Tan Sri Professor Chin Fung Kee Lecture

Modified Soil Mechanics from Practice to Theory

By

A.S.Balasubramaniam (Bala)
School of Engineering
Griffith University Gold Coast Campus
Queensland
Australia

Soil Mechanics Era

Classical Soil Mechanics

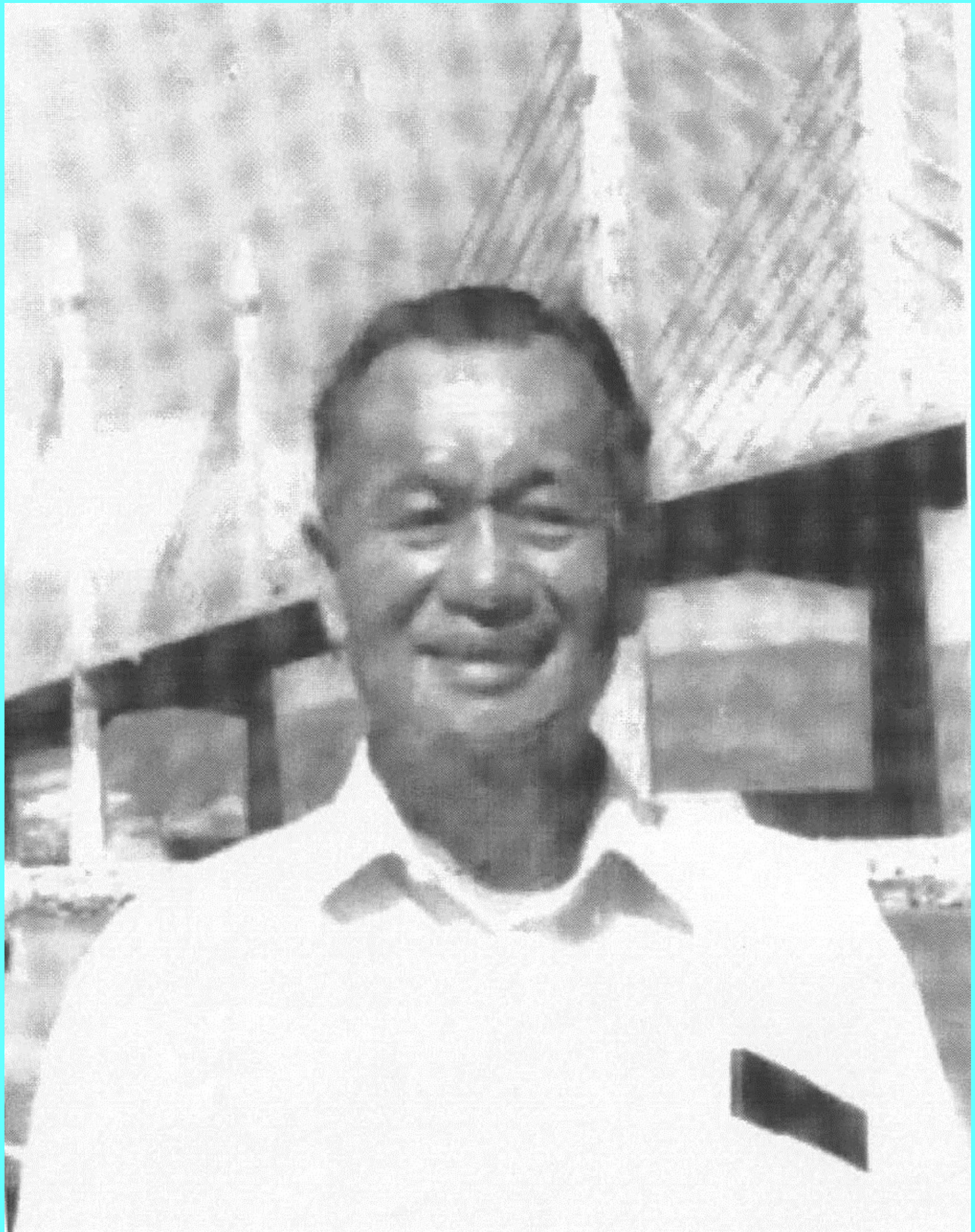
Critical State Soil Mechanics

Small Strain Behaviour

Political state soil Mechanics

Business Soil Mechanics

Miserable State Soil Mechanics



Choice of this Lecture

The choice of this lecture was entirely based on my experience over the years and is an area where basic soil mechanics, laboratory and field tests, instrumentation and analysis seem to interact in a coherant way

-Laboratory and Field tests

- Soil behavior

-Observational approach

- Analytical methods etc

Soil properties for routine calculations

Conventional calculations fall into two categories

Limit analysis

Deformation analysis

CHARLES AUGUSTIN COULOMB
(1736–1806)

From his portrait in the Louvre. Reproduced from Transactions of th Newcomen Society, Volume XVII, by permission

Deformation analysis

Disregards the soil strength

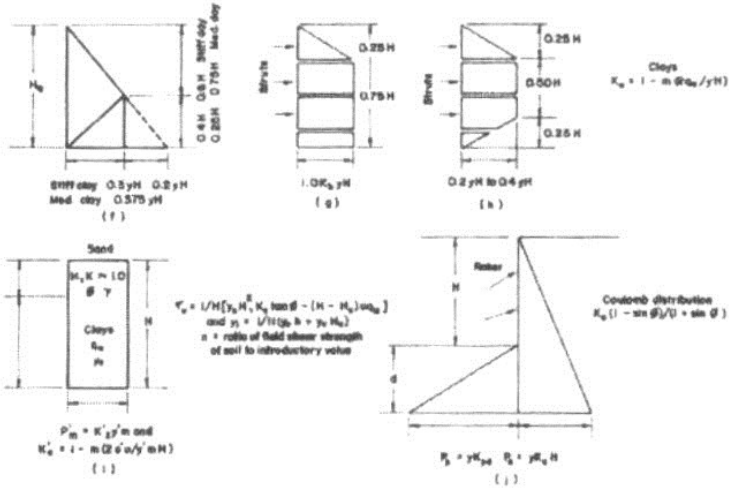
Deals only with

Deformation and consolidation properties

Peck believed in observational methods from full scale behavior

1. Earth pressure diagran from subway projects

2. Settlement profiles in tunneling

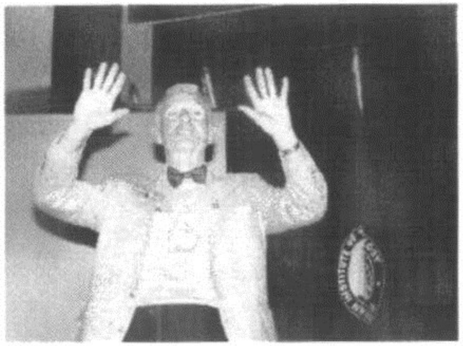


f) Tschebotarioff (1951)
g) Soft to Medium Clay, Terzaghi and Peck (1967)
h) Stiff Fissured Clay, Terzaghi and Peck (1967)
i) Layered soil,
j) Raker braced

Fig. 2.11 (f–j) Lateral Pressure Distributions for Design of Braced Structures

Bjerrum was a strong advocater of large scale field tests and observational approach from major projects with full instrumentation

1. Oslo subway earth pressure measurements
2. Large scale direct shear tests
3. Full scale Embankments
4. Slurry trench excavations
5. Full scale plate load tests
6. Instrumented pile load tests
7 Instrumentation of foundations, slopes, dams, offshore structures etc



Prof Lambe had a prediction symposium of an embankment in Boston Blue clay at the M.I.T. Campus

Prediction Type	When Prediction Made	Results known When Predictions Made
A	Before Event	-
B	During Event	No
B1	During Event	Yes
C	After Event	No
C1	After Event	Yes

Apparently Karl Terzaghi had little faith in single element tests, theories, and model tests both 1g and centrifugal tests with multiple g

Karl Terzaghi

Roscoe believed in good quality

- *Laboratory test data (from simple shear, Biaxial & Truly triaxial tests)*
- *X ray and Gamma ray techniques for local strain measurements & slip lines*
- *Scanning electron micrographs for studies on anisotropy and particle orientation in failure surfaces of thin sections*
- *Large scale 1-g model tests & Centrifugal model tests*

To Understand the Soil Behaviour in a unified manner

Skempton's early writings in the BRE days were possibly using total stress analysis and this is perhaps why he abandoned the idea of writing his early works as a text book

Professor A. W. Skempton

This is a good way of making enemies. But I guess as time goes on truth should prevail

Don't use the C word

Professor Andrew Schofield has developed arguably the two greatest advances in soil mechanics of the last 30 years – critical state soil mechanics and the use of the geotechnical centrifuge. As he retires he still has a mission to accomplish. He talks to Paul Wheeler.

Andrew Schofield, a professor of engineering at the University of Cambridge and a Fellow of the Royal Society, must at all be excused for retiring with a sense of smug satisfaction. His contributions to the development of theoretical soil mechanics are unquestionable. Instead, I find a man with missionary zeal.

He is initiating a campaign, although he denies it, that could reshape geotechnical design. If it is successful the C word will only remain in the engineers' vocabulary as "apparent cohesion".

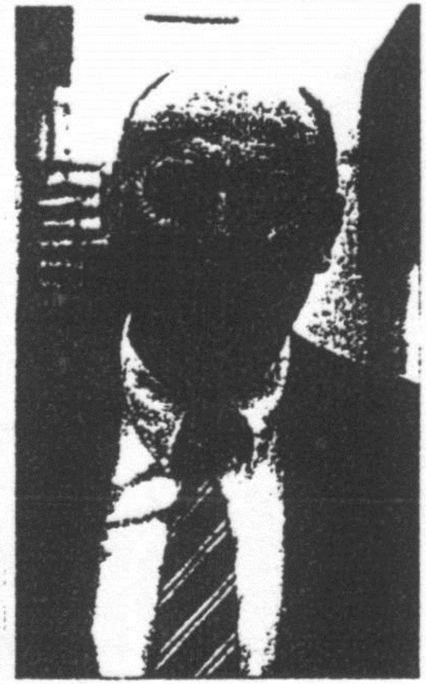
The peculiar thing is, this sudden vigour does not rely upon new data. It is essentially the same message made in *Critical State Soil Mechanics*, co-authored with the late Peter Wroth, and published in 1968.

"It's a pity I didn't make these points as strongly 30 years ago, but I didn't appreciate the importance," he says. "It's only gradually that certain things impact upon you and this insight is one of those.

"I am asking, does the industry really want its engineers to be taught something that is fundamentally wrong? Must Terzaghi's textbooks from 1943 still be gospel in 2000? I don't think so."

The argument, which Professor Schofield presents in abridged form on the following pages, is essentially that behaviour of remoulded soil (be it sand, silt or clay) is governed by friction and particle interlocking. The Mohr Coulomb equation, popularised by Terzaghi, and underpinning developments in soil mechanics since the 1930s, is simply wrong. Terzaghi, the grandfather of modern geotechnics, the man who made soil mechanics a science, made a mistake when he said soil's strength is provided by cohesion and friction.

"The key piece of data is the work of Hvorslev. Hvorslev and Terzaghi misunderstood the data, and I think that raises a very serious question. If a similar fundamental error was identified in, say, fluid mechanics, the senior designers in the industry would immediately want to know. If you told the designers of the Boeing company that their design was based on an erroneous concept they wouldn't hesitate. They would say [illegible]



Schofield: Must Terzaghi's textbook from 1943 still be gospel in 2000?

Reston, VA---In recognition of National Engineer's Week (February 22-26), the American Society of Civil Engineers announces the release of the first comprehensive biography of the renowned 'Father of Soil Mechanics'--Karl Terzaghi. Entitled ***"Karl Terzaghi: The Engineer as Artist,"*** this new book offers a first-hand look into the journey of the greatest innovator in geotechnical engineering history. After five years dedicated to researching, reading, interviewing acquaintances, and translating volumes of previously lost diaries, author Richard E. Goodman captures the essence of one of the most important civil engineers of our time.

Andrew Schofield quotes in Istanbul

Peck's Review of Taylor's Manuscript

I am convinced that the theories of soil mechanics and the results of laboratory tests serve only to guide the engineer towards a recognition of the factors which only affect the design and construction of a real project

From review sent to John Wiley by R.B.Peck, July 31 1944 quoted from page 213 " Karl Terzaghi; the Engineer as Artist" R.E.Goodman (1999)

From Schofield in Istanbul Conference

John Wiley & Sons reply to Terzaghi

... (Taylor's book) will be published by one of our competitors if we do not take it. Under the circumstances, we see nothing to do but publish it.

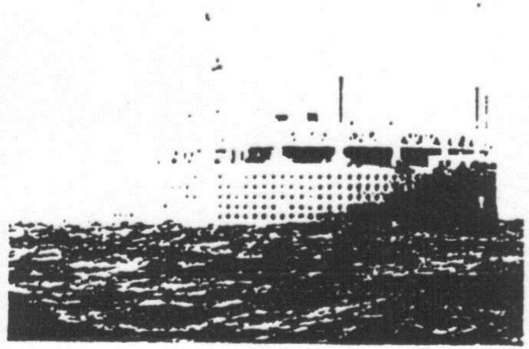
However, as I said in the first paragraph of this letter, we believe that each book will be judged on its own merits, and certainly we have no fears for the success of (Terzaghi & Peck).

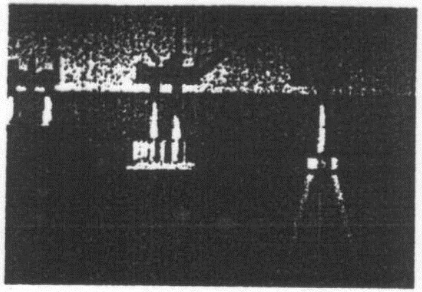
E P Hamilton (President) December 17, 1946

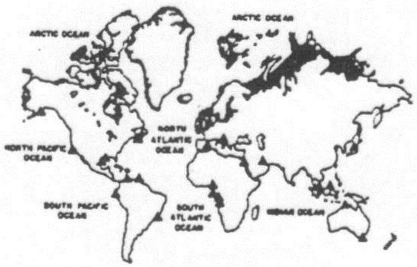
Andrew Schofield concentrated on

Critical state soil mechanics coupled with thermodynamics & plasticity theories

Centrifugal Model Tests



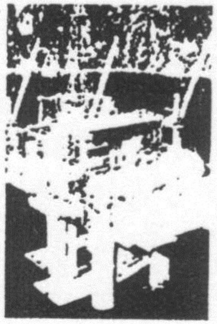


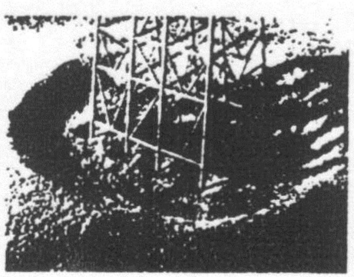


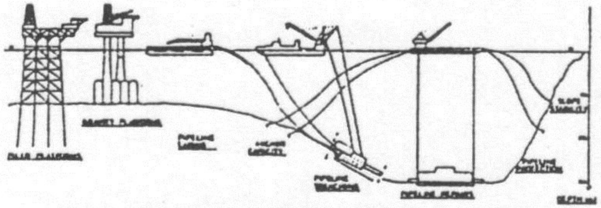
Major Regions of Petroleum Drilling Activity in World Oceans

Offshore

Geotechnics







Major construction activities in the North Sea requiring geotechnical engineering.

(After Lunne & Kleven)

Limit Equilibrium Analysis concerns only with:

1. **Equilibrium of Soil Mass , and deals with:**

   (a) **the weight of soil mass, and**

   (b) **the strength of soil**

It takes no account of deformations

Characteristic Directions, Discontinuities, Failure lines, Slip Lines

At the limiting stage in granular materials with plastic stress distribution discontinuities can occur

In the zone where such discontinuities occur the principal axes of stress and strain increments coincide and the material reaches a non-dilatant stage

Limit analysis in geotechnics takes advantages of these discontinuities in bearing capacity, slope stability and earth pressure calculations

Choice of factor of safety

Use of adequate safety factor also cuts down deformations under working conditions

Limit State Designs

1. Bearing Capacity of Shallow and Deep Foundations

2. Stability of Slopes

3. Earth Pressure Theories

Two types of analysis

1. Total stress analysis using undrained strength. When the water content remains constant.

2. Effective stress analysis

   a. Undrained analysis with excess pore water pressure due to shear.

   b. Drained analysis with full dissipation of excess pore water pressure due to shear

Total stress analysis

1. Undrained bearing capacity of shallow foundations in clays
   (Short term stability)

2. Deep foundations
   - Carrying capacity of shafts of piles in clay layers
   - End bearing of piles in clay layers

3. Short term stability of embankments and excavations in clays

4. Active and passive pressures under short term conditions in earth retaining structures

5. Undrained basal heave stability in clays during deep excavations

Undrained effective stress analysis

-Embankments and excavations in soft clays

Drained effective stress analysis

-Long term stability of excavations

-Earth pressures under long term conditions

Role of strength & deformation based analysis

1. Soil properties for routine calculations

    Limit analysis

    Deformation analysis

2. Elastic distribution, plastic distribution,dilatancy,slip lines

3. Total & effective stress analysis under undrained and drained conditions

4. **Stress paths & deformation analysis with pseudo-elastic parameters including consolidation**

5. **Critical state soil mechanics & numerical analysis**

6. **Pender type stress-strain model, small strain behaviour etc in deformation based analysis with critical state soil mechanics**

Critical State Soil Mechanics (CSSM)

In terms of Effective stresses, the laboratory and field behaviour of soils can be interpreted for excess pore water pressure development during undrained shear and the volumetric strains in the drained case. For both the undrained and drained cases shear strains can be computed and hence the axial strain which determines the settlement and the lateral strains which enables the calculation of lateral movements can be computed when stress increments are applied from any initial state of stress conditions upto failure

Critical State Soil Mechanics (CSSM)

1. CSSM helped to have a simple framework to tie together the water content and stresses for all types of stress paths in compression and in extension from the in-situ stress state to failure.

Thus in addition to the Mohr-Coulomb strength envelop in the stress path plot CSSM added the water content – strength relation used in total stress analysis

Theory of Elasticity

Limitations

1. Elastic stress distributions are continuous and therefore cannot accommodate failure planes or slip planes as used in limit analysis which are discontinuities and can only be formed in plastic stress distribution.

2. Shear modulus G is only related to the deviator stress increment and the shear strain increment.

   Bulk modulus K is only related to the mean normal stress increment and the volumetric strain increment

Theory of elasticity cannot explain the coupled behaviour of dilatancy in granular medium

Closed form solutions

Elasticity provides the widest class of closed form Solutions to Geotechnical Engineers.

Boussinesq solutions
Mindlin solutions

Linear elasticity enables the use of
Superposition principle
in obtaining stresses and deformations under complex loadings

Deformation analysis with parameters conventionally used in theory of elasticity

Young's modulus E

Poisson's ratio ν

Shear modulus G

Bulk modulus K

Engineering practice adopts first pair (E, ν)

Second pair (G, K) is more fundamental; separates pure shear and bulk behaviour

Type of analysis

Distinguish between undrained and drained behaviour

Also

Whether analysis is in terms of
Total stresses or
Effective stresses

Relevant elastic properties are either
(E_u , ν_u) or (E', ν')

Shear & Bulk Modulus

G & K' are functions of the mean normal stress and also the overconsolidation ratio

Undrained case-no volume change

$$\nu_u = \frac{1}{2}$$

and

$$K_u \to \infty$$

For most soils ν' is constant

Shear modulus is the same in total and effective stress conditions

$$\frac{E_u}{2(1+\nu_u)} = G_u = G' = \frac{E'}{2(1+\nu')}$$

Because of this relation it is preferable to use shear modulus. Also drained and undrained moduli are related

Wherever possible work in terms of effective stresses using either pair

(G, ν') or (G, K')

Soil is a frictional material

Friction in granular material with contacts need movements to be fully mobilized

Cambridge stress strain theories

Undrained stress path

- Calculates shear strain increment same as axial strain increment under axi-symmetric triaxial conditions.

Constant stress ratio consolidation

- Contribites volumetric strain and shear Increment with constant dilatancy ratio For each stress ratio

However in actual stress path method with constant deviator stress, when the pore pressure dissipates, the stress ratio reduces and do not remain constant

Stress path way of interpreting settlement components

Undrained stress path

- Gives immediate settlement or undrained settlement with outward lateral movement with zero volumetric strain

Consolidation path with pore pressure Dissipation with constant deviator stress

-Gives consolidation settlement and lateral contraction due to radial consolidation

During pore pressure dissipation and three dimensional consolidation, there is a reduction in stress ratio

Terzaghi's Soil Mechanics For Settlement computations

Voids ratio changes are used. Implied inside this concept is a sort of inverse modulus

$$a_v = -\frac{de}{d\overline{\sigma}}$$

$$m_v = \frac{1}{1+e_0}\left(-\frac{de}{d\overline{\sigma}}\right)$$

$$D = \frac{\Delta\overline{\sigma}}{\Delta\varepsilon_1} = \frac{1}{m_v}$$

Settlement computations in clays

Traditionally one dimensional settlement is computed for

- **Primary consolidation**
- **Secondary consolidation**

Whereas for many of the soil Mechanics Problems now, the lateral deformations are also important. These lateral deformations are not related to the one dimensional consolidation settlement in a traditional sense

Projects chosen

1. Trial embankments on Malaysian marine clays and
2. Full scale field tests of prefabricated vertical drains (PVD) for the second Bangkok International Airport

Both Projects involve ground improvement works in one form or another on soft marine clays

1. Trial embankments on Malaysian marine clays

2. Full scale field tests of prefabricated vertical drains (PVD) for the Second Bangkok International Airport

Ground improvement schemes included

- -Electro-osmosis
- -Chemical injection
- -Sand sandwich
- -Pre-loading with drains
- -Micropiles
- -Vacuum pre-loading
- -Sand compaction piles
- -Well point pumping
- -Pre-stressed spun piles

Trial embankments on

Malaysian marine clays

-Electro-osmosis

-Chemical injection

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-Pre-loading with
drains

-Micropiles

-Vacuum pre-loading

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Comments and conclusions on residual soil embankment built under controlled conditions for the prediction symposium

1. Traditional slip circle analysis is generally accepted as the best method. The problem is in the selection of the strength of the embankment material and the foundation soft clay layer

a. Neglecting the embankment strength resulted in lower embankment height

b. Residual soil when well compacted had good engineering properties both cohesion and friction

2. **Residual soils possibly can have a substantial tensile strength and can also withstand tensile cracks which begin to propagate from the lower side of the embankment when settlement takes place**

3. **Soft clays with volcanic origin can have a high permeability so that the end of construction can be in a drained mode rather than the usually assumed undrained mode.**
4. **Some degree of three dimensional effect could have been there while the analysis assumes two dimensional conditions**

Comments and conclusions on ground improvement schemes

1. **Many of the ground improvement schemes did not give satisfactory results as the persons responsible for the work have lost the interest for one reson or another**

a. The contractor on the electro-osmotic scheme delayed the switching of the current and there were frequent interruptions of the power supply, which was also operating only for about ten or twelve hours in a day

b. Tensile cracks were observed in many embankments, except for those with surcharge and drains

2. **In the high embankments undrained yielding and creep were high.**

3. **The field deformation analysis conducted by Loganathan based on the ideas of John Christian seem successful in estimating the undrained creep settlements.**

4. The PVD used was thought to have well resistance as reported in an ASCE paper. This was also considered as an effect of smearing. Sven Hansbo recently talked about non-Darcian flow as well.

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Comments and conclusions …. (contd.)

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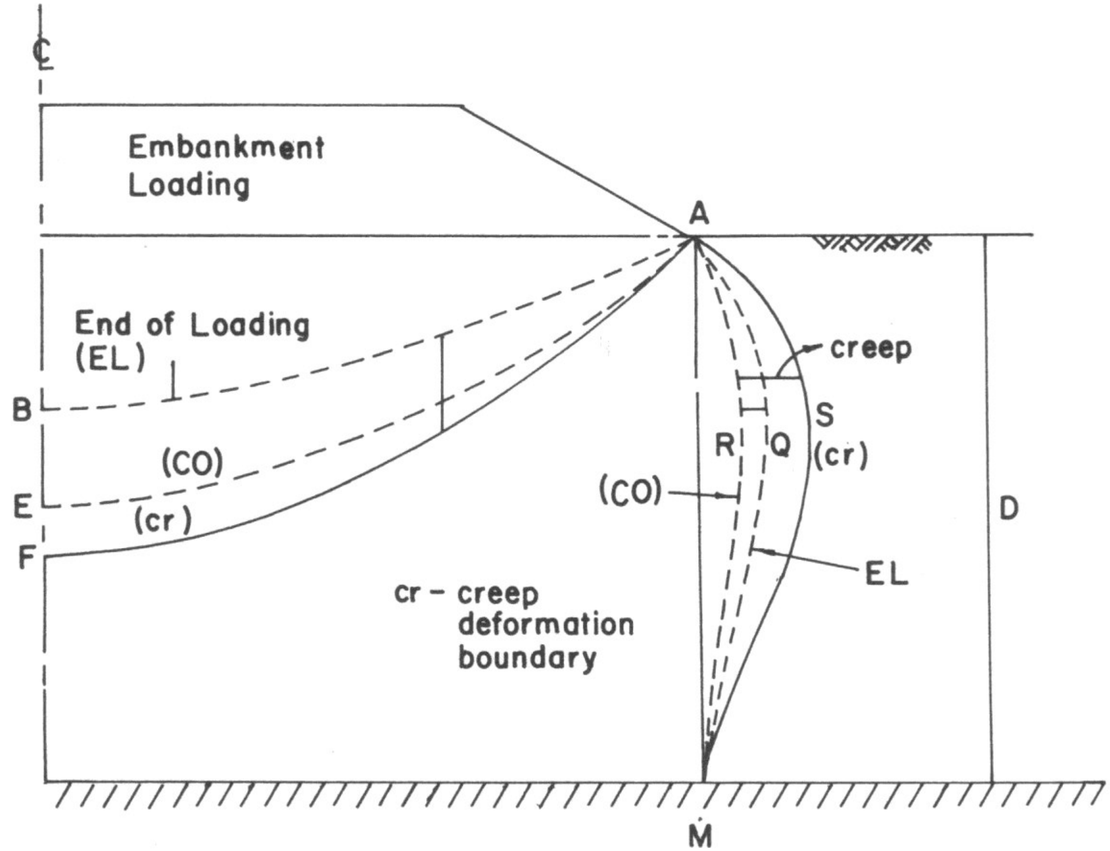

Embankment Foundation (Sub-soil) Deformation Pattern During Consolidation.

Full scale field tests of prefabricated vertical drains (PVD) for the Second Bangkok International Airport

Most painful Project

1. Selection of PVD

2. Construction in the rainy season under flooded conditions

3. Stability of the test embankments

4. Have to really prove that the settlement is due to consolidation and not from undrained yielding without any volume change

5. The piezometric draw-down due to subsidence made the computation of settlement from pore pressure dissipation difficult

6. Computations need to convince that the degree of consolidation estimated from pore pressure dissipation and settlement measurements are comparable

7. Undrained strength measurements should reflect the strength increase due to water content reductions.

8. Reason for continuing settlements

1. **Selection of PVD**
2. **Construction in the rainy season under flooded conditions**
3. **Stability of the test embankments**
4. **Have to really prove that the settlement is due to consolidation and not from undrained yielding without any volume change**
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6. **Computations need to convince that the degree of consolidation estimated from pore pressure dissipation and settlement measurements are comparable**
7. **Undrained strength measurements should reflect the strength increase due to water content reductions.**
8. **Reason for continuing settlements**

Concluding remarks on second international airport project ground improvement scheme --- test embankment with PVD

Salient Features

1. Selection of PVD
2. Construction in the rainy season under flooded conditions
3. Stability of the test embankments
4. Have to really prove that the settlement is due to consolidation and not from undrained yielding without any volume change

5. The piezometric draw-down due to subsidence made the computation of settlement from pore pressure dissipation difficult.
6. Computations need to convince that the degree of consolidation estimated from pore pressure dissipation and settlement measurements are comparable.
7. Undrained strength measurements should reflect the strength increase due to water content reductions.
8. Reason for continuing settlements.

The performance of the test embankment was satisfactory in the sense

1. The consolidation settlements were 90 pc of the total settlement.
2. The degree of consolidation computed from the pore pressure dissipation is of the same order as those computed from settlement measurements.

3. The strength increase was the same as the strength increase corresponding to water content reductions.

4. The undrained creep and secondary consolidation can be erased with the partial removal of surcharge.

Concluding remarks

The lecture looked at the chronological development in geotechnical analysis with

1. Closed form solutions using the theory of elasticity.

2. Limit analysis based on shear strength parameters.

3. Deformation based analysis based on pseudo elastic parameters including consolidation.

4. Critical state soil mechanics.

5. **Pender type stress-strain model and the use of small strain theory within critical state soil mechanics framework.**

The following concluding remarks can be made

(a) **Effective stress based limit analysis and the choice of appropriate strength parameters seem to provide adequate solutions where restricted deformations are not stipulated.**

(b) **Stress path method of settlement computations and the associated pseudo-elastic parameters are discussed.**

(c) The use of critical state soil mechanics in numerical analysis offered comprehensive solutions for most geotechnical analysis.

(d) Pender type of stress strain theory and the small strain behaviour within the critical state sol mechanics framework could help in deformation-based design with restricted deformations

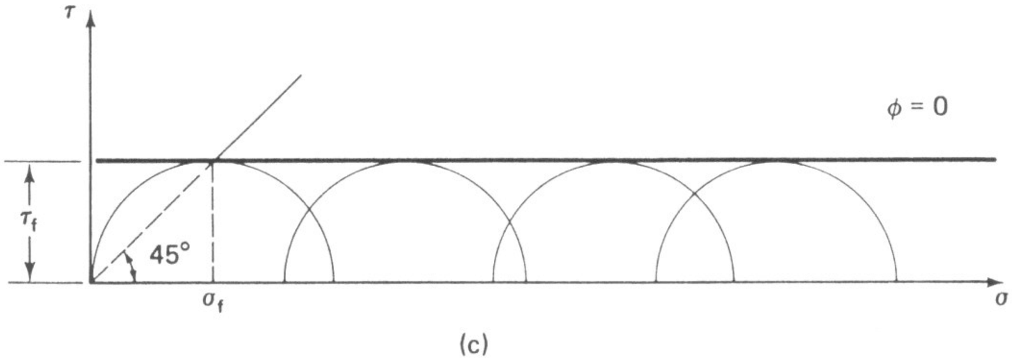


Fig. 10.9 (a) Stress conditions before failure; (b) stress conditions at failure; (c) Mohr failure envelope for a purely cohesive material (after Hirschfeld, 1963).

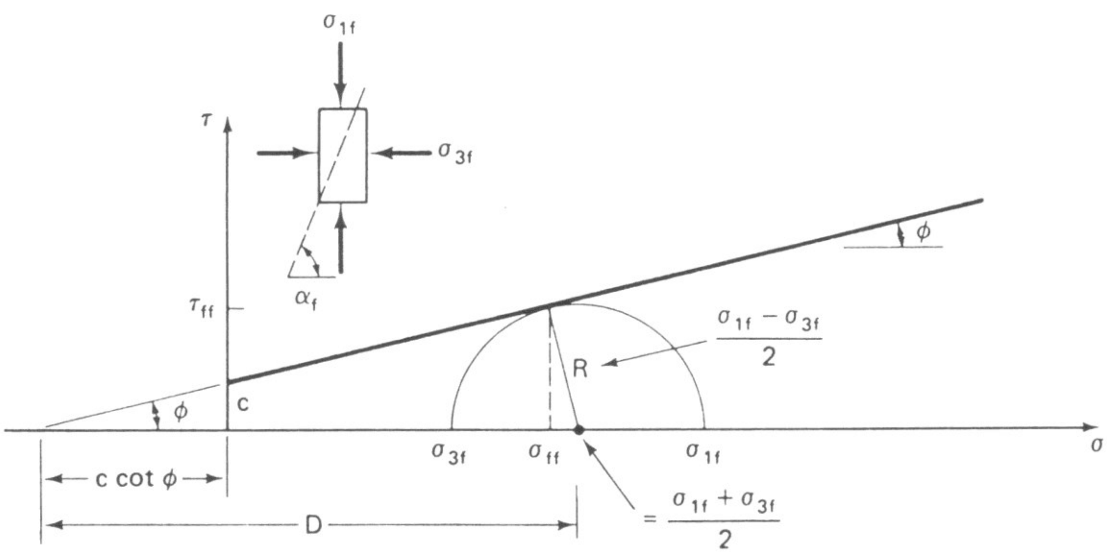


Fig. 10.10 Mohr-Coulomb strength envelope with one Mohr circle at failure.

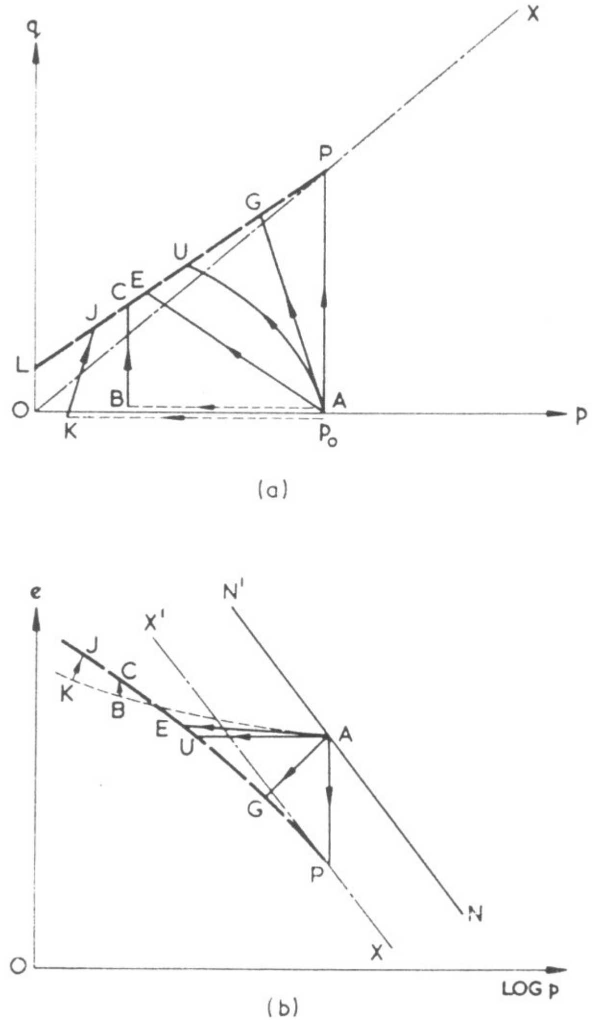
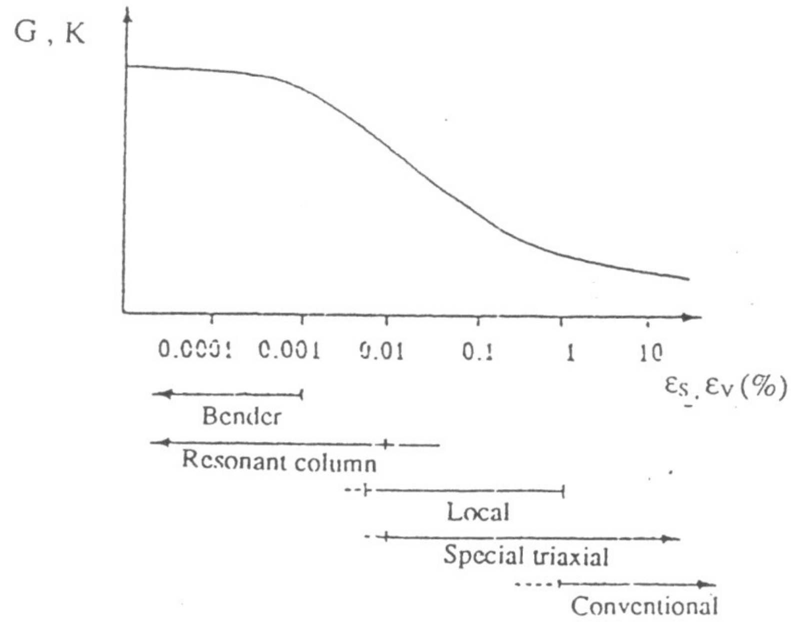
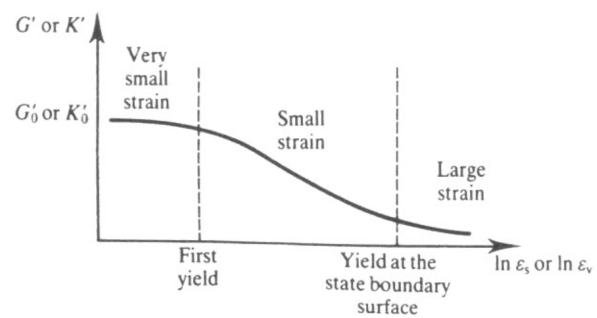


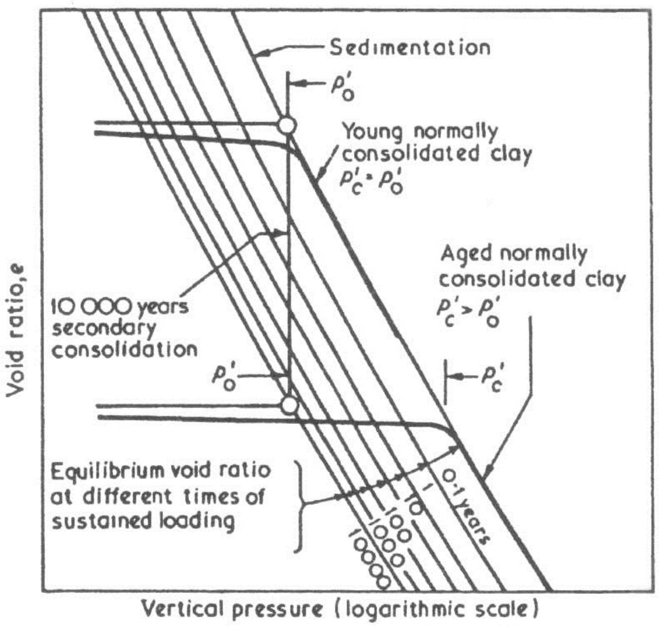
Fig. 1. The paths followed by specimens in Type 1 tests in the (q, p) space and $(e, \log p)$ space.



G , K
0.0001
0.001
0.01
0.1
1
10
εs , εv (%)
Bender
Resonant column
Local
Special triaxial
Conventional



G′ or K′
Very small strain
G′0 or K′0
Small strain
Large strain
First yield
Yield at the state boundary surface
ln εs or ln εv



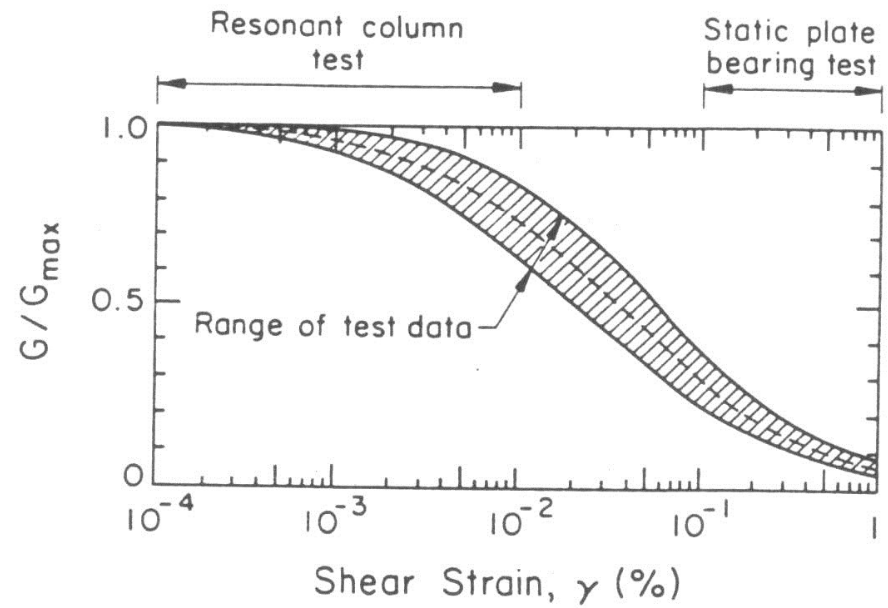


Figure 5-11. Shear Modulus versus Shear Strain for Sands

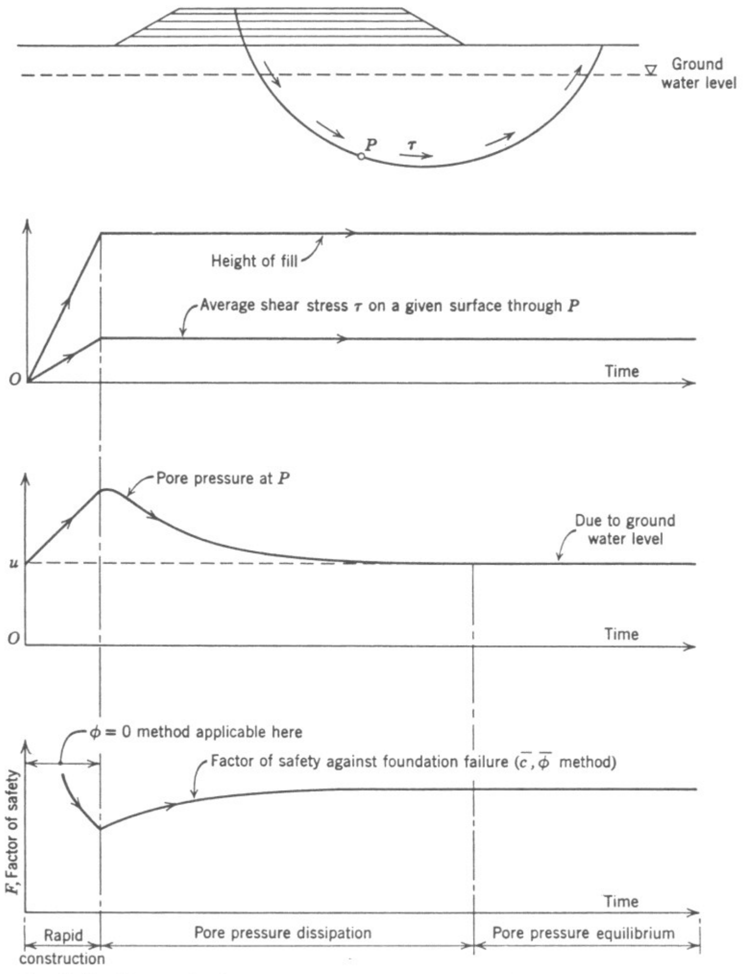


Fig. 31.5 Changes in shear stress, pore pressure, and safety factor during and after construction of embankment (From Bishop and Bjerrum, 1960).

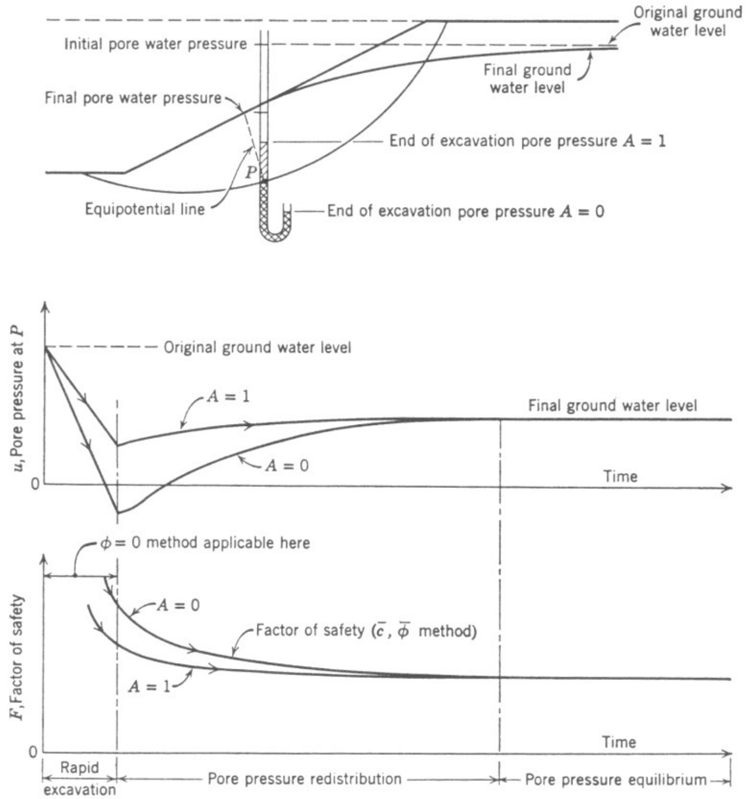


Fig. 31.2 Changes in pore pressure and safety factor during and after excavation of a cut in clay (from Bishop and Bjerrum, 1960).

Cambridge stress strain theories

Undrained stress path

- Calculates shear strain increment same as axial strain increment under axi-symmetric triaxial conditions.

Constant stress ratio consolidation

- Contributes volumetric strain and shear Increment with constant dilatancy ratio For each stress ratio

However in actual stress path method with constant deviator stress, when the pore pressure dissipates, the stress ratio reduces and do not remain constant