Experimental Investigation of Dynamic Properties of Cohesionless Soil through Cyclic Triaxial Tests

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Outline of the Presentation

- Introduction
- Equipment and Instrumentations
- Cyclic Triaxial Shear Tests: Dynamic Properties
- Cyclic Triaxial Shear Tests: Liquefaction Evaluation
- Seismic Ground Response Analysis (GRA)
- Conclusions
Introduction

- Damages during earthquakes
  - Ground deformation
  - Foundation failure of building, dam, bridges
  - Ground failure due to liquefaction
  - Occurrence of landslides (in hilly area)
    » For most of damages, dynamic response of soils is the governing factor

Dynamic Properties of Soil

- Soil is a three-phase material
  - Interaction of phases under applied static/cyclic load
    - Low strain and deformations/displacements
      » Wave propagation through soils (Geophysics)
    - Large strain and deformations/displacements
      » Loss of strength and stability of soil mass (Liquefaction, Landslides)
Dynamic Properties of Soil

- **Shear modulus**
  - Modulus of rigidity
  - *Shear stiffness of material*

- **Damping ratio**
  - Rate of decay of oscillation of seismic wave
  - *Dissipation of energy*

- **Liquefaction parameters**
  - Cyclic Stress Ratio (CSR) and Pore Pressure Ratio
    - *Liquefaction phenomenon*
      - Reduction in shear strength of soil under undrained shearing
      - Increase in pore pressure and a consequent reduction in effective stress

Phenomenon at Low and High Strain Levels

- **Low strain level**
  - Higher soil stiffness
  - Low damping ratio
  - Linear stress-strain behaviour of soil

- **High strain level**
  - Non-linear stress-strain behaviour of soil
  - High damping ratio
  - Significant volume change
Evaluation of Dynamic Properties of Soil

Field Tests

Low strain (< 0.01%)
- Seismic reflection
- Seismic refraction
- Steady-state vibration
- Spectral and Multichannel analysis of surface waves (SASW and MASW)
- Seismic borehole survey (cross-hole, down-hole and up-hole)
- Seismic cone tests

High strain (> 0.01%)
- Standard penetration test
- Cone penetration test
- Dilatometer test
- Pressuremeter test

Laboratory Tests

Low strain (< 0.01%)
- Resonant column test
- Ultrasonic pulse test
- Piezoelectric bender element test

High strain (> 0.01%)
- Cyclic triaxial test
- Cyclic direct shear test
- Cyclic torsional shear test

Model (Physical) Tests
- Shake table test
- Centrifuge test

Kramer (1996)
Cyclic Triaxial Equipment and Instrumentation

- Triaxial frame
  - Capacity – 100 kN
  - Pneumatic dynamic actuator
    - Different types of dynamic loading
      » Harmonic, Triangular, Haversine
      » Any user-defined random seismic motions
    - Different deformation rates
      » $10^{-5}$ - 10 mm/min
  - Base pedestal
    » 38 mm × 76 mm
    » 50 mm × 100 mm
    » 70 mm × 140 mm
Cyclic Triaxial Equipment and Instrumentation

- Triaxial cell
  - Confining pressure capacity – 2000 kPa
  - Air bleed valve at the top to apply vacuum or suction
    - *Maintain proper connection between submersible load cell and top cap*
  - Load-cell ram moves up and down during cyclic loading
    - *Connects the load-cell ram with the top plate*

- Dynamic actuator
  - Displacement capacity: 30 mm
  - Operational frequency range: 0.01-10 Hz
- Submersible load cell connected with ram-locking collar
  - Capacity: 25 kN
Cyclic Triaxial Equipment and Instrumentation

- **Air-water cylinder (AWC) units**
  - Pneumatic pressure converted to hydraulic pressure
  - One each for cell pressure and back pressure application
  - Capacity: 1000 kPa

- **Automatic volume change (AVC) unit**
  - Measurement of volume change via volume of water flowing out of the soil specimen
  - Solenoid valves for automatic control of flow direction

- **Pressure transducers**
  - Pore pressure
  - Cell pressure
  - Back pressure
  - **Capacity: 1000 kPa**

- **Dry air receiver unit**
  - Interface between air coming from a compressor and transmitted to servo-valves

- **Compact dynamic controller (CDC) unit**
  - Operational hub
  - Interface between the hardware and DYNATRIAX software
Cyclic Triaxial Equipment and Instrumentation

- On-sample transducers (LVDTs)
  - Measurement of local strains
    - Central region free from boundary effects
  - Water submersible transducers: Least count = 0.001 mm
  - 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

Methodology: Sample Preparation

- Sample preparation by dry pluviation technique
  - Height = 140 mm and diameter = 70 mm test specimens
- Saturation stage
  - Flushed CO₂ and de-aired water from bottom of the specimens
  - Alternatively increase CP and BP, maintain a constant difference of 10 kPa
    » Saturation stage terminated when B (Skempton’s parameter) ≥ 0.98
- Consolidation stage
  - Isotropic consolidation to achieve desired effective confining stress (σ'c) to be applied on the specimen
- Shearing stage
  - Cyclic shear (strain-controlled and stress-controlled)
Methodology: Shearing

- Shearing stages
  - Cyclic shear
    - Regular excitations
      - Strain-controlled cyclic tests on DBS and SBS
      - Stress-controlled cyclic tests on SBS
    - Irregular excitations
      - Stress-controlled cyclic tests on SBS
  - Bhuj, Tezpur and Kobe earthquake motions

*SBS – Saturated Brahmaputra Sand
*DBS – Dry Brahmaputra Sand

Waveform of Cyclic Shearing: Regular Loading

- Regular seismic excitations
  - Strain-controlled approach
    - Peak shear strain (γ) ranging from 0.015%-7% was chosen for cyclic strain approach
  - Stress-controlled approach
    - Cyclic stress ratio (CSR=σd/2σ'c) ranging from 0.05-0.4 was chosen for cyclic stress approach
Waveform of Cyclic Shearing: Irregular Loading

- Irregular seismic excitations
  - Stress-controlled approach
    \[ \tau = \frac{\text{acc}(g)}{g} \times \sigma \times r_d \] (Seed and Idriss, 1971)
    \[ r_d = 1.0 - 0.00765z; \text{ for } z \leq 9.15 \text{ m}; \text{ (Youd et al., 2001)} \]
    \[ r_d = 1.174 - 0.0267z; \text{ for } 9.15 \leq z \leq 23 \text{ m}; \text{ (Youd et al., 2001)} \]
    \[ \sigma_d = 2 \times \tau = 2 \times \frac{\text{acc}(g)}{g} \times \sigma \times r_d \]

Brahmaputra Sand

- Cohesionless soil (BS)
  - \( G = 2.7 \)
  - \( C_u = 1.47 \)
  - \( C_c = 1.09 \)
  - \( \gamma_d,_{\text{max}} = 16.84 \text{ kN/m}^3 \)
  - \( \gamma_d,_{\text{min}} = 13.85 \text{ kN/m}^3 \)
  - SP (Poorly graded sand)
  - Potentially liquefiable
Scope of the Experimental Investigation

- Evaluation of dynamic response of Brahmaputra sand
  - Dynamic properties
  - Liquefaction parameters
- Experimental investigations
  - Different testing conditions
    - Relative density ($D_r$)
    - Effective confining stress ($\sigma'_c$)
    - Shear strain amplitudes ($\gamma$) including high cyclic strains
    - Cyclic stress amplitudes (Cyclic stress ratio, CSR)
    - Strain-controlled and stress-controlled loading
      - Regular and irregular excitations
- Application of evaluated properties for 1-D Equivalent linear GRA analysis of Guwahati city

<table>
<thead>
<tr>
<th>Soil</th>
<th>$D_r$ (%)</th>
<th>$\sigma'_c$ (kPa)</th>
<th>$f$ (Hz)</th>
<th>$\gamma$ (%)</th>
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<tbody>
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</table>

- Cyclic shear test: Strain-controlled tests

- Cyclic shear test: stress-controlled tests

<table>
<thead>
<tr>
<th>Soil</th>
<th>$D_r$ (%)</th>
<th>$\sigma'_c$ (kPa)</th>
<th>$f$ (Hz)</th>
<th>CSR</th>
</tr>
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<td>0.1, 0.2, 0.3, 0.4</td>
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Test Parameters

- Cyclic shear test: irregular excitations

<table>
<thead>
<tr>
<th>Soil</th>
<th>Irregular excitation</th>
<th>PGA (g)</th>
<th>Relative density, $D_r$ (%)</th>
<th>Confining depth (m)</th>
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</thead>
<tbody>
<tr>
<td>Bhuj</td>
<td>0.103</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tezpur</td>
<td>0.360</td>
<td>30</td>
<td></td>
<td>5, 10, 15</td>
</tr>
<tr>
<td>Kobe</td>
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</tr>
<tr>
<td>Bhuj</td>
<td>0.103</td>
<td></td>
<td></td>
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<tr>
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<td>0.360</td>
<td>30, 60, 90</td>
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<tr>
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<td>60</td>
<td></td>
<td>10</td>
</tr>
<tr>
<td>Kobe</td>
<td>0.360</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Input and Output for Cyclic Loading

- Strain- and Stress-controlled regular loading
  - Strain is constant whereas, deviator stress and excess PWP changes
  - Stress is constant whereas, both strain and excess PWP changes
  - Stress, strain and excess PWP changes during entire period of shaking
Hysteresis during Cyclic Loading

- Typical hysteresis loops during regular and irregular cyclic loading

- Hysteresis loops during strain-controlled tests at different shear strains

- With the increase of shear strain the loops becomes gradually asymmetric
  - $\gamma \geq 0.15\%$
- Hysteresis loop is used to evaluate the dynamic properties of soils

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
    - **Secant shear modulus**: Line joining the origin and various points of the backbone curve
Shear Modulus Degradation Curve

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

Damping Ratio

- Symmetrical Hysteresis Loop (SHL) is conventionally used to evaluate the dynamic properties
  - Damping ratio is evaluated from the stored energy in 1st quadrant
- For Asymmetrical Hysteresis Loop (ASHL), since the stored energy is not equal in all quadrants, damping ratio based on SHL methodology will be inaccurate
  - ASHL methodology is used for proper estimation of dynamic properties
Shear Modulus of SBS: Strain Controlled Regular Cyclic Loading

- Shear modulus i.e. $G$ and $G_a$ based on the SHL and ASHL, respectively, are nearly same for $N = 1$
- Shear modulus ($G$) increases with the increase of confining pressure $\sigma'_c$

Modulus Reduction and Damping Ratio of SBS

- Chung et al. (1984) correlation was used to evaluate $G_{\text{max}}$
  \[
  G_{\text{max}} \text{(kPa)} = 523 \left( \frac{\text{OCR}}{0.3 + 0.7\sigma'} \right) P_a^{0.32} \left( \frac{\sigma'_c}{\sigma'} \right)^{0.8}
  \]
- Average values of $D^b$ (based on ASHL) exceeds $D$ (based on SHL) by 40-70%
  - Modified method (ASHL methodology) is proposed to estimate the dynamic properties
Modulus Reduction and Damping Ratio of DBS & SBS

- Slope of hysteresis loops for SBS decreases with the increase of number of loading cycles
  - *Due to the generation of pore water pressure*
- Slope of hysteresis loops for DBS increases with the increase of number of loading cycles
  - *Due to densification of soil specimen*

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Shear modulus of SBS & DBS is not affected by saturation for $N = 1$

- Damping ratio of SBS & DBS (based on ASHL) affected significantly by saturation for $N = 1$ for shear strain $> 0.5$
  - For DBS, $D^s$ (based on ASHL) exceeds $D$ (based on SHL) by 5-70% within the shear strain range 0.045-7%
Modulus Reduction and Damping Ratio of DBS & SBS

- Influence of loading frequency

- 40 loading cycles were applied
  - At CSR = 0.1, the D and D# are same, possibility of symmetrical hysteresis
  - At CSR = 0.2, D and D# are same up to γ = 0.3%, and then D marginally increased from D#
  - Degradation in damping ratio γ > 1.0%, similar to the strain-controlled loading
Cyclic Triaxial Equipment and Instrumentation

- On-sample transducers (LVDTs)
  - Measurement of local strains
    - Central region free from boundary effects
  - Water submersible transducers: Least count = 0.001 mm
  - 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

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Shear Modulus based on Local Strains

<table>
<thead>
<tr>
<th>Shear modulus (G, MPa)</th>
<th>Present study</th>
<th>From literatures</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>G (based on External LVDT, γ = 0.045%)</td>
<td>Chung et al. (1984)</td>
</tr>
<tr>
<td>$\sigma'$ (kPa)</td>
<td>50 90 100 150</td>
<td>50 67 69 94 84 114</td>
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<tr>
<td>$D_r$ (%)</td>
<td>30 90 30 90 30 90</td>
<td>-</td>
</tr>
</tbody>
</table>

- Shear modulus obtained from the on-sample LVDT at high cyclic strains (>0.04%) are in close agreement to that obtained from external LVDT
- On-sample transducers measure the strains from lower to higher ($3 \times 10^{-3}$% to 5%)
Factors Influencing Dynamic Characteristics

- From the investigations, it is observed that the dynamic properties of cohesionless soils significantly influenced by
  - Cyclic strain amplitude
  - Relative density
  - Frequency of loading cycle
  - Effective confining pressure
  - Number of loading cycles

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
    - Phenomenon mostly observed in coarse-grained silty soils
  - Cyclic mobility or strain softening
    - Phenomenon mostly observed in fine-grained soils
Initiation of Liquefaction

• Initial liquefaction (Seed and Lee, 1966)
  - Phenomena at which the increase in pore pressure is equal to the initial effective confining pressure ($u/\sigma_3 = 1$)
  - Liquefaction can be expected at depths where the loading exceeds the resistance.

• Evaluation of liquefaction potential
  - Cyclic stress approach
  - Cyclic strain approach

Evaluation of Liquefaction Potential

• Cyclic Stress Approach (Seed and Idriss, 1971)
  - Earthquake-induced loading expressed in terms of cyclic shear stresses
  - Compared with the liquefaction resistance of the soil

  - Cyclic shear stress: $\tau_{cy} = 0.65 \tau_{max}$
  - $\tau_{max} = \frac{a_{max}}{\gamma} \sigma_v r_d$
    - $a_{max}$ = peak acceleration of seismic wave (in g)
    - $\sigma_v$ = total vertical stress
    - $r_d$ = stress reduction factor
Evaluation of Liquefaction Potential

- Cyclic Strain Approach (Dobry et al. 1982)
  - Earthquake-induced loading is expressed in terms of cyclic strain
  - Cyclic strain \( \gamma_{cyc} = 0.65 \frac{\sigma_{max}}{g} \frac{\sigma_{v'd}}{g\gamma_{v'v}} \)

- Cyclic strength (i.e. resistance to liquefaction) is expressed in term of cyclic stress ratio (CSR)
  - CSR_{field} = \frac{\sigma_{v'}}{\sigma_{v}}
  - CSR_{triaxial} = \frac{\sigma_{a}}{2\sigma_{v'}}
  - CSR_{field} = 0.9 (CSR_{triaxial})

Cyclic Shear Tests: Liquefaction Potential Evaluation

- Strain-controlled tests on SBS subjected to regular excitations
- Stress-controlled tests on SBS subjected to regular excitations
- Stress-controlled tests on SBS subjected to irregular excitation using Bhuj, Tezpur and Kobe earthquake motions
Regular Excitations (Strain-Controlled): SBS

- Variation of \( r_u \) at different \( \gamma, \sigma_c' \) and \( D_r \)

- \( r_u \) significantly affected by \( N, \gamma \) and \( \sigma_c' \) whereas, negligibly by \( D_r \) (for \( N = 1 \))

- Liquefaction resistance decreases with increase of \( N \) and \( \gamma \), whereas, increases with the increase of \( \sigma_c' \) and \( D_r \)

- Decrease in liquefaction resistance indicate increase in liquefaction potential, and vice-versa

Regular Excitations (Stress-Controlled): SBS

- Variation of \( r_u \) and \( \gamma \) with loading cycles at different \( D_r \)

- Liquefaction resistance increases with increase in \( D_r \)

<table>
<thead>
<tr>
<th>CSR ( )</th>
<th>( D_r ) (%)</th>
<th>( \sigma_c' ) (kPa)</th>
<th>( N ) for liquefaction</th>
<th>( \gamma_{max} ) (%)</th>
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<td>0.05, 0.1, 0.2, 0.3</td>
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Irregular Excitations (Stress-Controlled): SBS

- Effect of $\sigma'_u$

<table>
<thead>
<tr>
<th>Input motion</th>
<th>$\sigma'_u$ (kPa)</th>
<th>$D_r$ (%)</th>
<th>CSR$_{max}$</th>
<th>$\tau_{max}$ (%)</th>
<th>$\tau_{max}$ (kPa)</th>
<th>$G$ (MPa)</th>
<th>Excess PWP ratio ($r_u$)</th>
<th>Liquefaction</th>
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<tbody>
<tr>
<td>Bhuj (0.36g)</td>
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</table>

Dynamic Response under Irregular Excitations

- Hysteresis loops during irregular loading are highly irregular/asymmetrical
- Random values of $\gamma$ from 0.001% to 5% was chosen
- Shear modulus was evaluated from the shear stress corresponding to these $\gamma$
- $r_u$ values corresponding to $\gamma$ from 0.001% to 5%
Optimum Magnitudes for Liquefaction Initiation in Saturated Cohesionless Soils

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

<table>
<thead>
<tr>
<th>Field or laboratory cycle building condition</th>
<th>Soil type</th>
<th>Supporting data</th>
<th>References and figures in this paper</th>
<th>Cycle shear strain needed to trigger liquefaction, $\gamma_{max} (%)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clean and sandy soils</td>
<td>Clean and sandy soils</td>
<td>Dobry et al. (2015), Dobry et al. (2015)</td>
<td>0.5 or 1.0</td>
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</tbody>
</table>

Ground Response Analysis

- Evaluation of ground response
  - Predict ground surface motions for evaluation of design ground response spectra
  - Evaluate dynamic stresses and strains for evaluation of liquefaction hazards
  - Determine earthquake induced forces that lead to instability of earth and earth-retaining structures

- Types of Ground Response Analysis
  - Linear, Equivalent linear or Nonlinear
  - 1-D, 2-D or 3D
  - Total stress GRA or Effective Stress GRA

One-Dimensional Ground Response Analysis

- Basic mechanism
  - Body waves generated by the fault mechanism undergoes multiple refraction through low-velocity shallow layers
    - Strike the shallow layers in near vertical orientation
- Basic assumptions
  - All boundaries are horizontal and infinitely extended
  - Response of the soil is primarily due to the vertically propagating SH-waves travelling from the bedrock

Ground Response Analysis

- Evaluate dynamic properties of soil
- Input: dynamic properties
- Soil Layer n
- Soil Layer n-1
- Half-Space Layer
- Apply motion at base layer
- Output: acceleration
- Output: response spectrum
- Output: Fourier amplitude ratio
- Iteration procedure: Analysis
- Ordonez (2011)
Ground Response Analysis

• Methodology
  ➢ DEEPSOIL: A computer program
    ❖ One-dimensional equivalent linear approach
    ❖ Based on the solution of wave motion through Fast Fourier Transformation Algorithm
      » Consider the response associated with vertical propagation of shear waves through the linear viscoelastic system
    ❖ Account nonlinear dynamic soil properties for the use of equivalent linear analysis through an iterative procedure
      » Iterative procedure: for the evaluation of modulus and damping compatible with the effective strains generated in each layer
        • Limitation: incapable to represent the actual change in soil stiffness during earthquake

Study Region: Ground Response Analysis

• Guwahati city (North-East India) situated at 26.18°N & 91.75°E
  ➢ Several tectonic faults (Raghukanth and Dash, 2010)
    ❖ As per IS:1893-2002
      » Design PGA for Maximum Considered Earthquake (MCE) is 0.36g
      » Design PGA for Design Basis Earthquake (DBE) is 0.18g
Input Parameters

- Boreholes – Four typical borehole profiles
- Material properties
  - Evaluated (experimentally)
    - For both Sand and Clay
  - Existing (from literature)
    - Seed and Idriss (SI) (1970) - Sand
    - Vucetic and Dobry (VD) (1991) - Clay
- Three strong motions
  - Bhuj motion (0.103g), Tezpur motion (0.36g) & Kobe motion (0.834g)

Material properties

- Evaluated (experimentally)
  - For both Sand and Clay
- Existing (from literature)
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Three strong motions

- Bhuj motion (0.103g), Tezpur motion (0.36g) & Kobe motion (0.834g)

Response of Soil Profile due to Bhuj Motion

- Experimental data shows significantly higher values near ground surface, compared to VD-SI model
  - Deamplification in acceleration was observed with experimental data, when a strong motion encounters a loose stratum
- Significant higher strain observed near soft layer with present dynamic model
  - Due to the degradation behavior of damping ratio of soil
  - Possibility of liquefaction or cyclic mobility
    - γ > 0.5%, as per previous results on liquefaction studies
Response of Soil Profile due to Bhuj Motion

- Amplification ratio, at BRGN and STGN site, showed 30-40% difference based on Experimental and VD-SI models.

- Amplification and deamplification of strong motion also depend on the damping behavior of soil.

PGA Contours based on Bhuj Motion

- Based on Experimental soil model
- Based on VD-SI soil model
Typical Response of Soil Profile

Comparison of percentage difference in PGA, PSA and FAR obtained using VD-SI and Experimental data for GRA Guwahati city using Bhuj, Tezpur and Kobe motions

<table>
<thead>
<tr>
<th>Earthquake</th>
<th>Average value</th>
<th>Experimental model</th>
<th>VD-SI model</th>
<th>Difference (%)</th>
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<tbody>
<tr>
<td>Bhuj</td>
<td>0.27</td>
<td>0.287</td>
<td>6.29</td>
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<tr>
<td>Tezpur</td>
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<td>0.437</td>
<td>2.97</td>
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<td>Kobe</td>
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<td>1.039</td>
<td>38.53</td>
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<tr>
<td>Kobe</td>
<td>2.60</td>
<td>3.228</td>
<td>24.15</td>
<td></td>
</tr>
</tbody>
</table>

Summary and Final Remarks

- Cyclic Triaxial Tests provides a comprehensive understanding of the dynamic response of soils and estimation of dynamic properties
  - Strain dependent shear modulus
  - Strain dependent damping
  - Liquefaction parameters and potential

- New insight into the estimation of damping ratio (D, D^#) from asymmetric hysteresis loops developed at high cyclic strains
  - D (SHL) decreases beyond γ ≈ 0.5%, while D^# (ASHL) decreases beyond γ ≈ 1%
  - For SBS, D^# (ASHL) exceeds D (SHL) by 40-70% within a shear strain range 0.015-4.5%
  - For DBS, D^# exceeds D by 5-70% within a shear strain range 0.045-7%

- Application of on-sample transducers provide immense scope to ascertain the dynamic properties over a wide strain range from a single test (3×10^{-3} – 7 %)
  - Not possible to achieve by simply using conventional external transducers
Summary and Final Remarks

- Development of guidelines for liquefaction initiation and address liquefaction potential of cohesionless soil
  - *Brahmaputra Sand* ($D_r = 30-90\%$) liquefies under the following optimum conditions:
    - $PGA \geq 0.36g$, $CSR \geq 0.3$ and $\gamma_{\text{max}} > 0.5\%$
    - Limiting value of $\gamma = 0.5\%$ should be adopted for liquefaction evaluation study of loose cohesionless specimens
    - Limiting value of $\gamma = 1.0\%$ should be adopted for liquefaction study of dense cohesionless specimens

- Seismic ground response analysis
  - Degradation of damping ratio at high shear strains ($\gamma > 0.8\%$) significantly affects the ground response analysis, especially when a strong motion encounters a loose stratum
    - Use of regional dynamic soil properties is highly recommended for proper estimation of ground response under different degrees of shaking

Acknowledgments

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Selected Publications


Further Interaction

- [http://www.iitg.ac.in/arindam.dey/homepage/index.html](http://www.iitg.ac.in/arindam.dey/homepage/index.html)

- [https://www.researchgate.net/profile/Arindam_Dey11](https://www.researchgate.net/profile/Arindam_Dey11)
Thank You for Patient Hearing