Faculty Development Program

Geotechnical Engineering for Sustainable and Resilient Infrastructure: Foundations for a Greener Future

CV Raman Global University, Odisha

Soil Dynamics and Seismic Geotechnics

Dynamic Soil Properties: Importance and Assessment

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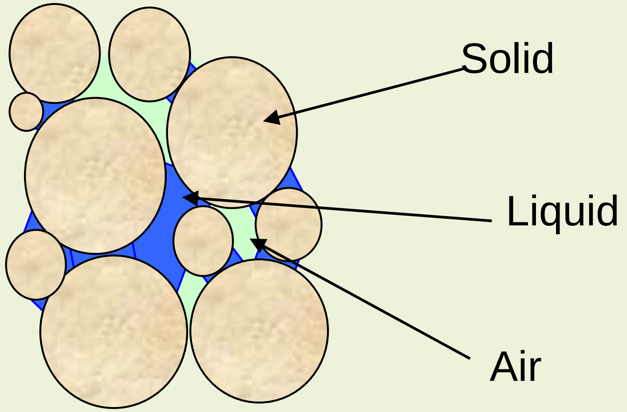
Presentation Schedule

- Introduction to dynamic properties of soils
  - Why we should be interested?
  - What are the dynamic properties?
  - What are the factors influencing dynamic properties?
- Assessing the 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

Introduction to
Dynamic Soil Properties

Dynamic Properties of Soil

- 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

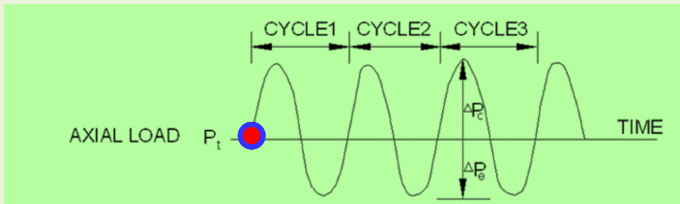


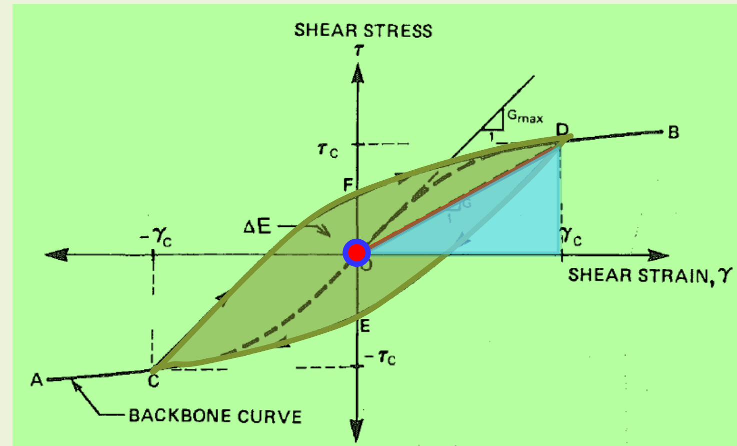
Dynamic Properties of Soil

- 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

Dynamic Properties of Soil

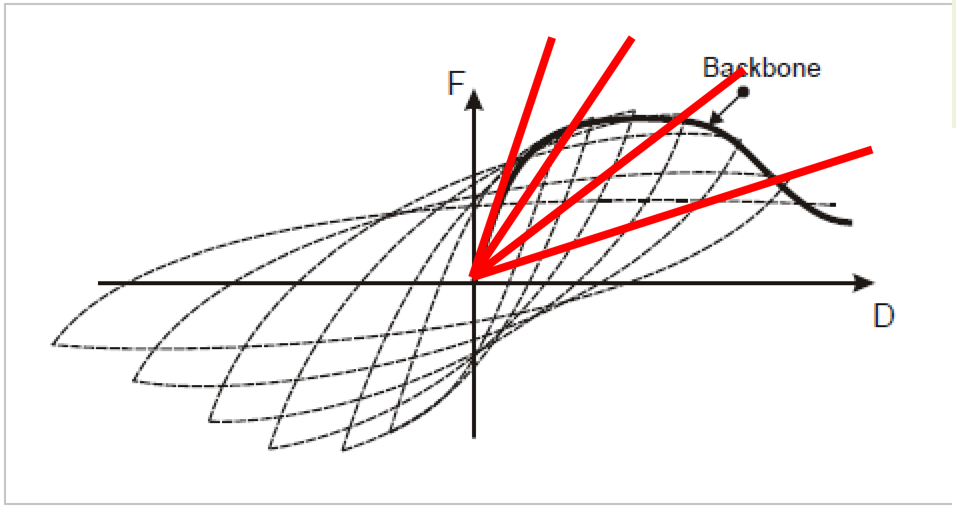


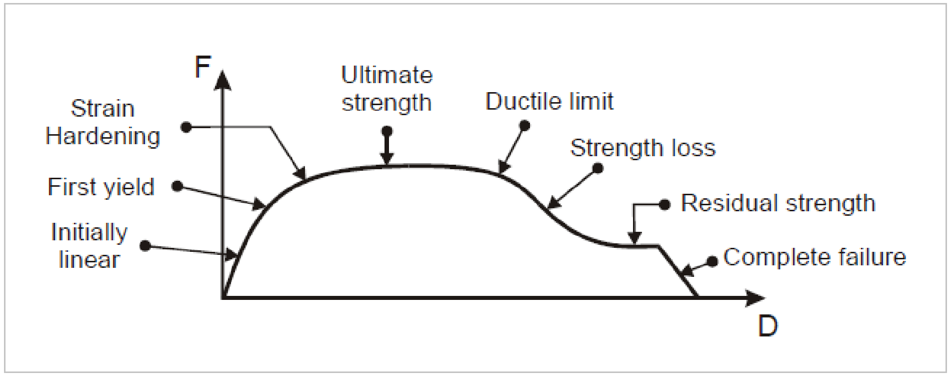


- Strain-dependent shear modulus
  - ❖ Modulus of rigidity
    - Shear stiffness of material and its decay
- Strain-dependent damping ratio
  - ❖ Rate of decay of oscillation of seismic wave
    - Dissipation of seismic energy
- Liquefaction parameters
  - ❖ Cyclic Stress Ratio (CSR) and excess Pore-water 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

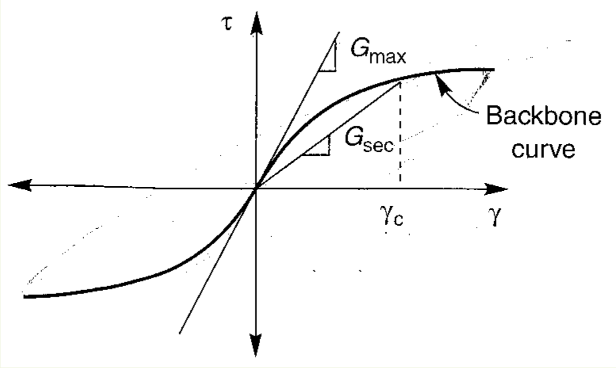
- Hysteresis loop and Backbone curve
  - ❖ Effect of cyclic shear strain amplitude on shear modulus
    - Backbone/Skeleton curve: Line joining the peak shear stress at each cycle of shear strain corresponding to the cyclic strain amplitude of each cycle
      - Characteristics of the backbone curve
        - 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



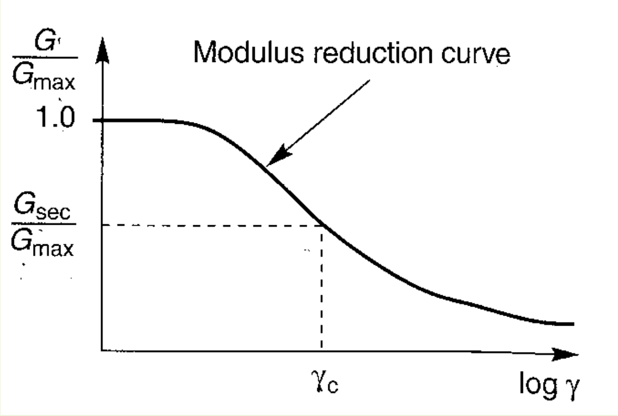


Modulus Reduction Curve

- 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

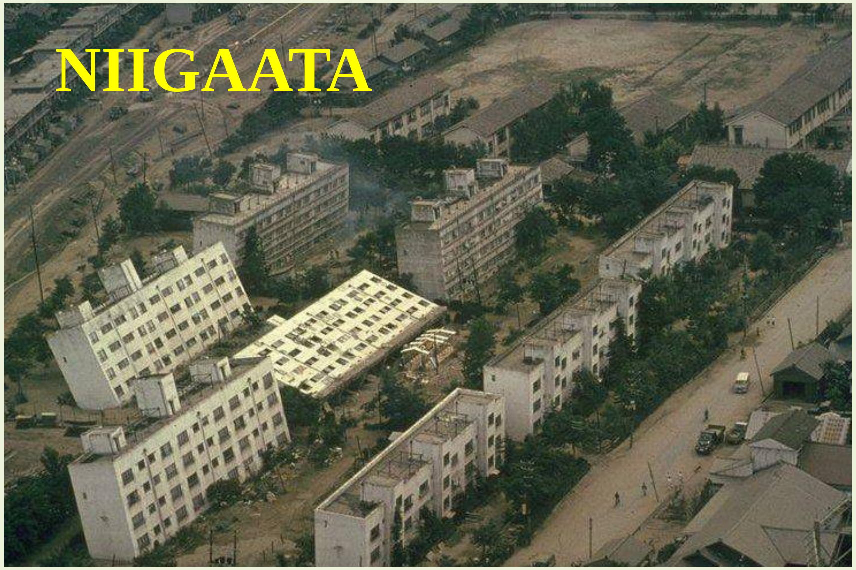


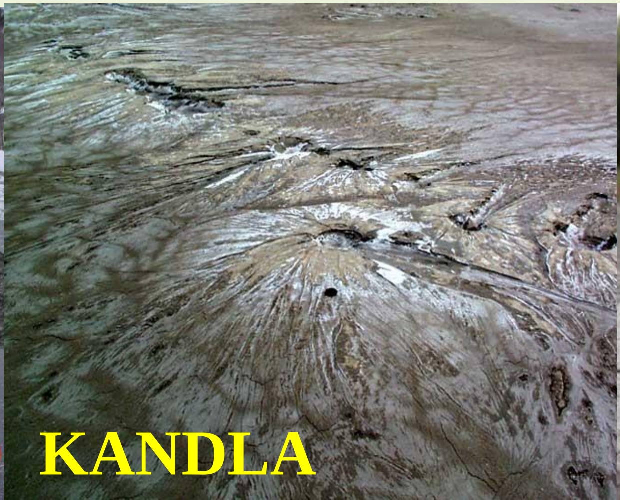
  - ❖ Slope at the origin of backbone curve
    - Largest value of G_{sec}
      - Referred as Maximum Shear Modulus (G_{max})



  - ❖ Modulus ratio (G_{sec}/G_{max})
    - G_{sec}/G_{max} = 1at γ_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

Manifestation of Liquefaction



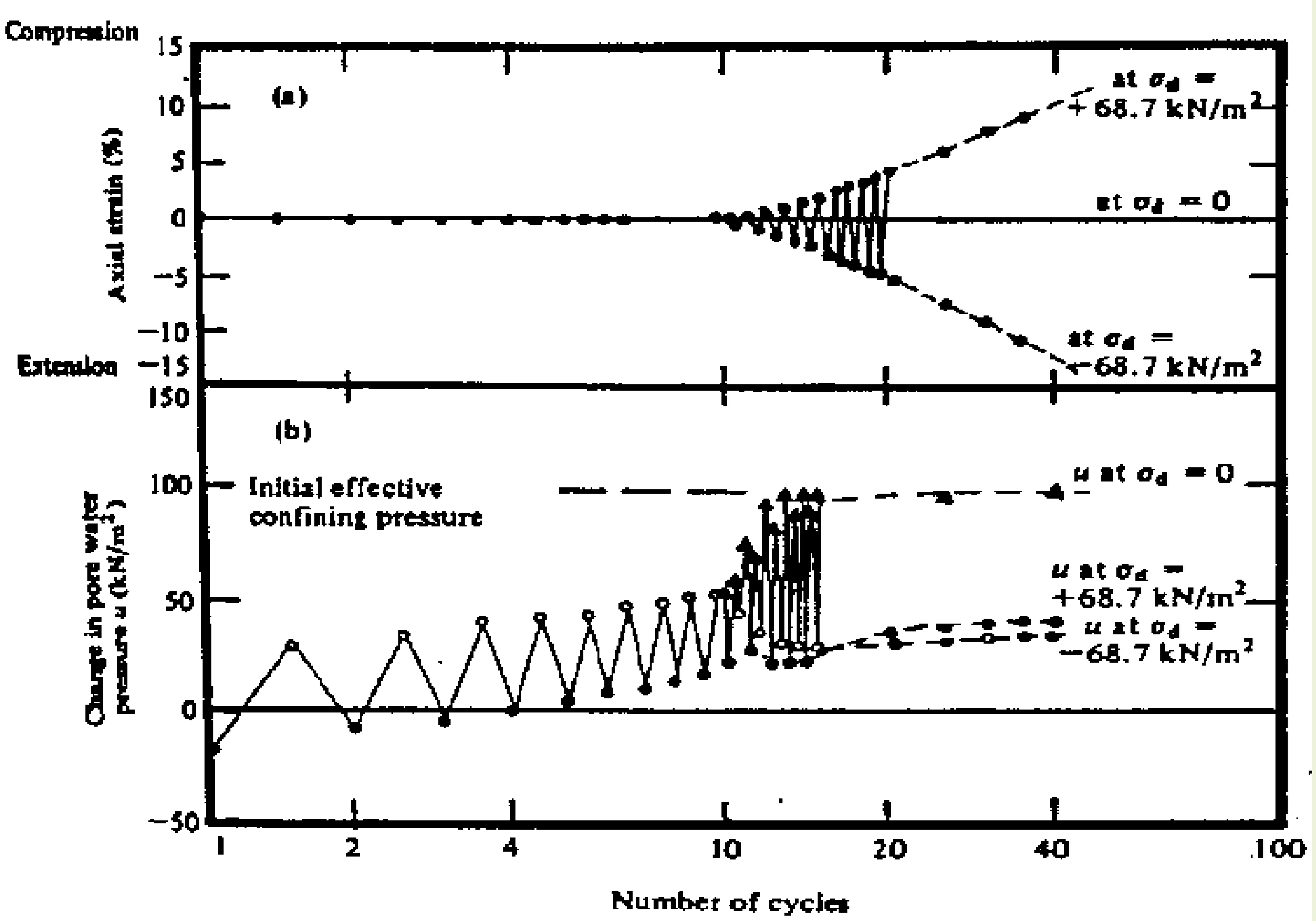


Liquefaction

- Liquefaction
  - Phenomenon at which shear strength decreases
    - Effective stress (σ')= total stress (σ) – pore pressure (u)
- Types of Liquefaction
    - Based on soil type and shear stress condition
  - Flow liquefaction or flow failure
    - Soil become 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

- **Seed and Lee (1966)**



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: $\tau_{cyc} = 0.65\ \tau_{max}$

$$\tau_{max} = \frac{a_{max}}{g}\ \sigma_v r_d$$

a_{max} = peak acceleration of seismic wave (in g)

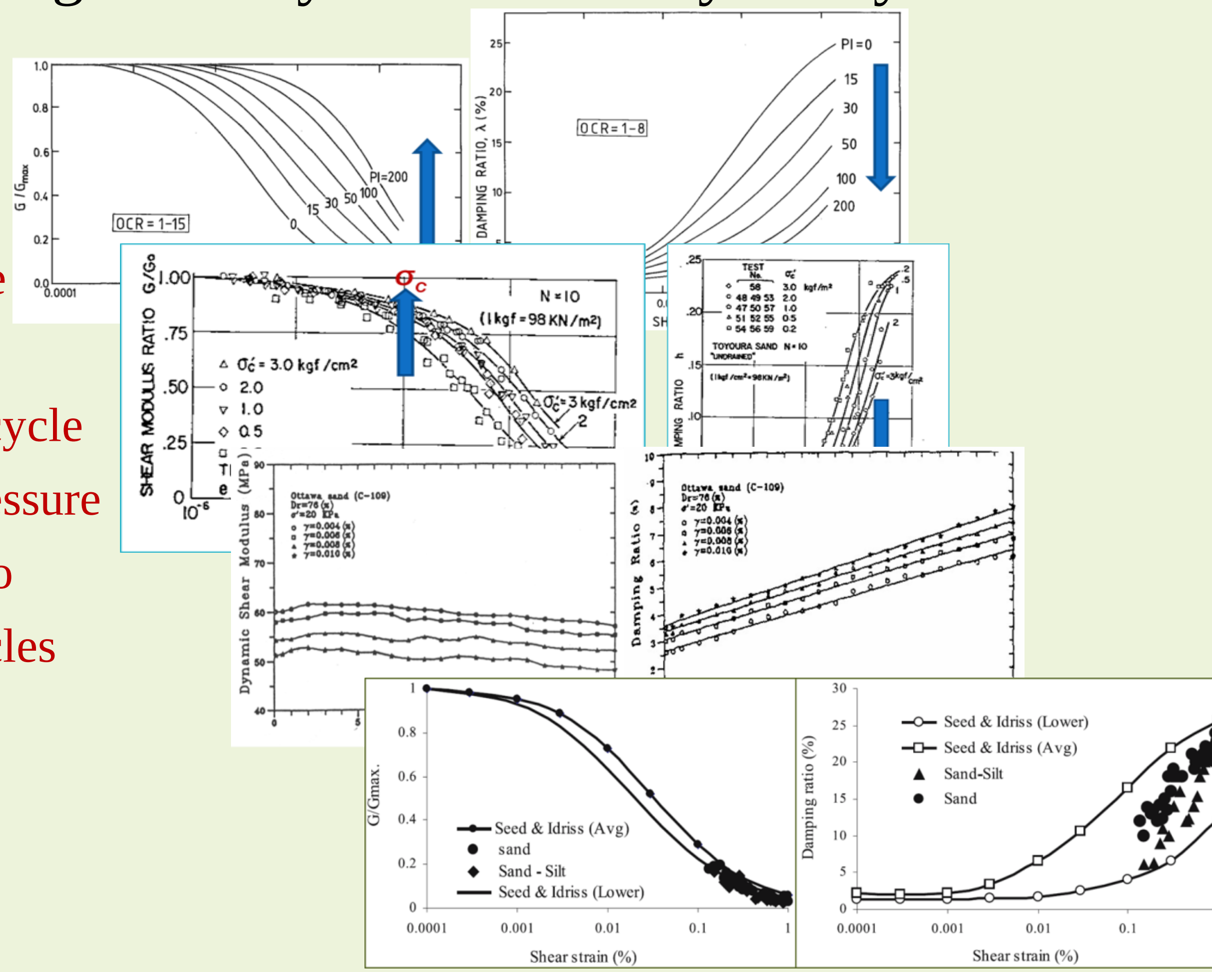
σ_v = total vertical stress

r_d = stress reduction factor

- Cyclic Strain Approach **(Dobry et al. 1982)**
  - ❖ Earthquake-induced loading is expressed in terms of cyclic strain
  - ❖ Cyclic strain (γ_{cyc}) = $0.65 \frac{a_{max}}{g} \frac{\sigma_v r_d}{G_{\gamma=\gamma_{cyc}}}$

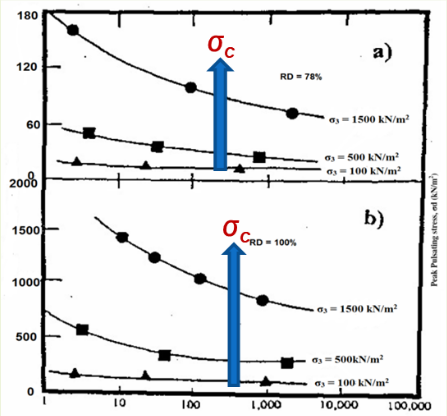
Factors influencing Dynamic Properties

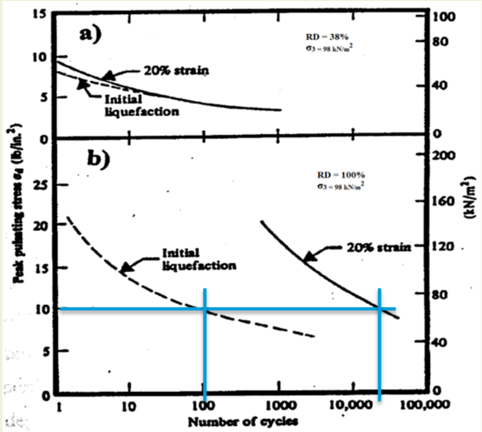
- From the literature it has been observed that the dynamic properties of soils significantly influenced by many factors like:
  - ❖ Soil type
  - ❖ Plasticity index
  - ❖ Cyclic strain amplitude
  - ❖ Relative density
  - ❖ Frequency of loading cycle
  - ❖ Effective confining pressure
  - ❖ Overconsolidation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

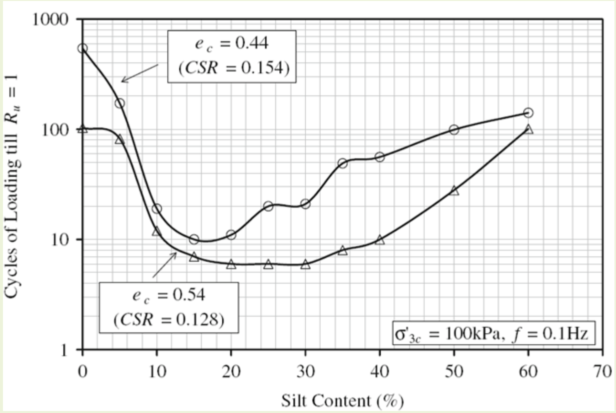


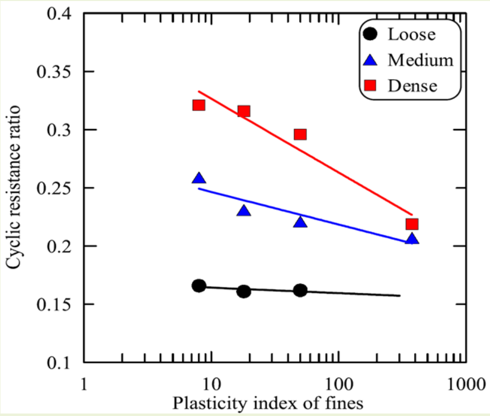
Factors influencing Liquefaction Potential

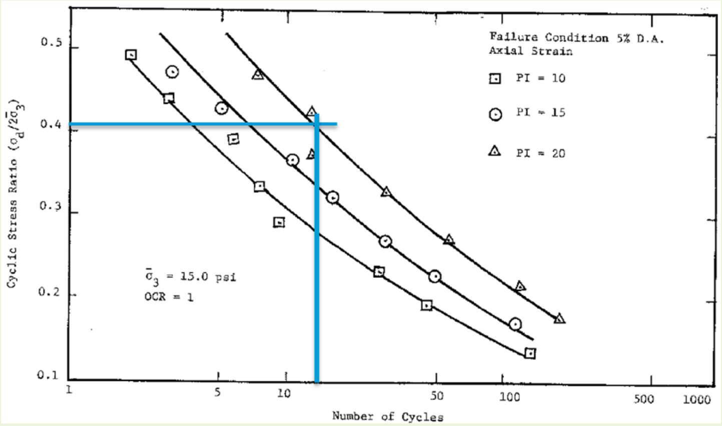
- Liquefaction potential affected by many factors:
  - ❖ Cyclic stress ratio
  - ❖ Initial shear stress condition
  - ❖ Shear strain amplitude
  - ❖ Relative density
  - ❖ Fine content
  - ❖ Plasticity index





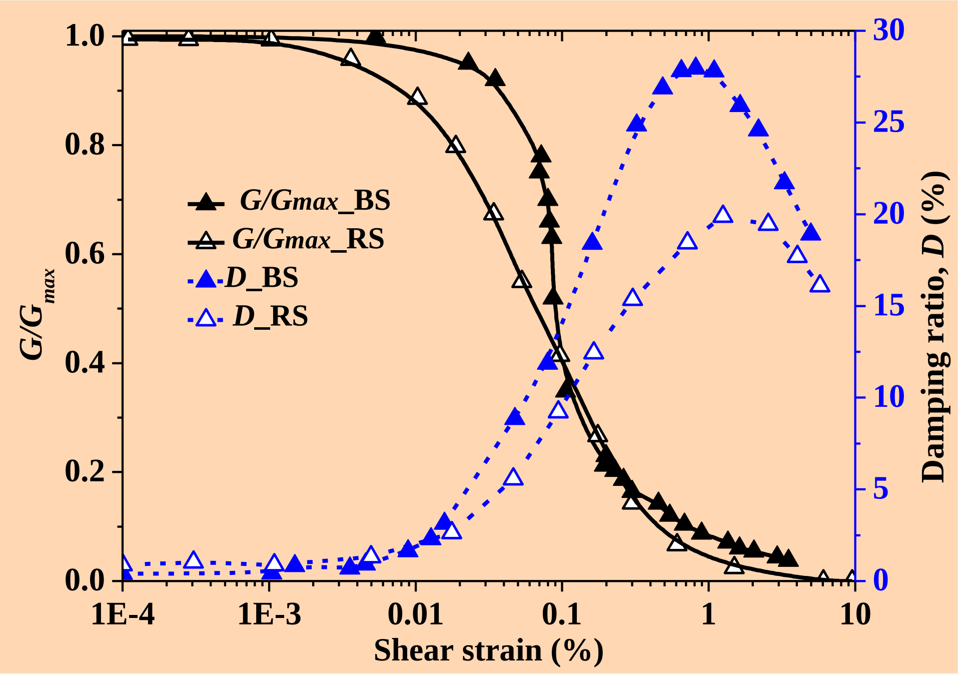


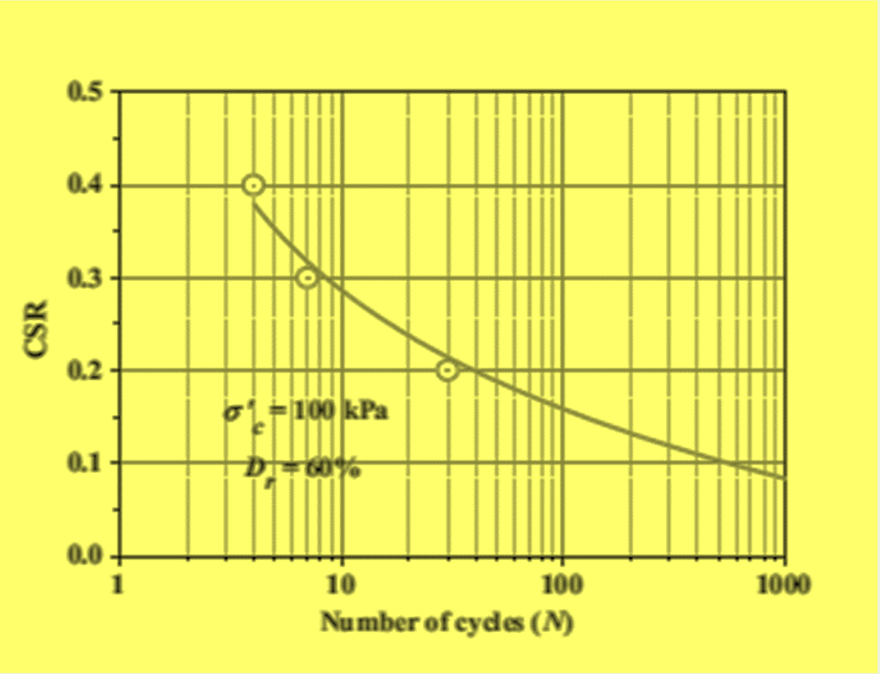




Dynamic Properties of Soil

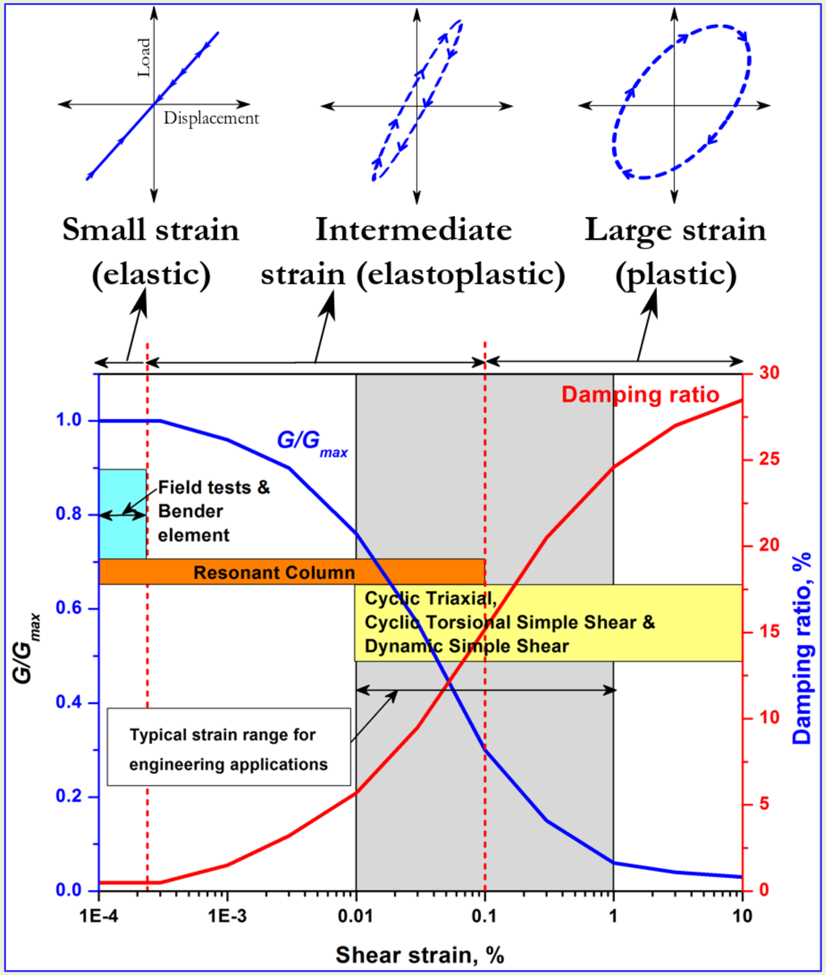
- Strain-dependent shear modulus and damping ratio
- Cyclic stress ratio and Number of cycles for liquefaction





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 V_s: **Imai and Tonouchi (1977)**

$$V_s = \sqrt{G_{\max} / \rho}$$

$$V_s = 91N^{0.337}$$

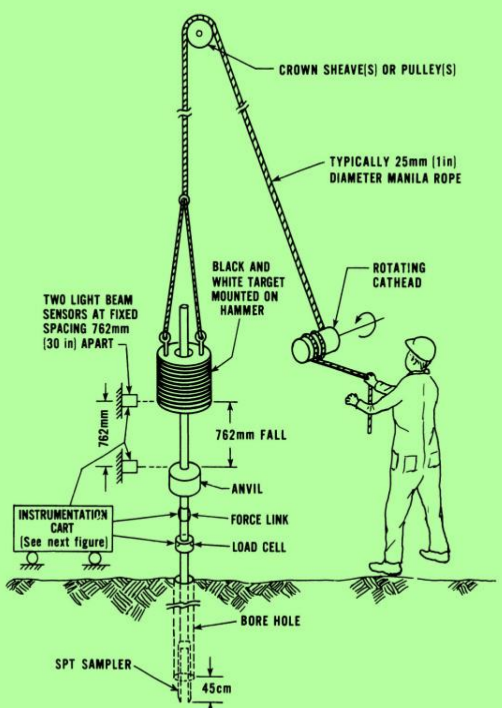


Figure 2-1. Sketch of instrumentation set up to measure fall height, velocity just before impact, and force in the drill stem.

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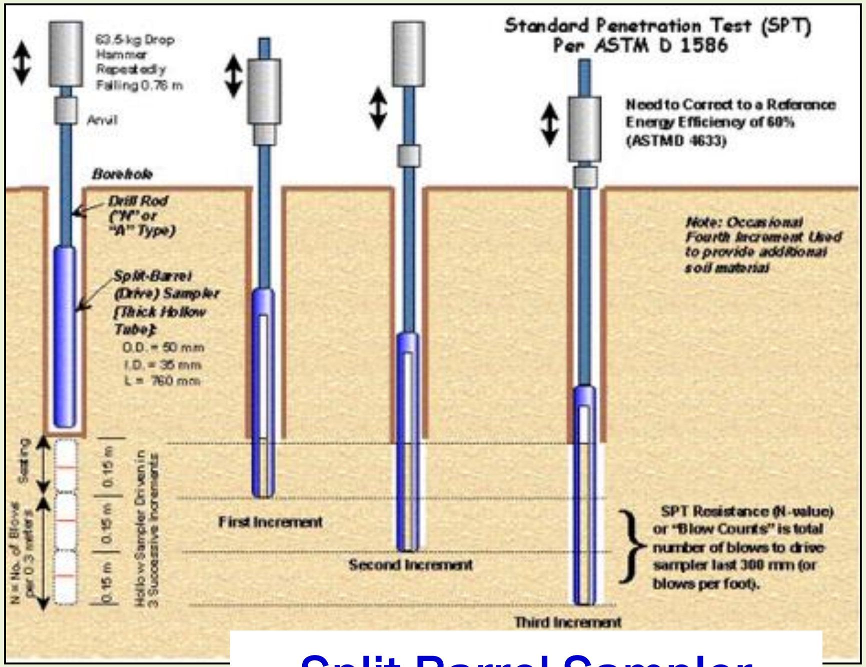
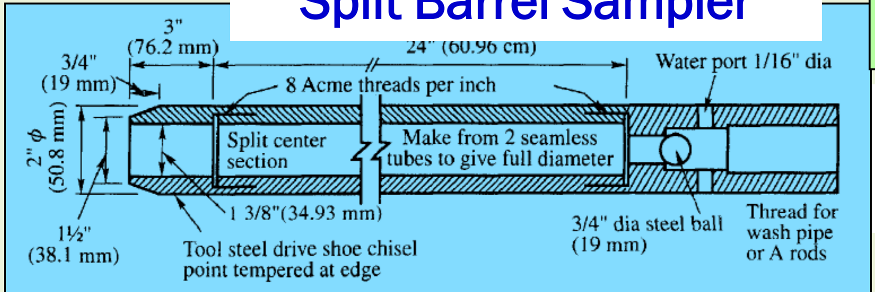
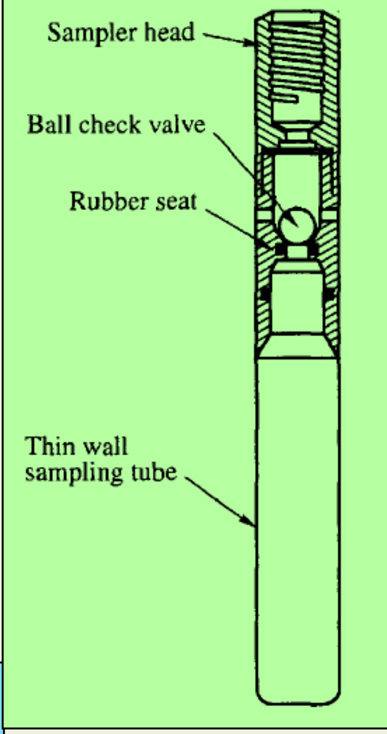


Split Barrel Sampler

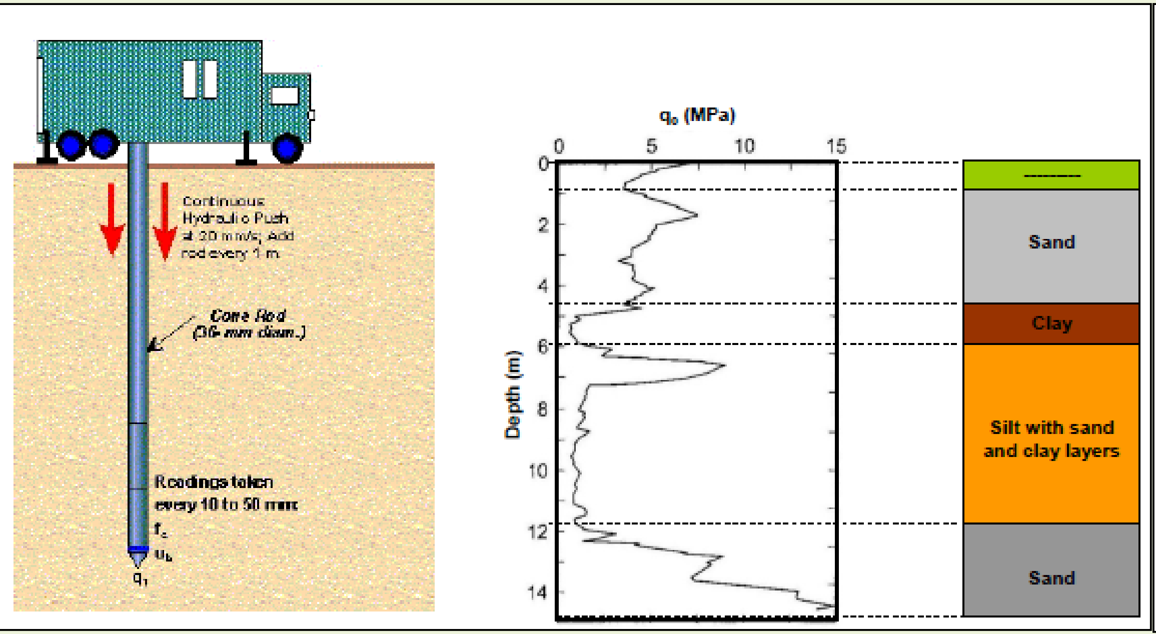


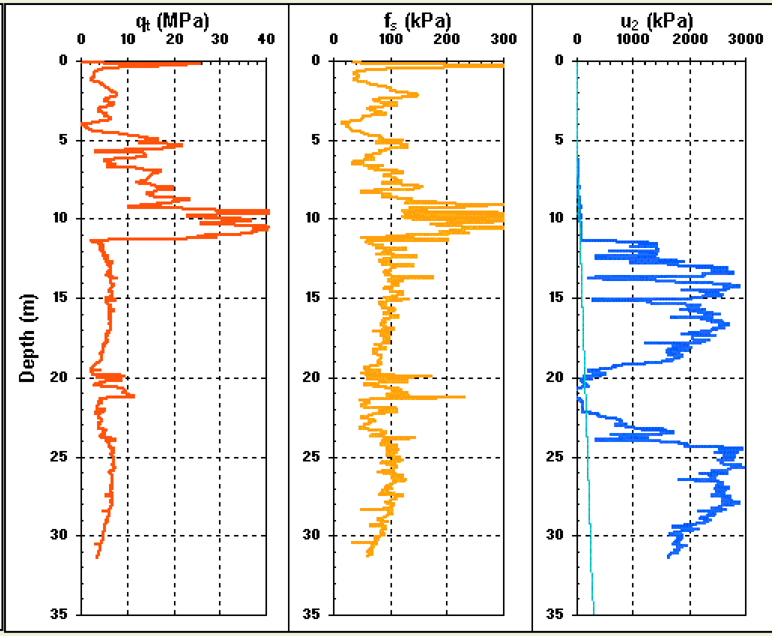


Thin Shelby Tube Sampler

Seismic Cone Penetration Test (CPT)

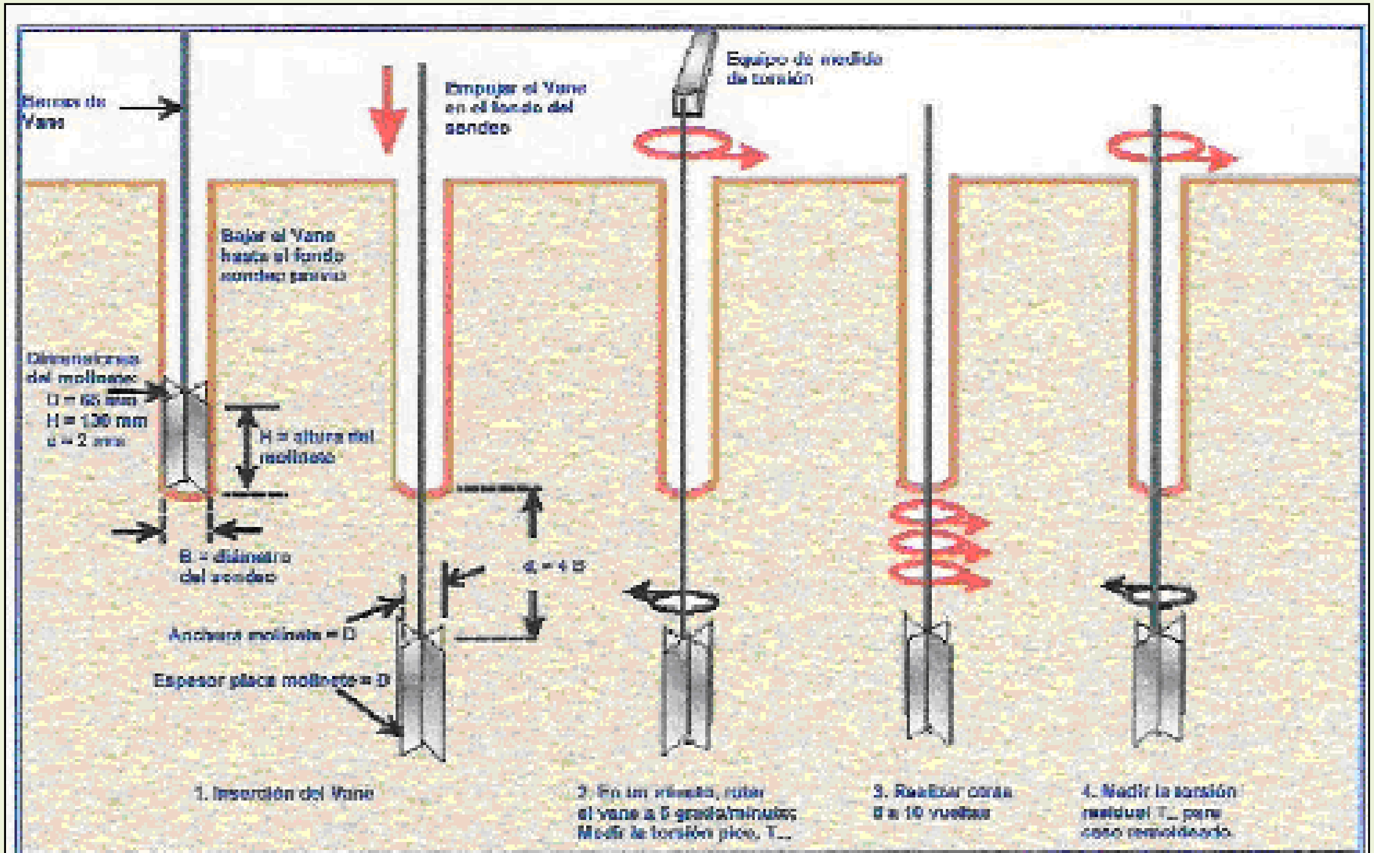
- Characterization of in-situ cyclic shear strength of soil
  - ❖ In-situ Cone Penetration Test (CPT) – Soils having fine contents
    - Skin friction, End bearing resistance and pore-water pressure





Vane Shear (VST)

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

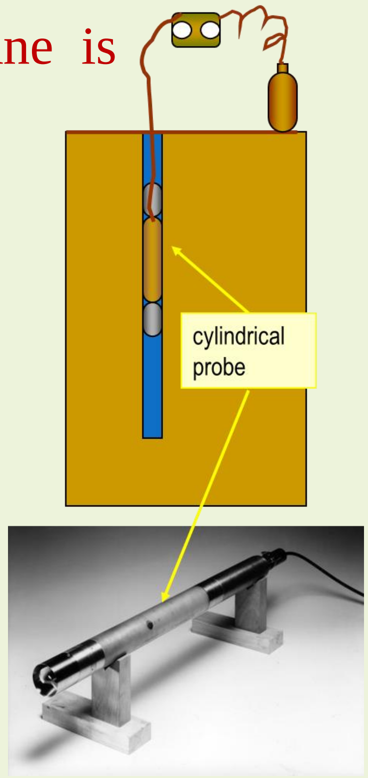


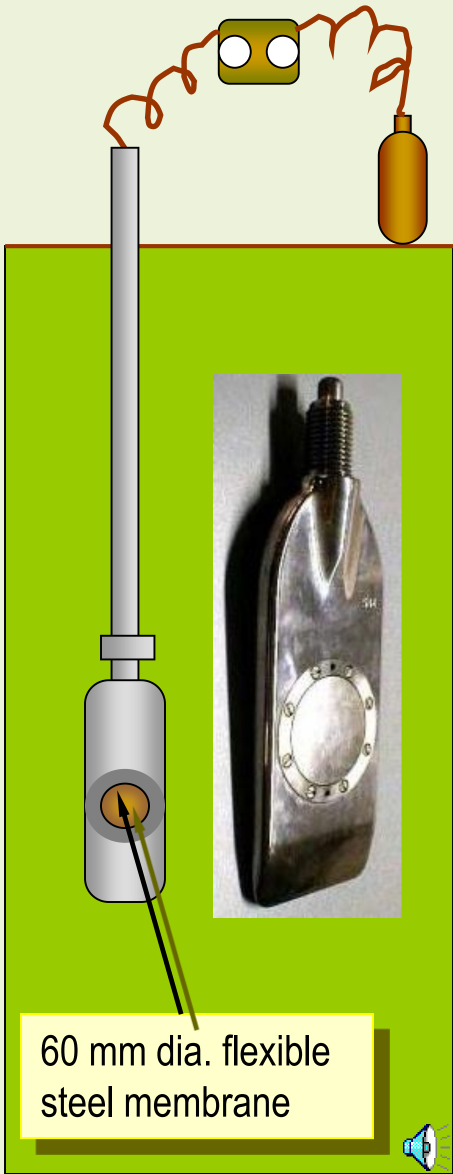
Dilatometer and Pressuremeter Tests (DMT and PMT)

- 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_0, OCR, c_v, k, *soil stiffness*

• *Material Index:*	$I_D = (p_1 - p_o)/(p_o - u_o)$
• *Dilatometer Modulus:*	$E_D = 34.7(p_1 - p_o)$
• *Horizontal Stress Index:*	$K_D = (p_o - u_o)/\sigma_{vo}'$

- $I_D < 0.6$, clay
- $0.6 < I_D < 1.8$, silts
- $I_D > 1.8$. sands

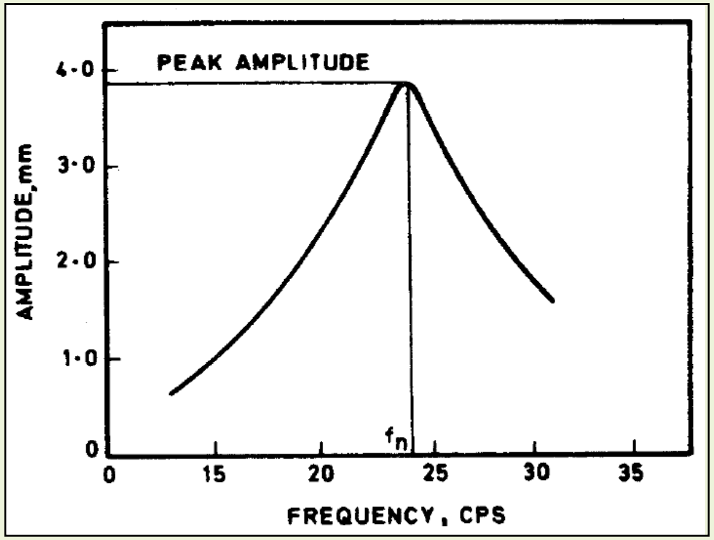




Block Vibration Test

- Block Vibration Test **(IS 5249: 1992)**
  - ❖ Estimate the dynamic properties
    - Coefficient of elastic compression (C_u)
    - Young's modulus (E)
    - Damping Ratio (ξ)

$$A_z = \frac{a_z\left(mm/s^2\right)}{4\pi^2 f^2}$$



Dynamic Parameters of Foundation Soil

- Coefficient of elastic compression of soil

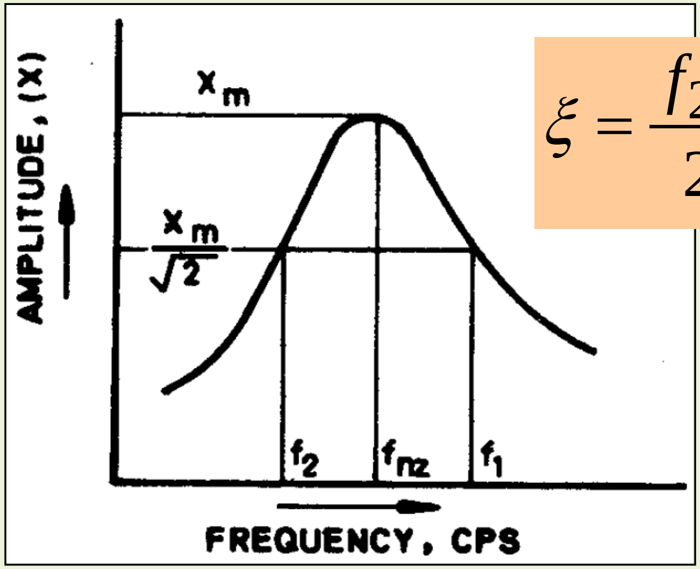
$$C_u = \frac{4\pi^2 f_{nz}^2 m}{A}$$

  - f_{nz} = Natural frequency (Hz)
  - m = Mass of the block, exciter and motor (kg.s²/m)
  - A = Contact area of the block with the soil (m²)
- Coefficient of elastic compression for actual foundation
  - A_1 → Area of the foundation

$$C_{u1} = C_u\sqrt{\frac{A}{A_1}}, \quad A_1 \le 10\text{ m}^2$$

$$C_{u1} = C_u - 10, \quad A_1 > 10\text{ m}^2$$

- Damping coefficient of soil
  - Half-power bandwidth method



$$\xi = \frac{f_2 - f_1}{2 f_{nz}}$$

Dynamic Parameters of Foundation Soil

- Modulus of elasticity of soil
  - ❖ C_s = Coefficient depending on L/B ratio
  - ❖ B, L = Width and Length of the block
  - ❖ μ = Poisson's ratio of soil

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

C_s (Barkan, 1962)

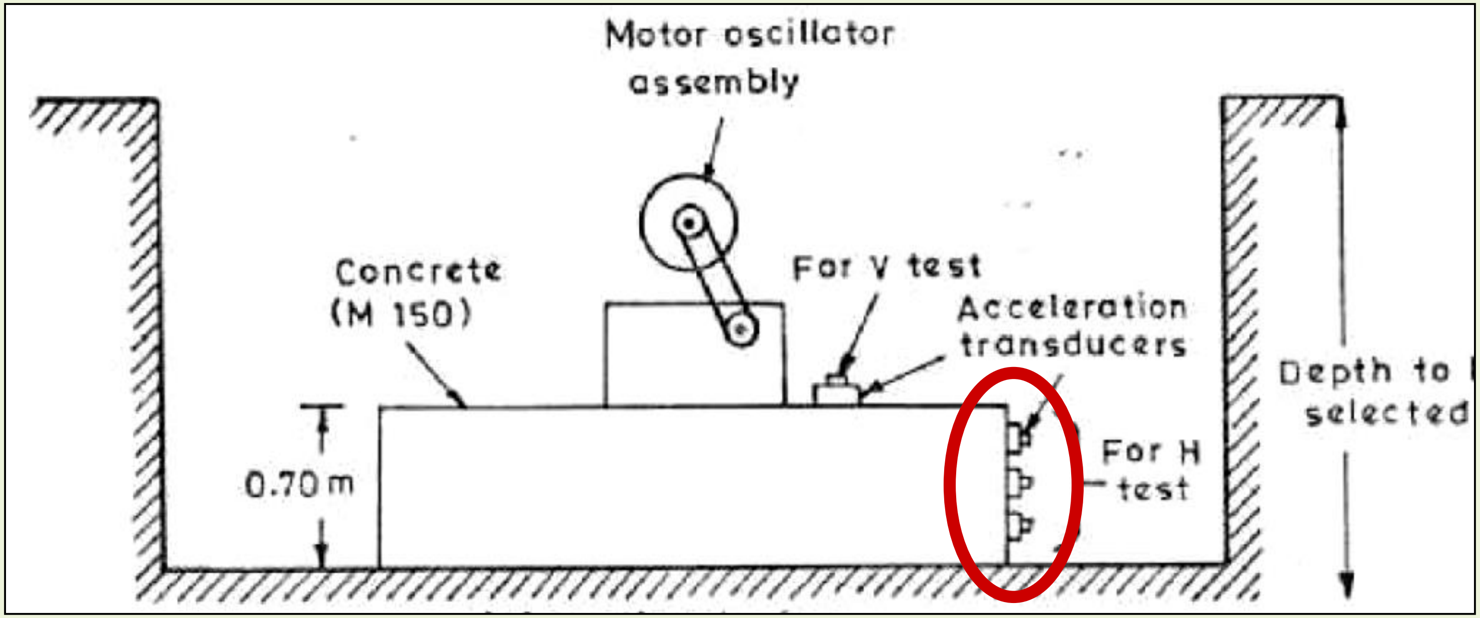
L/B	C_s
1.0	1.06
1.5	1.07
2.0	1.09
3.0	1.13
5.0	1.22
10.0	1.41

Poisson's ratio

Types of Soil	Poisson's ratio
Clay	0.5
Sand	0.30 to 0.35
Rock	0.15 to 0.25

Horizontal Block Resonance Test

- Oscillator direction and Transducers position are changed



- *Amplitude of horizontal vibrations*
- *Coefficient of uniform elastic shear*

$$A_x = \frac{a_x\left(mm/s^2\right)}{4\pi^2 f^2}$$

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

$$r = M_m / M_{m0}$$

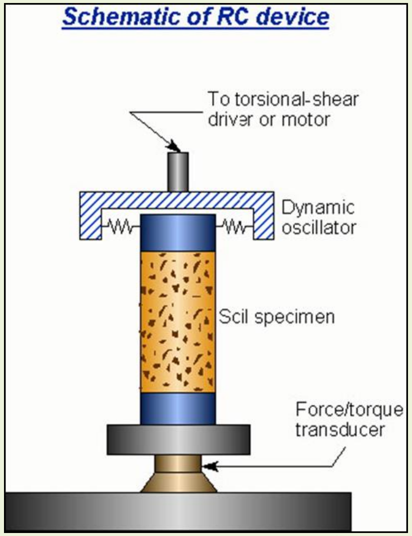
$$I_0 = 3.46I / M_{m0}$$

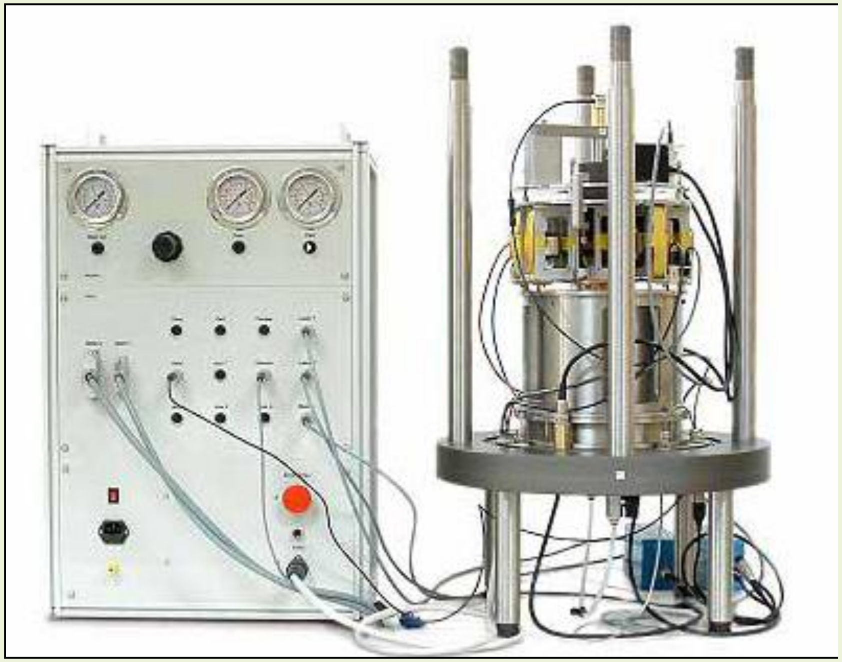
Low-Strain Laboratory Element Tests

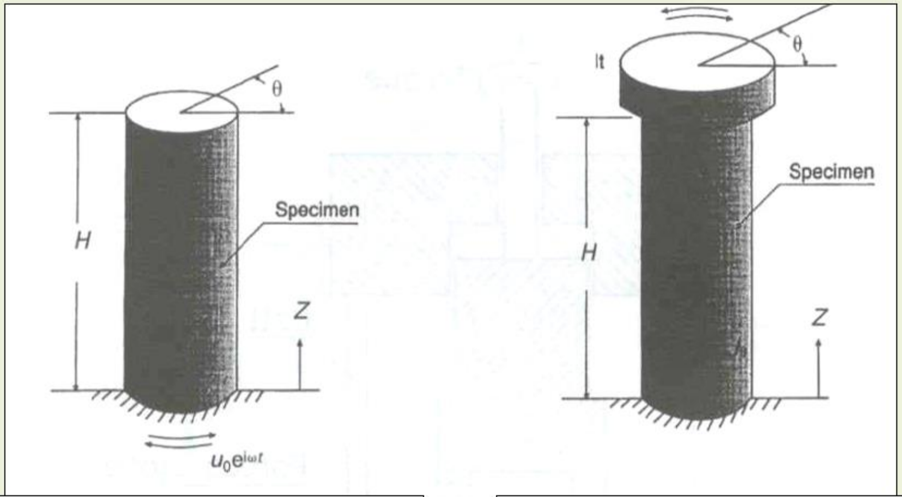
Determination of G_{max}

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







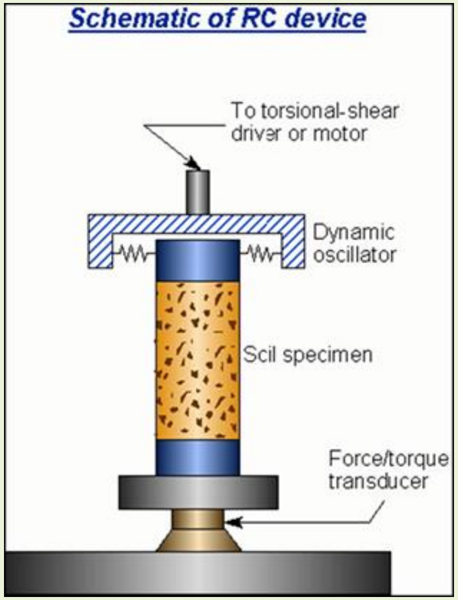
Excited at the bottom and the response is picked up at the top (velocity or acceleration)

Driving force is applied on the top & response pickup is also placed on the top

Free-Free **Fixed-Free**

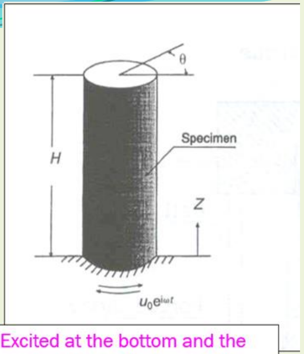
Resonant Column test

- 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



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

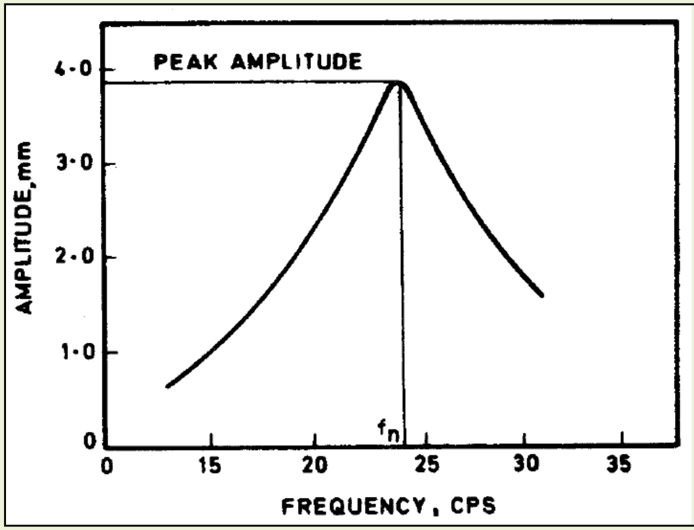
Free-Free

- Source and receiver at the other ends of the sample
- Longitudinal excitation
  - ❖ Longitudinal wave velocity

$$v_c = \frac{\omega_n L}{\pi} = \frac{2\pi f_n L}{\pi} = 2 f_n L \qquad v_c = \sqrt{\frac{E}{\rho}}$$

  - ❖ 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 shear 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 → Cross-sectional area of the sample
    - L → Length of the sample
    - γ → Unit weight of soil
    - m → Mass of the attachments on the top of the specimen

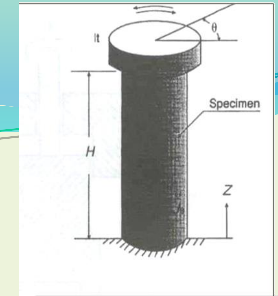
$$\alpha = \frac{\omega_n L}{v_c} = \frac{2\pi f_n L}{v_c}$$

  - ❖ Longitudinal wave velocity

$$v_c = \frac{2\pi f_n L}{\alpha}$$

  - ❖ Dynamic low-strain elastic modulus

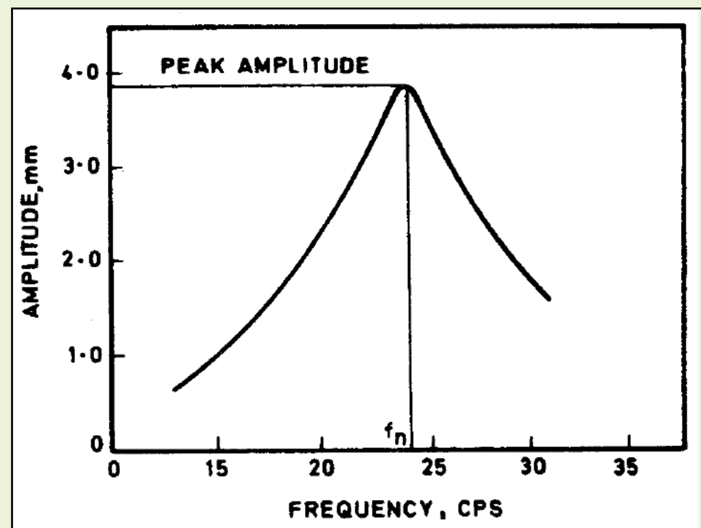
$$E = \rho v_c^2 = \rho\left(\frac{2\pi f_n L}{\alpha}\right)^2 = 39.48\frac{\rho f_n^2 L^2}{\alpha^2}$$



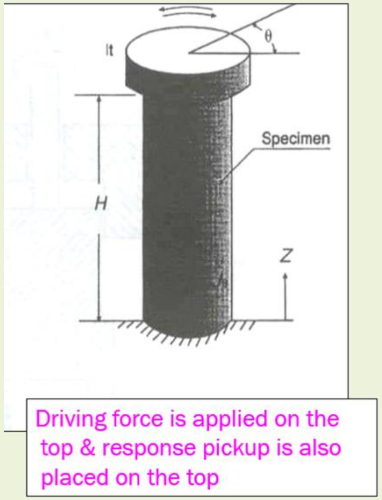
Driving force is applied on the top & response pickup is also placed on the top

Fixed-Free

$(AL\gamma)/W$	α (radians)
0.1	0.32
0.3	0.53
0.5	0.66
0.7	0.75
1	0.86
2	1.08
4	1.27
10	1.43



Fixed-Free Conditions



Fixed-Free

- Source and receiver at the same end of the sample
- Torsional excitation

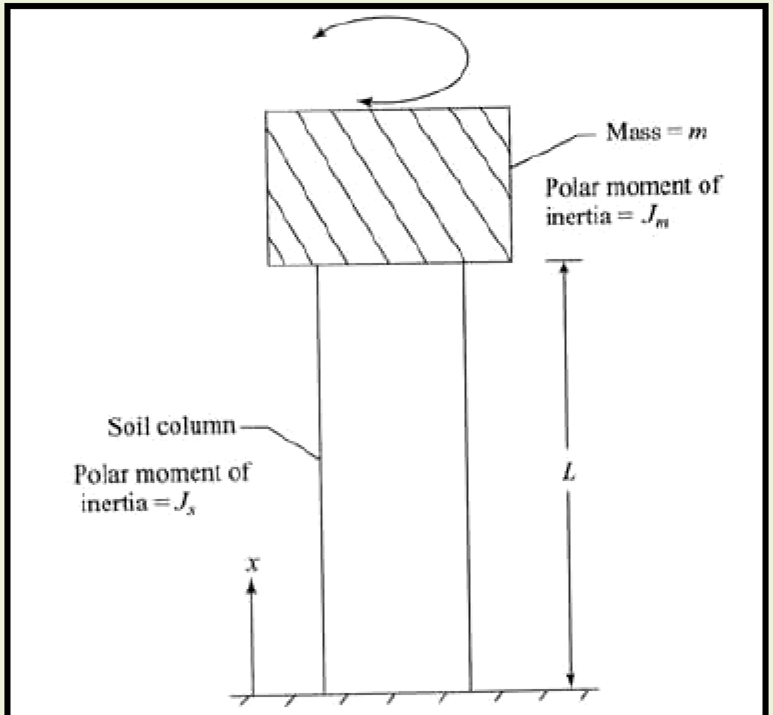
$$\frac{J_s}{J_m} = \alpha \tan \alpha$$

  - ❖ Wave velocity at modal vibrations
    - J_s → Mass polar moment of inertial of the soil specimen
    - J_m → Mass polar moment of inertia of the attachments

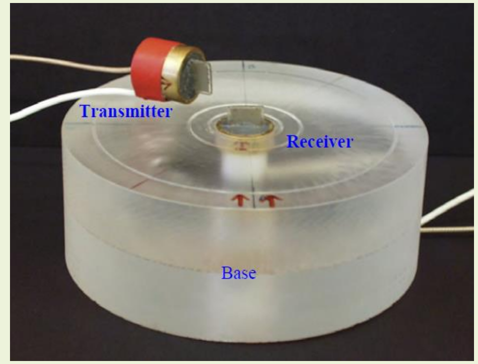
$$\alpha = \frac{\omega_n L}{v_s} = \frac{2\pi f_n L}{v_s}$$

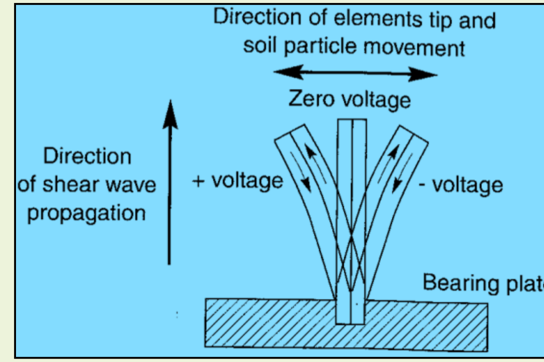
  - ❖ Shear wave velocity $v_s = \frac{2\pi f_n L}{\alpha}$
  - ❖ Dynamic low-strain shear modulus

$$G = \rho v_s^2 = 39.48 \frac{\rho f_n^2 L^2}{\alpha^2}$$

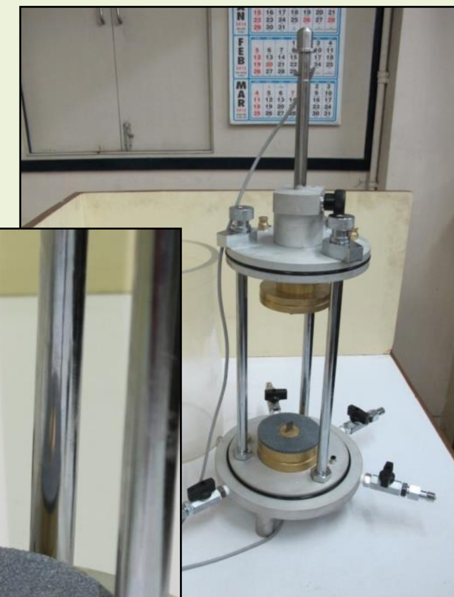


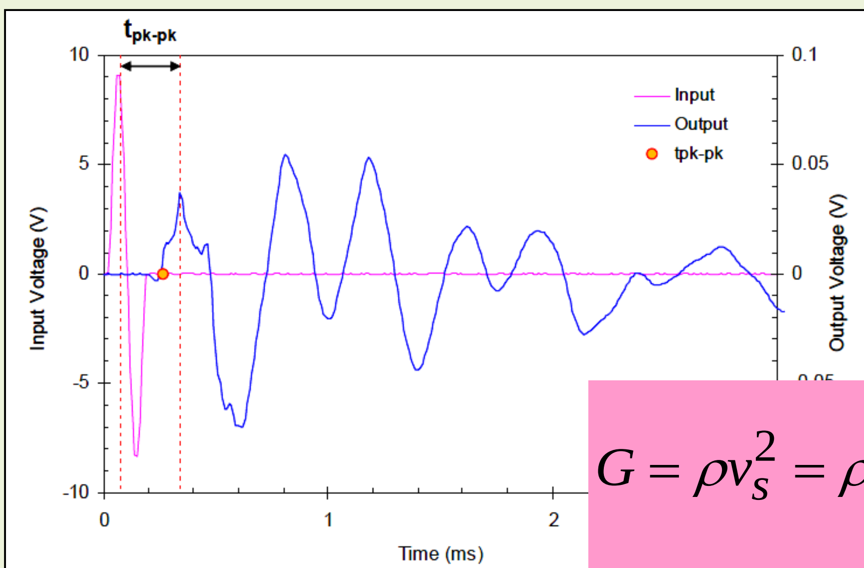
Bender Element Test



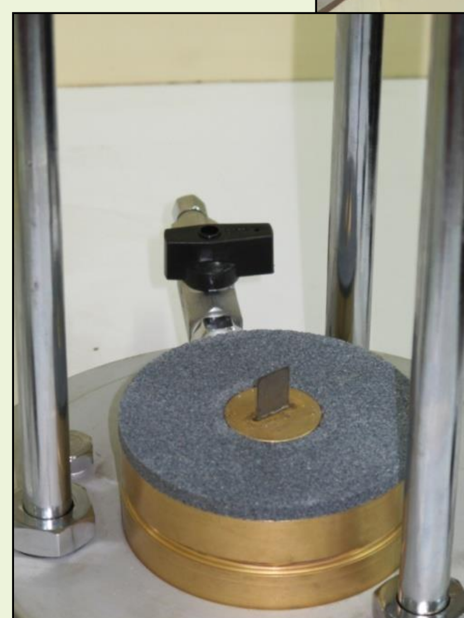


- Bender elements
  - ❖ Bonded piezo-electric materials
    - The element bends due to contrasting expansion and contraction due to passage of voltage (transmitter)
    - Similarly, a lateral deflection of the bender element produces voltage (receiver)





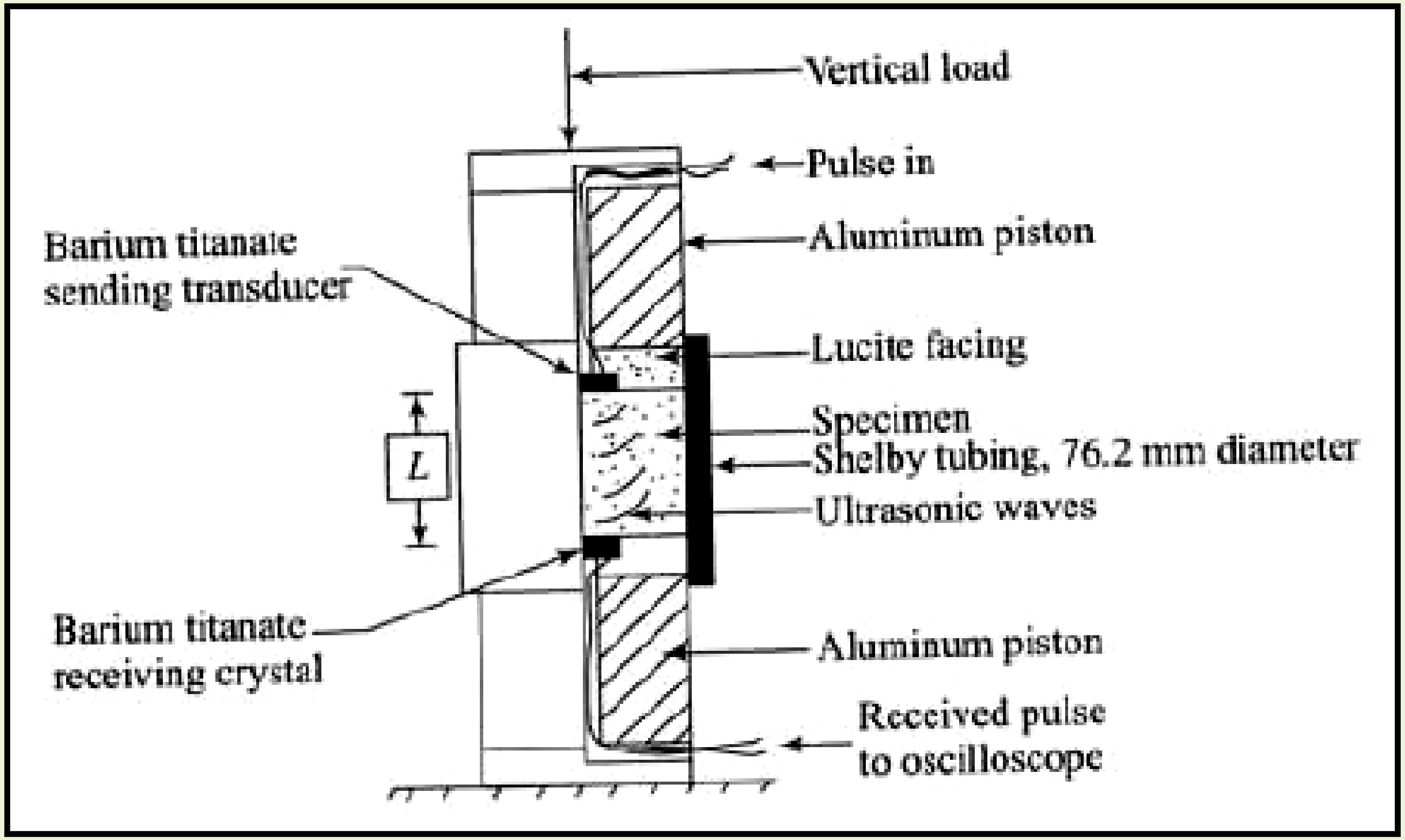
$$G = \rho v_s^2 = \rho \frac{L^2}{t_{pk-pk}^2}$$



Ultrasonic Pulse Test

- Shear modulus

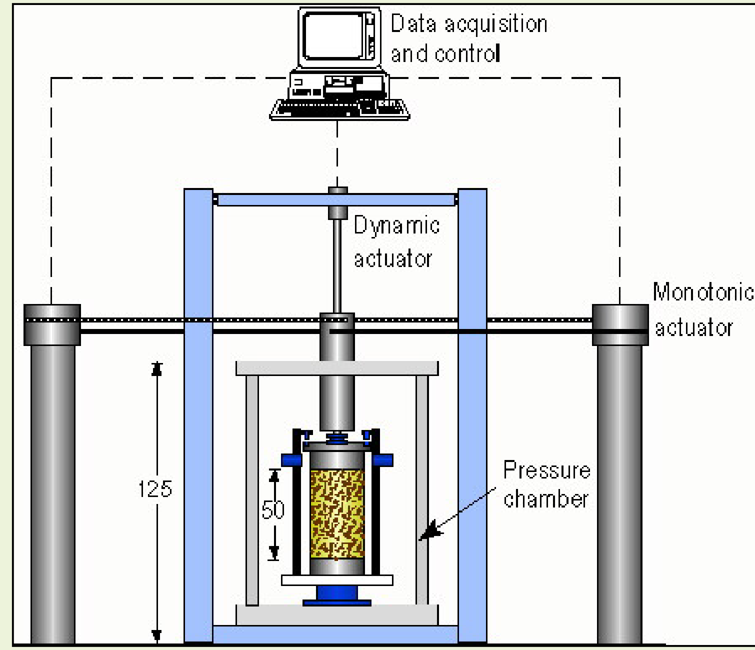
$$G = \rho v_s^2 = \rho \frac{L^2}{t_c^2}$$



High-Strain Laboratory Element Tests

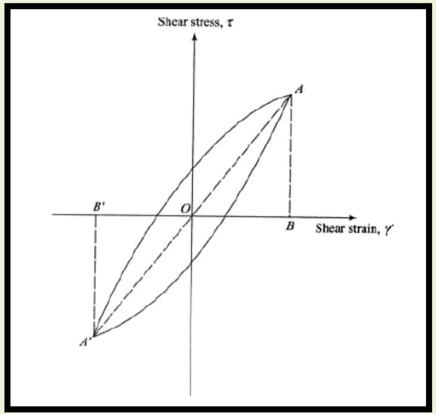
Cyclic Triaxial Test

- 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

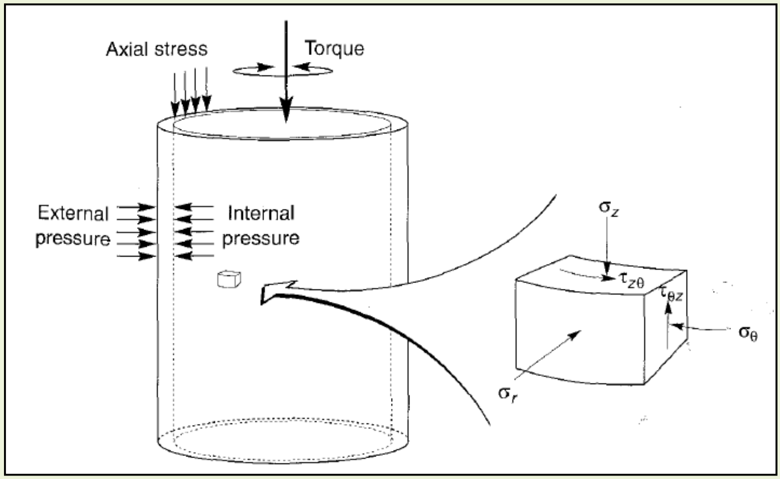


Cyclic Torsional Simple Shear Test

- 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

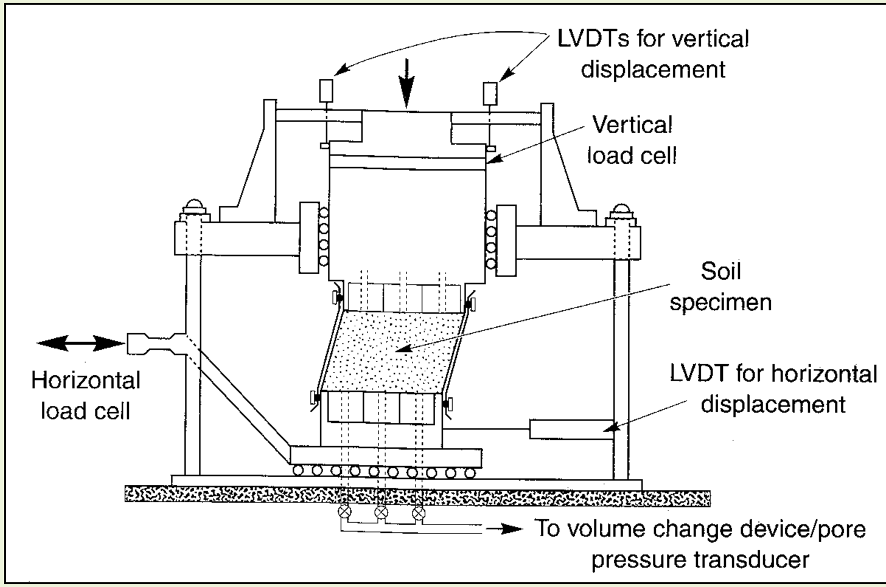


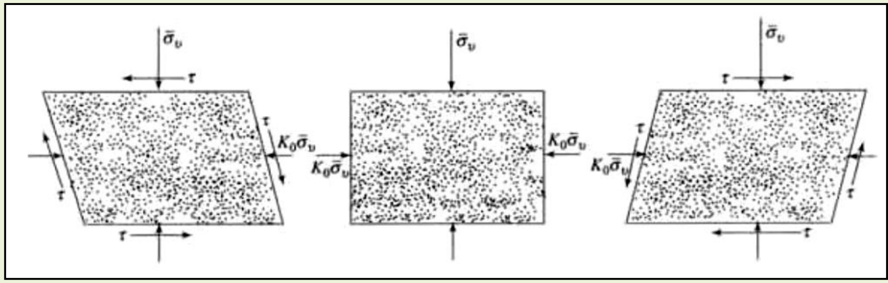
$$\tau_h = \frac{3T}{2\pi}\left(\frac{1}{r_2^3 - r_1^3}\right)$$



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



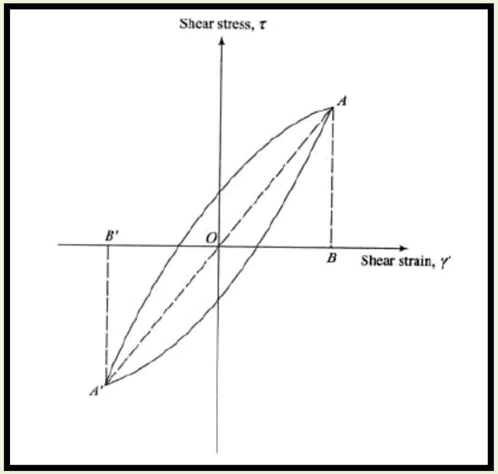


Operating strain range

10^{-2} % to 5 %

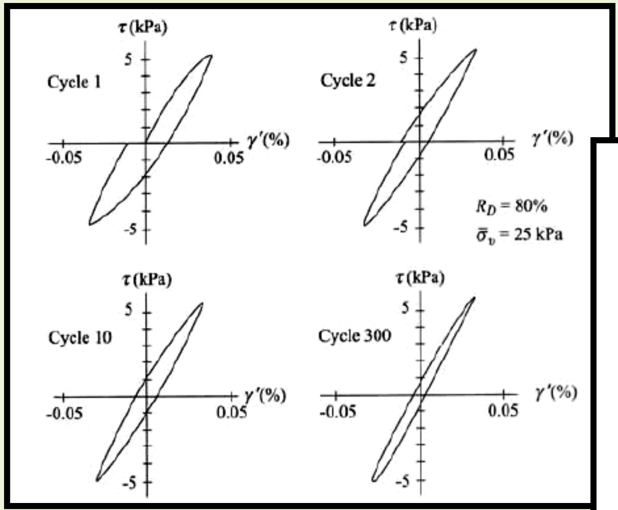
Cyclic Simple Shear Test

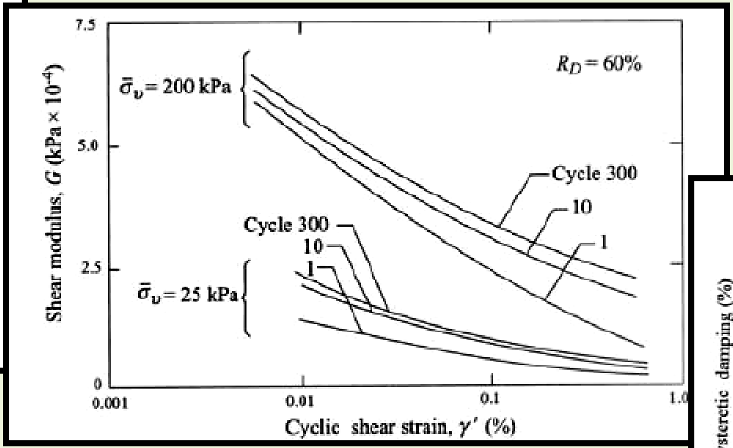
- Determination of shear modulus and damping ratio
  - ❖ Plot of shear stress vs shear strain for the cyclic loading gives Hysteresis loop

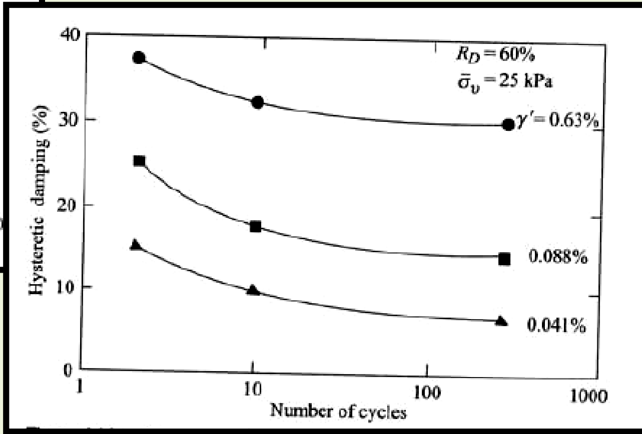


$$G = \frac{\text{Stress amplitude (AB)}}{\text{Strain amplitude (OB)}}$$

$$D = \frac{1}{\pi}\frac{\text{Area of hysteresis loop}}{2\left(\Delta\ \text{AOB} + \Delta\ \text{A'OB'}\right)}$$

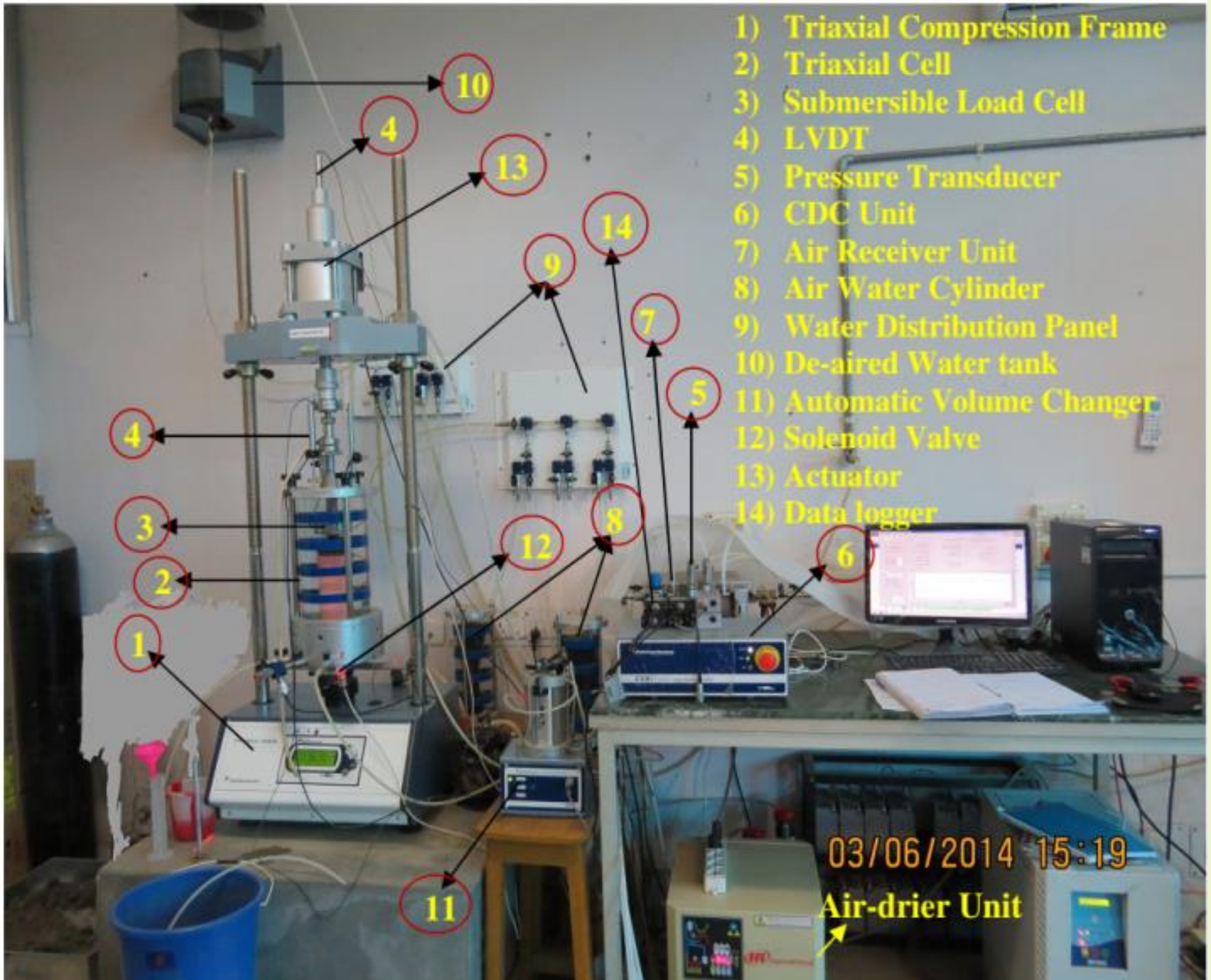






Cyclic Triaxial Test Apparatus at IIT Guwahati

Wyekham-Farrance Triaxial System



Submersible load cell

Axial LVDTs

Radial LVDT

Specification of the Equipment/Instrumentation

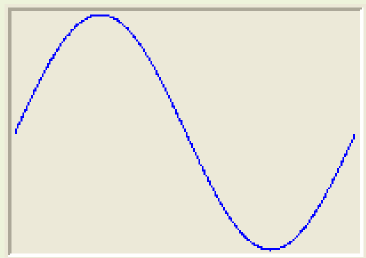
- Specification of instrumentations: working range
  - *Actuator operating frequency range : 0.01-10 Hz*
  - *Measuring capacity external LVDT: 0-50 mm*
  - *Pressure transducers: 0-1000 kPa*
  - *Triaxial cell capacity: 0-2 MPa*
  - ***Submersible load cell: 25 kN***
    - **Working pressure range: 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

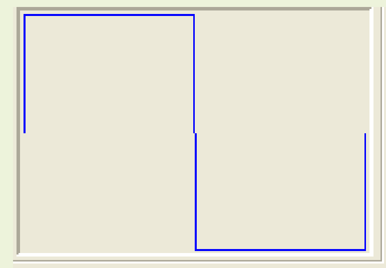
Applied Waveforms

- Investigate any vibration problem using regular waveforms



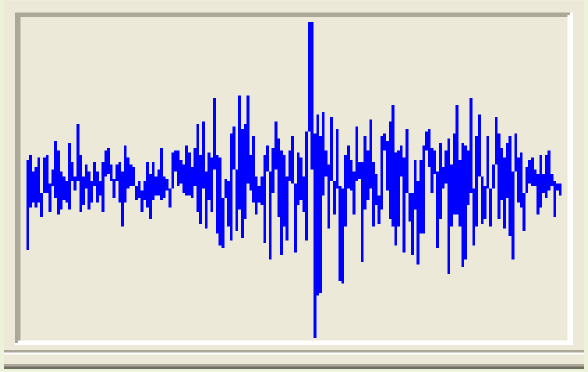
Sine

Triangle



Square

- User defined irregular seismic waveforms



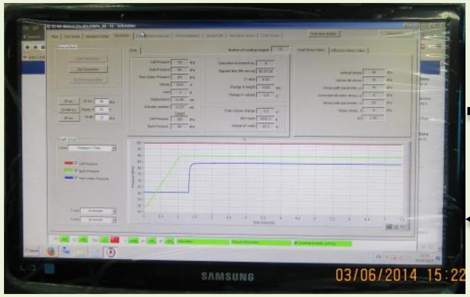
- This allows the input of user defined or imported waveshapes
- User waveform cell – for loading in a pre-defined wave shape file
- A wave shape file is a .udw file, which is created using the program 'UDW Generator' that accompanies the software.

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



Personal Computer & Software

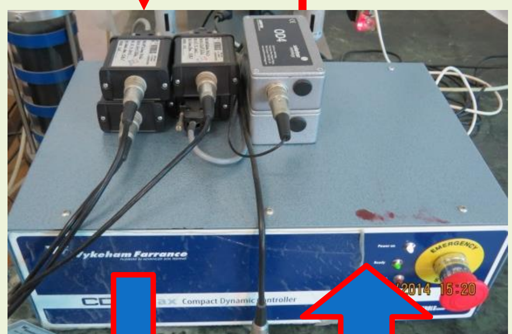
Test routine information

Gathering data

Compact Dynamic Controller

Input and Output from the CDC

PC & Software



CDC

DRIVING UNITS

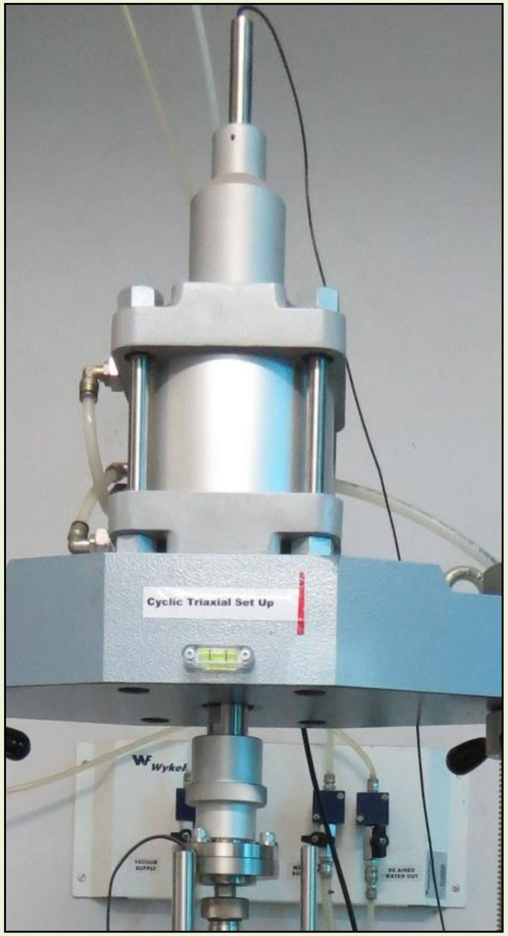
- Actuator
- Triaxial Frame
- Cell pressure
- Back Pressure
- ON/OFF Valves
- Volume Change

MEASUREMENTS

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

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
  - *Resular and Irregular loadings*
    - *Stress controlled tests*
    - *Strain controlled tests*



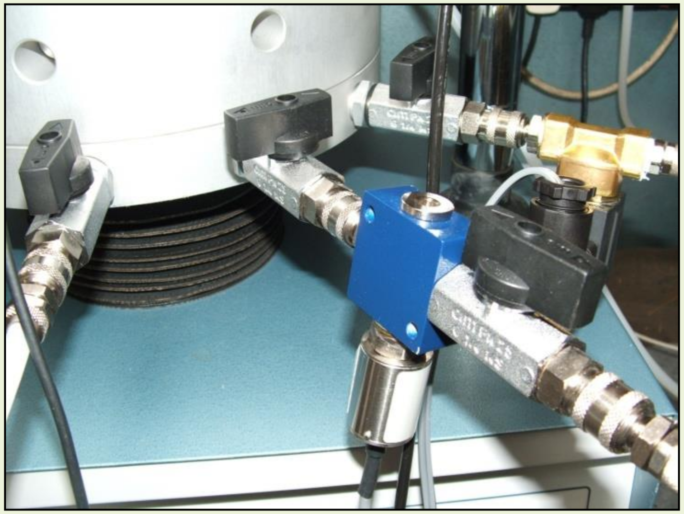
Air Receiver Unit and AVC

- 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

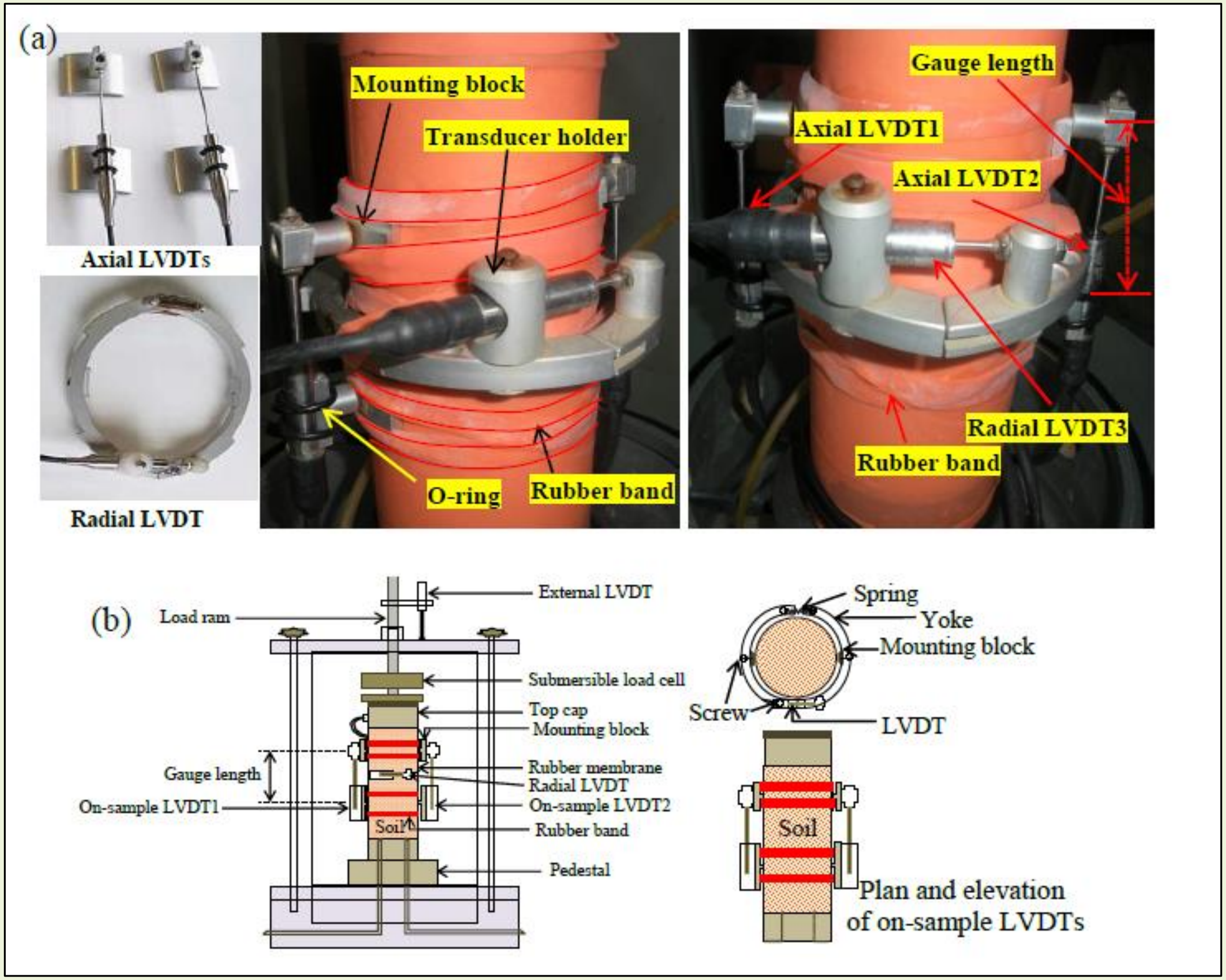
- Three pressure transducers
  - *Two of them are for control and data acquisition*
    - Cell and back pressure.
  - *One for measuring pore water pressure*



* 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

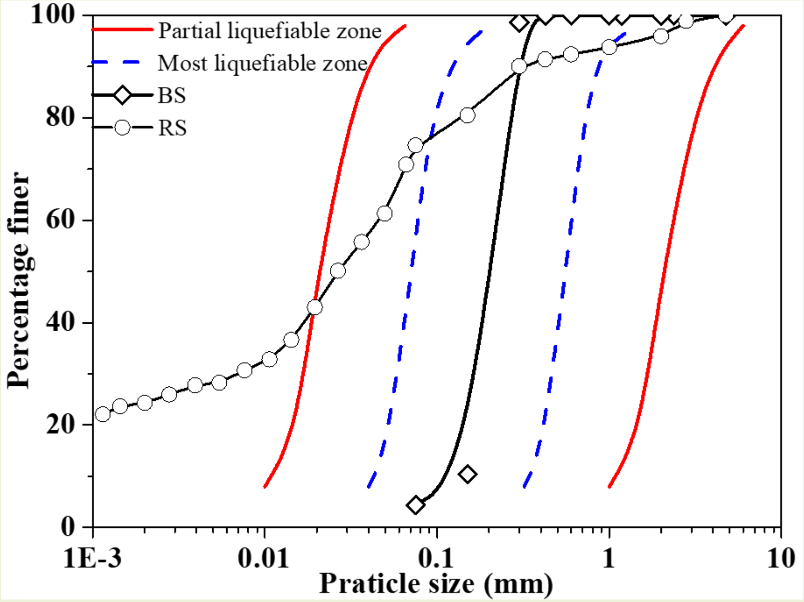


Various Stages of Cyclic Triaxial Test

- 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*

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 (γ = 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

Soil	D_r (%)	σ'_c (kPa)	f (Hz)	γ (%)
SBS	30	50	1	0.015, 0.045, 0.075, 0.15, 0.30,0.45,0.60, 0.75, 1.0, 1.5, 3.0
		100		0.045, 0.075, 0.15, 0.30,0.45,0.60, 0.75, 1.5
		150		0.045, 0.075, 0.15, 0.30, 0.45, 0.60, 0.75
	60	50	0.5, 1, 2, 3, 4	0.15, 0.60, 1.0, 1.5, 3.0, 4.5
		100		
		150		
	90	50	1	0.045, 0.075, 0.15, 0.30, 0.45, 0.60, 0.75, 1.5
		100		0.045, 0.075, 0.15, 0.30, 0.45, 0.60, 1.0, 1.5, 2.0
		150		0.045, 0.075, 0.15, 0.30, 0.45, 0.60, 0.75, 1.0, 1.5, 2.0
DBS	60	50	1	0.045, 0.075, 0.15, 0.30, 0.60, 0.75, 1.0, 1.5, 3.0, 4.5, 6.0,7.0
		100		0.045, 0.075, 0.15, 0.30, 0.45, 0.75, 1.5, 3.0, 5.0, 7.0
		200		0.075, 0.10, 0.30, 0.45, 0.60, 0.75, 1.5, 3.0, 4.5, 6.0

  - Stress-controlled test with regular loading

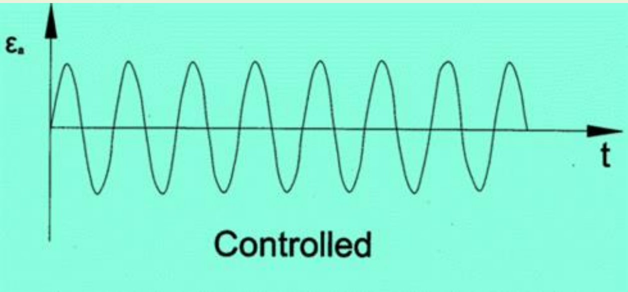
Soil	D_r (%)	σ'_c (kPa)	f (Hz)	CSR
SBS	30, 60, 90	50, 100, 200	1	0.05, 0.1, 0.2, 0.3
	60	100	0.1, 0.5, 1, 2, 4	0.1, 0.2, 0.3, 0.4
RS	MDD 1.5 g/cc	100	1	0.1, 0.2, 0.3, 0.4

  - Stress-controlled irregular seismic excitation

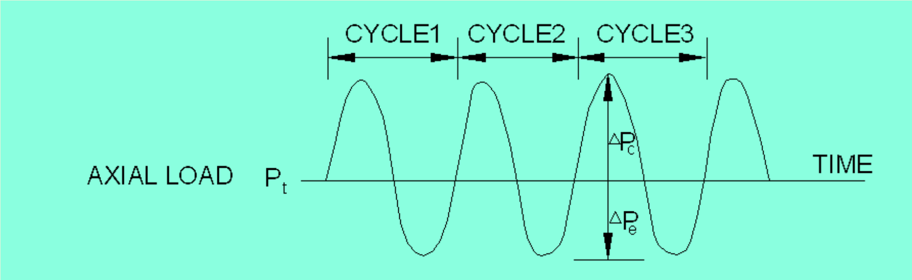
Soil	Irregular excitation	PGA (g)	Relative density, D_r (%)	Confining depth (m)
SBS	Bhuj	0.103	30	5, 10, 15
	Tezpur	0.360		
	Kobe	0.834		
	Bhuj	0.103	30, 60, 90	10, 15
	Tezpur	0.360		
	Kobe	0.834		
	Bhuj	0.103	60	10
	Tezpur			
	Kobe			
	Bhuj	0.360	60	10
	Tezpur			
	Kobe			

Waveforms of Cyclic Shearing

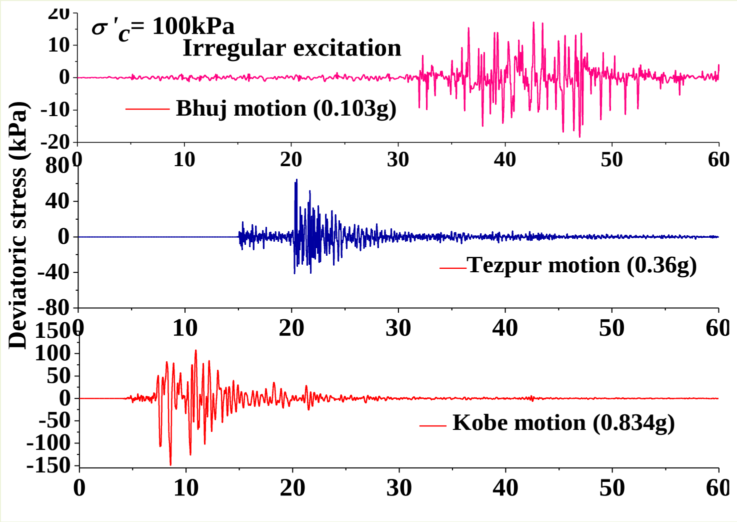
- Regular seismic excitations
  - *Strain-controlled approach*



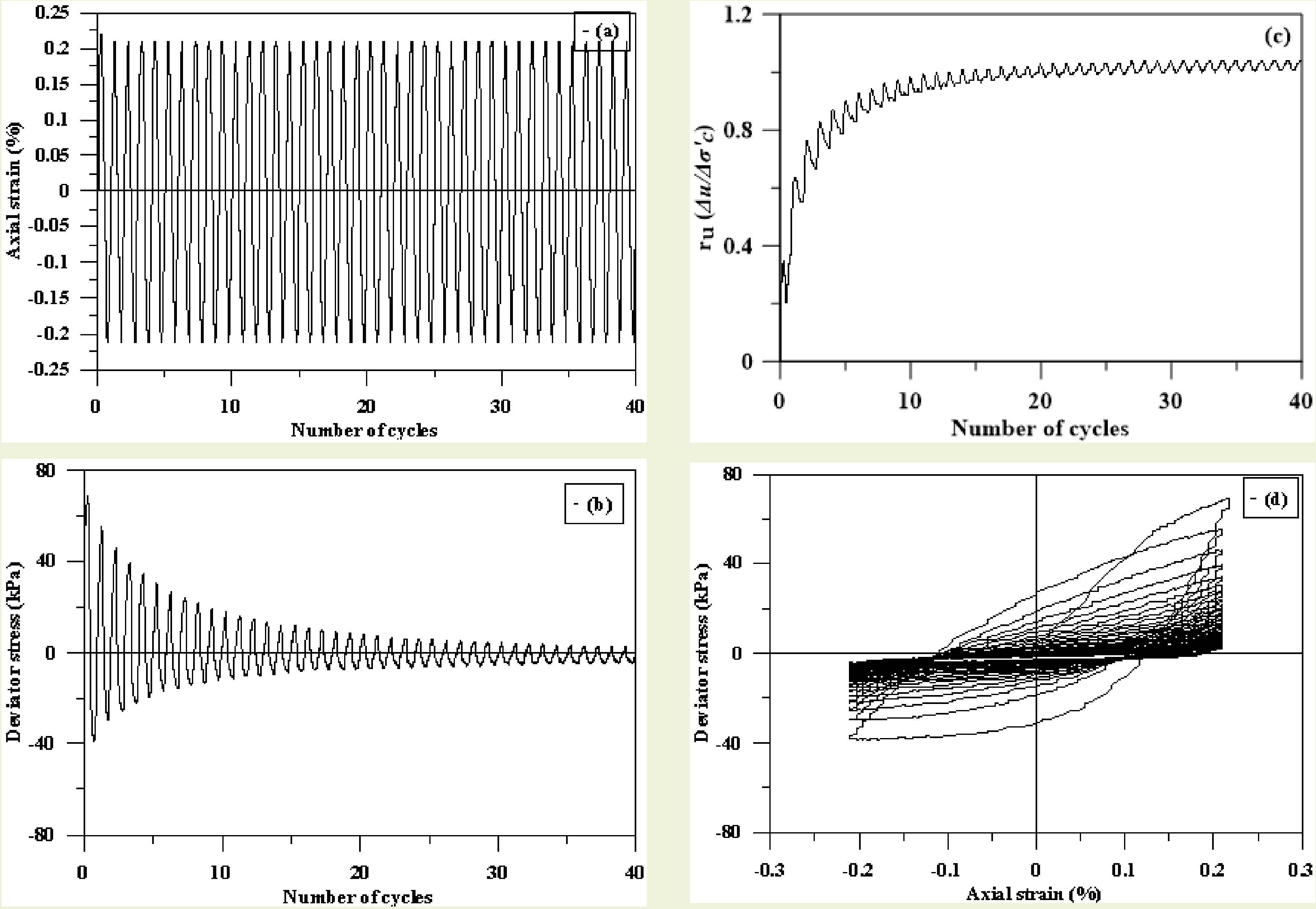
  - *Stress-controlled approach*



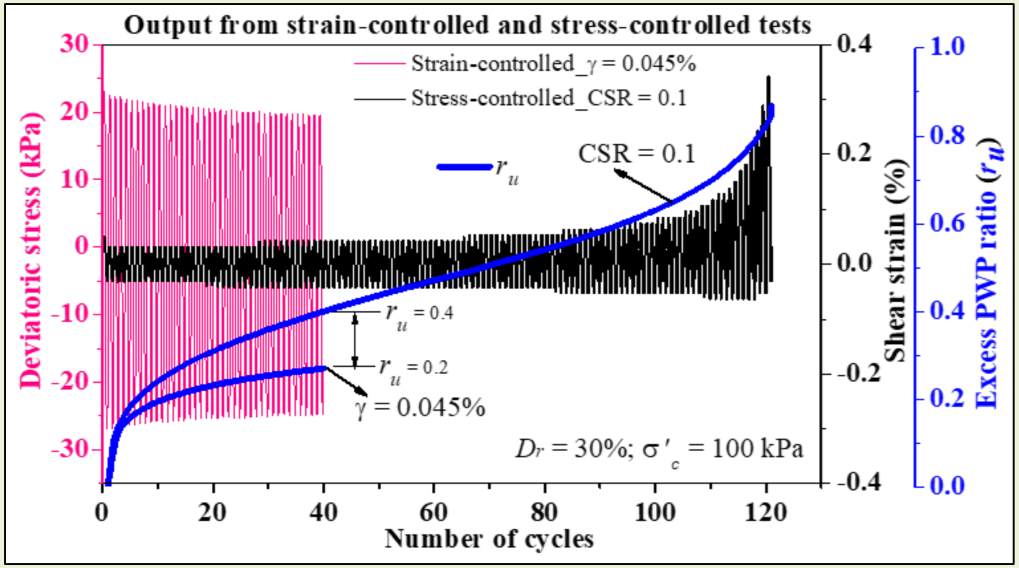
- Irregular seismic excitation
  - *Bhuj, Kobe and Tezpur strong motions*

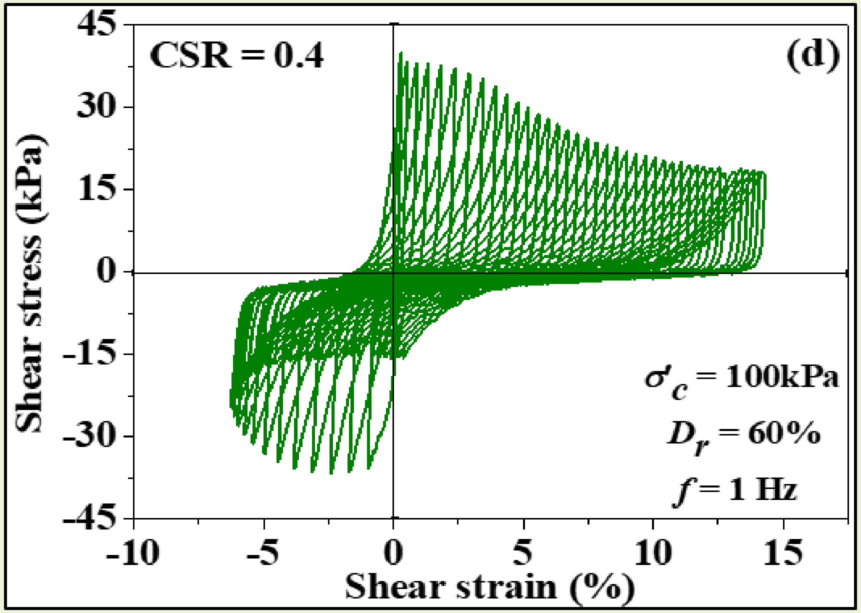


Typical Result from Strain Controlled Regular Excitation

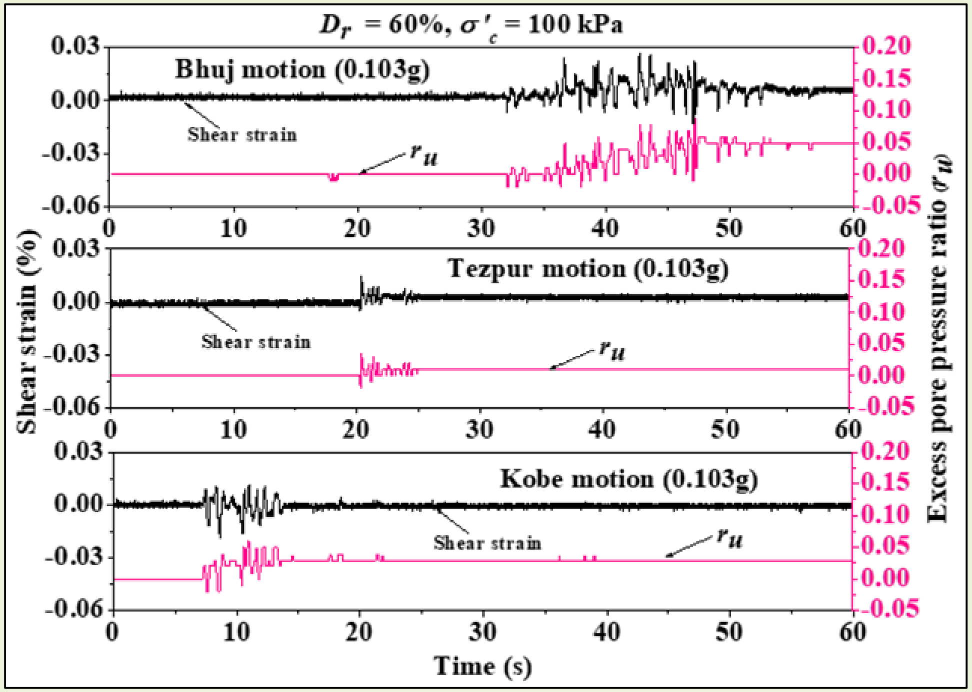


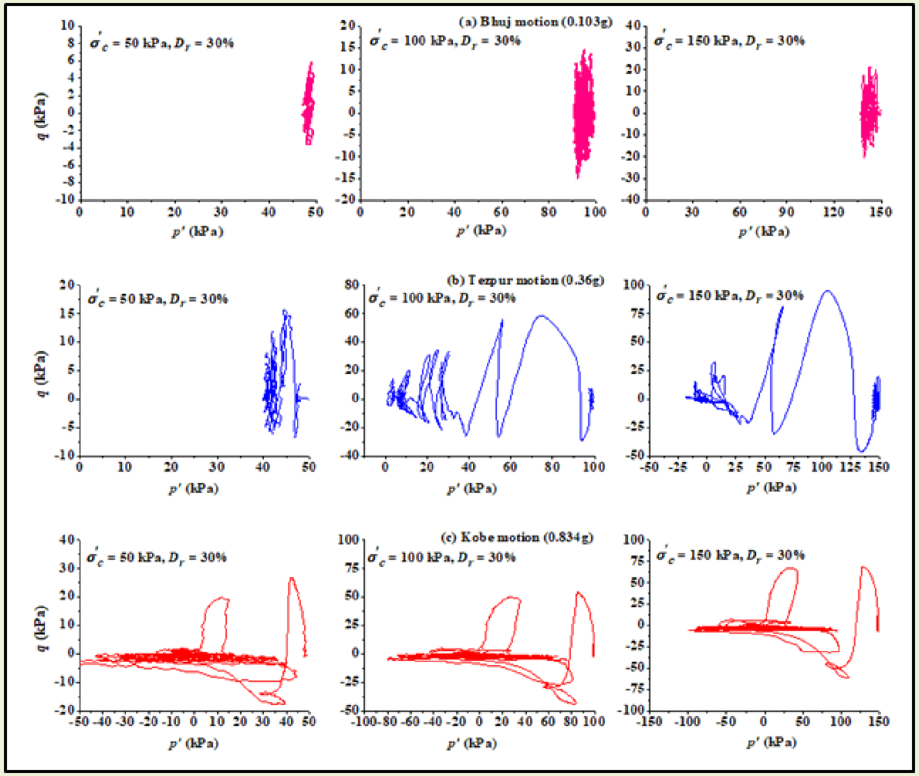
Typical Result from Stress Controlled Regular Excitation



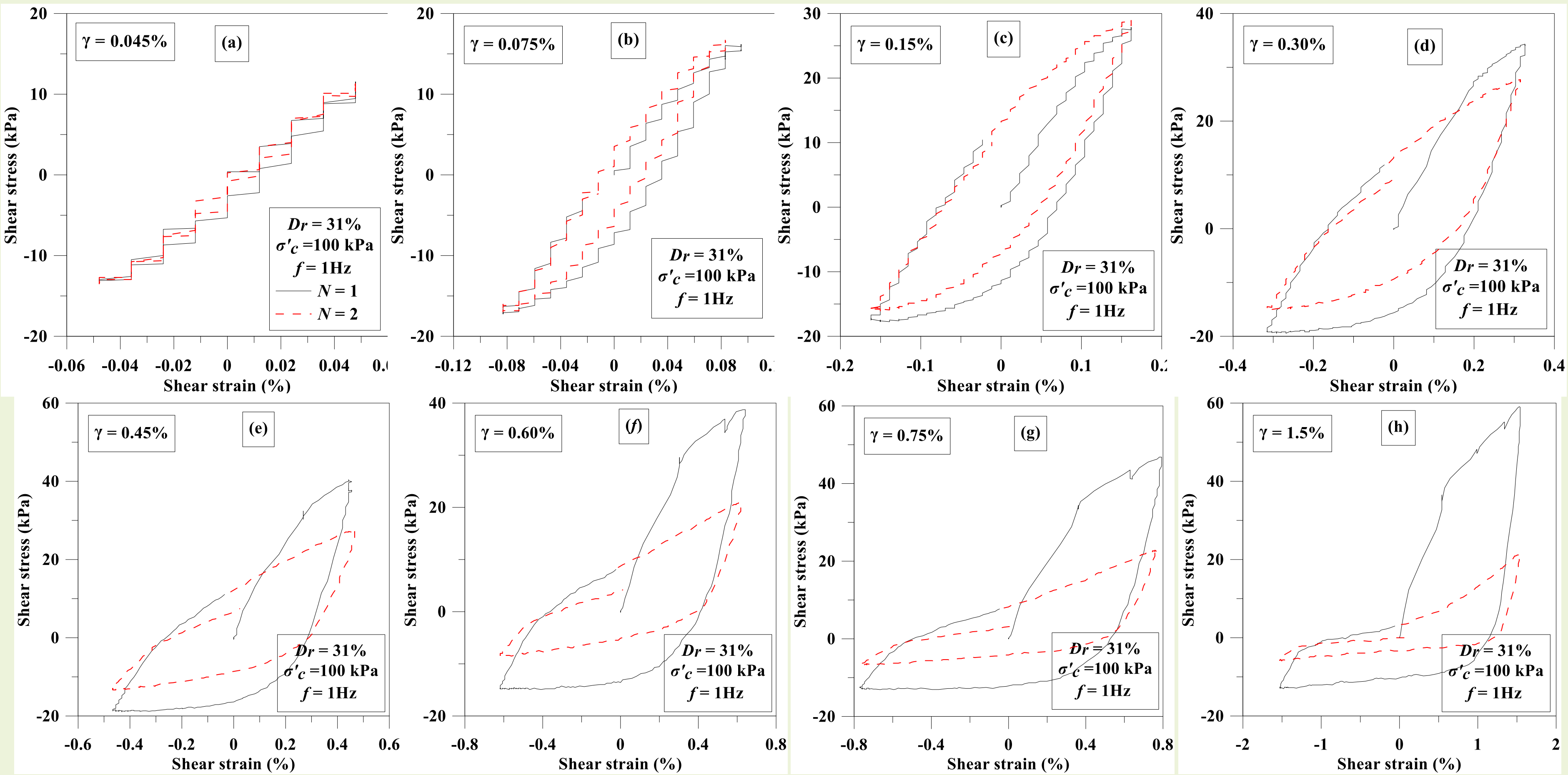


Typical Result from Stress Controlled Irregular Excitation



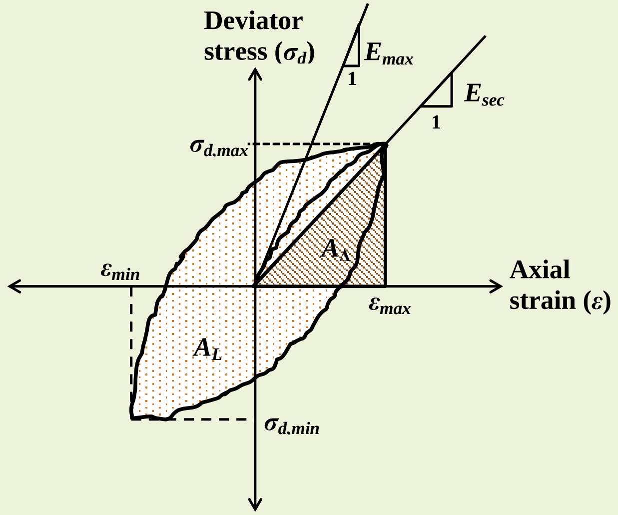


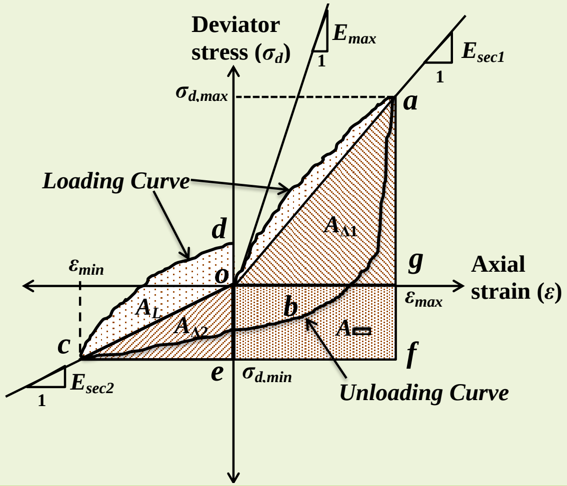
Evolution of Hysteresis Loop with Shear Strains



Beyond γ = 0.15%, the hysteresis loop attains an asymmetrical shape from the 1st cycle itself

Evaluation of Shear Modulus





Symmetrical hysteresis loop

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

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

Asymmetrical hysteresis loop

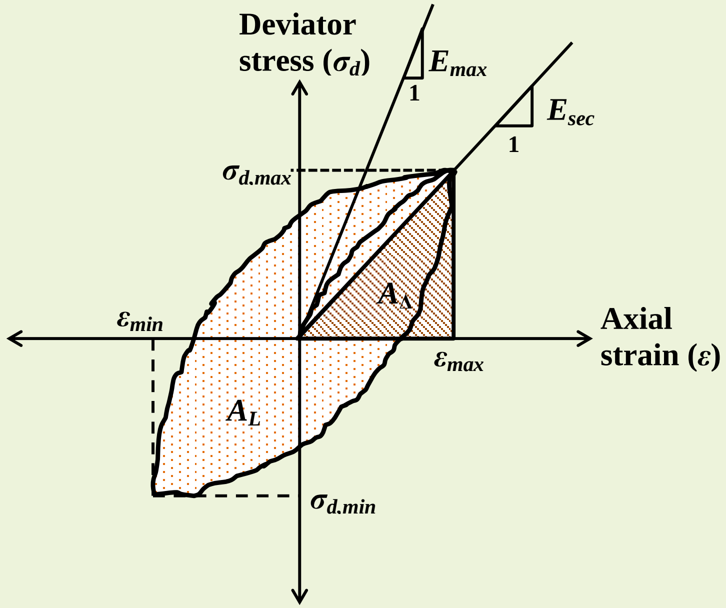
$$E = \frac{E_{\sec 1, Compression} + E_{\sec 2, Extension}}{2}$$

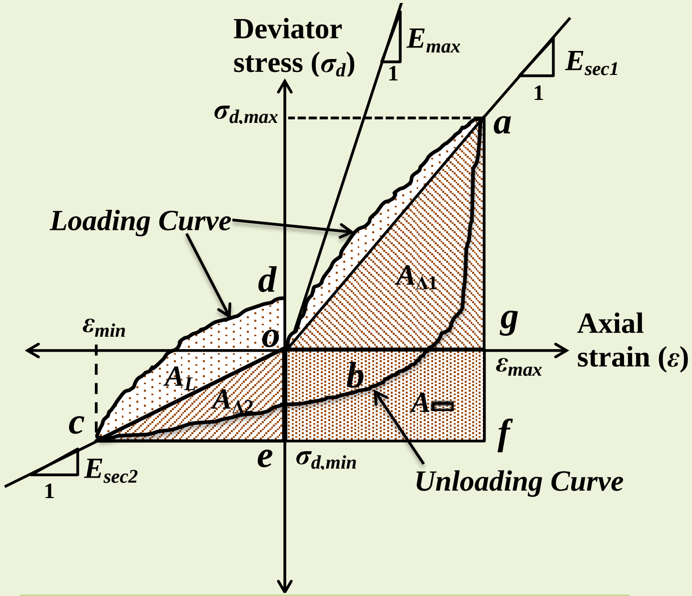
$$G = E / [2(1+\upsilon)]$$

$$G_{\max}(\text{kPa}) = [523(OCR)^k / (0.3 + 0.7e^2)](p_a^{0.52} \times \sigma_0^{'\,0.48}) \qquad \sigma_0^{'} \text{ in kPa}$$

(Chung *et al.*, 1984)

Evaluation of Damping Ratio





Symmetrical hysteresis loop

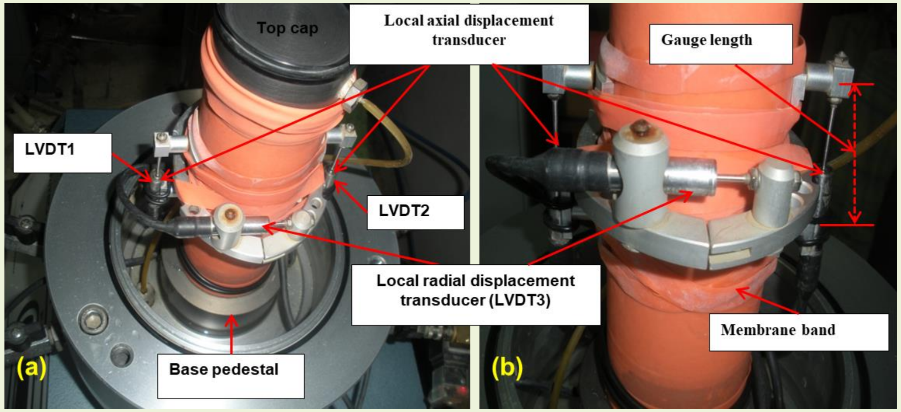
$$D = \frac{1}{4\pi} \times \frac{A_L}{A_\Delta}$$

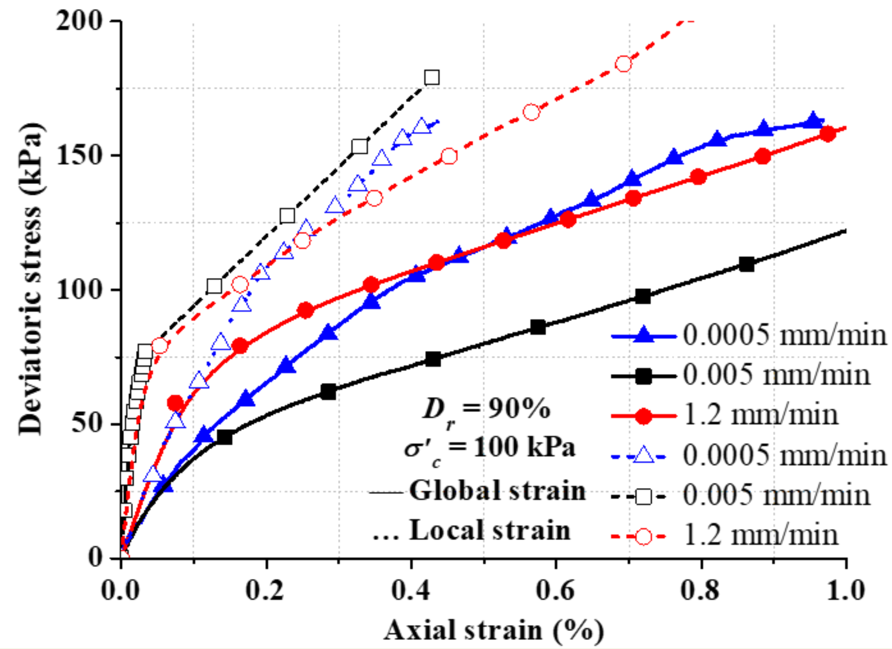
Asymmetrical hysteresis loop

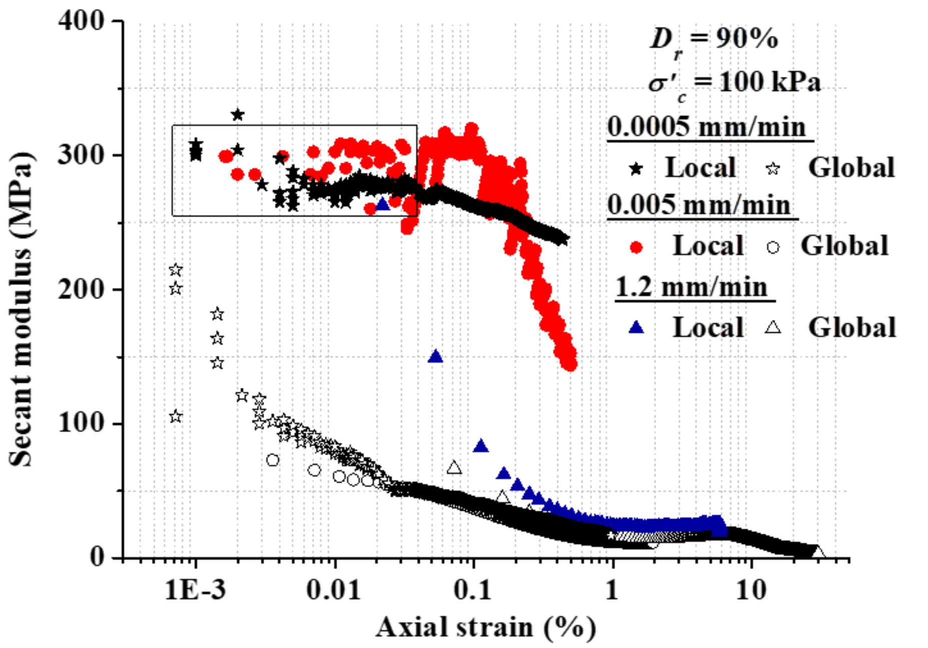
$$D^{\#} = \frac{1}{\pi} \times \frac{A_{L(o-a-b-c-d)}}{A_{\Delta 1} + A_{\Delta 2} + A_{\square}}$$

Local Response using On-Sample LVDTs

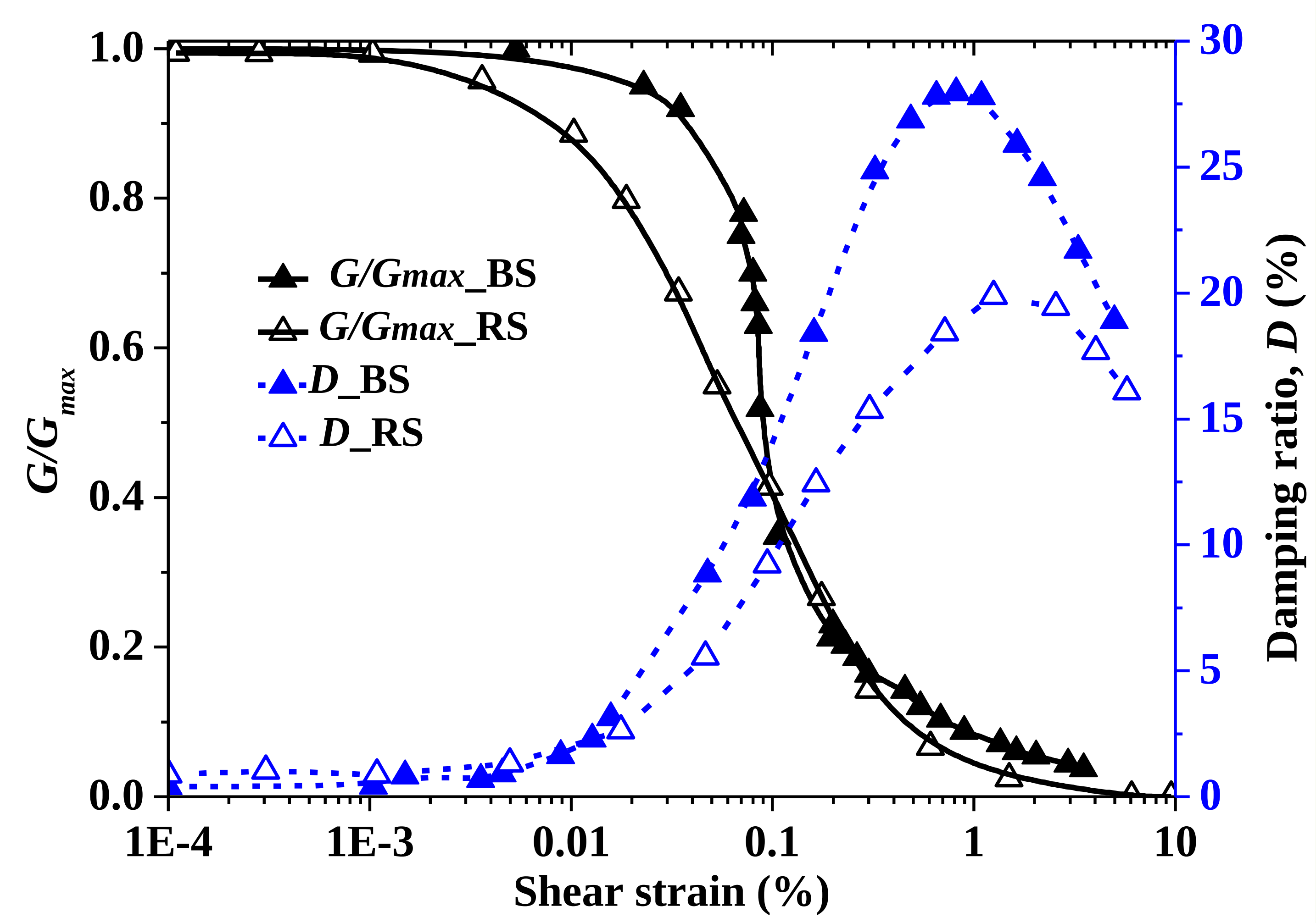
- *Soil properties using on-sample LVDTs*
  - On-sample LVDTs measure local axial strain
    - 50 - cyclic triaxial tests conducted







Material Curves for BS and RS

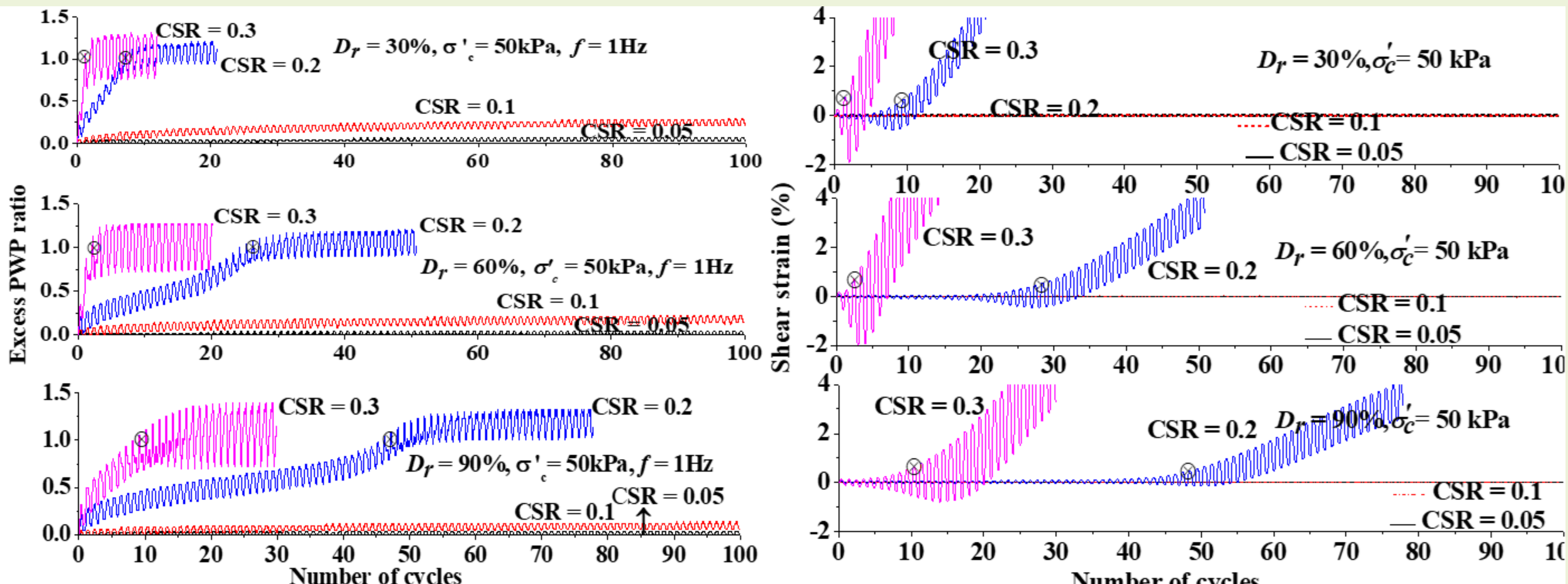


Evaluated material curves for BS and RS can be used in further GRA studies

Liquefaction Studies on Saturated BS

- Stress-controlled regular excitations

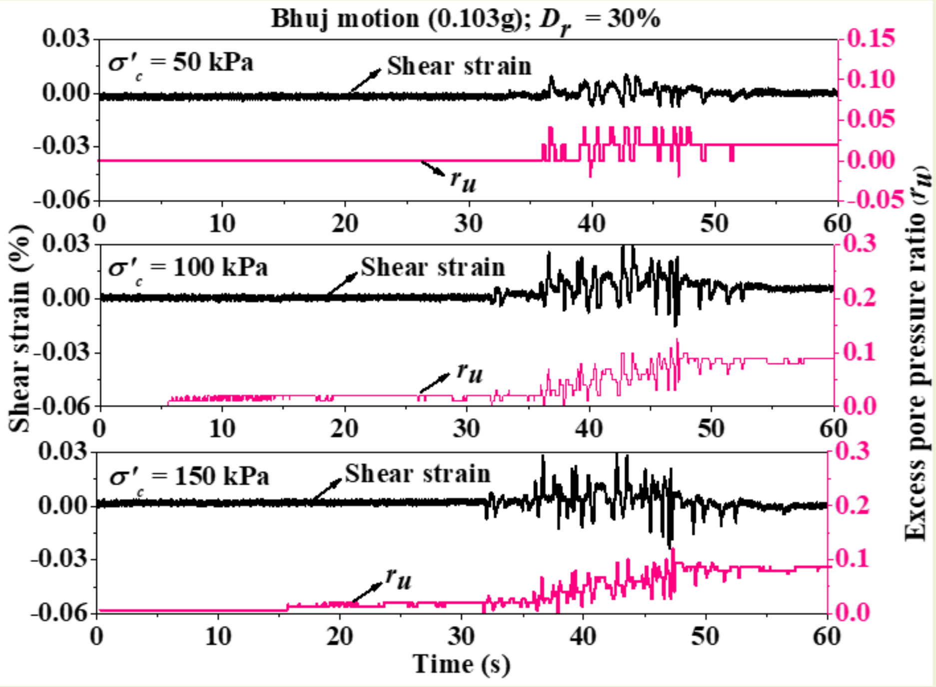
CSR	D_r(%)	σ'_c (kPa)	N for liquefaction	γ_{max} (%)
0.05, 0.1, 0.2, 0.3		50	NL, NL, 8, 2	0.02, 0.02, 0.75, 1.4
0.1, 0.2, 0.3	30	100	125, 4, 1.5	0.6, 2.5, 1.5
0.1, 0.2		200	62, 3	1.5, 2.0
	30		NL, NL, 10, 2	0.02, 0.02, 0.5, 1.4
0.05, 0.1, 0.2, 0.3	60	50	NL, NL, 30, 3	0.02, 0.02, 1.0, 1.0
	90		NL, NL, 50,10	0.02, 0.02, 1.0, 1.0

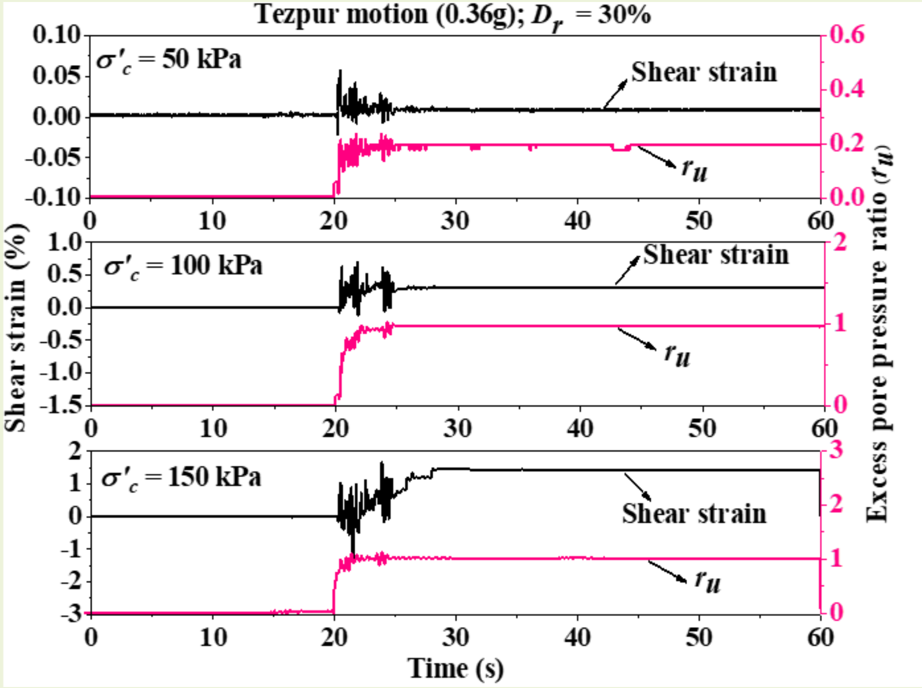


Liquefaction Studies on Saturated BS

- Stress-controlled irregular excitations

CSR	D_r (%)	σ'_c (kPa)	N for liquefaction	γ_{max} (%)
0.05, 0.1, 0.2, 0.3	30	50	NL, NL, 8, 2	0.02, 0.02, 0.75, 1.4
0.1, 0.2, 0.3		100	125, 4, 1.5	0.6, 2.5, 1.5
0.1, 0.2		200	62, 3	1.5, 2.0
0.05, 0.1, 0.2, 0.3	30	50	NL, NL, 10, 2	0.02, 0.02, 0.5, 1.4
	60		NL, NL, 30, 3	0.02, 0.02, 1.0, 1.0
	90		NL, NL, 50,10	0.02, 0.02, 1.0, 1.0





Liquefaction Criteria for Saturated BS

- **BS (D_r = 30%-90%) liquefy under the following optimum conditions**
  - **PGA ≥ 0.36g**
  - **CSR ≥ 0.3**
  - **γ_{max} > 0.5%**
  - **Limiting value of γ = 0.5% is to be adopted for liquefaction evaluation study for BS soil at loose condition**
  - **Limiting value of γ = 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

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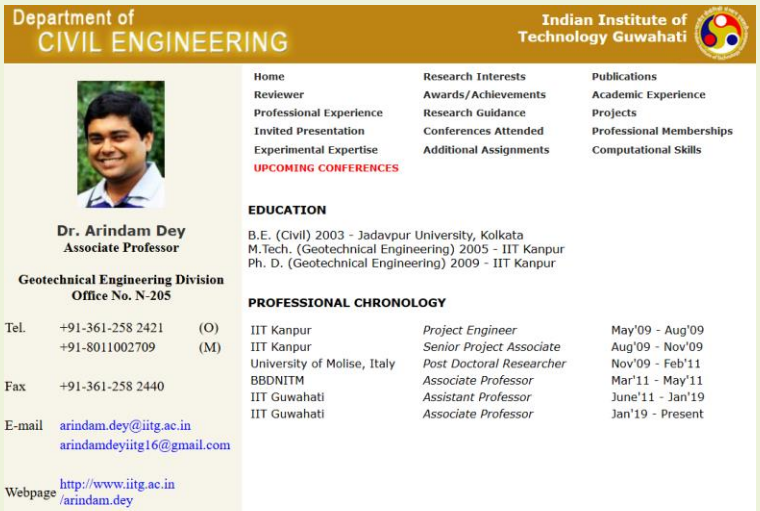
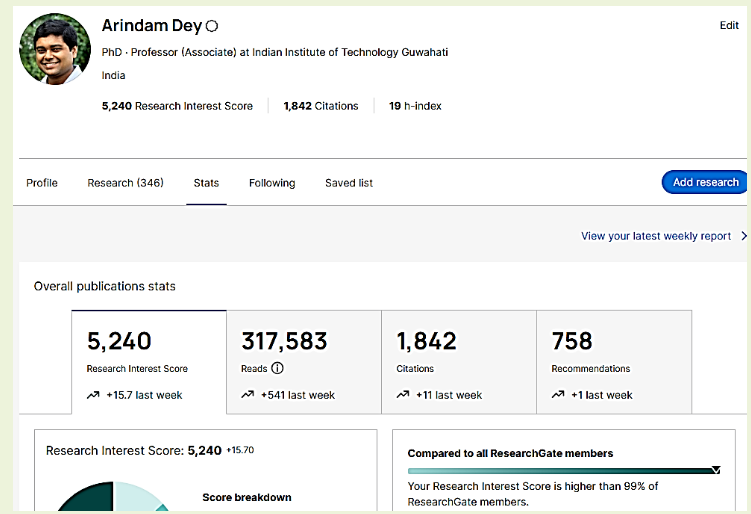
Selected Publications

- Kumar, S. S., Murali Krishna, A. and **Dey, A.** (2018) *Local strain measurements in triaxial tests using on-sample transducers* in ***Geotechnical Characterisation and Geoenvironmental Engineering, Lecture Notes in Civil Engineering*** *Vol. 16*, Ed. V. K. Stalin, M. Muttharam, Springer, Singapore, pp. 93-101: ISBN No. 978-981-13-0899-4.
- Kumar, S. S., Murali Krishna, A. and **Dey, A.** (2018) "Dynamic properties and liquefaction behaviour of cohesive soil of Northeast India under staged cyclic loading" ***Journal of Rock Mechanics and Geotechnical Engineering*** (DOI: 10.1016/j.jrmge.2018.04.004)
- Kumar, S. S., **Dey, A.** and Murali Krishna, A. (2018) "Response of Saturated Cohesionless Soil Subjected to Irregular Seismic Excitations" ***Natural Hazards***, Vol. 93, Iss. 1, pp. 509-529 (DOI: 10.1007/s11069-018-3312-1)
- Kumar, S. S., **Dey, A.** and Murali Krishna, A. (2018) "Importance of site-specific dynamic soil properties for seismic ground response studies" ***International Journal of Geotechnical Earthquake Engineering***, Vol. 9, Iss. 1, pp. 78-98. (DOI: 10.4018/IJGEE.2018010105)
- Basu, D., **Dey, A.** and Kumar, S. S. (2017) "One-dimensional effective stress non-Masing nonlinear ground response analysis of IIT Guwahati" ***International Journal of Geotechnical Earthquake Engineering***, Vol. 8, No. 1, pp. 1-27 (DOI: 10.4018/IJGEE.2017010101)
- Kumar, S. S., Murali Krishna, A. and **Dey, A.** (2017) "High strain dynamic properties of perfectly dry and saturated cohesionless soil" ***Indian Geotechnical Journal***, Vol. 48, Iss. 3, pp. 549-557. (DOI: 10.1007/s40098-017-0255-5)
- Kumar, S. S., Murali Krishna, A. and **Dey, A.** (2017) "Evaluation of dynamic properties of sandy soil under high cyclic strains" ***Soil Dynamics and Earthquake Engineering***, Vol. 97, pp. 157-167. (DOI: 10.1016/j.soildyn.2017.05.016)

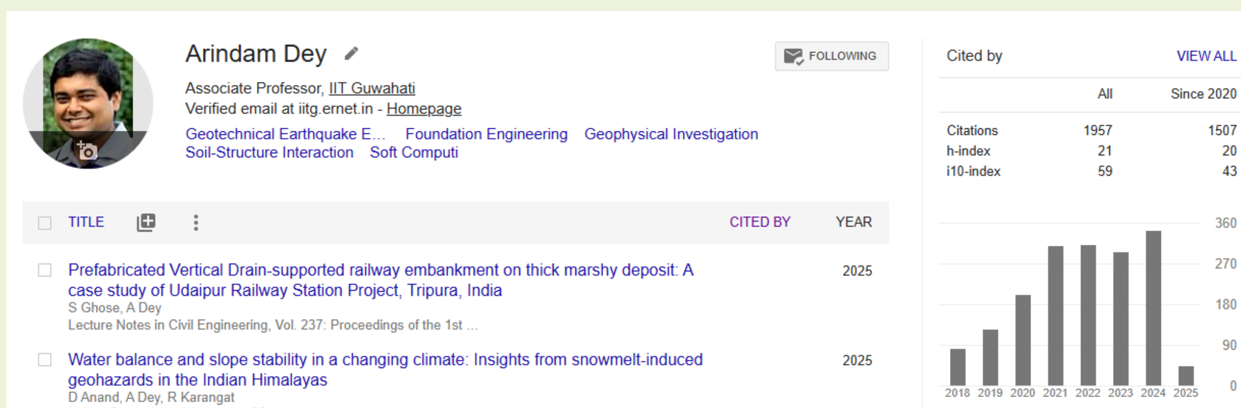
Further Interaction

- Webpage
- Researchgate





- Google Scholar



Thank You for Patient Hearing