SOIL MECHANICS AND MODELING; AND 40-YEARS OF TROPICAL SOILS PRACTICE IN NIGERIA

By

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1/1 Introduction - Definition

- Soil mechanics is study of properties of engineering soils and predicts responses to load induced stresses
- Properties of interest include shear strength, volumetric compressibility & seepage for natural soils or modified for application in construction of earthen structures.
- It is the branch of civil engineering concerned with characterization of the subsurface, determination of engineering soil properties and the analysis, design and construction of geotechnical systems
- Almost all civil engineering structures are built on soils, or below the surface and used are used as construction material for building earth structures such as pavements, embankments, slopes, and dams.

1/2 Introduction - Definition

- Knowledge of the mechanics of flow of water through soils pore space is necessary to solve problems of permeability and seepage.
- It is often named Soil Mechanics and Foundation Engineering,

Geotechnical Engineering

and also Geomechanics

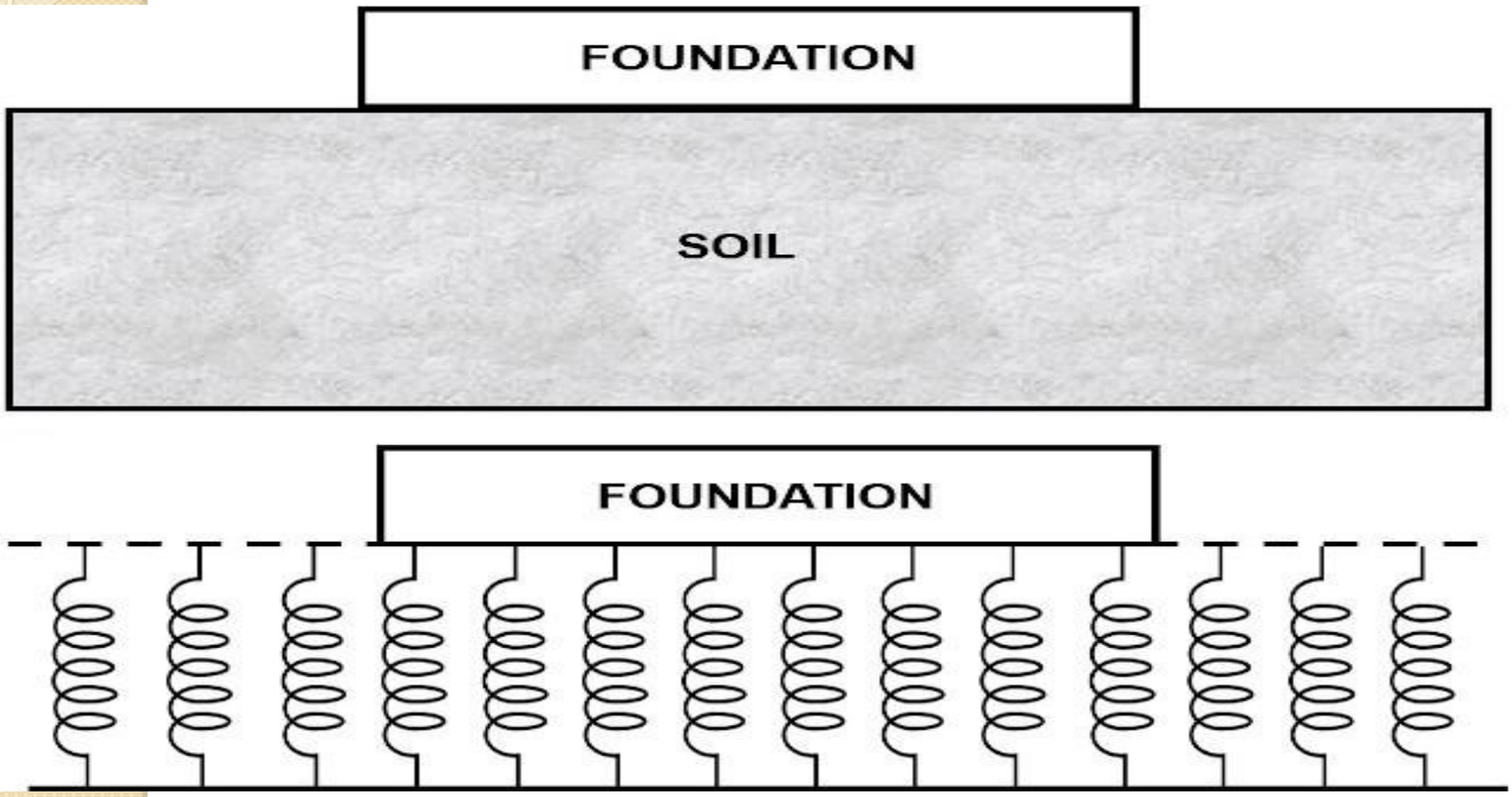
(Soil and Rock Mechanics).

Granular and Clayey Soils

2/1 Soil Behaviour Modelling

- Modeling in soil mechanics is essentially a simplification of real life difficult problems, particular complex Maths
- It is an integral part of all geotechnical engineering analysis and design process that deploy soil properties.
- Contemporarily, Soil behaviour modelling uses ***Constitutive models, Numerical modelling, intelligent models, and Centrifuge modelling***.
- Constitutive soil models describe material behaviour while experimental and intelligent models simulate soil/geotechnical systems under various loading and environmental conditions.
- Complex problems may be analysed using ***numerical techniques*** such as ***finite difference, finite element, and discrete element methods***.

2/2 Soil Behaviour Modelling



Typical Soil-Foundation Interaction Modelling (Reality-top, and Theoretical-bottom)

2/3 Soil Behaviour Modelling - Examples

- Traditionally, modeling could include making predictions of stresses induced by the interactions of civil engineering systems with the soil;
- Also displacements as result of imposed loads; development of PWPs & their effects on the stability;
- Analyzing the stability of slope and bearing capacity of shallow and deep foundations.
- Unlike materials like steel (even concrete), soil is much more complex material.
- Typical 'engineering properties' of soil, such as 'strength' and 'stiffness' depend on many other properties and on the particular conditions that apply in any peculiar situation.

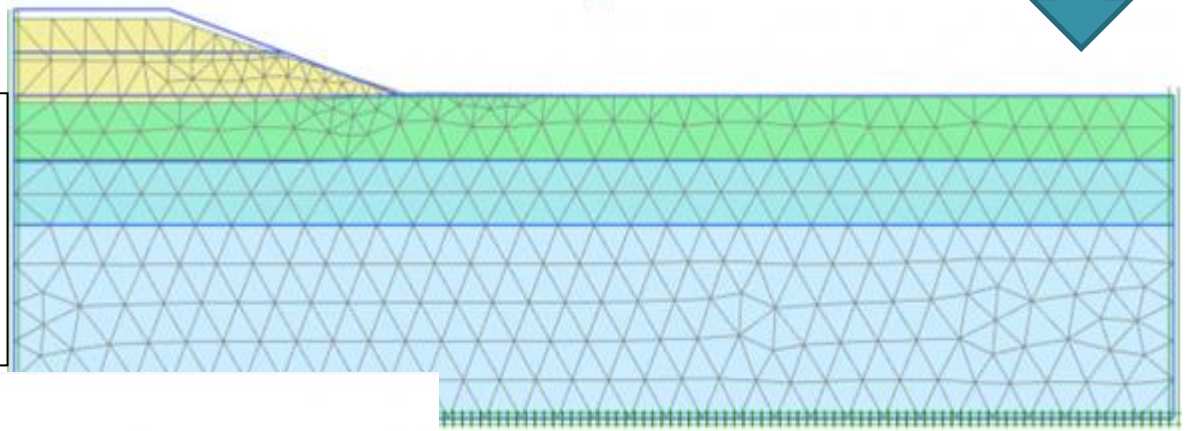
2/4 Soil Behaviour Modelling - Examples

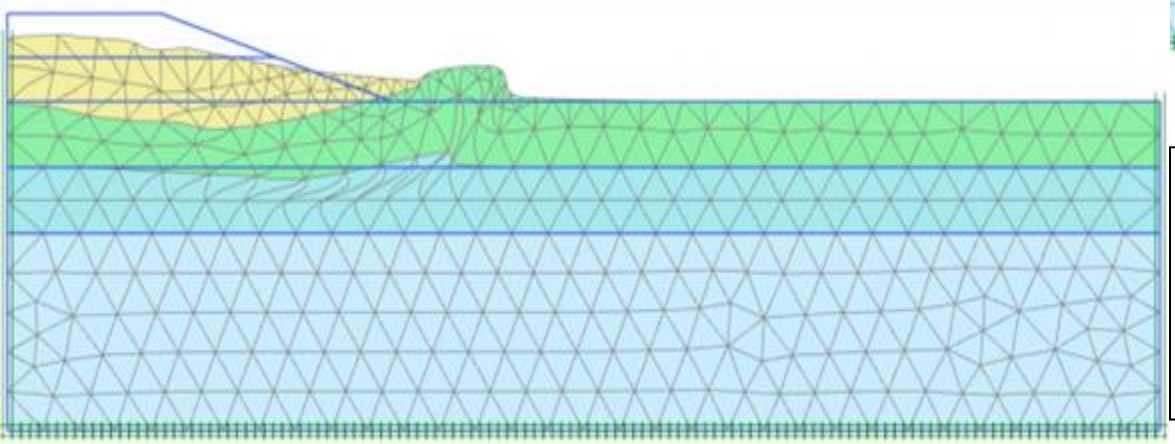
- Example, soil strength and stiffness depend on the stress level, the loading direction, the strain level, short or long term, density, over-consolidation degree, and several more.
- Stress-dependency and strain-dependency of stiffness and strength are some of the 'features of soil behaviour'.
- Other features are compaction and dilatancy, drained or undrained state (the latter involves a simultaneous PWP change), creep, anisotropy, structure, and several more.
- Geotechnical Finite Element (FE) programs, like PLAXIS 2D/3D Ultimate, use constitutive models to simulate mechanical behaviour of soil (stress and strain - and time), a qualitative description of the soil in the computer program.

2/5 Soil Behaviour Modelling - Examples

The linear elastic perfectly plastic Mohr-Coulomb model is a simple combination of Hooke's law of isotropic elasticity and the generalized Mohr-Coulomb failure criterion formulated in a non-associated plasticity framework. Typical Numerical Modelling: The Soft-Soil & Soft-Soil Creep Model

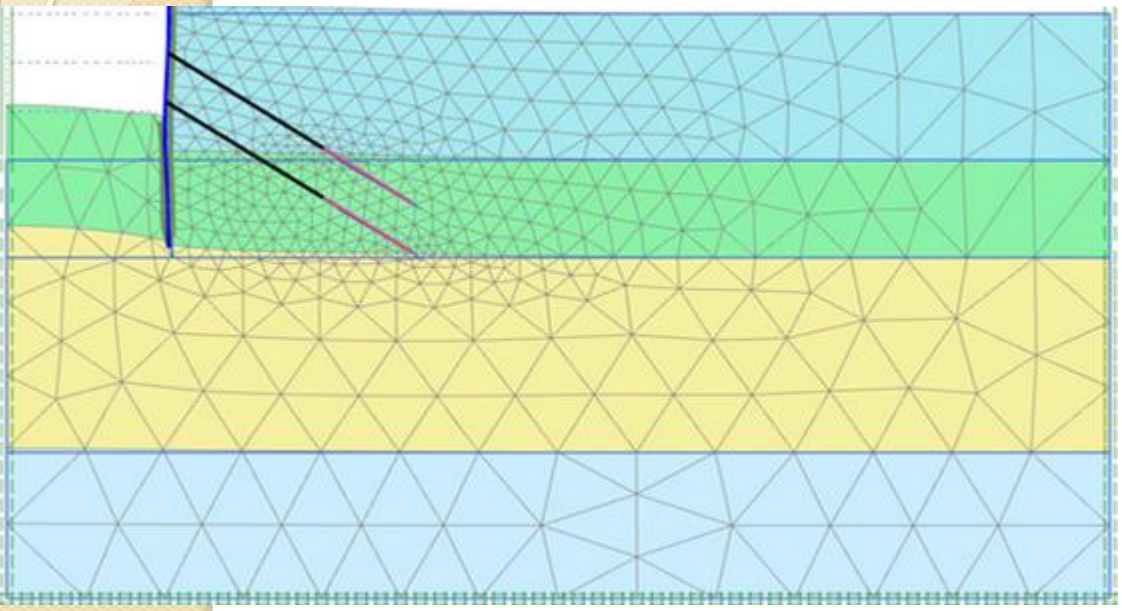
Using Mohr-Coulomb Model with Effective Strength parameters, No failure (Stable)



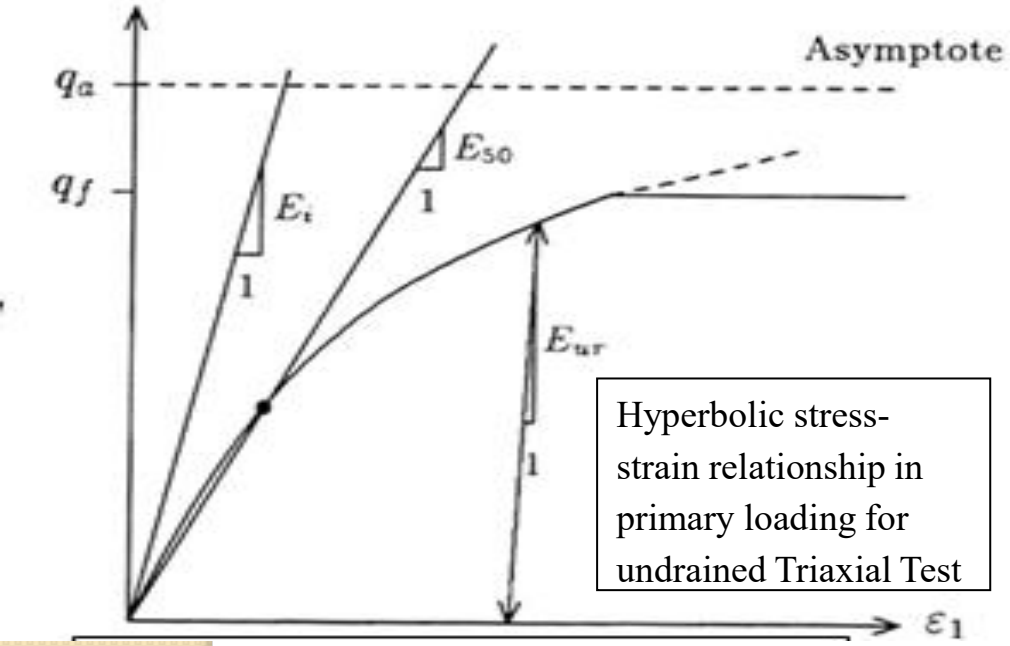


Using Mohr-Coulomb Model with Effective Strength parameters, Failure (unstable)

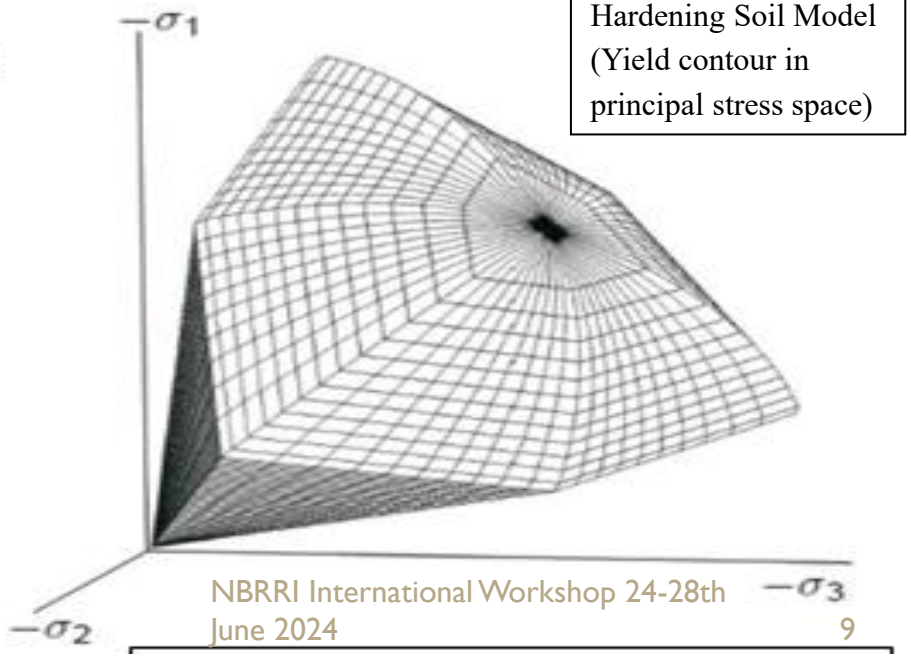
2/6 Numerical Modelling for the Hardening Soil Model



Numerical Analysis of a Deep Excavation (unrealistic heave of the soil behind the retaining wall)



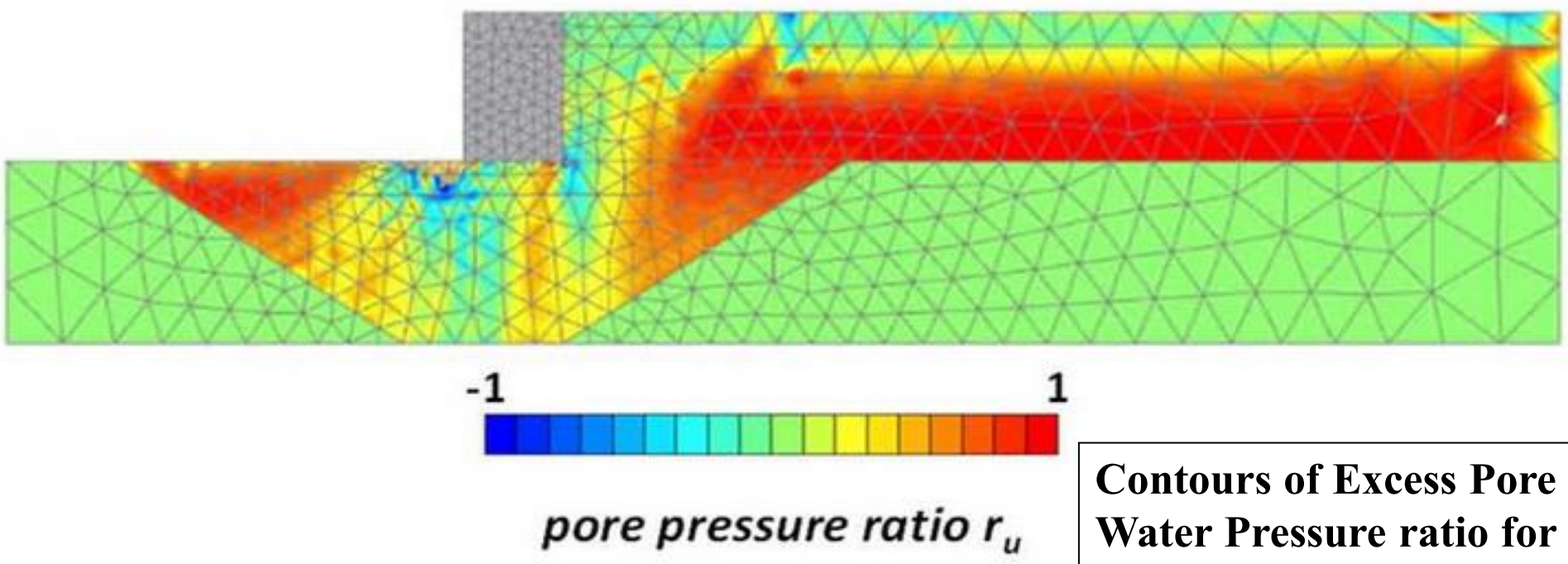
Hyperbolic stress-strain relationship in primary loading for undrained Triaxial Test



Hardening Soil Model (Yield contour in principal stress space)

2/7 Soil Behaviour Modelling – Hardening Model

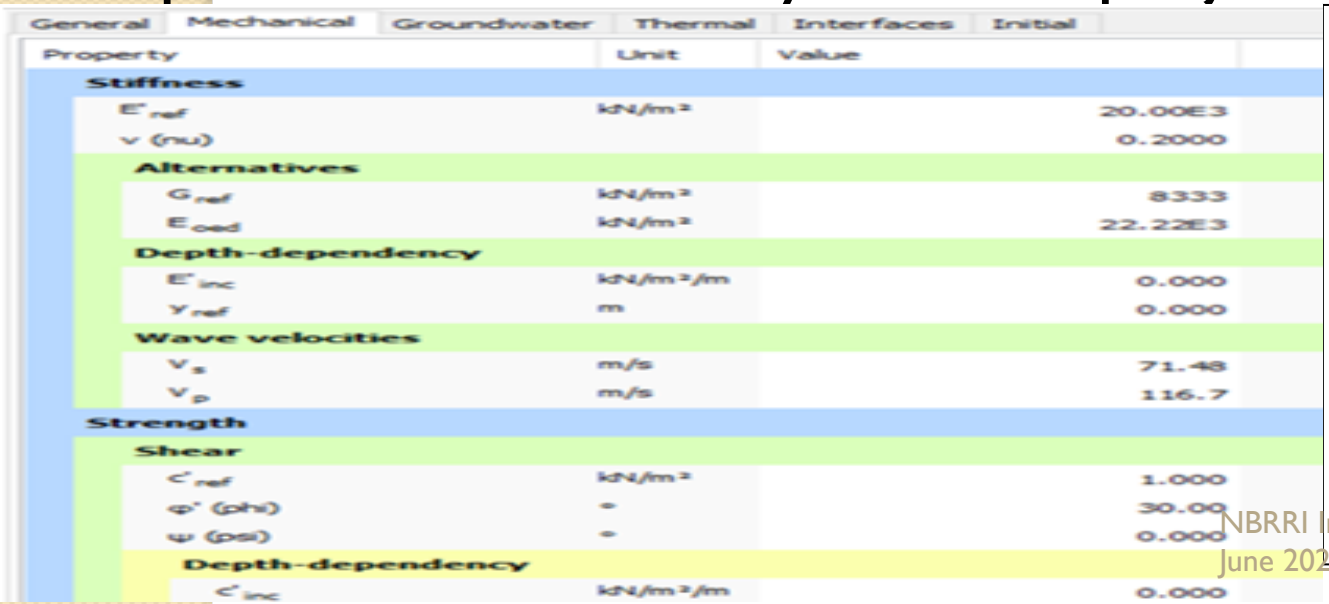
- Model parameters for the Hardening Soil are determined and, the 'digital soil' can be tested in the PLAXIS 2D/3D Ultimate Soil Test facility.
- It is an advanced model for simulating the behaviour of different types of soil, both soft soils and stiff soils.



Contours of Excess Pore Water Pressure ratio for dynamic analysis using PLAXIS 2D

2/7 Soil Behaviour Modelling – Soil Parameters

- Challenge encountered in defining Soil parameters to represent the materials for analysis.
- These can be obtained from laboratory tests like Triaxial & Oedometer, OR empirical correlations of field tests like SPT & Plate Loading. The execution of site-specific
- PLAXIS **SoilTest** calibrates parameters for Soils analysis simulating triaxial and oedometer tests in order to replicate the laboratory tests on projects.

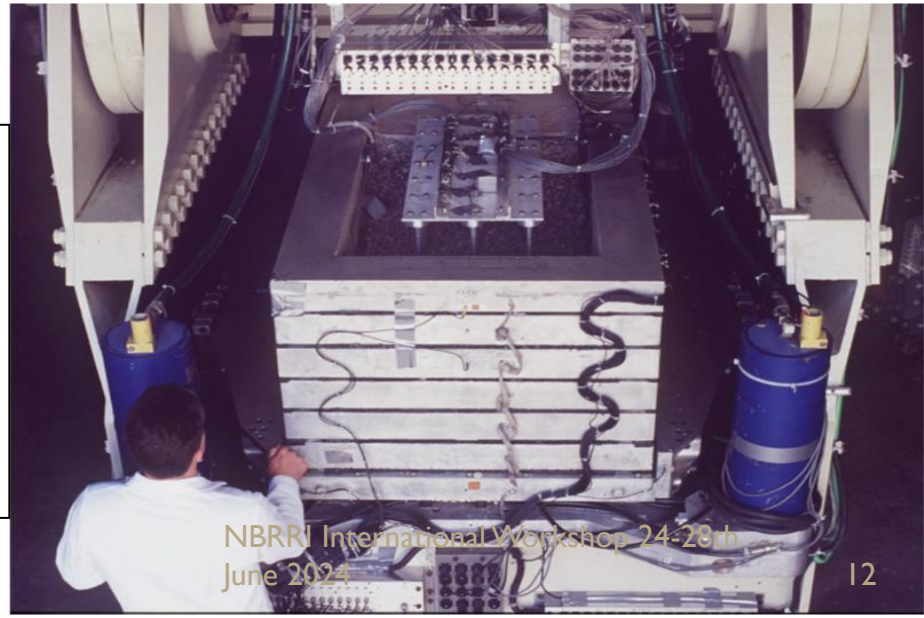


Soil mechanical parameters tab of the PLAXIS material set window for Mohr-Coulomb model (Silty soil).

2/8 Soil Behaviour Modelling – Centrifuge Modelling

- Modelling of complex geotechnical problems on a small scale is difficult due to the non-linearity and stress dependency of soil's behaviour. Nonetheless, the response of a soil-structure system can be simulated on a small scale by **Centrifuge Modelling**.
- Such a testing process utilizes centrifugal forces to re-create the in-situ stress conditions with 'Dimensional Analysis

Model of a Port Structure loaded on a UC Davis Centrifuge



2/9 Soil Behaviour Modelling – PLAXIS 2D versions

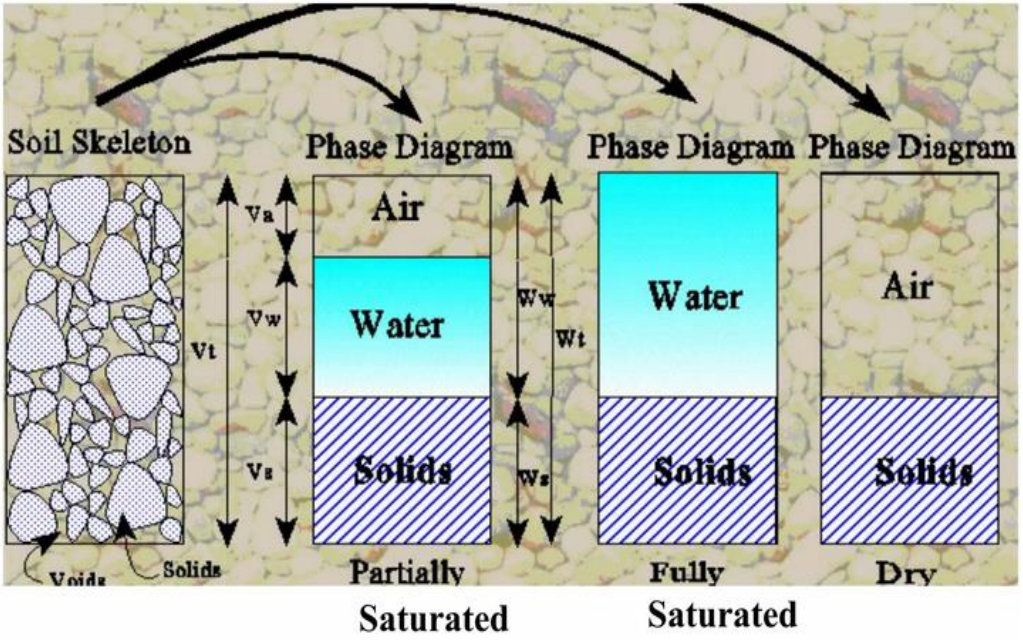
- PLAXIS 2D Soil Mechanics Software to perform deformation and safety analysis for soils and rocks
- PLAXIS 2D Advanced for basic Plaxis 2D plus Creep, flow-deformation coupling, consolidation analysis, and steady state groundwater flow
- PLAXIS 2D Ultimate for 2D Advanced plus analysis of the effects of vibrations, simulating hydrological time-dependent variations of water levels or flow functions, etc.
- PLAXIS 2D Worksuite is most comprehensive including 2D Ultimate plus PLAXIS 2D LE for Limit equilibrium analysis

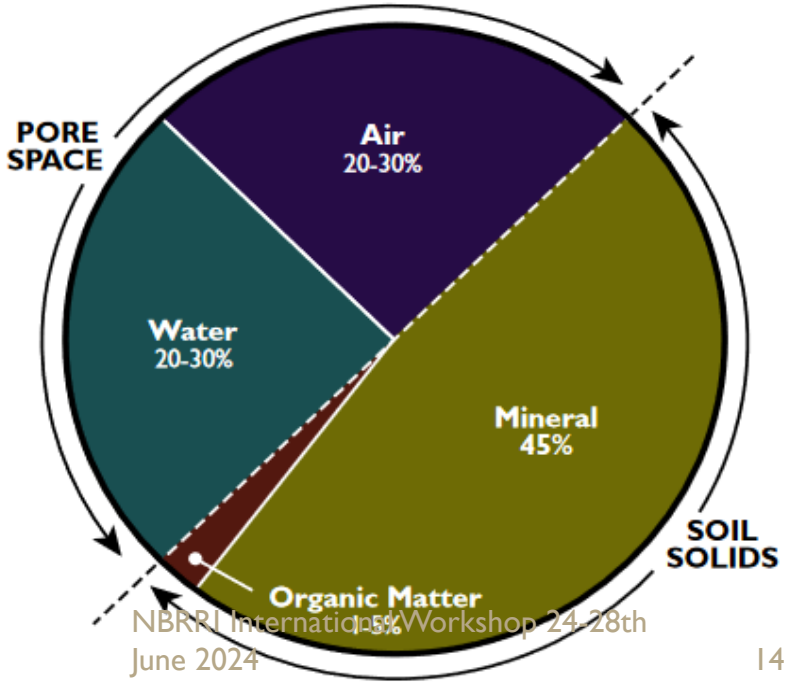
PLAXIS 2D Soil Mechanics Software versions

Others based on principles of mechanics validated by experimental data fed into systems for numerical modelling are **finite element or finite difference, d**ifferent constitutive models, etc.

3/1 Application to Practical Soil Mechanics – Soil Properties

- The complex relationship of stresses and strains for soils involved in field applications and projects that need to be modelled are derived from mathematical equations that predict the soil behaviour.
- These applications need to be thoroughly understood in order for models to be formed from their basic relationships





3/2 Application to Practical Soil Mechanics – Soil Properties

- Index properties include various indices that help determine engineering behaviour: LL, PL, w - $w - \rho/\gamma$ and volumetric change relationships to pore spaces, etc, shown

Moist unit weight (γ)		Dry unit weight (γ_d)		Saturated unit weight (γ_{sat})	
Given	Relationship	Given	Relationship	Given	Relationship
w, G_s, e	$\frac{(1+w)G_s\gamma_w}{1+e}$	γ, w	$\frac{\gamma}{1+w}$	G_s, e	$\frac{(G_s+e)\gamma_w}{1+e}$
S, G_s, e	$\frac{(G_s+Se)\gamma_w}{1+e}$	G_s, e	$\frac{G_s\gamma_w}{1+e}$	G_s, n	$[(1-n)G_s+n]\gamma_w$
w, G_s, S	$\frac{(1+w)G_s\gamma_w}{1+\frac{wG_s}{S}}$	G_s, n	$G_s\gamma_w(1-n)$	G_s, w_{sat}	$\left(\frac{1+w_{sat}}{1+w_{sat}G_s}\right)G_s\gamma_w$
w, G_s, n	$G_s\gamma_w(1-n)(1+w)$	G_s, w, S	$\frac{G_s\gamma_w}{1+\left(\frac{wG_s}{S}\right)}$	e, w_{sat}	$\left(\frac{e}{w_{sat}}\right)\left(\frac{1+w_{sat}}{1+e}\right)\gamma_w$
S, G_s, n	$G_s\gamma_w(1-n)+nS\gamma_w$	e, w, S	$\frac{eS\gamma_w}{(1+e)w}$	n, w_{sat}	$n\left(\frac{1+w_{sat}}{w_{sat}}\right)\gamma_w$
		γ_{sat}, e	$\gamma_{sat}-\frac{e\gamma_w}{1+e}$	γ_d, e	$\gamma_d+\left(\frac{e}{1+e}\right)\gamma_w$
		γ_{sat}, n	$\gamma_{sat}-n\gamma_w$	γ_d, n	$\gamma_d+n\gamma_w$
		γ_{sat}, G_s	$\frac{(\gamma_{sat}-\gamma_w)G_s}{(G_s-1)}$	γ_d, G_s	$\left(1-\frac{1}{G_s}\right)\gamma_d+\gamma_w$
				γ_d, w_{sat}	$\gamma_d(1+w_{sat})$

3/3 Applications – Elements of Stress Analysis

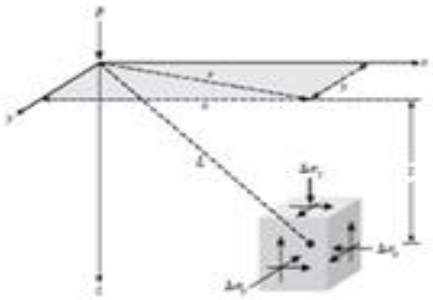
- Induced stresses in soils due to foundation loading to avert shear failure, contain settlements, ground facilities rupture..

The most important original solution was given by BOUSSINESQ (1885) for the distribution of stress within a linear elastic half space resulting from a point load normal to the surface as shown

$$\Delta\sigma_z = \frac{3P}{2\pi}\frac{z^3}{L^5} = \frac{3P}{2\pi}\frac{z^3}{(r^2+z^2)^{5/2}}$$

$$\Delta\sigma_z = \frac{P}{z^2}\left\{\frac{3}{2\pi}\frac{1}{[(r/z)^2+1]^{5/2}}\right\} = \frac{P}{z^2}I$$

$$I = \frac{3}{2\pi}\frac{1}{[(r/z)^2+1]^{5/2}}$$



Corner of the rectangular area

The increase in the stress, at point A caused by the entire loaded area can now be determined by integrating the preceding equation. We obtain

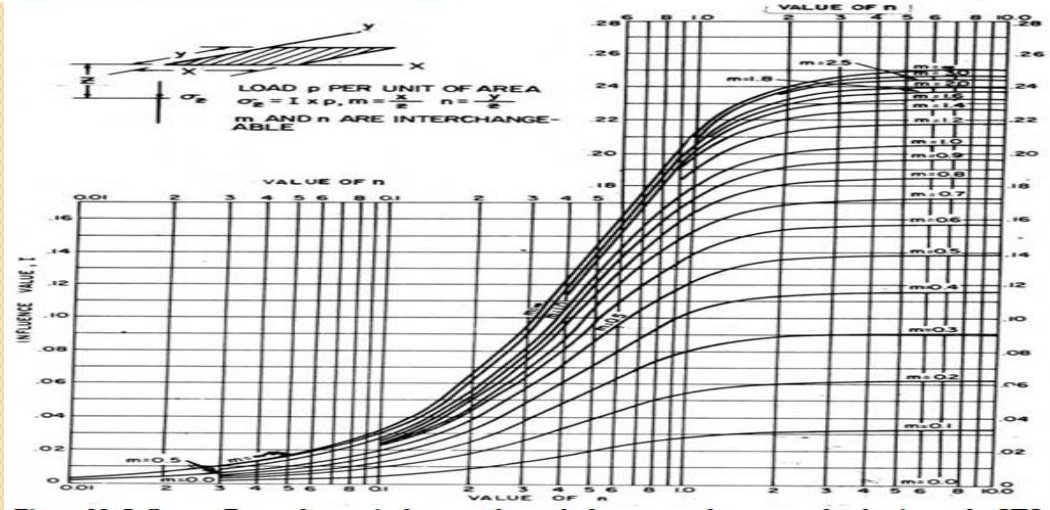
$$\Delta\sigma_z = \int d\sigma_z = \int_{y=0}^{B}\int_{x=0}^{L}\frac{3qz^3(dx\,dy)}{2\pi(x^2+y^2+z^2)^{5/2}} = qI$$

$$I = \frac{1}{4\pi}\left[\frac{2mn\sqrt{m^2+n^2+1}}{m^2+n^2+m^2n^2+1}\left(\frac{m^2+n^2+2}{m^2+n^2+1}\right) + \tan^{-1}\left(\frac{2mn\sqrt{m^2+n^2+1}}{m^2+n^2-m^2n^2+1}\right)\right]$$

$$n = \frac{L}{z}$$

$$m = \frac{B}{z}$$

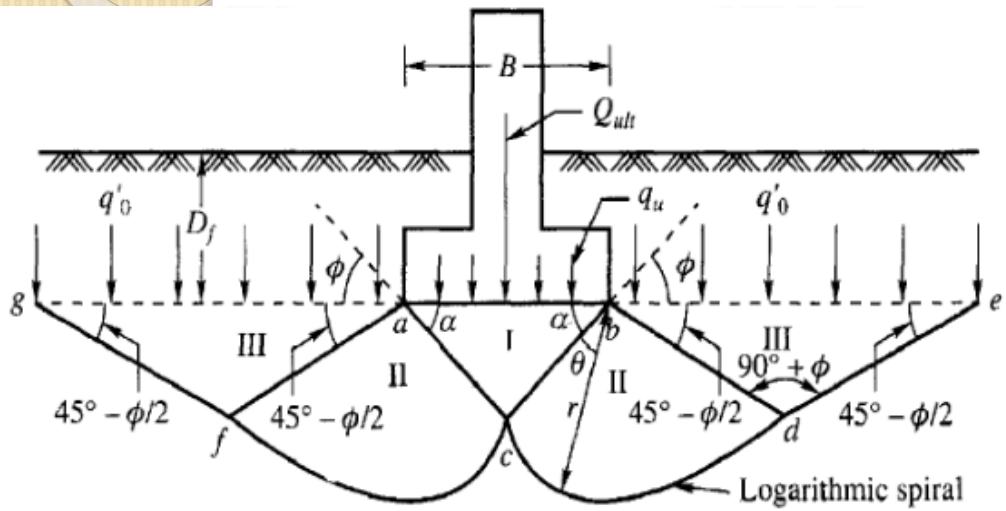
The arctangent $[arc.tan^{-1}(\ldots\ldots)$ Term in the expression MUST be a +ve angle in radians. When $m^2 + n^2 + 1 < m^2.n^2$, it becomes a negative angle. So a term π (pi) should be added to that angle – Professor Danladi S. MATAWAL

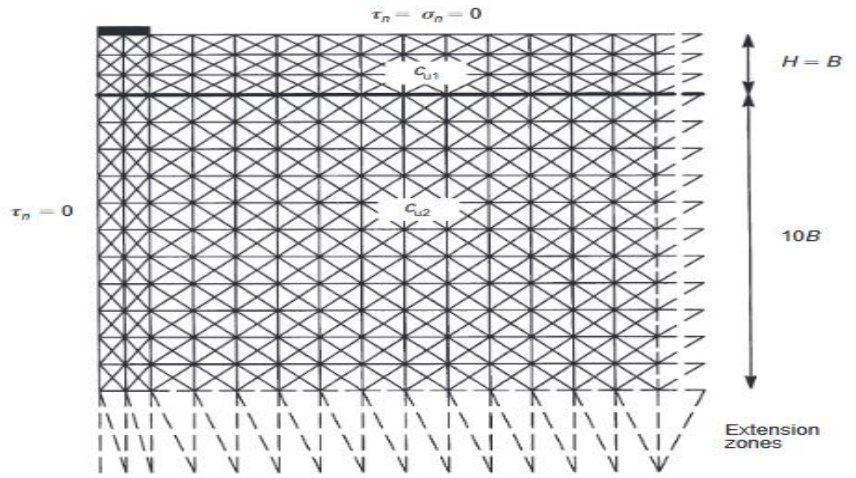


Stresses induced below foundations based on principles of elasticity, Complex solution eased by Influence chart $(\Delta\sigma = q.I_\sigma)$

3/4 Applications – Ultimate Bearing Capacity of Soils

- Induced stresses lead to catastrophic failure if they exceed q_{ult} ➔ Terzaghi's Limiting Equilibrium Failure Mechanism
- Finite Element Soluion (LB, D/B =1.0), BC equatn & Factors





$$q_{ult} = cN_c s_c d_c i_c g_c b_c + \bar{q} N_q s_q d_q i_q g_q b_q + 0.5\gamma B' N_\gamma s_\gamma d_\gamma i_\gamma g_\gamma b_\gamma$$

$$\phi = 0$$

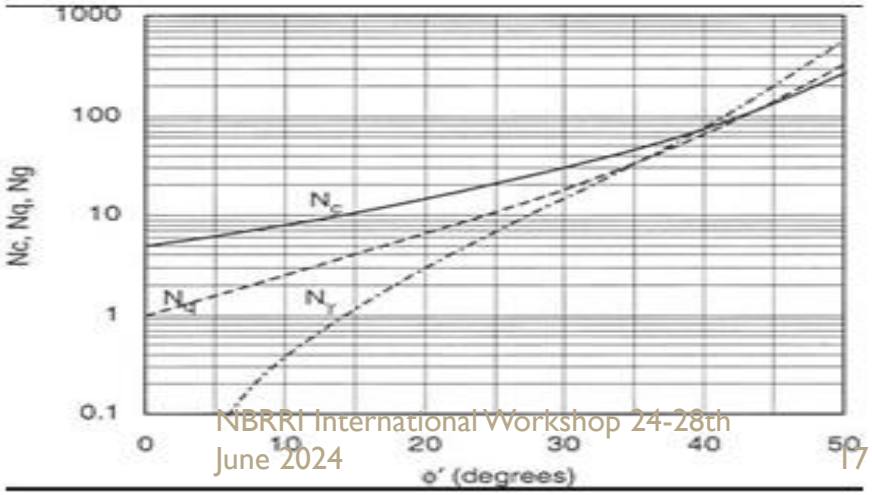
$$q_{ult} = 5.14 s_u (1 + s'_c + d'_c - i'_c - b'_c - g'_c) + \bar{q}$$

$$N_q = e^{\pi \tan\phi} \tan^2\left(45 + \frac{\phi}{2}\right)$$

$$N_c = (N_q - 1)\cot\phi$$

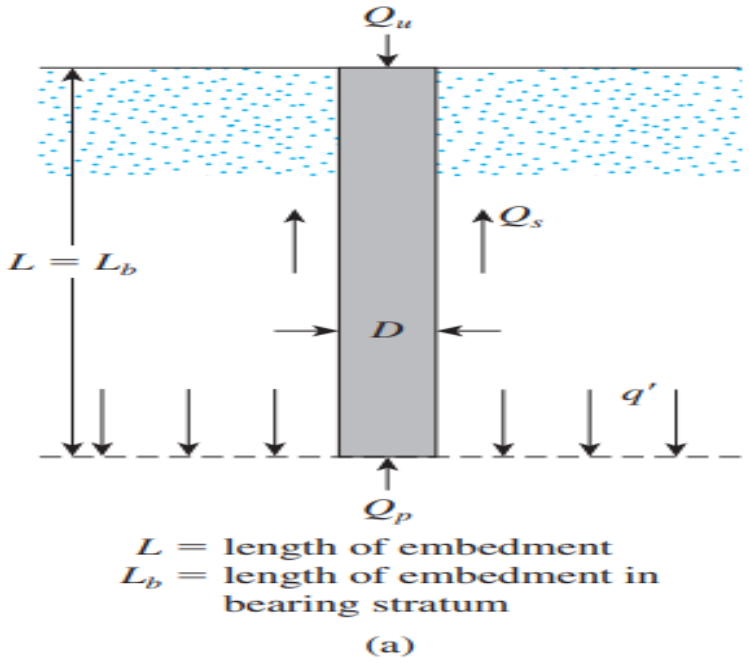
$$N_\gamma = 1.5(N_q - 1)\tan\phi$$

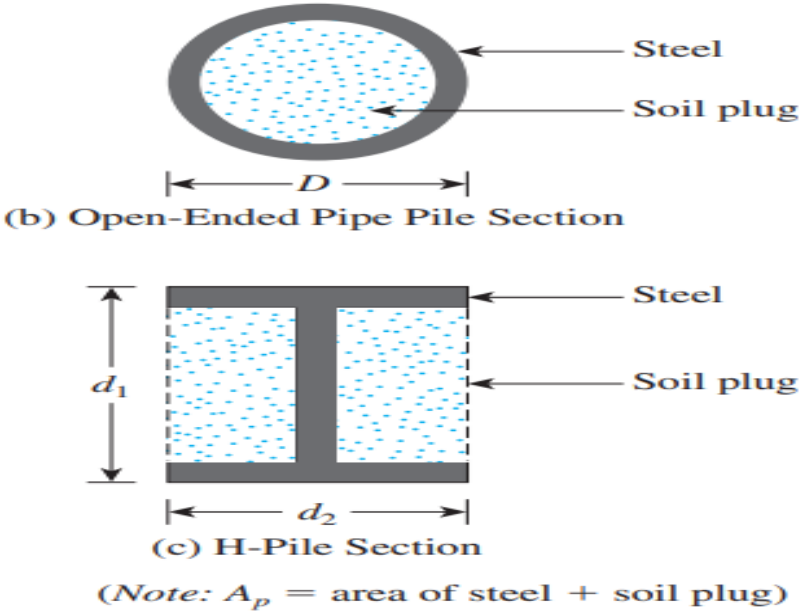
Brinch Hansen Bearing Capacity Factors



3/5 Applications – Pile Foundations (Deep Footings $\frac{D}{B} > 1.0$)

- Induced stresses lead to catastrophic failure if they exceed q_{ult} ➔ Terzaghi's Limiting Equilibrium Failure Mechanism
- Finite Element Soluion (LB, D/B =1.0), BC eqtn & Factors



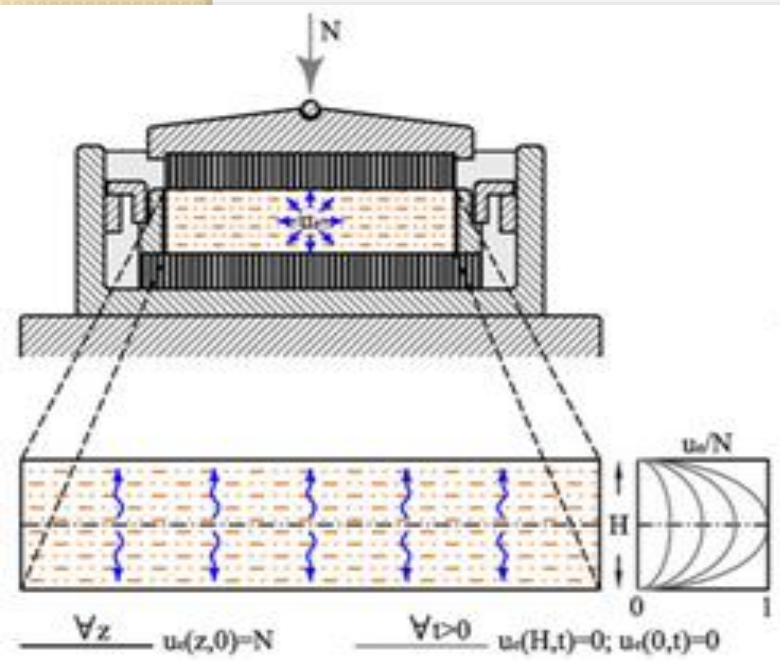


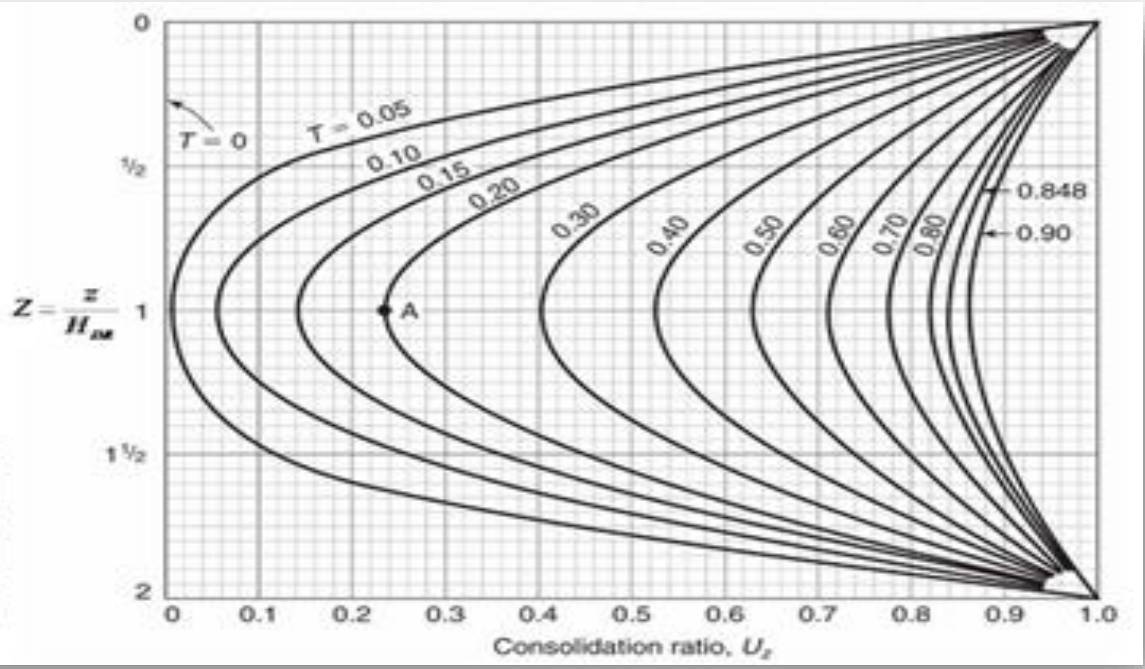
➔ **Dynamic Formulae, Static formulae, Pile Loading & Penetration Tests;** In the static formulae, the capacity is assumed to be the sum of Skin Friction & End-Bearing Resistance; that is: $Q_u = Q_s + Q_p =$

$\sum_{z=0}^{z=L} \mu . k_s . \sigma'_v . A_s + q_{up} . A_p$

3/6 Applications – Theoretical Consolidation & Settelement

- $C_x.\frac{\partial^2 u}{\partial x^2} + C_y.\frac{\partial^2 u}{\partial y^2} + C_z.\frac{\partial^2 u}{\partial z^2} = \frac{\partial u}{\partial t}$: 3-D cartesian coordinates
- **1 – D Model** ***is*** $C_z.\frac{\partial^2 u}{\partial z^2} = \frac{\partial u}{\partial t}, C_v = \frac{k}{\gamma_w.m_v}$ for $T_v = \frac{C_v.t}{H^2}$
- The Oedometer Cell & Isochrones of Consolidation



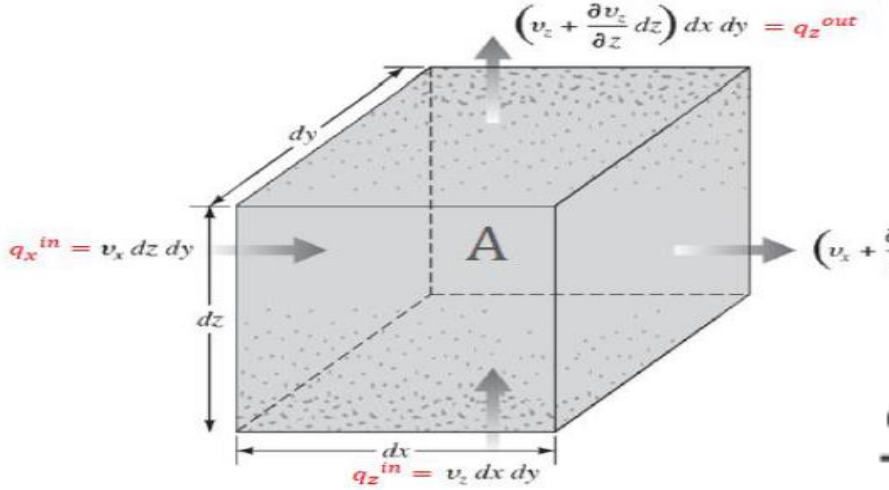


Total Settlement: $\rho_t = \rho_i + \rho_c + \rho_s$; The consolidation settlement in NC soils: $\rho_c = \frac{C_c}{1+e_o}.\log(\frac{\sigma'_o + \Delta\sigma'}{\sigma'_o})$ OR $\rho_c = m_v.\Delta\sigma'.H$

3/7 Applications – criteria for Settlement (total/differential)

Type of structure	Type of damage/concern	Criterion	Limiting value(s)
Framed buildings and rein-	Structural damage	Angular distortion	1/150 – 1/250
forced load bearing walls	Cracking in walls and partitions	Angular distortion	1/500
			(1/1000-1/1400) for end bays
	Visual appearance	Tilt	1/300
	Connection to services	Total settlement	50 – 75 mm (sands)
			75 – 135 mm (clays)
Tall buildings	Operation of lifts & elevators	Tilt after lift installation	1/1200 –1/2000
Structures with unreinforced	Cracking by sagging	Deflection ratio	1/2500 (L/H =1)
load bearing walls			1/1250 (L/H = 5)
	Cracking by hogging	Deflection ratio	1/5000 (L/H = 1)
			1/2500 (L/H = 5)
Bridges – general	Ride quality	Total settlement	100 mm
	Structural distress	Total settlement	63 mm
	Function	Horizontal movement	38 mm
Bridges – multiple span	Structural damage	Angular distortion	1/250
Bridges – single span	Structural damage	Angular distortion	1/200

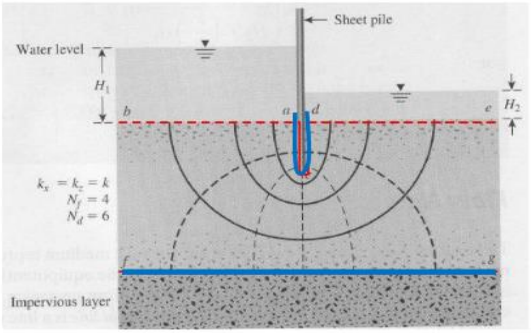
3/8 Applications – Seepage & Ground Water Control



$$\left[\left(v_x + \frac{\partial v_x}{\partial x} dx\right) dz\, dy + \left(v_z + \frac{\partial v_z}{\partial z} dz\right) dx\, dy\right] -$$

$$- \left[v_x\, dz\, dy + v_z\, dx\, dy\right] = 0$$

$$\frac{\delta^2 h}{\delta x^2} + \frac{\delta^2 h}{\delta y^2} + \frac{\delta^2 h}{\delta z^2} = 0$$



Boundary Conditions

Consider Point X

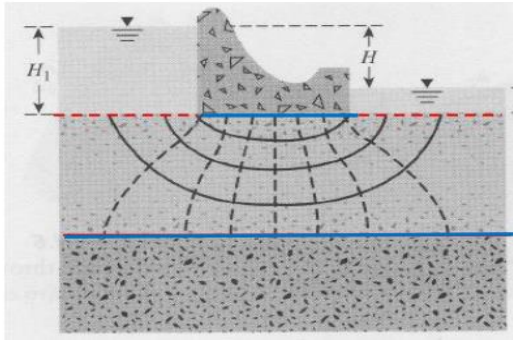
Total head = h - # of drops from upstream x Δh

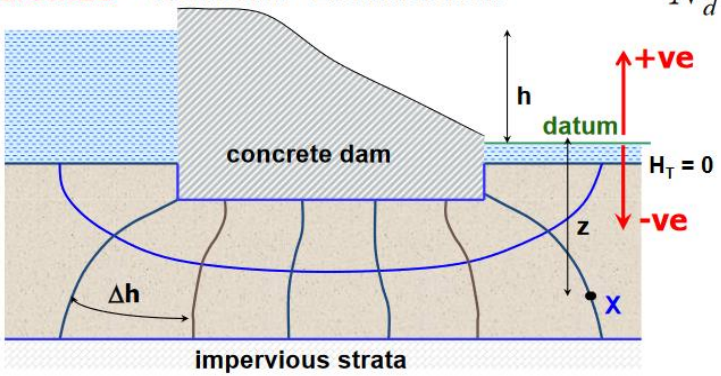
Elevation head = -z

Pressure head = Total head – Elevation head

$$h = \frac{u}{\gamma_w} + Z$$

$$= \frac{h}{N_d}$$





Blue : Flow line
Red :Equipotential line

Laplace Transform Seepage Equation can be solved by different techniques like Analytical Methods (Separation of Models, Laplace Transform, Fourier Series), Numerical Methods (Finite Elements, Finite Difference), and Graphical Method (Flow Nets trial-and-error sketching).

3/9 Applications – Slope Stability Analyses

$$F_s = \frac{\sum_{i=1}^{n} [(W_i + X_{i+1} - X_i - u_i b_i) \tan \phi_i' + c_i' b_i] / m_{\alpha i}}{\sum_{i=1}^{n} W_i \sin \alpha_i}$$

$$\sum_{i=1}^{n} (T_i \cos \alpha_i - N_i \sin \alpha_i) = 0$$

The simplified Bishop method assumes that the contribution of vertical interslice forces to the factor of safety is neglected, hence

$$F_s = \frac{\sum_{i=1}^{n} [(W_i - u_i b_i) \tan \phi_i' + c_i' b_i] / m_{\alpha i}}{\sum_{i=1}^{n} W_i \sin \alpha_i}$$

and substitute equations (3) and (4) into the above equation, one obtains:

$$\sum_{i=1}^{n} \Big[(W_i + X_{i+1} - X_i)(\cos \alpha_i \tan \phi_i' / F_s - \sin \alpha_i) - (u_i b_i \tan \phi_i' - c_i' b_i) / (F_s \cos \alpha_i) \Big] \Big/ m_{\alpha i} = 0$$

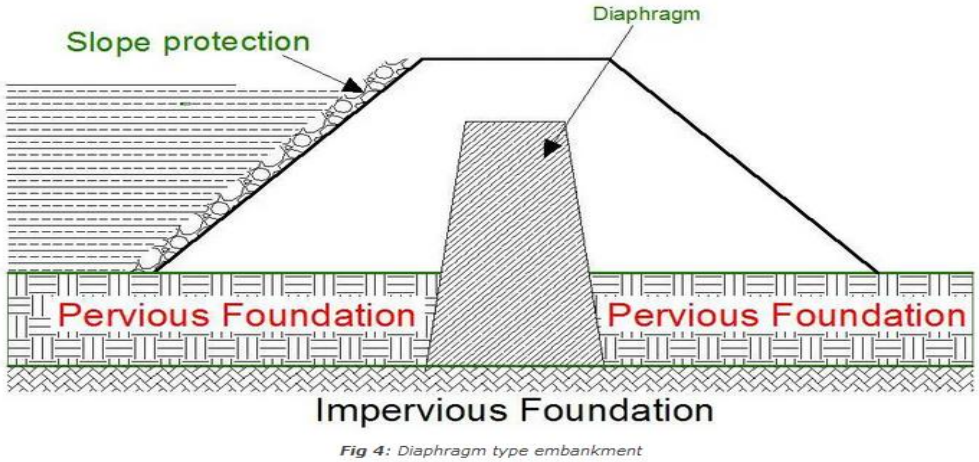


Fig 4: Diaphragm type embankment

Analyses of landslides, rock toppling and falls, slope designs for natural and manmade embankments and cuts for earthdams, highways and railways. Complex equations (Bishop Rigorous & Bishop Simplified programmed for its trial-and-error iteration mathematics) amenable to numerical computer based techniques and modelling.

3/10 Earth Pressures & Retaining Wall Structures – Other Topics

$$P_a = \tfrac{1}{2}\, k_a.\gamma_s.H^2 \quad \frac{1}{(Sin\ \alpha.Cos\ \delta)} \quad k_a = \frac{Sin^2(\alpha+\varphi).Cos\ \delta}{Sin\ \alpha.Cos\ (\alpha-\delta)\left[1+\sqrt{\frac{Sin(\varphi+\delta)\ .\ Sin(\varphi-\beta)}{Sin(\alpha-\delta)\ .\ .Sin(\alpha+\beta)}}\right]^2}$$

Component $\perp^r$ to back of wall is: $P_{an} = P_a.\cos\ \delta = \frac{\gamma_s.H^2.k_a}{2.\sin\ \alpha}$

- Retain or stabilize vertical or sloping cuts and embankments, SPWs, unstable sliding or falling cliffs, cuts, valleys, rivers and valleys.
- Solutions involve mathematics of failure mechanism, limit analyses, limiting equilibrium of admissible stress and collapse/failure states subjected to bound theories.

3/11 Earth Pressures & Retaining Wall Structures

Difficult and complex engineering problems, challenges and projects especially the design and construction:

- Bridges, Tunnels
- Tall structures/Skyscrapers
- Basements
- Foundations to withstand vibrations in earthquakes and turbines supports in power generating stations
- Airport complexes
- Dam foundations, Caissons
- Wind turbine foundations
- Towers and masts, and many more.

4/1 40 Years of Tropical Soil Mechanics in Nigeria

- Tropical Soil Mechanics has been driven by the common very basic needs for adequate road facilities for transportation and communication in Africa from the 1960s;
- In Nigeria, the fundamental foundations for many infrastructures including national inter-state and regional roads and other massive needs in housing and water facilities were primarily laid in the 1970s for commerce, agriculture, etc;
- There was also increased activities in other sectors like housing, earth dams, ports, big and huge buildings, power complexes and other infrastructure.
- All these implied that the use of soils for foundations and construction became both intensive and extensive.
- Together with researches in the ever expanding universities and research institutes like ***Nigerian Building and Roads Research Institute, NBRRI,*** soil mechanics became more significantly understood.;

4/2 40 Years of Tropical Soil Mechanics in Nigeria

- Engineering consultants and contractors in the exploitation of the the subsoil for deep foundations like Piles, Cofferdams, Caissons, Sheet Pile walls, cut-off trenches for all types of dams and boreholes drilling for water supply, as well as mining (later oil exploitation) have provided more to the general scientific principles of soil mechanics and the soils of Nigeria became more exposed and known;
- Hence while Nigeria is still being classified in the realms of developing economies, the subject of soil mechanics and the frontier of knowledge of Nigerian soils have metamorphosed into the era of the developed economies;
- We now have specific and peculiar soils in Nigeria called Laterites and Lateritic Soils, expansive black cotton soils, the red Residual soils, collapsible and other metastable soils.

4/3 40 Years of Tropical Soil Mechanics - Milestones

- Milestones attained through programmes in engineering consultancy and construction, especially highways, buildings and dam construction,; as well as designed researches and interventions that emphasized the importance of soil mechanics in Nigeria.
- The term laterites and lateritic soils and other problem soils of the tropics have emerged clear engineering definitions of the range of their properties.
- Tropical black clays (expansive black cotton soils) have been identified as difficult soils for foundations and road building. We are now also aware of possibilities of the existence soils believed to be susceptible to collapse.

4/4 40 Years of Tropical Soil Mechanics in Nigeria

- Suitable classification systems for lateritic materials that adequately describe their engineering properties are available from literary published works. Investigators like Ola, and from many NBRRI works, my own works and others, have evaluated the engineering characteristics and found typically good laterites as high as A-2 soils (and up to A-4) on the AASHTO classification scale with the bulk of them being stiff sandy clays.
- Sampling laterites for laboratory tests does not constitute any challenge because unless there are seepage pressures, the sampling tubes soil recovery rate is perfect undisturbed sampling.. SPT, Plate Loading and other Penetration techniques can be adopted in sands and gravels whose recoveries are almost always nearly impossible.
- 5. It is now true that the extensive quarrying and mining of good laterites from available heaps and borrow pits, especially for the construction of roads, has greatly depleted their availability and new sources have to be explored for exploitation. But we need to note that numerous roads have been studied by NBRRI and available as Technical Reports.

4/5 40 Years of Tropical Soil Mechanics in Nigeria

- Test means and materials for stabilizing sub-standard lateritic and other problem soils in Nigeria as well as use of some viable alternatives to soils in the construction of road soil foundation layers have been investigated.
- Cement stabilization is now common, so is use of stone base courses has become a viable option being embraced continually, while pozzolana and SCMs materials including geopolymer cement from metakaolin and use of acetylene welding wastes as binder material for stabilization has been embraced;
- From other studies and workshops/conferences like this one, there are efforts to develop suitable specifications, design standards and criteria for the satisfactory use of these materials in highways and airfields.
- Pavement condition survey reports provide suitable means for evaluating procedures and proposing modifications or changes.
- Laboratory and Field techniques in soil mechanics havee been developed for lateritic materials, including and especially black cotton expansive soils.

4/6 40 Years of Tropical Soil Mechanics in Nigeria

- Beyond roads and highways, experiences gained from practical experience reveal application potentials of lateritic soils to other engineering construction like earth dams, slopes, foundations and as building materials.
- Our expertise of stabilization empowers us to facilitate the construction of adequate roads by minimizing volume change or swelling to tolerable limits of expansive clays
- Collaborating with other African countries have revealed the presence of tropical red residual soils in similar climes. It has been confirmed that some of these are true lateritic soils under the chemical criterion, while others have undergone or are still undergoing laterization, but leaching of the silica and bases is incomplete. There is no practical means of distinguishing between the two, the engineering properties of both groups are quite similar.
- Most lateritic soils contain an appreciable clay fraction which generally displays properties that are similar to those of other tropical soils which are only partially laterized. The more descriptive terms ferruginous soil, ferrallitic soil, and ferrisol are recommended in lieu of lateritic soil

5/1 Summary, Conclusion and Recommendations

- Almost all civil engineering structures are built on soils, so Soil Mechanics is important for infrastructure.
- Understanding and predicting Soil behaviour is complex as it is stress-dependent and its stress-strain relations nonlinear.
- Thus modelling that simulate its behaviour to make predictions of stresses based on fairly accurate emulation of practical problems is considered an almost perfect process of obtaining realistic results.
- To derive soil's mechanical properties, in-situ and laboratory testing are performed and constitutive models based on the analytical solutions are used to simulate its behaviour.

5/2 Summary, Conclusion and Recommendations

- Thus we often tend to opt for soil behaviour modeliing using *Constitutive models, Numerical modeling, intelligent models, and Centrifuge modeling*.
- Geotechnical Finite Element (FE) programs, like PLAXIS 2D/3D, which are qualitative descriptions of soil behaviour in the computer program have become very useful for many soil mechanics problems.
- Highlights are made of the areas of application and some of the mathematical principles upon which the constitutive and other modelling techniques are based to emphasize the need to be firmly grounded in the theory and analyses of soil mechanics in order to transit into modelling.
- Finally, discussing on the contributions of research and literary activity in soil mechanics to the development of Nigeria, we appreciate that there have been lots of activities that have given prominence to tropical laterites and lateritic soils with highlights of problematic clays like the black cotton expansive soils.

5/2 Summary, Conclusion and Recommendations

- Existing and ongoing researches have built an indigenous knowledge base expected to be invaluable in the area of alternative binders and other stabilization processes for improving poor soils for application in replacement of excellent lateritic soils resources depleted for construction in the country.
- However significant works undertaken in Universities and Nigerian Building and Road Research Institute, NBRRI, need to be collated on a national database to be domiciled in NBRRI.
- Areas of significant contribution like the NBRRI digitized subgrade soils map seems not to be at the front burner of development any longer. This is recommended for re-invigoration while a major scientific forum should be organized by NBRRI on Nigerian soils research for the categorization of these soils and mapping of their measured properties.
- The PLAXIS 2D/3D modelling software for Soil behavioural development needs to be embraced, domesticated and popularised in Nigeria by NBRRI for its numerous applications potency and identified usefulness in solving soil mechanics problems.

THANK YOU!