Soil Dynamics

Module 4 : Dynamic Soil Properties – Cyclic Stress Ratio, Evaluation of CRR, Correction Factors, Corrections for SPT

Simplified Procedure for Liquefaction

→ Most basic procedure used in engineering practice for assessment of liquefaction potential is the "Simplified Procedure" originally by Seed and Idriss (1971), subsequently updated and refined (see Youd and Idriss, 1997, Youd et al. 2001 and Seed et al. 2003)

→ Compares a cyclic resistance ratio with the earthquake-induced cyclic stress ratio at a given depth for a specified design earthquake.

CRR: cyclic resistance ratio of the soil layer; cyclic stress ratio required to induce liquefaction for a cohesionless soil stratum of given properties at a given depth.

Simplified Procedure for Liquefaction

CSR: seismic demand on a soil layer; based on a peak ground surface acceleration and an associated moment magnitude.

→ Allows a factor of safety against liquefaction, FS_I , to be calculated for a soil stratum at a given depth.

$$FS_I = \frac{CRR_{7.5}}{CSR}$$

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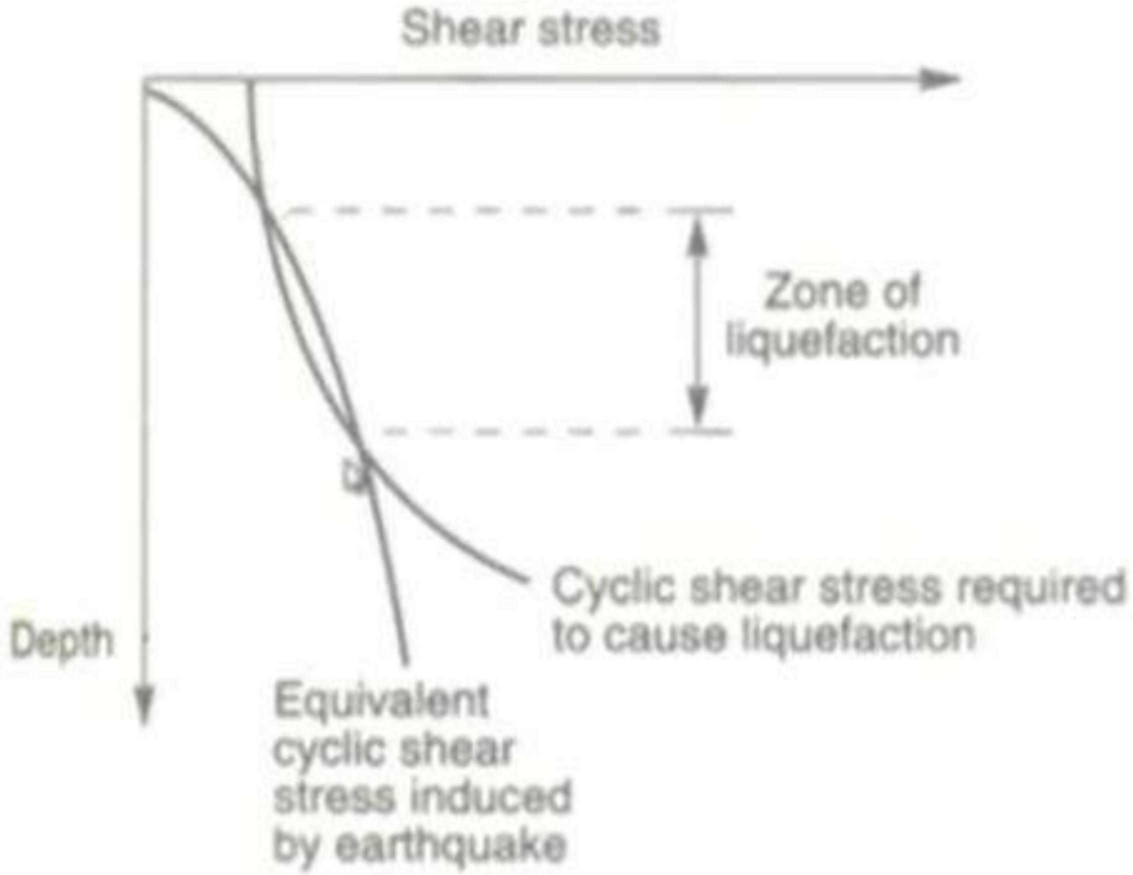
Liquefaction (contd.)



Process by which zone of liquefaction is identified.

Acceptable Factor of Safety

- 1.3 is recommended, but depends on severity of hazard, importance and vulnerability of structure, tolerable settlements or level of risk acceptable to owner or regulating body, confidence and certainty in underlying data and assumptions

- Lower factor of safety (1.1) may be acceptable for single family dwellings, for example, where potential for lateral spreading is low and differential settlement is hazard of concern, where post-tensioned floor slabs are specified.

Cyclic Stress Ratio (CSR)

- Seismic demand on a soil layer

Equation formulated by Seed and Idriss (1971)

$$CSR = \left(\frac{\tau_{av}}{\sigma'_{v0}}\right) = 0.65.\left(\frac{a_{max}}{g}\right)\left(\frac{\sigma_{v0}}{\sigma'_{v0}}\right).r_d$$

a_{max} = peak horizontal acceleration at the ground surface generated by the earthquake

g = acceleration due to gravity

σ_{v0} = total vertical overburden stress

σ'_{v0} = effective vertical overburden stress

r_d = stress reduction co-efficient (flexibility of the soil)

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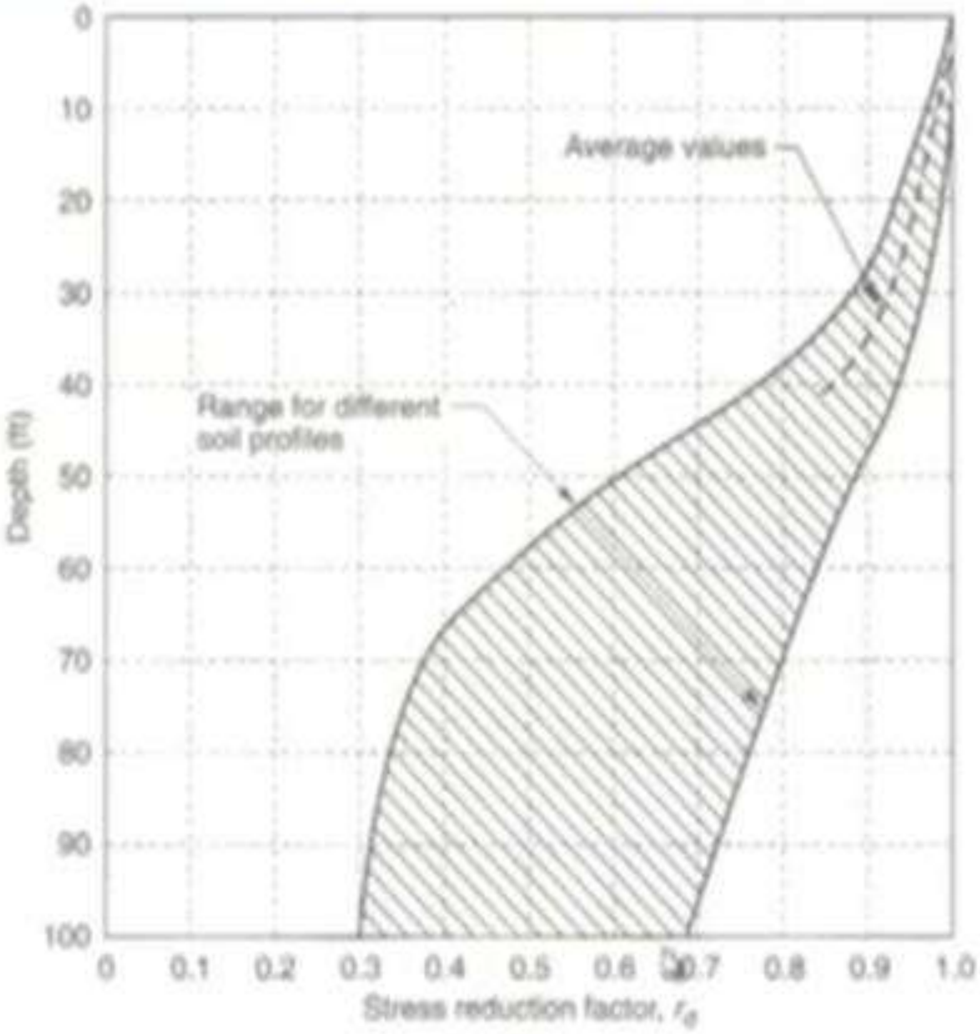
Liquefaction (contd.)

Stress Reduction factor to estimate the variation of cyclic shear stress with depth below level or gently sloping ground surfaces.

(after Seed and Idriss, 1971.)



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Liquefaction (contd.)

Stress Reduction Coefficient, r_d

→ For routine practice for noncritical projects, use Liao and Whitman (1986) equations,

$\mathbf{r_d = 1.0 - 0.00765z}$ for $z \leq 9.15\text{m}$

$\mathbf{r_d = 1.174 - 0.0267z}$ for $9.15\text{m} < z \leq 23\text{m}$

→ New procedures are under development and verification (Robertson and Wride 1998, Seed et al. 2003) but uncertainty remains

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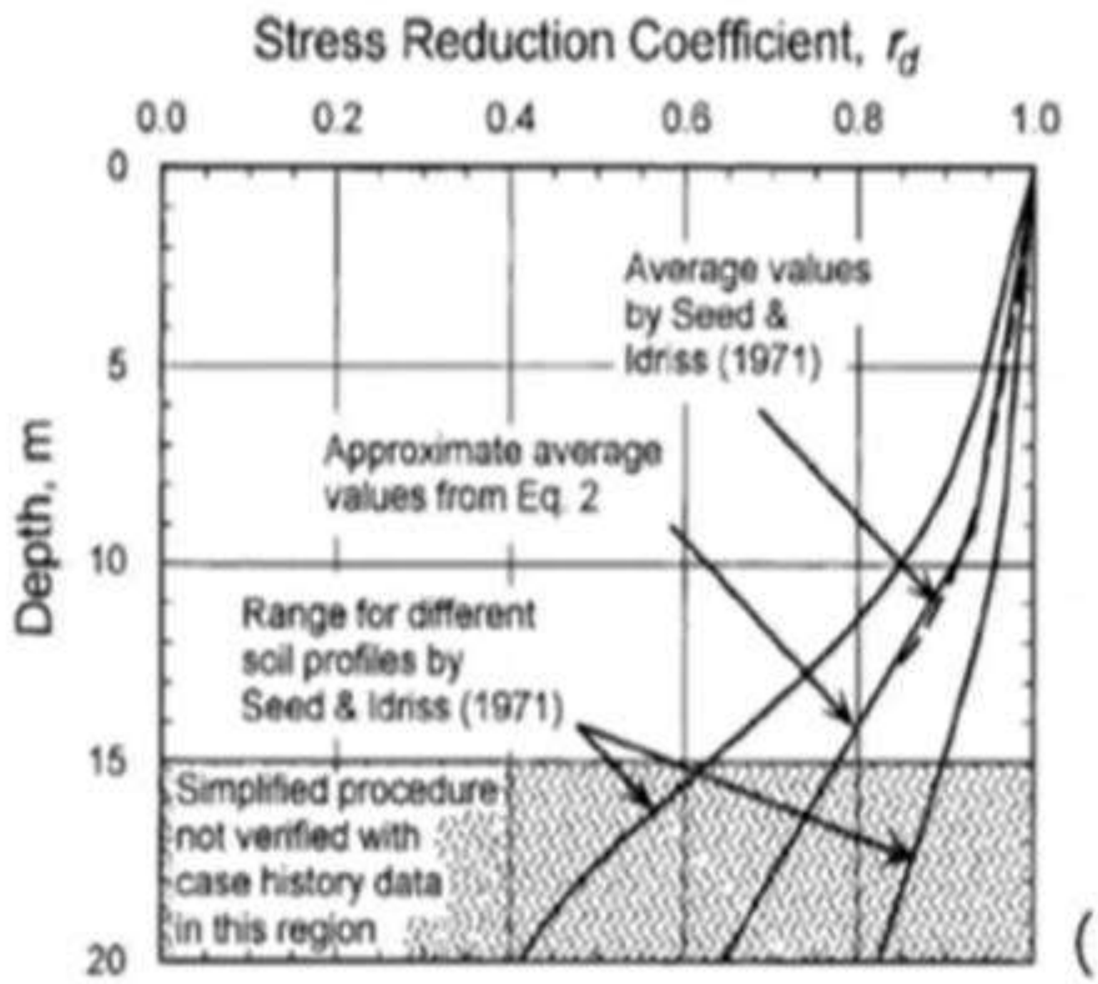


(Blake, 1996)

$$r_d = \frac{(1.000 - 0.4113z^{0.5} + 0.04052z + 0.001753z^{1.5})}{(1.000 - 0.4177z^{0.5} + 0.05729z - 0.006205z^{1.5} + 0.001210z^{2})}$$

From Youd et al. (2001)

Evaluation of CRR

→ Cyclic resistance of a layer; cyclic stress required to induce liquefaction

→ Based on semi-empirical correlations from database of field experience of sites which did not liquefy; using values of SPT $N_{1,60cs}$ or CPT q_{c1Ncs} or V_{s1}

→ The charts are developed for moment magnitude 7.5, any other magnitude requires a correction

→ Corrections are also required for overburden stress and presence of a driving static shear stress (a slope)

Corrections to CRR

Regardless of the investigative method, three corrections should be applied to the CRR

- Magnitude correction, k_M
- Overburden correction, k_σ
- Sloping ground (driving static shear stress) correction, k_α

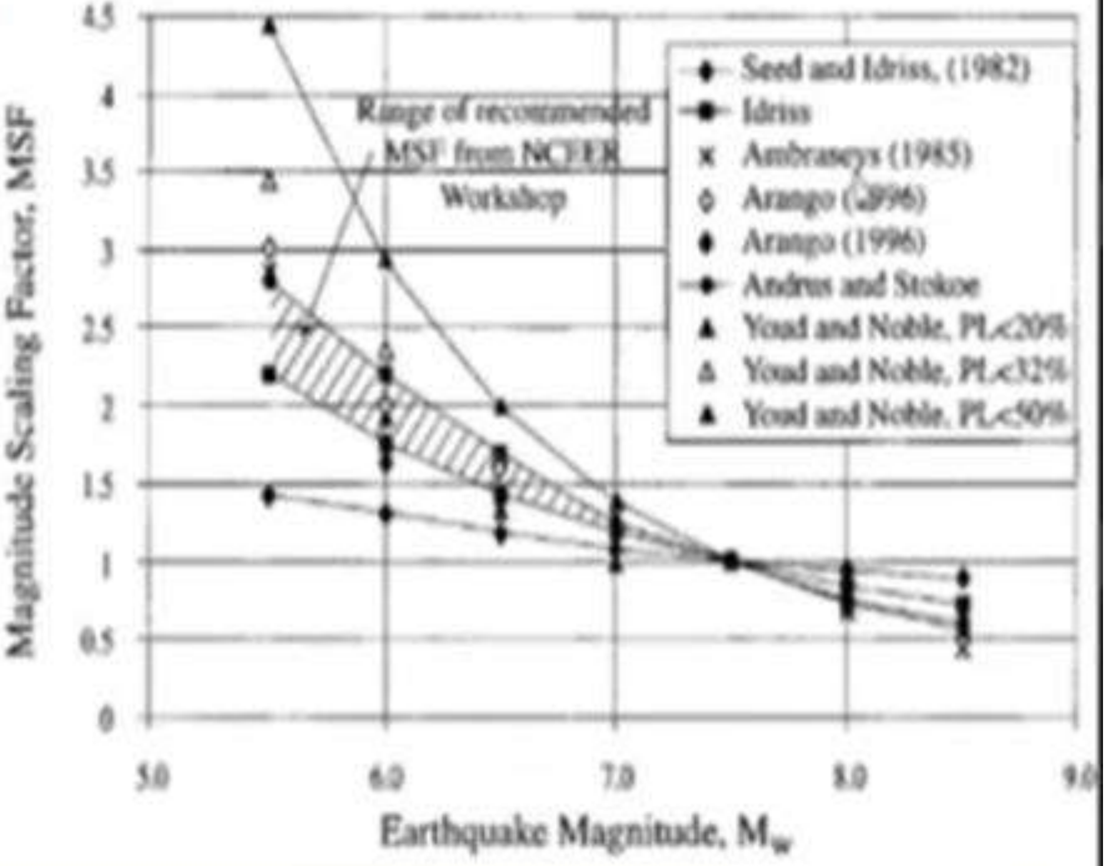
$$FS_1 = \frac{CRR_{7.5}}{CSR} = \frac{CRR \cdot k_M \cdot k_\sigma \cdot k_\alpha}{CSR}$$

Magnitude Correction Factor, k_M

Empirical correlations are based on moment magnitude 7.5; for any other magnitude, a correction is required.

$$MSF = \frac{10^{2.24}}{M_w^{2.56}}$$

[After Youd et al. (2001)]



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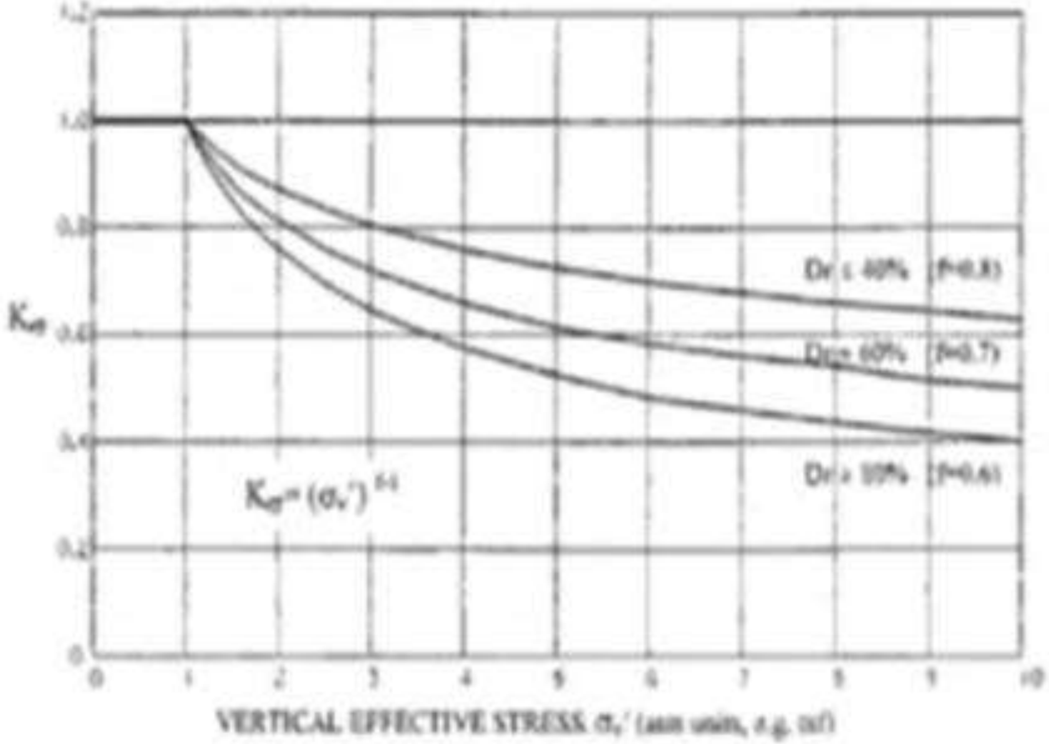
Overburden Correction Factor, k_σ

→Laboratory tests indicate that liquefaction resistance increases (nonlinearly) with increasing confining stress

→A correction for overburden stress is recommended

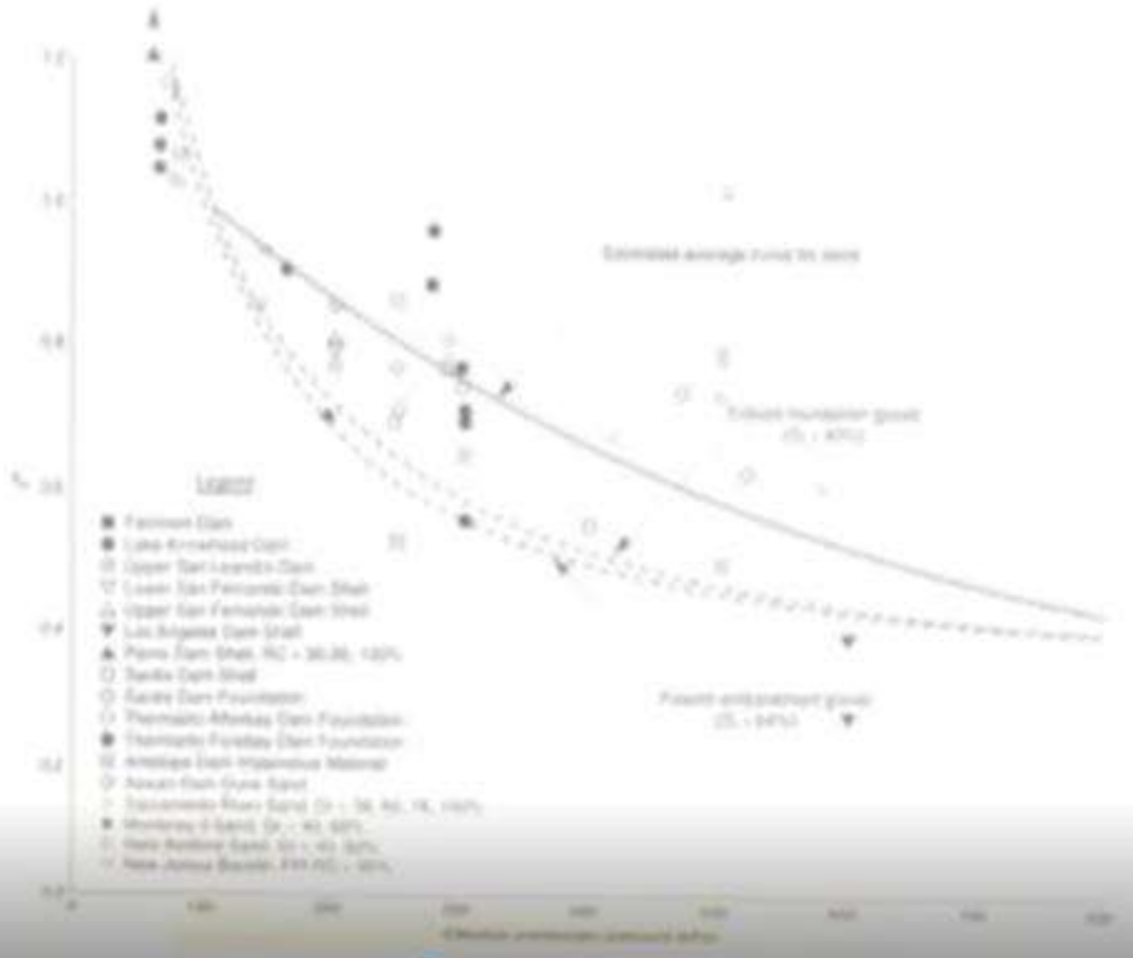
$k_\sigma = (\sigma_v')^{f-1}$

The exponent f is function of site condition, relative density, stress history, aging.



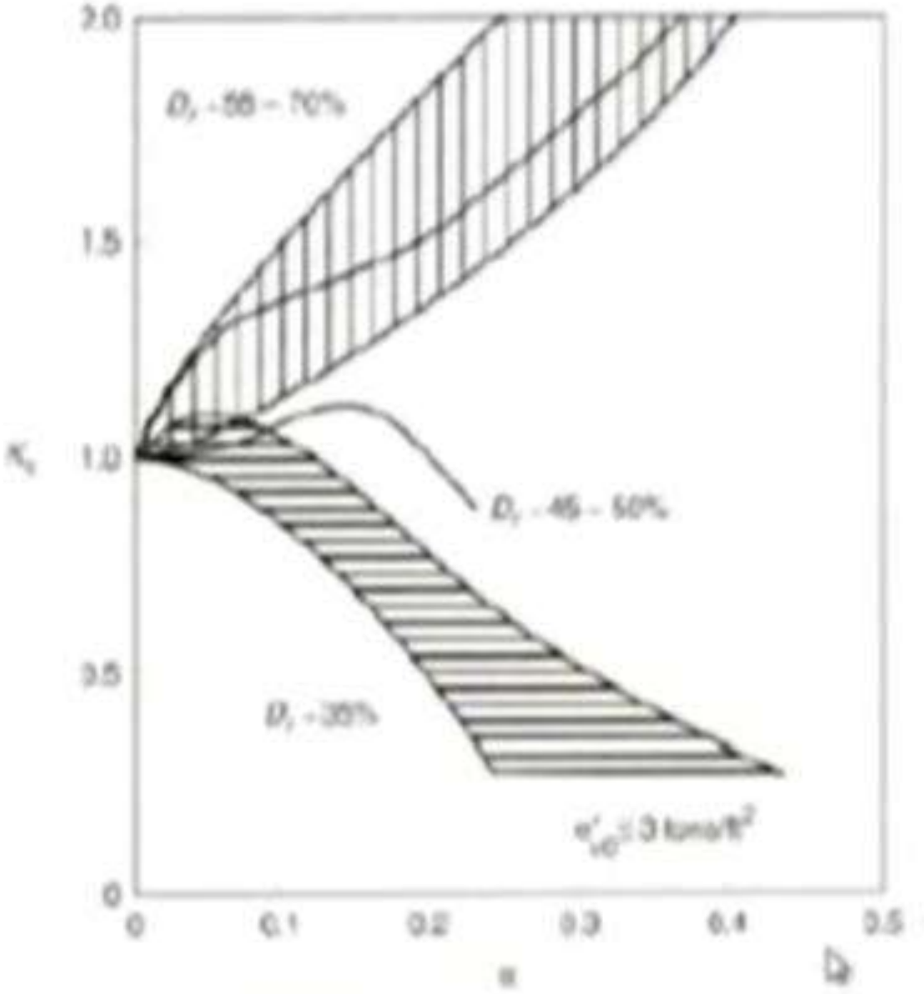
[After Youd et al. (2001)]

Overburden Correction Factor, k_σ



Variation of correction factor, K_σ , with effective overburden pressure. [After Marcuson et al. (1990)]

Sloping Ground Correction Factor, k_α



After Youd et al. (2001)

Measurement of G_{max}

Usually accomplished by measuring shear wave velocity (V_s)

$$G_{max} = \rho V_s^2$$

(1) Direct field measurement

- Seismic reflection
- Seismic refraction
- Seismic cross-hole
- Seismic downhole, uphole
- SASW, MASW
- Suspension logger

(2) Indirect field measurement

- Correlation to $(N_1)_{60}$, q_{c1}, etc.

(3) Laboratory measurement

- Resonant column
- Bender element
- Cyclic triaxial, shear, torsion tests

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Use of SPT Result for Liquefaction

- Standard penetration test (SPT) consists of driving a thick-walled sampler into a granular soil deposit
- Generally, should be used only for cohesionless soils; it is not applicable for soils with plastic fines or gravels
- SPT gives a measure of in situ density
- Corrected SPT "N" values are widely used in semiempirical estimation of liquefaction

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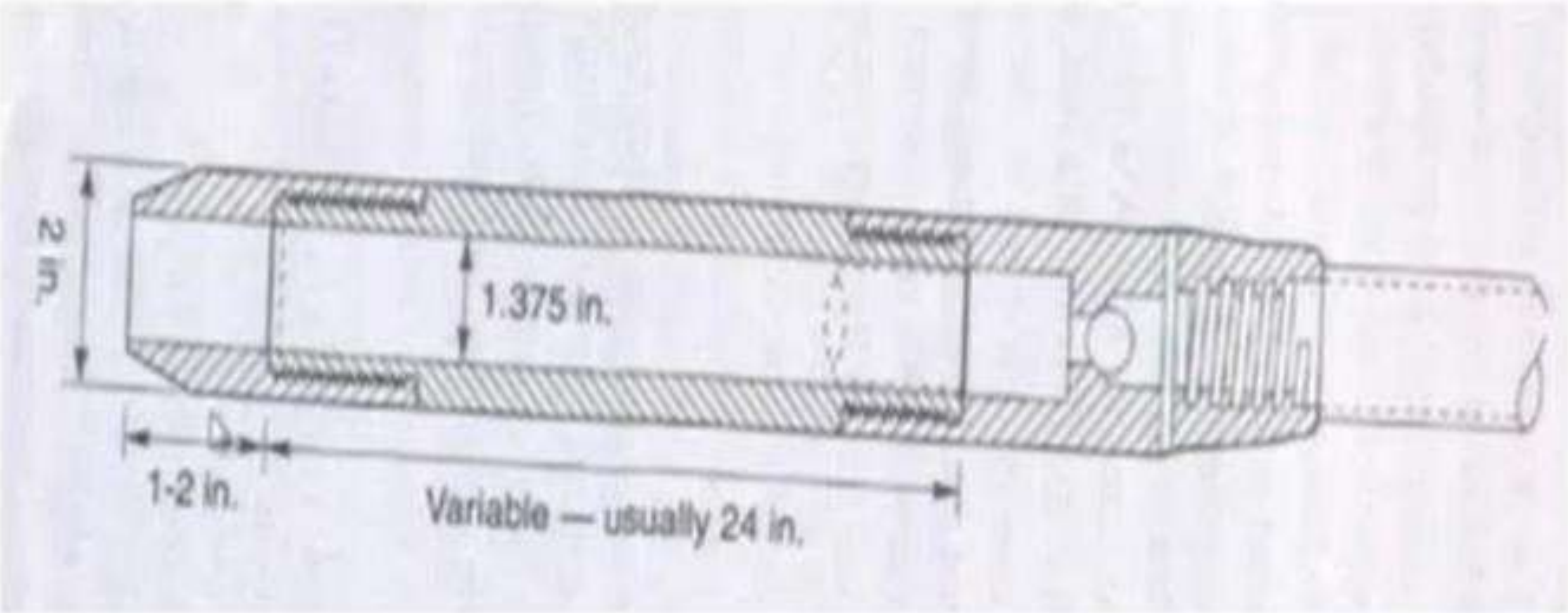
Specifications for SPT

- Sampler: Per ASTM D 1586-99 (2000), SPT sampler has an inside barrel of diameter D = 3.81 cm (1.5 in) and an outside diameter F = 5.08 cm (2 in)
- Driving hammer: 63.5 kg (140 lb) hammer falling a distance of 0.76 m (30 in)
- Driving distance and rate: total of 45 cm (18 in), with number of blows recorded for each 15 cm (6 in) interval, at a rate of 30-40 blows per minute
- Gives a measured SPT Value which is the total number of blows required to drive the hammer through the last 30 cm

SPT Sampler Tube



Corrections for SPT

A number of corrections are recommended to convert the N value measured in the field to a corrected and normalized $(N_1)_{60}$ value

$$(N_1)_{60} = N_M C_N C_E C_B C_R C_S$$

where,

N_M = measured standard penetration resistance

C_N = depth or overburden correction factor

C_E = hammer energy ratio (ER) correction factor

C_B = borehole diameter correction factor

C_R = rod length correction factor

C_S = correction factor for samplers with or without liners

Sources: Youd and Idriss (1997), Martin and Lew (1999)

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Overburden Correction for SPT

$$(N_1)_{60} = N_M C_N C_E C_B C_R C_S$$

$$C_N = \left(\frac{P_a}{\sigma_{v0}} \right)^{0.5}$$

$P_a = 100$ kPa

$0.4 \le C_N \le 1.7$

Normalized to an effective overburden pressure of 100 kPa (1.044 tsf). This normalized blow count is designated as N_1.

Note: use σ'_{V0} at time of drilling (not as-built)

Energy Correction for SPT

$$(N_1)_{60} = N_M C_N C_E C_B C_R C_S$$

$$C_E = \frac{ER(\%)}{60}$$

- Most important factor affecting SPT results is the ENERGY delivered to the sampler (measure it if possible)
- Depends primarily on the type of hammer/anvil system and the method of hammer release (hammer strikes rod eccentrically, lack of hammer free fall, new stiff rope, more than two turns around cathead, incomplete release of rope each drop...)
- Expressed in terms of the rod energy ratio (ER)
- ER of 60% has generally been accepted as the reference value (safety hammer, N.A. practice)

Testing Procedure Corrections for SPT

$$(N_1)_{60} = N_M C_N C_E C_B C_R C_S$$

- Borehole Diameter Correction, C_B - larger gives lower N_M

  C_B = 1 for 65-115 mm diameter (preferred dia.)

  C_B = 1.05 for 150 mm diameter

  C_B = 1.15 for 200 mm diameter

- Short Rod Correction, C_R - shorter drill rods give higher N_M

  C_R = 0.75 for rod length less than 4m

  C_R = 0.85 for 4m to 6m rod length

  C_R = 0.95 for 6m to 10m rod length

  C_R = 1 for rod length between 10m and 30m

- Missing Sampling Liner correction, C_S

  C_S = 1.2 for sampler without liners

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Summary of SPT Corrections

[after Youd et al. (2001)]

Factor	Equipment variable	Term	Correction
Overburden pressure	—	C_N	$(P_a/\sigma'_{vo})^{0.5}$
Overburden pressure	—	C_N	$C_N \leq 1.7$
Energy ratio	Donut hammer	C_E	0.5–1.0
Energy ratio	Safety hammer	C_E	0.7–1.2
Energy ratio	Automatic-trip Donut-type hammer	C_E	0.8–1.3
Borehole diameter	65–115 mm	C_B	1.0
Borehole diameter	150 mm	C_B	1.05
Borehole diameter	200 mm	C_B	1.15
Rod length	<3 m	C_R	0.75
Rod length	3–4 m	C_R	0.8
Rod length	4–6 m	C_R	0.85
Rod length	6–10 m	C_R	0.95
Rod length	10–30 m	C_R	1.0
Sampling method	Standard sampler	C_S	1.0
Sampling method	Sampler without liners	C_S	1.1–1.3

SPT as per Indian Standard of Practice

- Note that the Indian Standard (IS 2131 – 1981) recommends corrections for only overburden and dilatancy (fines below the water table).

- If any deviations from the standard procedure are made, it is necessary to make the aforementioned correction, especially the energy correction and the short rod correction.

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SPT Fines Correction for Liquefactio

If the SPT $(N_1)_{60}$ values are to be used in the simplified liquefaction triggering analyses, the values must be converted to equivalent clean sand values. If the fines content is greater than 5%, use the following correction

$$\left(N_1\right)_{60,CS} = \left(N_1\right)_{60} C_{FINES}$$

where,

$$C_{FINES} = \left(1 + 0.004 FC\right) + 0.05 \frac{FC}{N_{1,60}}$$

which is valid for fines contents (FC) less than 35%

SPT in Gravel

- Limited effectiveness, at best, because of the large size of particles compared to size of sampler
- Often, misleadingly high values are obtained. As a general rule, any SPT N value over 50 should be thrown out (of liquefaction analysis)
- Can look at incremental (i.e., per inch blow counts), to distinguish between N values obtained in matrix material vs. those affected by large particles
- Try another method (Becker Penetrometer)

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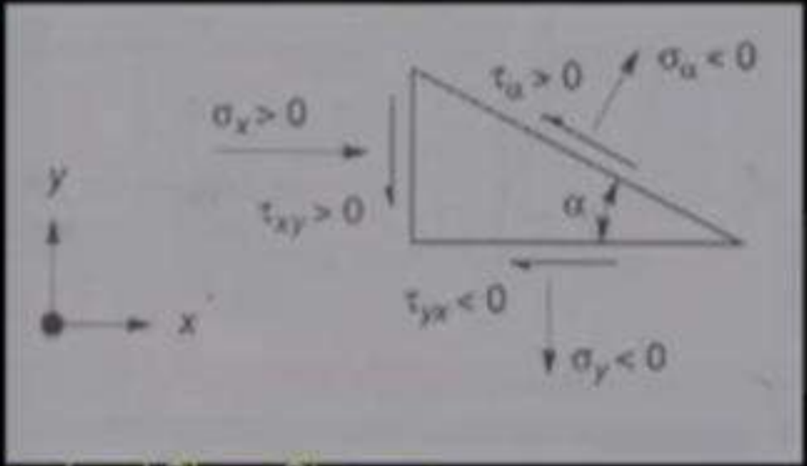
Mohr's Circle

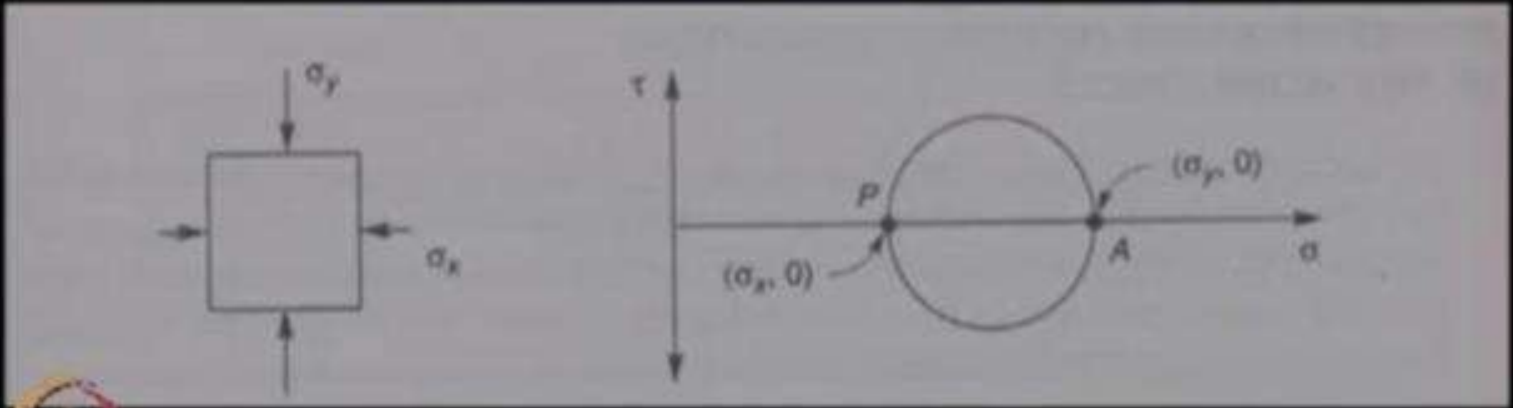
Representation of stresses in soil element
Stresses presented in 2D Mohr's Circle

$$\sigma_\alpha = \frac{\sigma_x + \sigma_y}{2} + \frac{\sigma_y - \sigma_x}{2}\cos 2\alpha - \tau_{xy}\sin 2\alpha$$

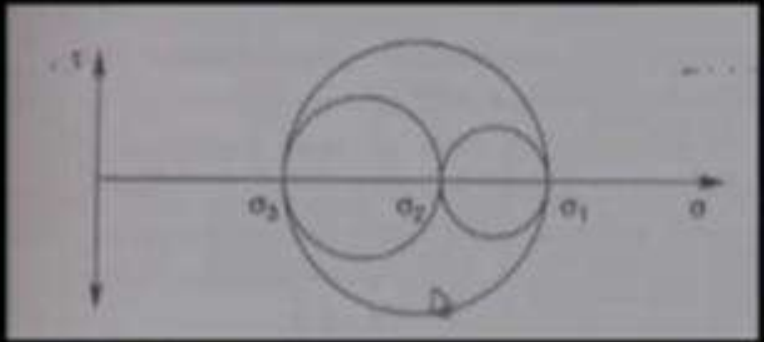
$$\tau_\alpha = \frac{\sigma_x - \sigma_y}{2}\sin 2\alpha - \tau_{xy}\cos 2\alpha$$



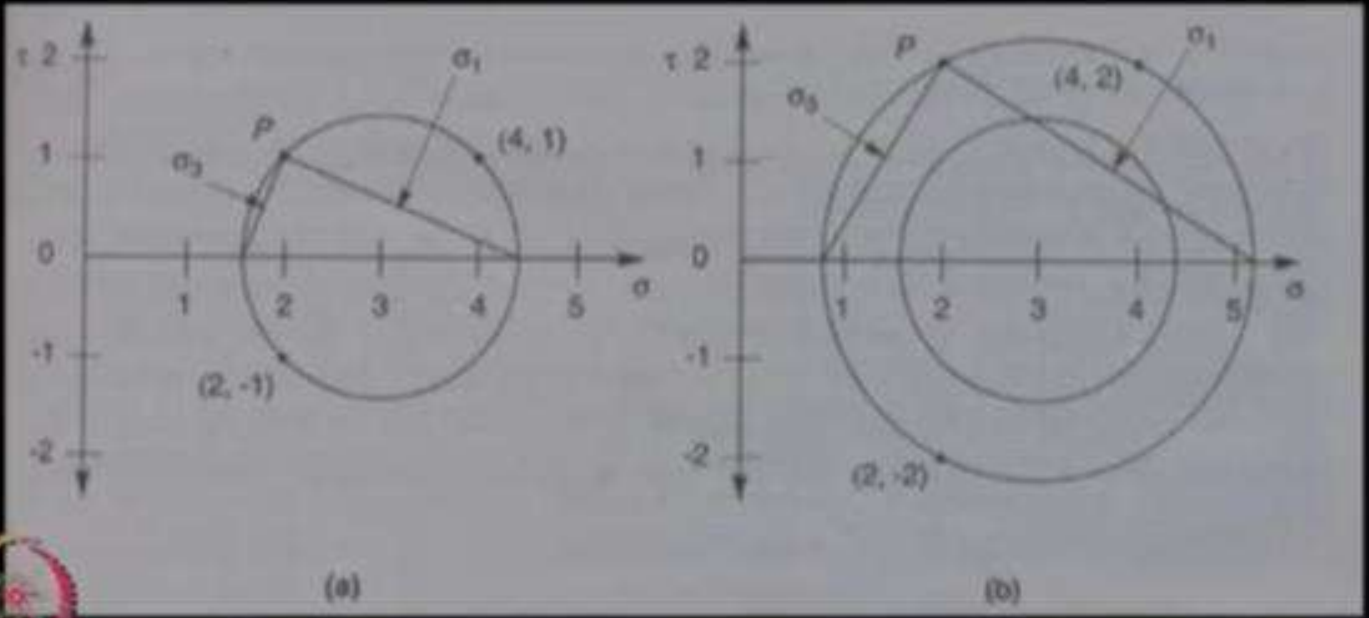
Sign conventions for Normal and Shear Stresses



's Circle of Stresses for element subjected to major principal stresses σ_y and minor principal stresses σ_x. Location of pole is denoted by P.



Mohr's Circle of Stresses including intermediate principal stress σ_2



Orientation of P. Stress Axes for a) $\tau_{xy} = 1$ and b) $\tau_{xy} = 2$. Note the rotation of P.

Important Soil Properties

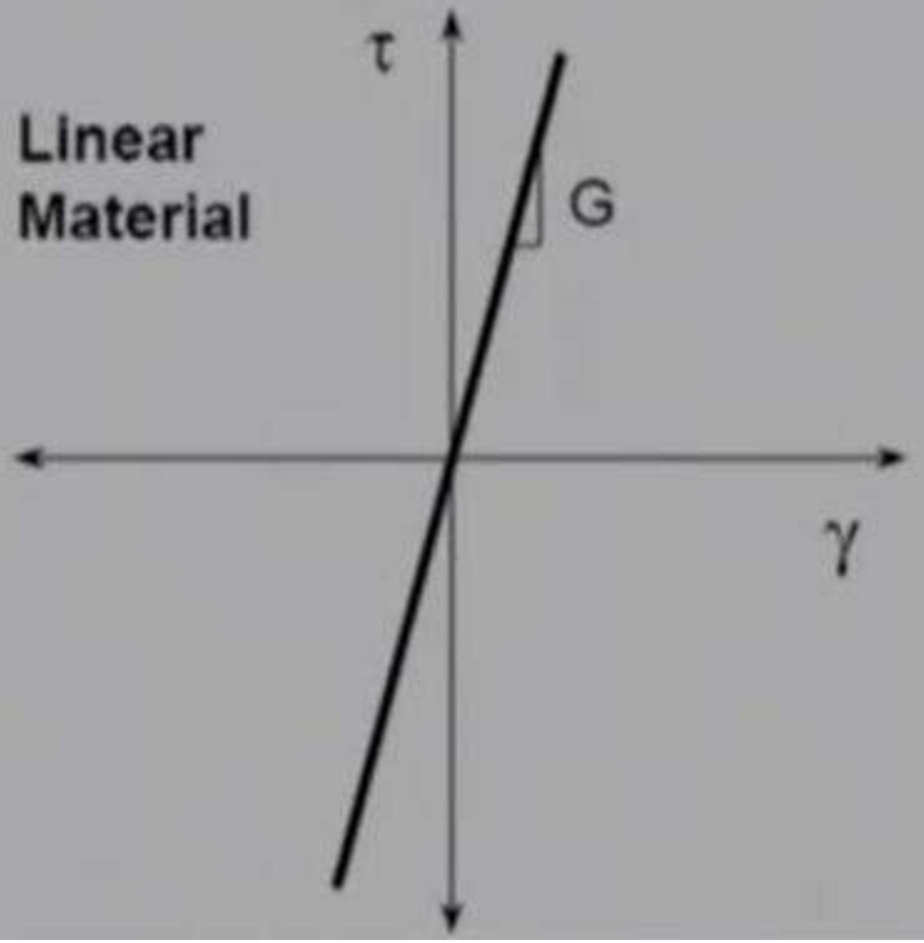
Density (Unit Weight) - Mass/Volume
(Weight/Volume)

Shear Modulus

Damping characteristics

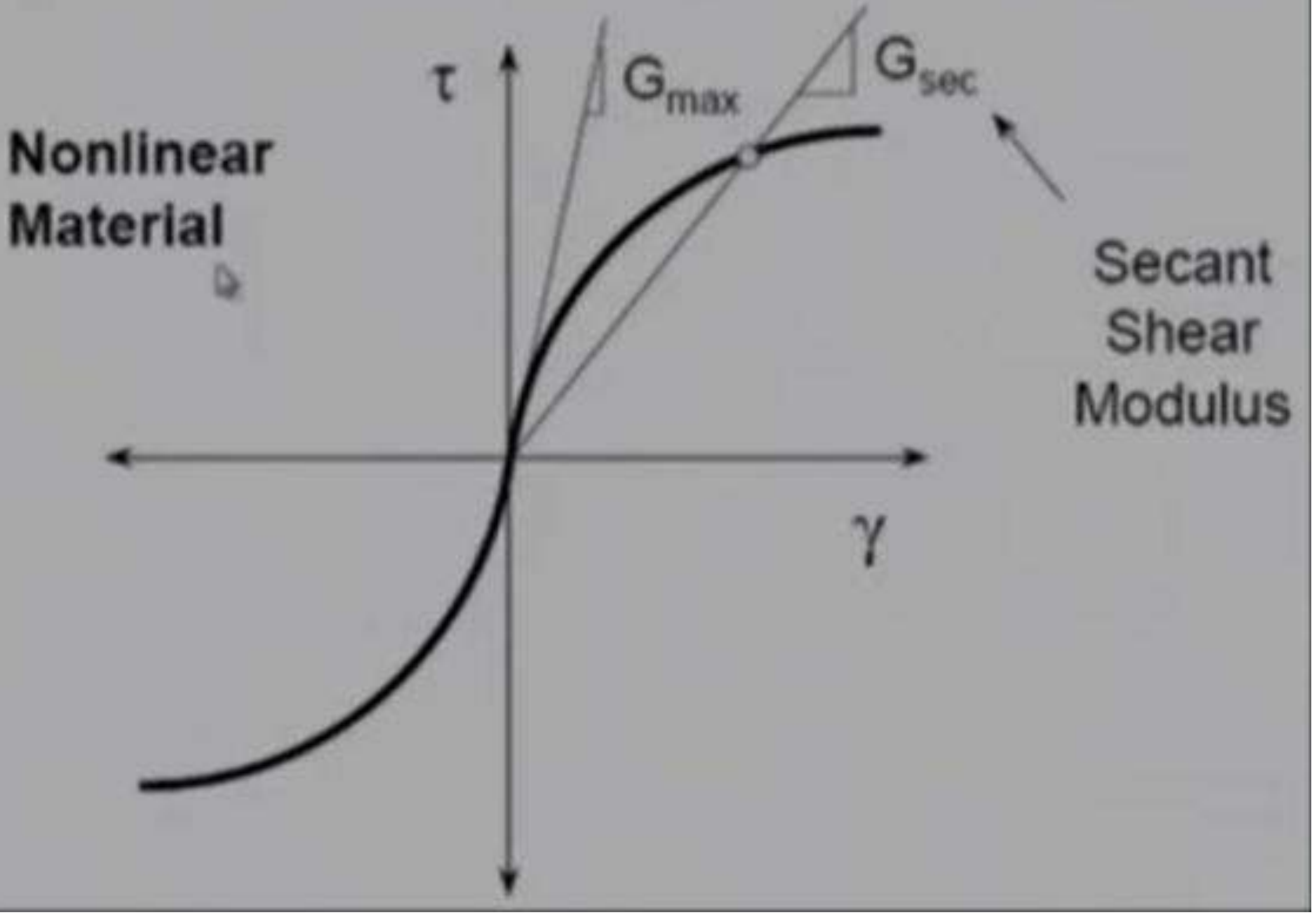
Shear Modulus

Defined as ratio of shear stress to shear strain



Shear Modulus

Defined as ratio of shear stress to shear strain



Shear Modulus

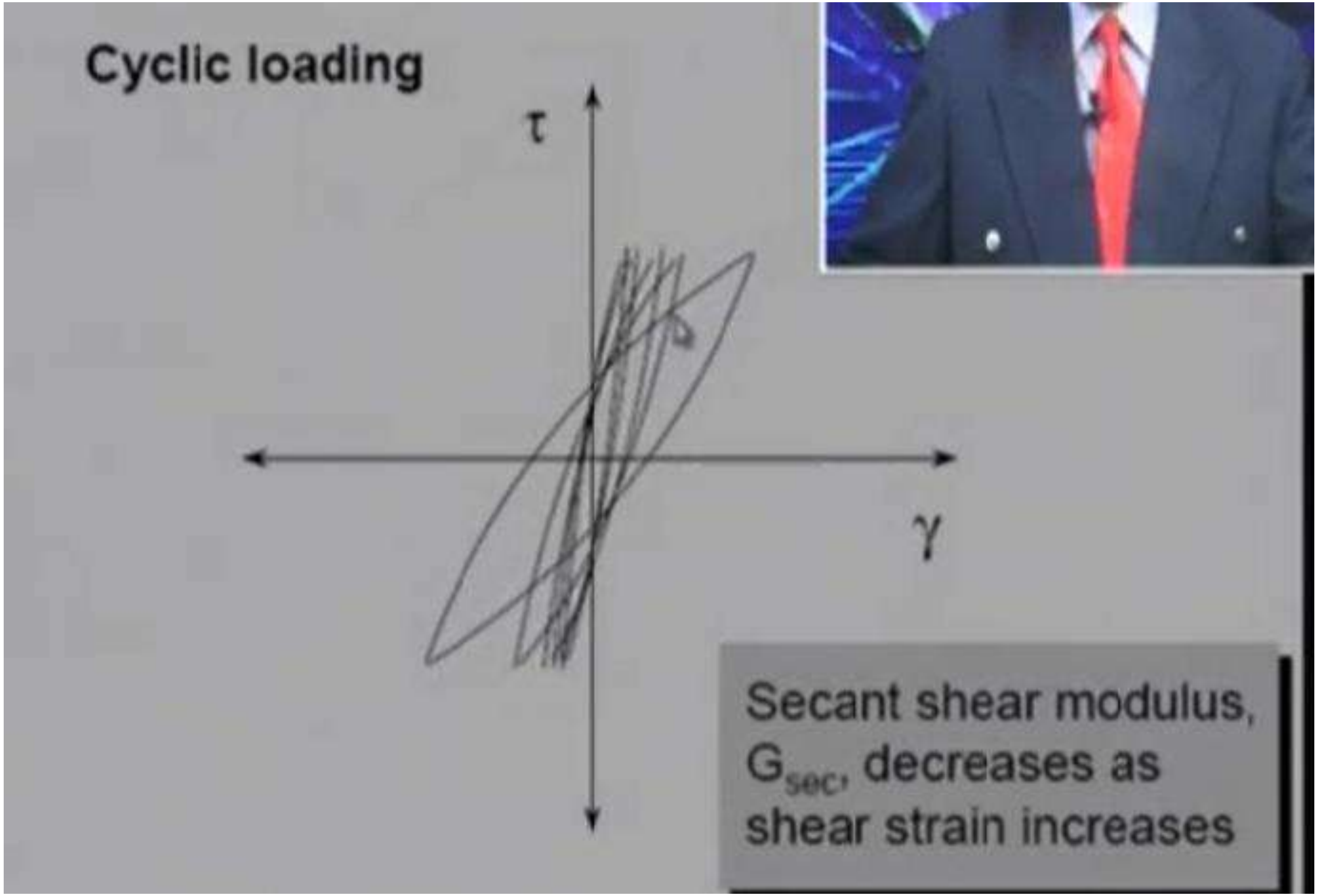
$$G_{sec} = \tau / \gamma$$

$$G_{tan} = d\tau / d\gamma$$

Which to use?

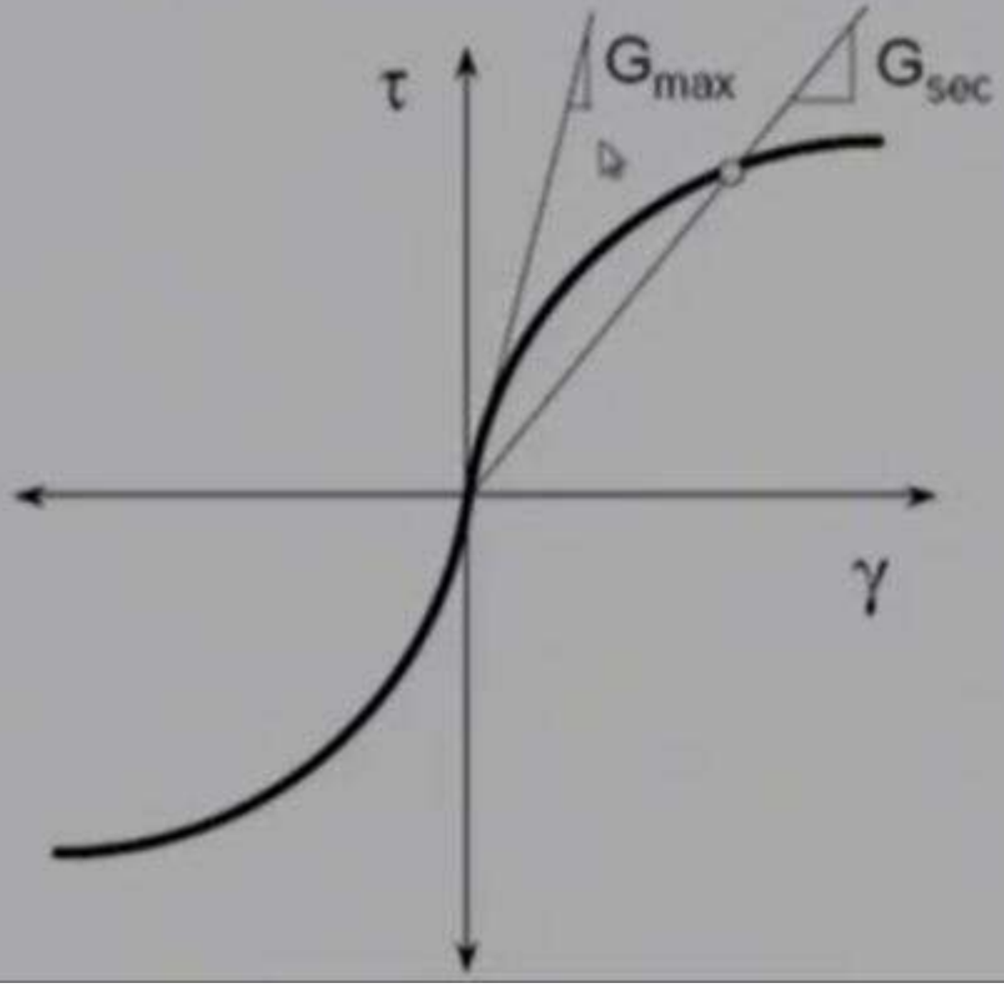
Equivalent linear analysis $\rightarrow$ G_{sec}

Nonlinear analysis $\rightarrow$ G_{tan}


Cyclic loading
τ
γ
Secant shear modulus, G_sec, decreases as shear strain increases

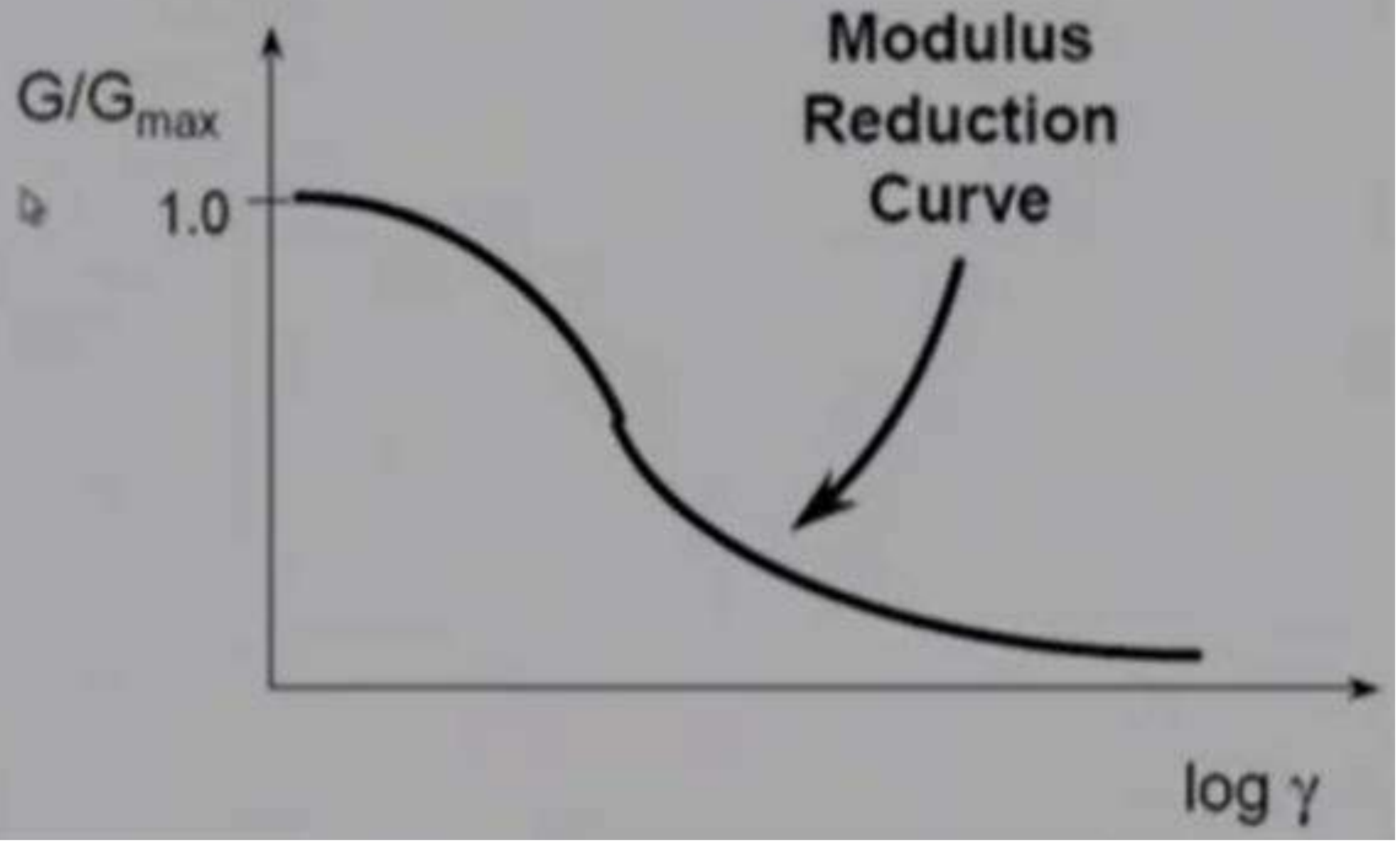
Shear Modulus

Equivalent linear approach



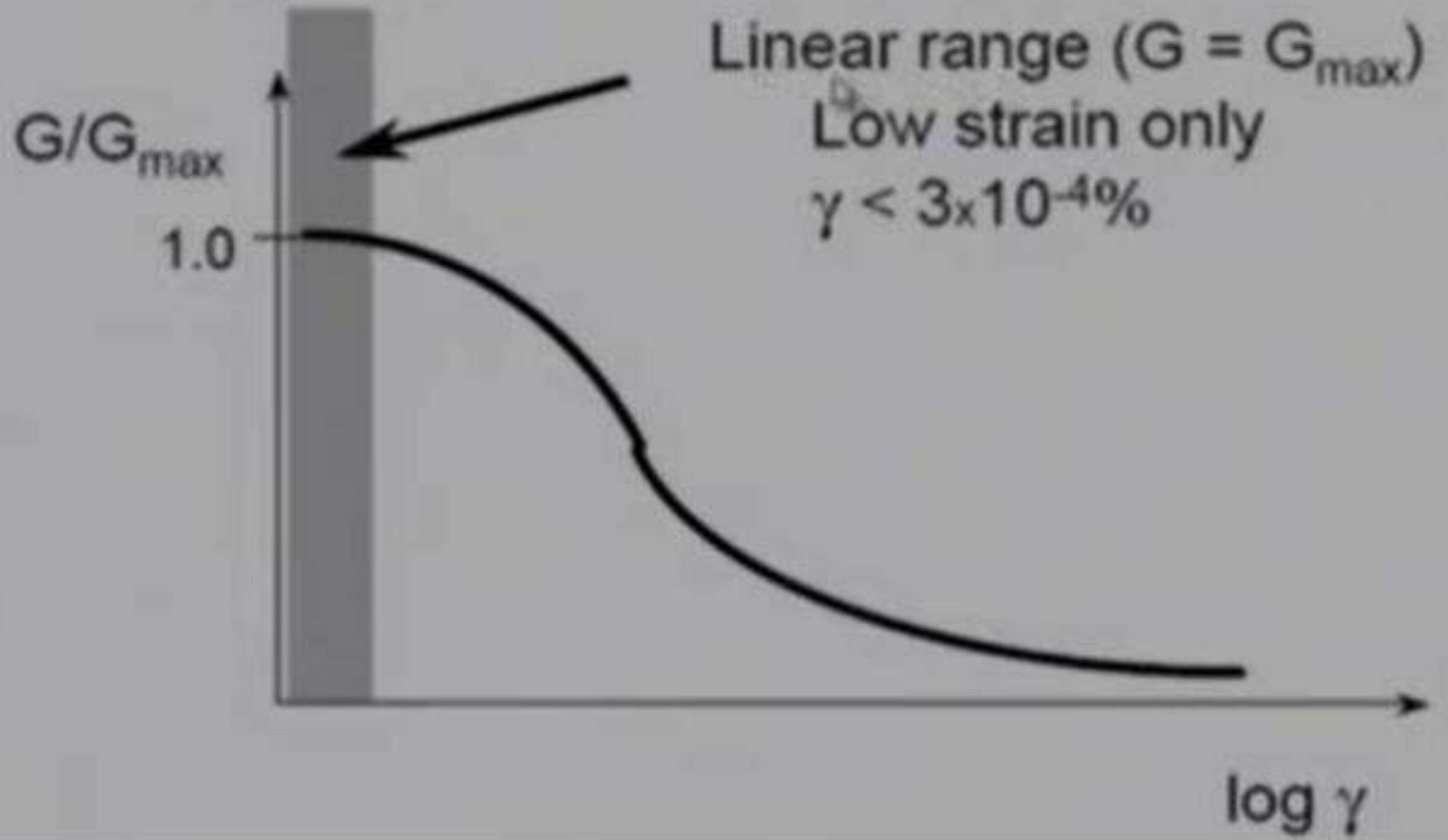
Shear Modulus

Equivalent linear approach



Shear Modulus

Equivalent linear approach



What is Liquefaction ?

Liquefaction occurs in saturated soils

All pores are completely filled with water;

Soil is no more thirsty!!

 The water in the pores exerts the pressure

on soil particles called Pore Pressure that

influences how tightly the soil particles are

pressed together

Why does the Liquefaction occur?

Prior to an earthquake: the pore pressure is low

- Earthquake shaking causes pore pressure to Increase:

Undrained Condition!!

- Pore pressure = Overburden press/Confining stress
- Effective stress is Zero;

NO Shear Strength!!

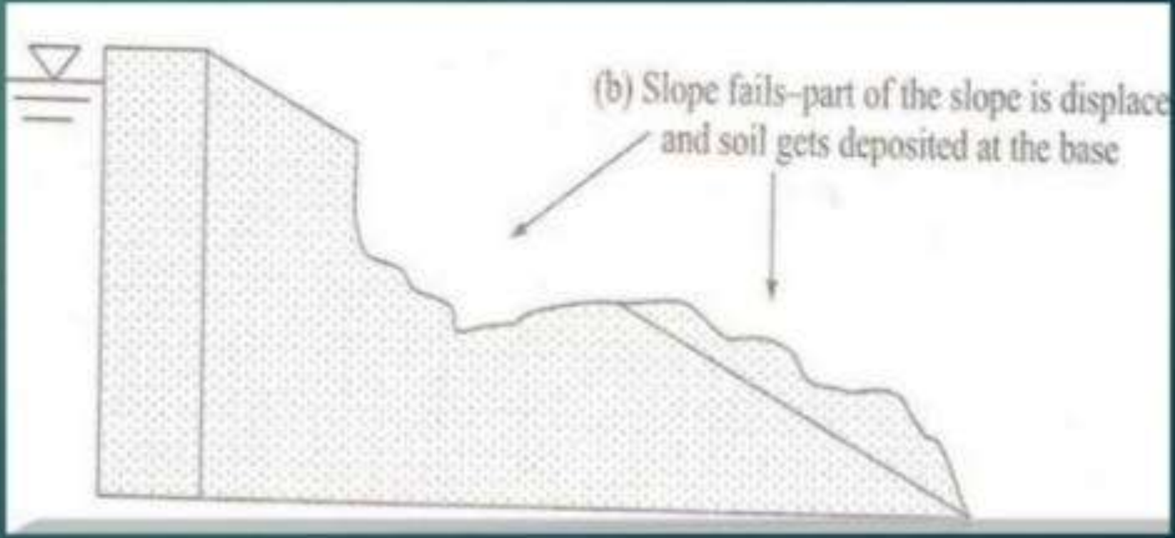
- Soil particles starts readily move with respect to each other due to zero shear strength.
- LIQUEFACTION …occurs!!

What is soil liquefaction:- Liquefaction is the phenomena when there is loss of strength in saturated and cohesion-less soil because of increased pore water pressures and hence effective stress is reduce due to dynamic loading.

- During liquefaction the water pressure become high enough to counteract the gravitational pull on the soil particles and effectively float or suspend the particles.
- Then soil particle move freely with respect to each other. due to this the strength of soil decreases and the ability of a soil deposit to support foundations for buildings and bridge is reduce.

- **Sand boil:-** Sand-laden water can be ejected from a buried liquefied layer and erupt at the surface to form sand volcanoes. The surrounding ground often fractures and settles.

- **Flow failures:-** Flow failures are the most catastrophic ground failures caused by liquefaction. These failures commonly displace large masses of soil laterally. Flows develop in loose saturated sands or silts on relatively steep slopes,



Factors Affecting Soil Liquefaction

- Soil Type
- Grain size and its distribution
- Initial relative density
- Vibration characteristics
- Location of drainage and dimension of deposit
- Surcharge load
- Method of soil formation
- Period under sustained load
- Previous strain history
- Trapped Air

Consequence of Liquefaction

- Settlements
- Lateral spreads
- Lateral flows
- Loss of lateral support
- Loss of bearing support
- Flotation of bearing supports