horizontal shear stresses to the top or bottom of the specimen, the test specimen deforms like the element of soil subjected to vertically propagating S-waves.
  - Shear modulus and damping ratio
  - Liquefaction parameters for saturated cohesionless soils
    - Pore-water pressure can be measured

**Operating strain range**
10⁻² % to 5 %

Cyclic Simple Shear Test

- **Determination of shear modulus and damping ratio**
  - Plot of shear stress vs shear strain for the cyclic loading gives Hysteresis loop

\[
G = \frac{\text{Stress amplitude (AB)}}{\text{Strain amplitude (OB)}}
\]

\[
D = \frac{1}{\pi} \frac{\text{Area of hysteresis loop}}{2(\text{AOB} + \Delta \text{AOB}')}
\]
Cyclic Torsional Simple Shear Test

- **Salient features**
  - *Torsional loading of a cylindrical soil specimen to generate shear stress*
    - Can impose cyclic shear stresses on horizontal planes with continuous rotation of principal stress axes
  - Similar to Resonant Column test under torsion
  - Estimate shear stress v/s shear strain for different values of Torque to get the hysteresis loop
    - Estimate the shear modulus and damping ratio

\[
\tau_h = \frac{3T}{2\pi} \left( \frac{1}{\nu^3 - \eta^3} \right)
\]
Wyekham-Farrance Triaxial System

Specification of the Equipment/Instrumentation

- Specification of instrumentations: working range
  - Actuator operating frequency range: 0.01-10 Hz
  - Measuring capacity external LVDT: 0-50 mm
  - Pressure transducers: 0-1000 kPa
  - Triaxial cell capacity: 0-2 MPa
  - **Submersible load cell**: 25 kN
    - Working pressure range: 0-2 MPa
  - **On-sample transducers (LVDTs)**
    - Water submersible transducers
    - Measuring capacity of both axial and radial deformations: 0-10 mm
    - Working pressure range: 0-3.4 MPa
    - Working temperature range: -20°C to +125°C
      - Least count = 0.001 mm
Triaxial Cell

- Triaxial cells allow testing of specimen sizes 38, 50, 70, 100 & 150 mm diameter
- Five pressure ports
  - Two for pore water pressure
  - Two for back pressure
  - One fill/empty
- Maximum working pressure of triaxial cell 2000 kPa
- The cell is equipped to accept the following:
  - On sample transducers
  - Bender elements
  - Mid height pore water pressure transducers
  - Submersible load cells
  - Suction top caps

Applied Waveforms

- Investigate any vibration problem using regular waveforms

![Waveforms](image)

- User defined irregular seismic waveforms
  - This allows the input of user defined or imported wave shapes
  - User waveform cell – for loading in a pre-defined wave shape file
  - A wave shape file is a .udw file, which is created using the program ‘UDW Generator’ that accompanies the software.
Dynatriax and Compact Dynamic Controller (CDC)

- The DynaTriax is a pneumatic system, which requires clean dry compressed air delivered at 800 kPa continuous running pressure
  - A source of de-aired water is also required for saturating the specimen

The CDC unit is the hub of the cyclic triaxial system
- All test information is entered into the software
- This information is sent to the CDC

Input and Output from the CDC

- Actuator
- Triaxial Frame
- Cell pressure
- Back Pressure
- ON/OFF Valves
- Volume Change

- Axial Force
- Axial Displacement
- Cell Pressure
- Back Pressure
- Volume Change
- Pore Pressure

- PC & Software
- CDC

Personal Computer & Software

Test routine information

Gathering data
Load / Displacement Actuator

- Salient features
  - Double acting
  - Digitally controlled
  - Fitted with LVDT transducer ± 15 mm

- Requires air power supply
  - 800 kPa continuous running pressure

- Designed for static/dynamic tests
  - Regular and Irregular loadings
    - Stress controlled tests
    - Strain controlled tests

Air Receiver Unit and AVC

- Cell pressure and back pressure are controlled by digitally controlled valves with the transducers mounted adjacent to the valve
  - The valves are mounted on air receiver unit with air filter to ensure clean air is supplied to the valves

- Automatic Volume Changer (AVC) Unit
  - The volume change transducer is controlled by the software
  - Measurement of volume change during a test
Pressure Transducers

- Three pressure transducers
  - Two of them are for control and data acquisition
    - Cell and back pressure.
  - One for measuring pore water pressure

* Pore water pressure is measured at the base of the triaxial cell using a pressure transducer

On-Sample Transducers

- Two axial and one radial Hall-type displacement transducers
Various Stages of Cyclic Triaxial Test

- Methodology of conducting a Cyclic Triaxial test
  - Sample preparation
  - Saturation stage
  - Consolidation stage
  - Shear loading stage
  - Post tests processing

- Handout for conducting a Cyclic Triaxial Test is available in Researchgate
  - [https://www.researchgate.net/publication/331858999_Cyclic_Triaxial_Handout_A_Handout_to_Perform_Cyclic_Triaxial](https://www.researchgate.net/publication/331858999_Cyclic_Triaxial_Handout_A_Handout_to_Perform_Cyclic_Triaxial)

Dynamic Characterization of Brahmaputra Sand and Red Soil using Cyclic Triaxial Test

- **Materials**
  - Types of soil: cohesionless and cohesive soil
    - Brahmaputra sand (BS) and Red loam soil (RS) of Assam region

- **Methodology and Type of tests**
  - Cyclic triaxial tests
    - Regular excitations
      - Strain-controlled ($\gamma = 0.015-7.0\%$)
      - Stress-controlled (CSR = 0.05-0.3)
    - Irregular excitations
      - Stress-controlled (Bhuj, Tezpur and Kobe earthquake motions)
Test Parameters

- Cyclic shear test
  - Strain-controlled tests with regular loading

- Stress-controlled test with regular loading

- Stress-controlled irregular seismic excitation

### Waveforms of Cyclic Shearing

- Regular seismic excitations
  - Strain-controlled approach

- Stress-controlled approach

- Irregular seismic excitation
  - Bhuj, Kobe and Tezpur strong motions
Typical Result from Strain Controlled Regular Excitation

Typical Result from Stress Controlled Regular Excitation
Typical Result from Stress Controlled Irregular Excitation

Beyond $\gamma = 0.15\%$, the hysteresis loop attains an asymmetrical shape from the 1st cycle itself.
**Evaluation of Shear Modulus**

**Symmetrical hysteresis loop**

\[
E = \frac{\sigma_d}{\varepsilon} = \frac{(\sigma_{d,max} - \sigma_{d,min})}{(\varepsilon_{max} - \varepsilon_{min})}
\]

\[
G = E / [2(1 + \nu)]
\]

**Asymmetrical hysteresis loop**

\[
E = E_{sec1,Compression} + E_{sec2,Extension}
\]

\[
G = E / [2(1 + \nu)]
\]

\[
G_{max} \text{ (kPa)} = [523(OCR)^k / (0.3 + 0.7\varepsilon^2)](p_{st}^{0.52} \times \sigma_0^{0.48}) \quad \sigma_0 \text{ in kPa}
\]

(Chung et al., 1984)

---

**Evaluation of Damping Ratio**

**Symmetrical hysteresis loop**

\[
D = \frac{1}{4\pi} \times \frac{A_L}{A_{\Delta}}
\]

**Asymmetrical hysteresis loop**

\[
D' = \frac{1}{\pi} \times \frac{A_{L,(a-b-c-d)}}{A_{\Delta 1} + A_{\Delta 2} + A_{\Delta}}
\]
Local Response using On-Sample LVDTs

- Soil properties using on-sample LVDTs
  - On-sample LVDTs measure local axial strain
    - 50 - cyclic triaxial tests conducted

Material Curves for BS and RS

Evaluated material curves for BS and RS can be used in further GRA studies
Liquefaction Studies on Saturated BS

• Stress-controlled regular excitations

<table>
<thead>
<tr>
<th>CSR</th>
<th>Df (%)</th>
<th>( \sigma' ) (kPa)</th>
<th>N for liquefaction</th>
<th>( \tau_{100} ) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.05, 0.1, 0.2, 0.3</td>
<td>30</td>
<td>50</td>
<td>NL, NL, 8, 2</td>
<td>0.02, 0.02, 0.75, 1.4</td>
</tr>
<tr>
<td>0.1, 0.2, 0.3</td>
<td>100</td>
<td>125</td>
<td>4, 1.5</td>
<td>0.6, 2.5, 1.5</td>
</tr>
<tr>
<td>0.1, 0.2</td>
<td>200</td>
<td>62.3</td>
<td>3</td>
<td>1.5, 2.0</td>
</tr>
<tr>
<td>0.05, 0.1, 0.2, 0.3</td>
<td>30</td>
<td>50</td>
<td>NL, NL, 10, 2</td>
<td>0.02, 0.02, 0.5, 1.4</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>50</td>
<td>NL, NL, 30, 3</td>
<td>0.02, 0.02, 1.0, 1.0</td>
</tr>
<tr>
<td></td>
<td>90</td>
<td>NL, NL, 50, 10</td>
<td>0.02, 0.02, 1.0, 1.0</td>
<td></td>
</tr>
</tbody>
</table>

11/02/2020

Liquefaction Studies on Saturated BS

• Stress-controlled irregular excitations

<table>
<thead>
<tr>
<th>CSR</th>
<th>Df (%)</th>
<th>( \sigma' ) (kPa)</th>
<th>N for liquefaction</th>
<th>( \tau_{100} ) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.05, 0.1, 0.2, 0.3</td>
<td>30</td>
<td>50</td>
<td>NL, NL, 8, 2</td>
<td>0.02, 0.02, 0.75, 1.4</td>
</tr>
<tr>
<td>0.1, 0.2, 0.3</td>
<td>100</td>
<td>125</td>
<td>4, 1.5</td>
<td>0.6, 2.5, 1.5</td>
</tr>
<tr>
<td>0.1, 0.2</td>
<td>200</td>
<td>62.3</td>
<td>3</td>
<td>1.5, 2.0</td>
</tr>
<tr>
<td>0.05, 0.1, 0.2, 0.3</td>
<td>30</td>
<td>50</td>
<td>NL, NL, 10, 2</td>
<td>0.02, 0.02, 0.5, 1.4</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>50</td>
<td>NL, NL, 30, 3</td>
<td>0.02, 0.02, 1.0, 1.0</td>
</tr>
<tr>
<td></td>
<td>90</td>
<td>NL, NL, 50, 10</td>
<td>0.02, 0.02, 1.0, 1.0</td>
<td></td>
</tr>
</tbody>
</table>
Liquefaction Criteria for Saturated BS

- BS ($D_r = 30\%-90\%$) liquefy under the following optimum conditions
  - $\text{PGA} \geq 0.36\text{g}$
  - $\text{CSR} \geq 0.3$
  - $\gamma_{\text{max}} > 0.5\%$
  - Limiting value of $\gamma = 0.5\%$ is to be adopted for liquefaction evaluation study for BS soil at loose condition
  - Limiting value of $\gamma = 1.0\%$ is to be adopted for liquefaction study for BS soil at dense condition

Summary

- Introduced dynamic properties of soils and its influencing factors
- Discussed about various tests available for evaluating dynamic properties
  - Categories of tests
  - Various types of high strain field tests
  - Various types of low strain laboratory element tests
  - Various types of high strain laboratory element tests
- Elaborately discussed cyclic triaxial test
  - The apparatus and its components
  - Dynamic characterization of Brahmaputra Sand (BS) and Red Soil (RS)
  - Liquefaction Criteria for Brahmaputra Sand
Acknowledgments

Dr. Shiv Shankar Kumar
Assistant Professor
NIT Patna, Bihar

Dr. A. Murali Krishna
Associate Professor
IIT Tirupati, Andhra Pradesh

Selected Publications


Further Interaction

- http://www.iitg.ac.in/arindam.dey/homepage/index.html

- https://www.researchgate.net/profile/Arindam_Dey11

Takeaway
Thank You for Patient Hearing