A Review of Deep Excavation in Infrastructure Projects

by
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CONTENT

- Introduction
- Theoretical Background
- Case Study
  - Case A
  - Case B
- Conclusion & Recommendation

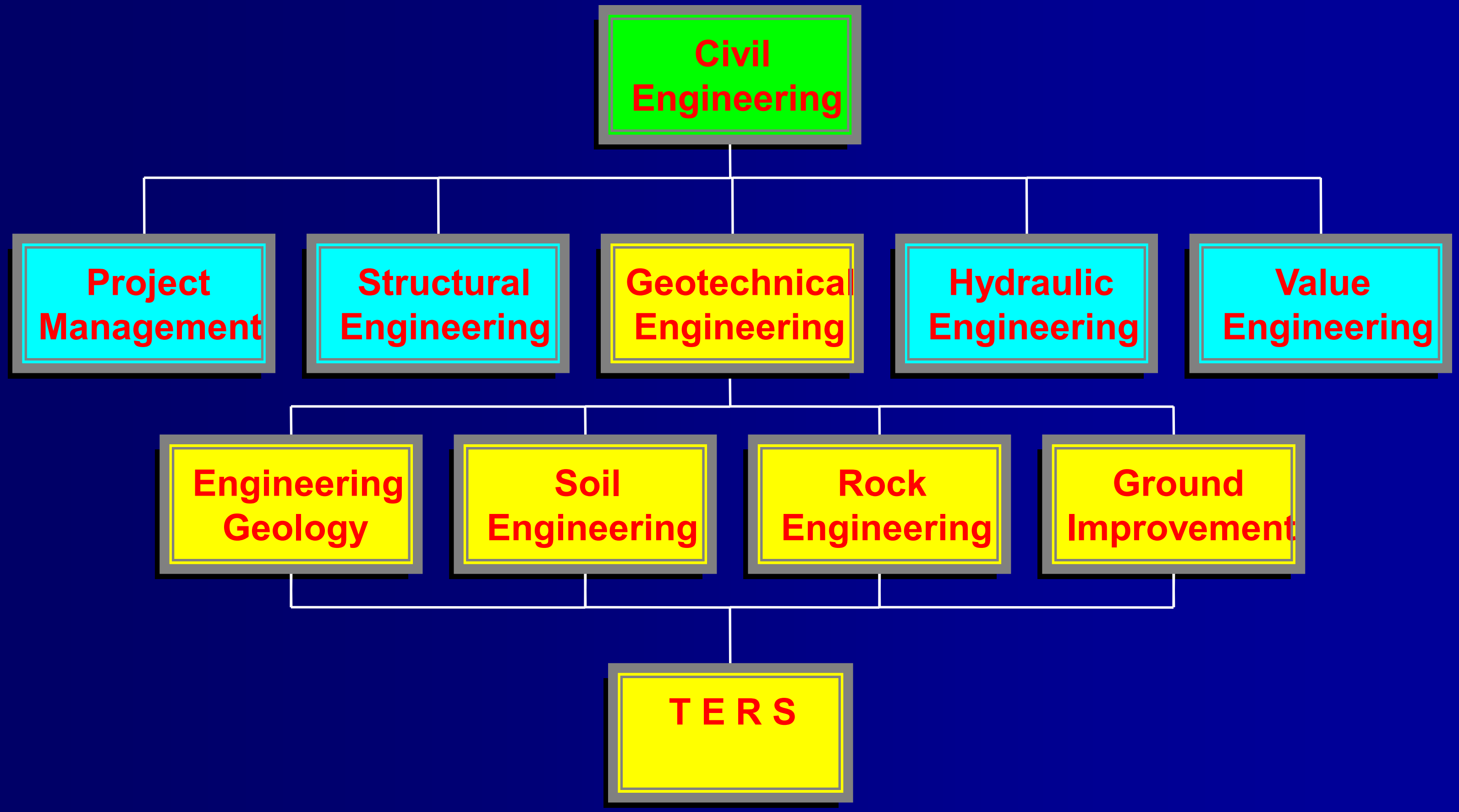
INTRODUCTION

DEEP EXCAVATION WORKS:

- ***Design Stage***
  **** Analysis (more in geotechnical)***
  **** Design (more in structural)***

- ***Construction Stage***
  **** Construction (more in structural)***
  **** Monitoring (more in geotechnical)***
  **** Quality Control (geotechnical & structural)***

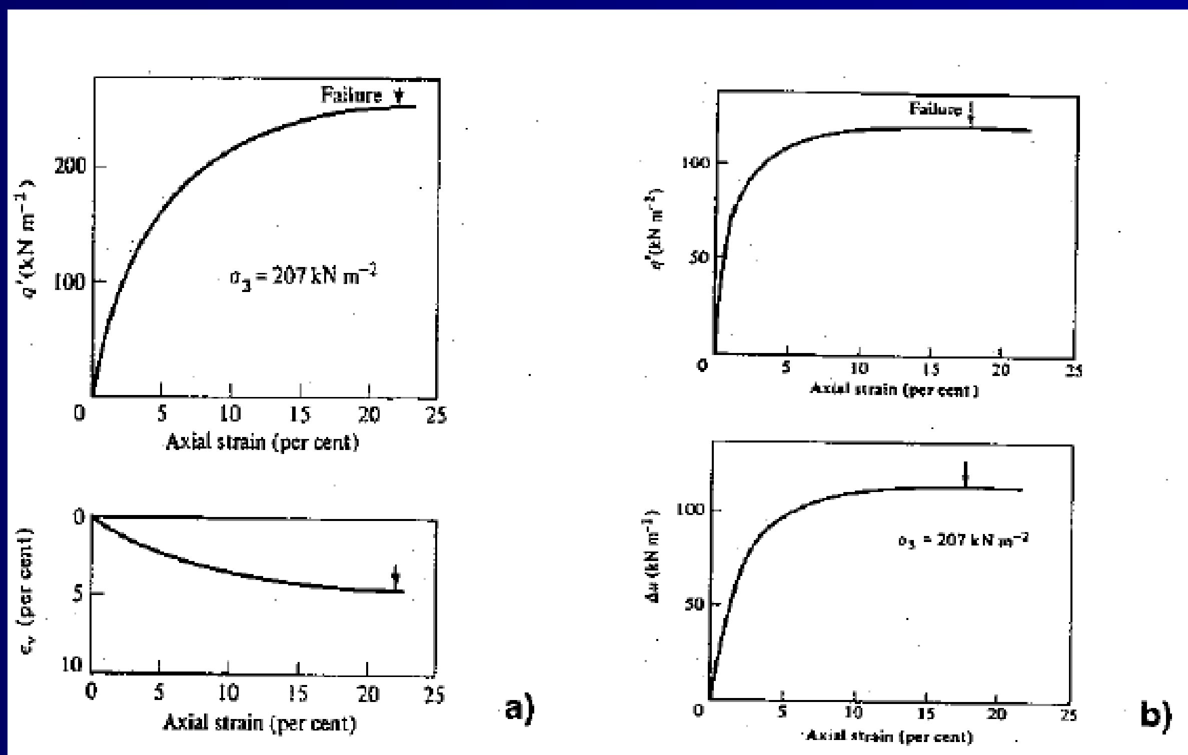
Geotechnical Engineering



Theoretical Background

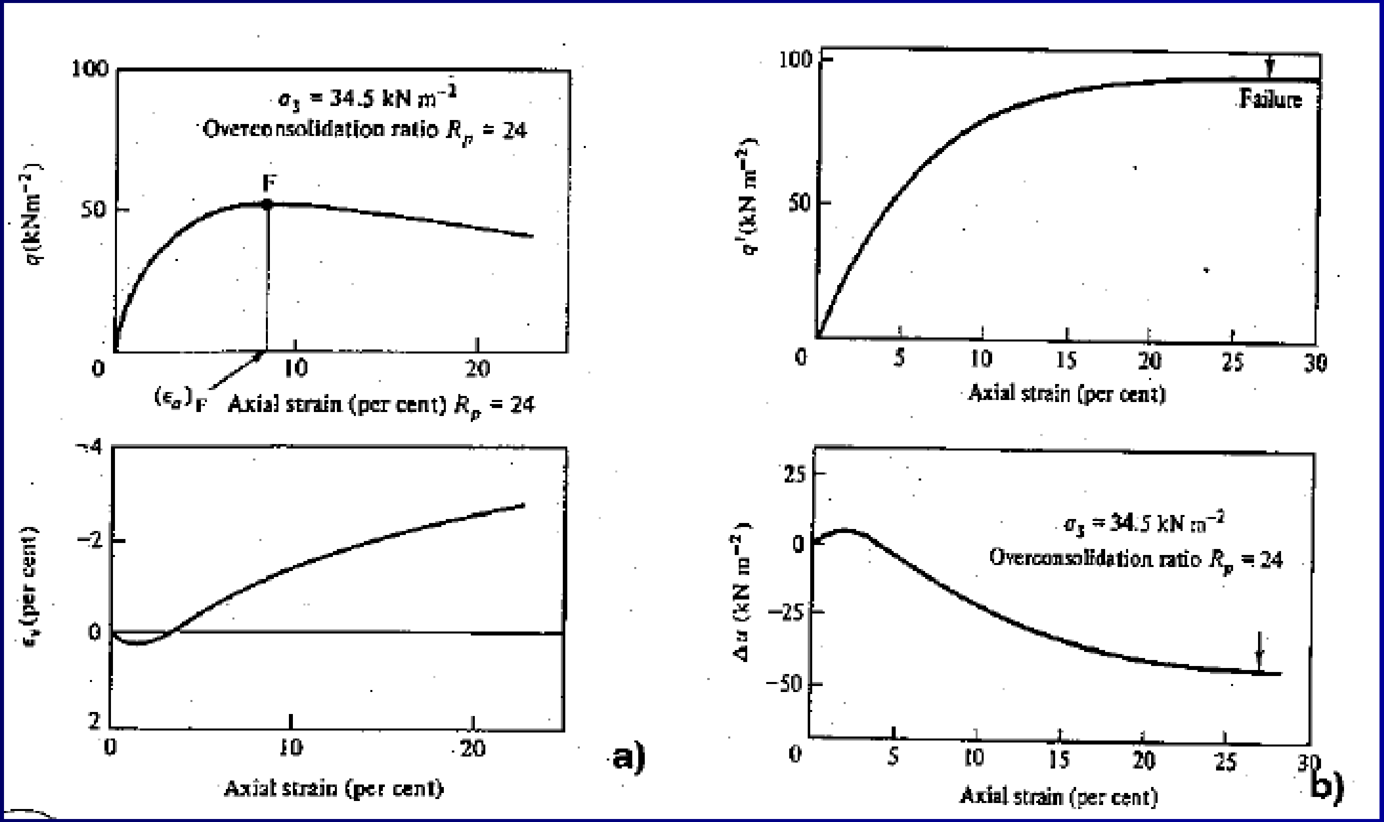
TRIAXIAL TEST (NC) – DRAINED / UNDRAINED

DRAINED UNDRAINED



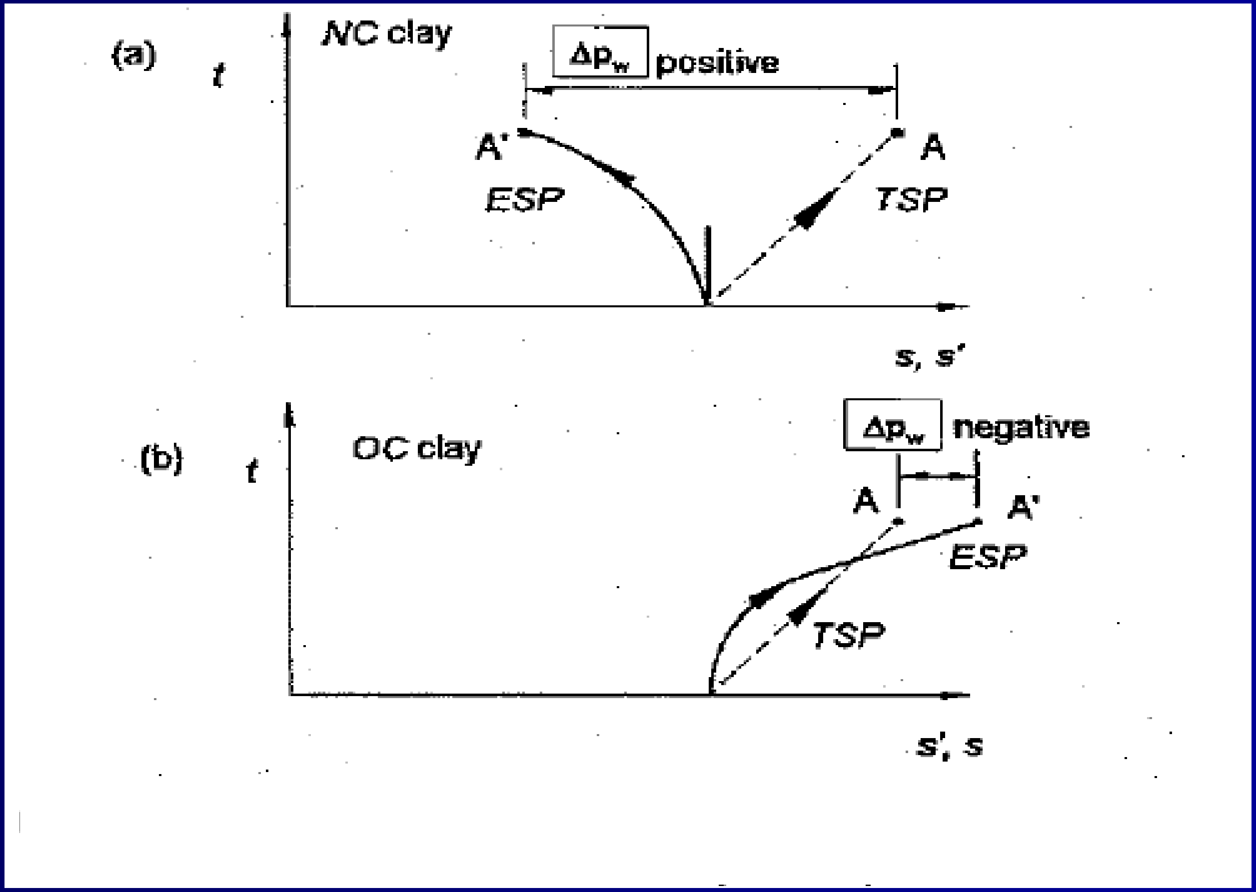
TRIAXIAL TEST (OC) – DRAINED / UNDRAINED

DRAINED UNDRAINED

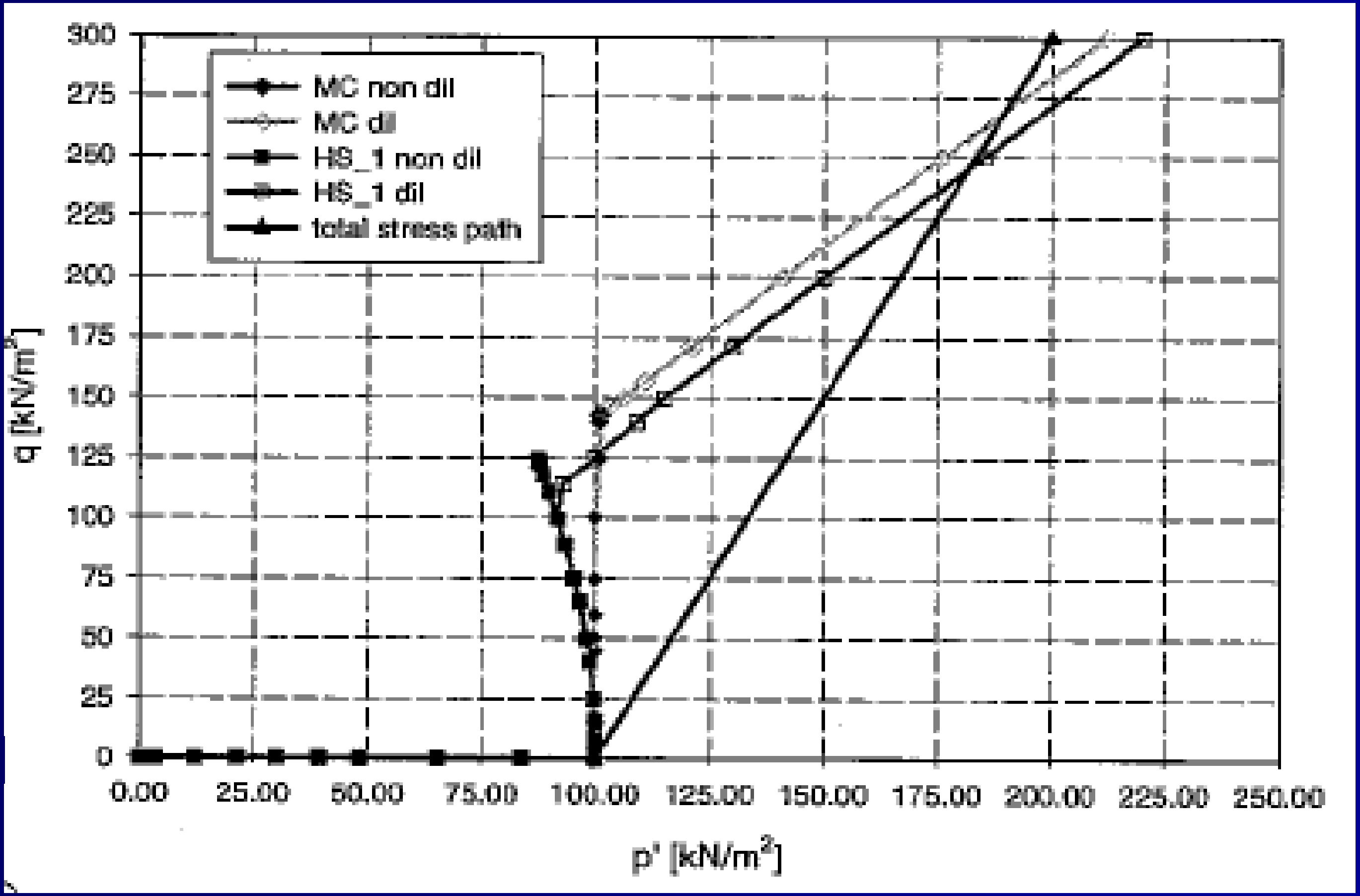


TRIAXIAL TEST UNDRAINED

Typical results from undrained triaxial tests on (a) normally consolidated and (b) overconsolidated clay (from Ortigoa, 1995)



COMPARISON MC – HS / INFLUENCE ψ



Simulation of undrained triaxial compression test- MC / HS model – q vs p’

Plane Strain Stress Paths

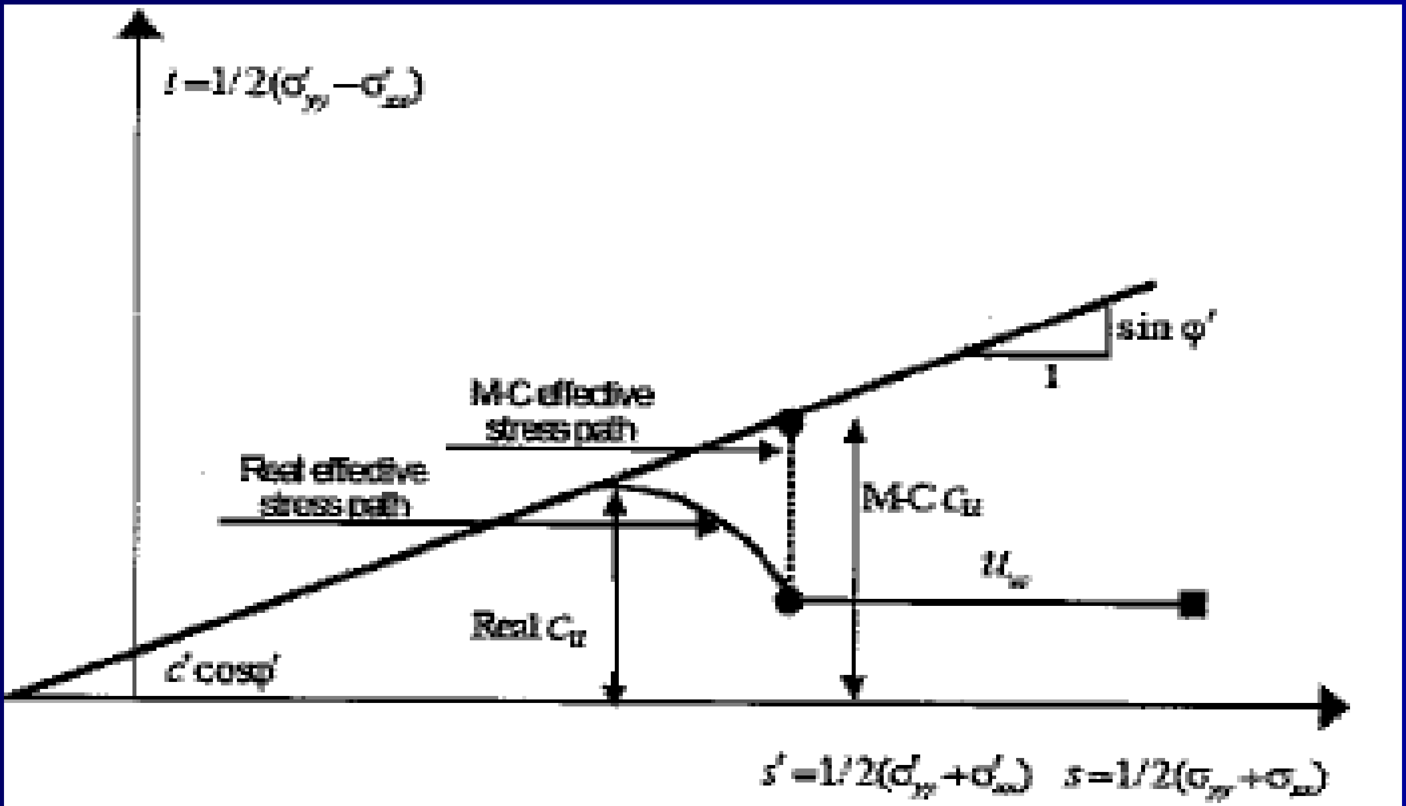
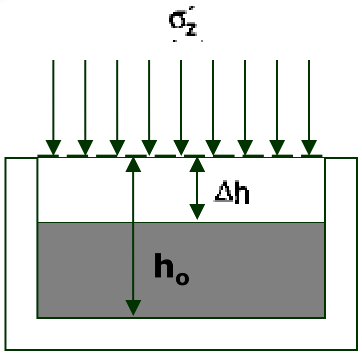
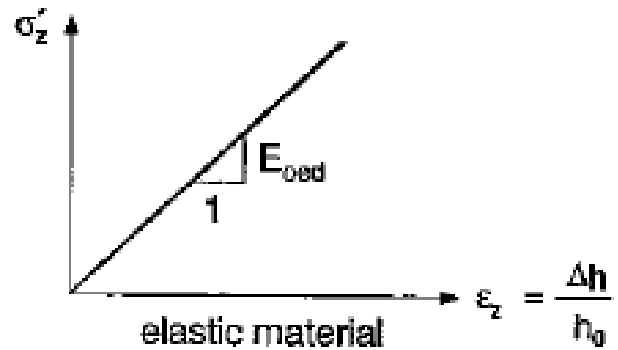


Figure A1.3 Undrained effective stress paths and undrained shear strengths for a soft normally consolidated soil and for a soil obeying the Mohr-Coulomb model

Oedometer test on an elastic material



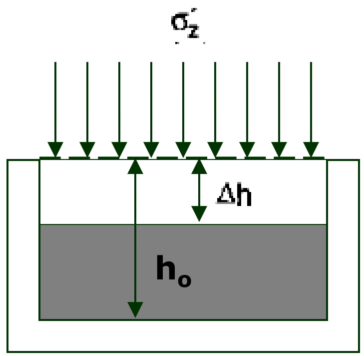


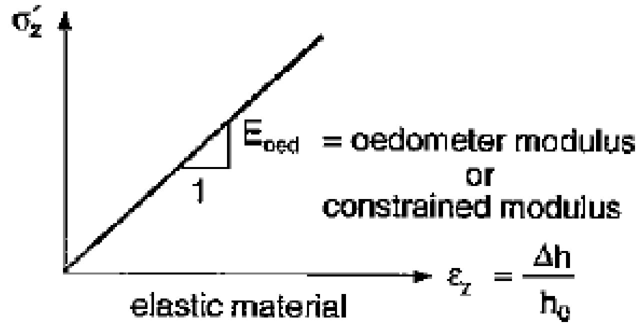
$$\left.\begin{array}{l}(1)\ldots\quad \varepsilon_x = \frac{1}{E}\left(\sigma'_x - \nu\sigma'_y - \nu\sigma'_z\right) = 0 \\ (2)\ldots\quad \varepsilon_y = \frac{1}{E}\left(\sigma'_y - \nu\sigma'_z - \nu\sigma'_x\right) = 0\end{array}\right\} \Rightarrow \sigma'_x = \sigma'_y = \frac{\nu}{1-\nu}\sigma'_z$$

hence: $K_0 = \frac{\nu}{1-\nu}$

For $\nu = ⅓$ one obtains $K_0 = 0.5$.
Normally consolidated soils have $K_0 \approx 0.5$

Oedometer test on an elastic material





$$\text{(3)...}\quad \varepsilon_z = \frac{1}{E}\left(\sigma'_z - \nu\sigma'_x - \nu\sigma'_y\right)$$

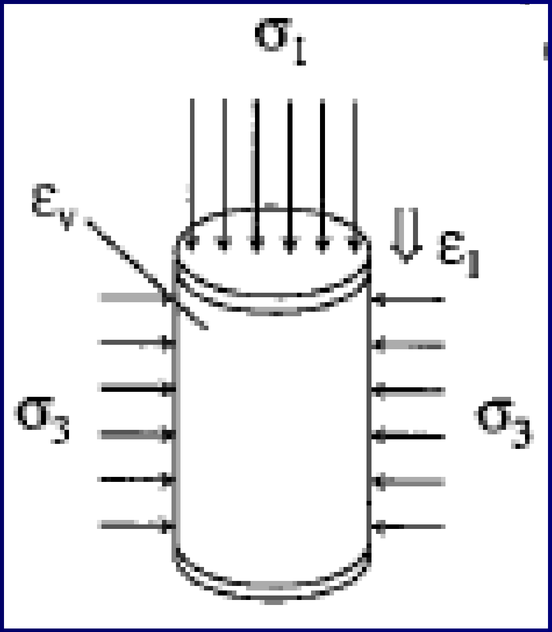
$$\sigma'_x = \sigma'_y = \frac{\nu}{1-\nu}\sigma'_z$$

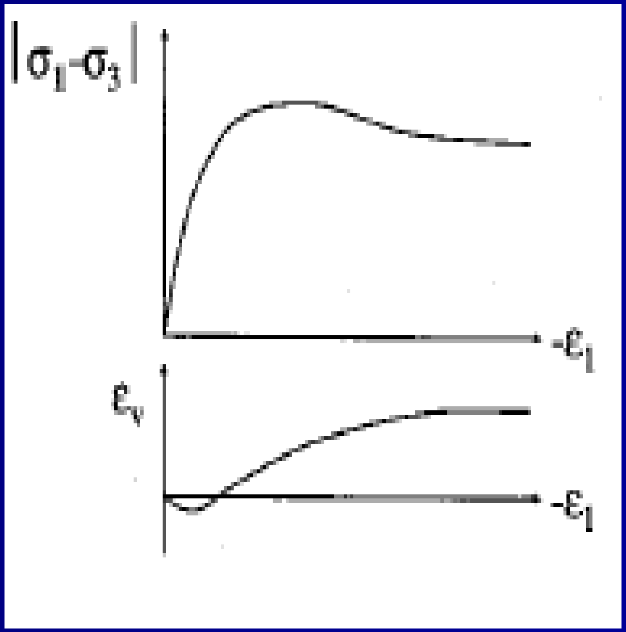
$$\Rightarrow \quad \varepsilon'_z = \frac{(1-2\nu)(1+\nu)}{(1-\nu)}\cdot\frac{\sigma'_z}{E}$$

hence: $$E_{oed} = \frac{(1-\nu)}{(1-2\nu)(1+\nu)}\cdot E$$

Stress Paths in Standard Soil Tests

- Standard drained triaxial test (CD test)

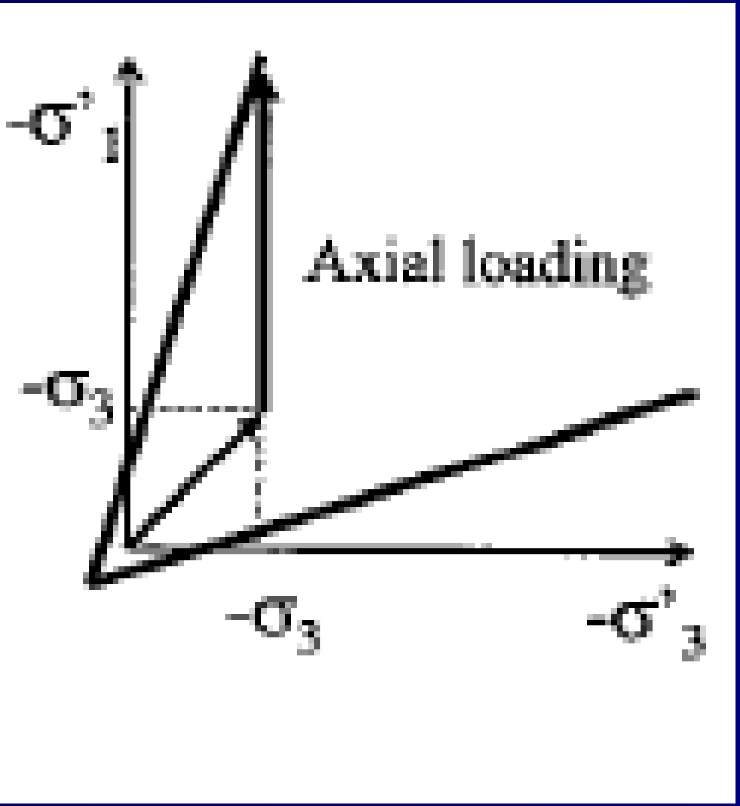


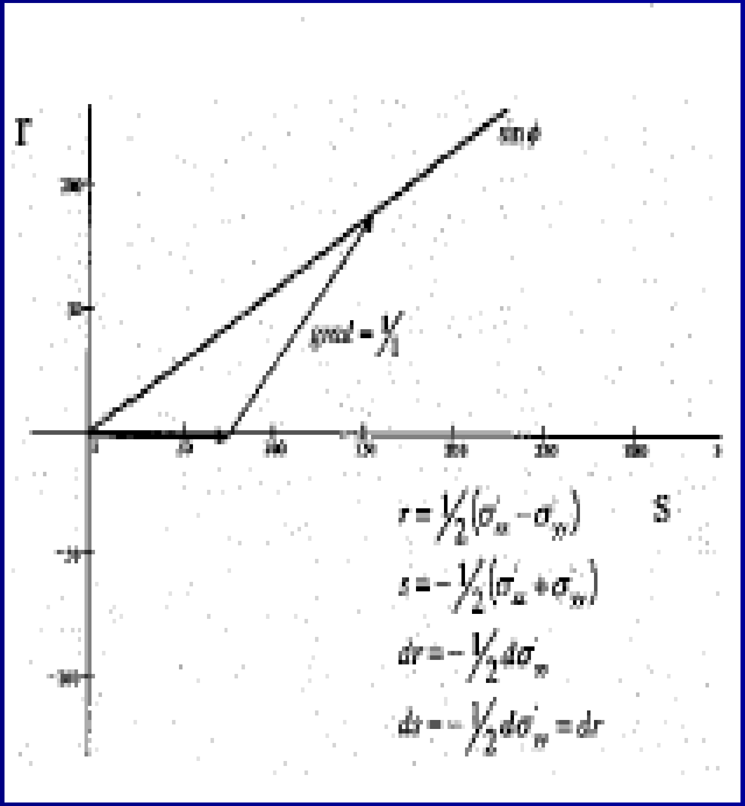


Stress-strain diagram

Stress Paths in Standard Soil Tests

- Standard drained triaxial test (CD test)

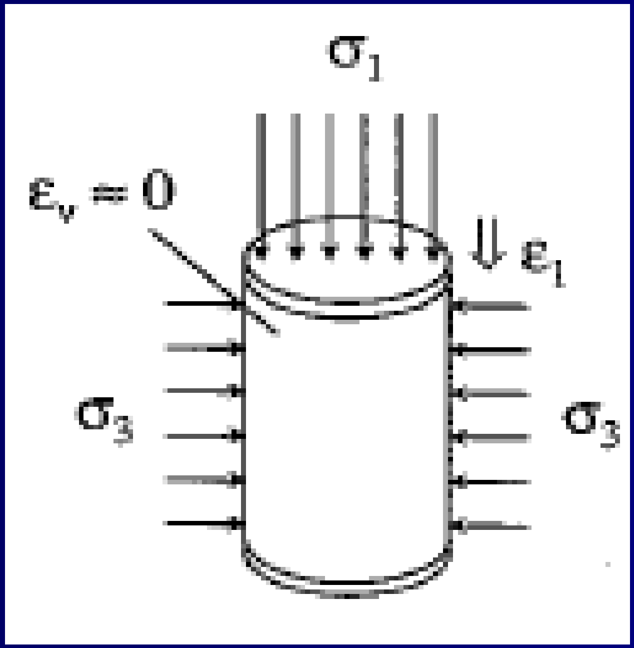


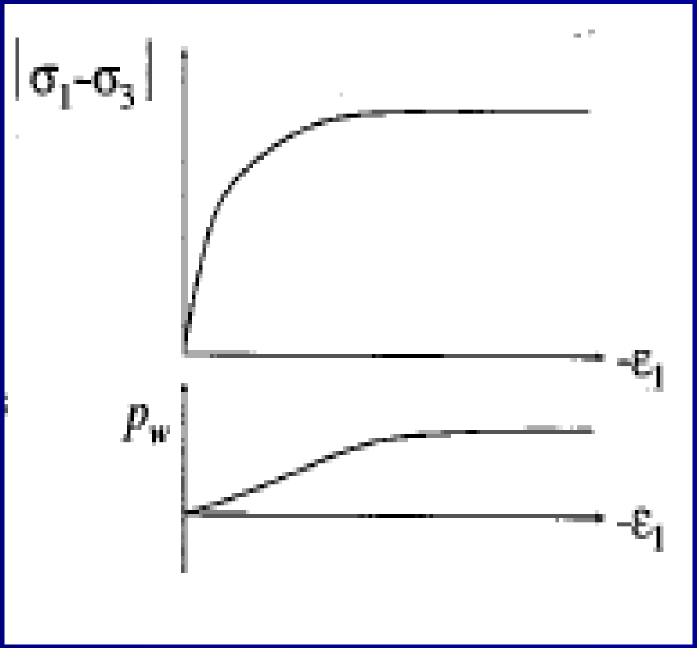


Stress paths

Stress Paths in Standard Soil Tests

- Standard drained triaxial test (CU test)

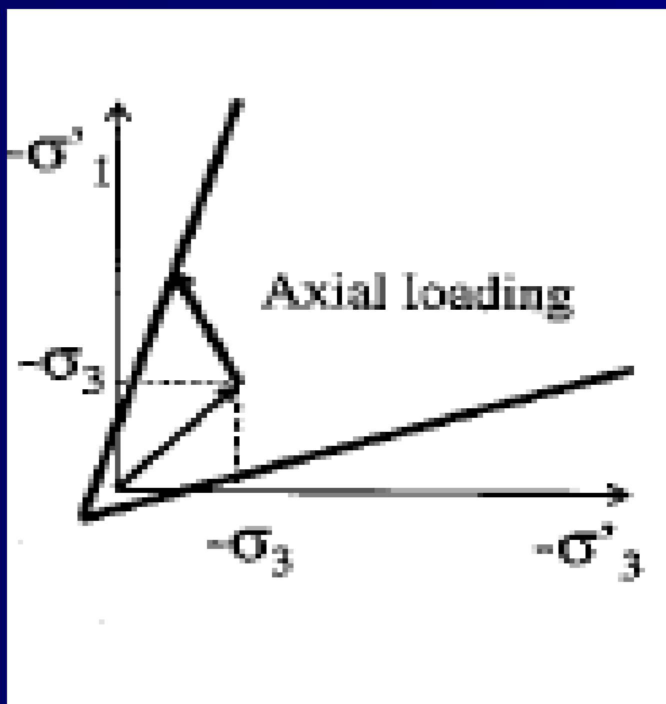


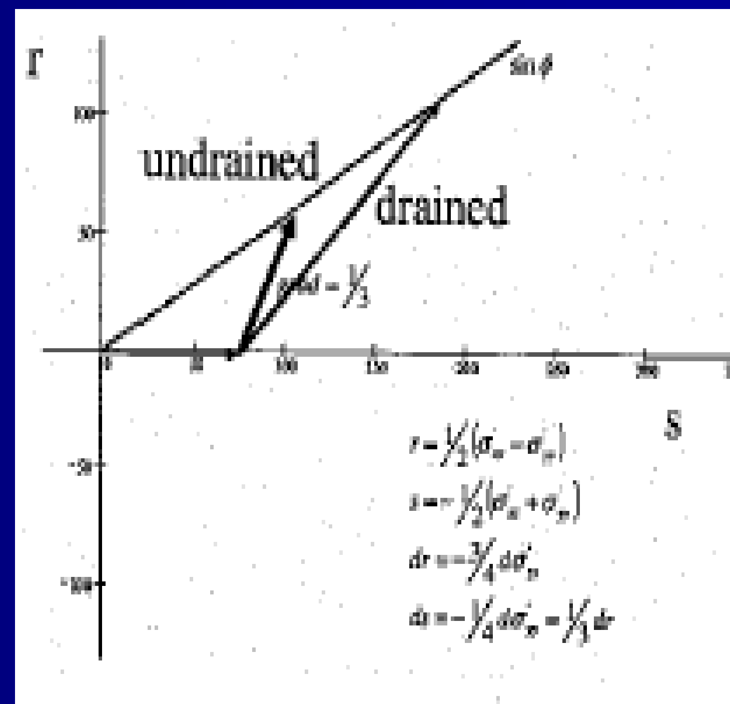


Stress-strain diagram

Stress Paths in Standard Soil Tests

- Standard drained triaxial test (CU test)

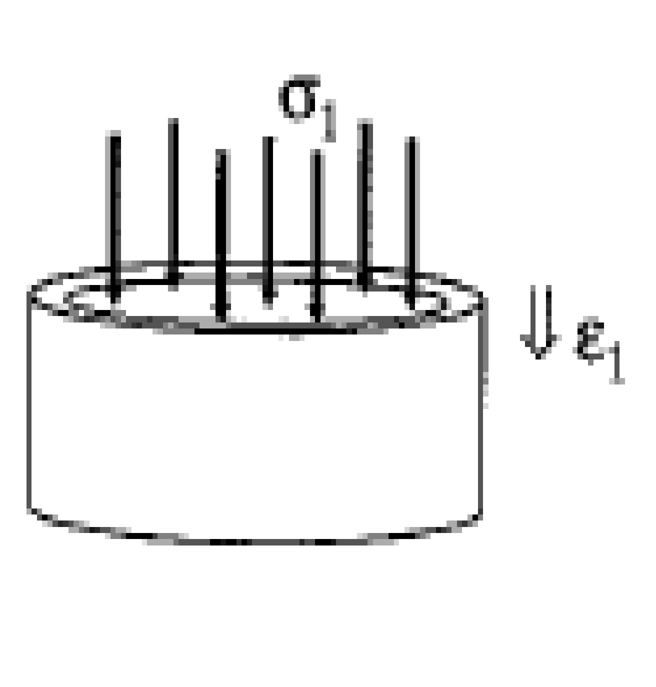


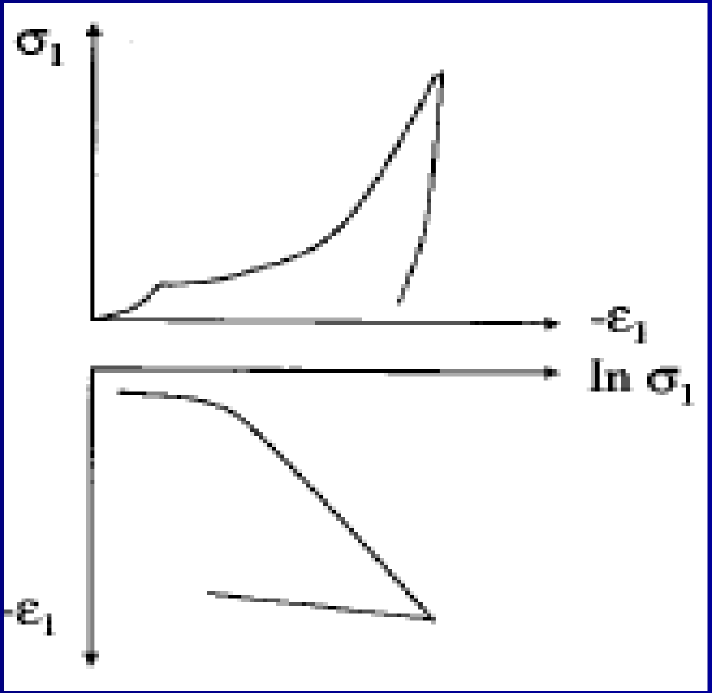


Stress paths

Stress Paths in Standard Soil Tests

- Oedometer Loading Test

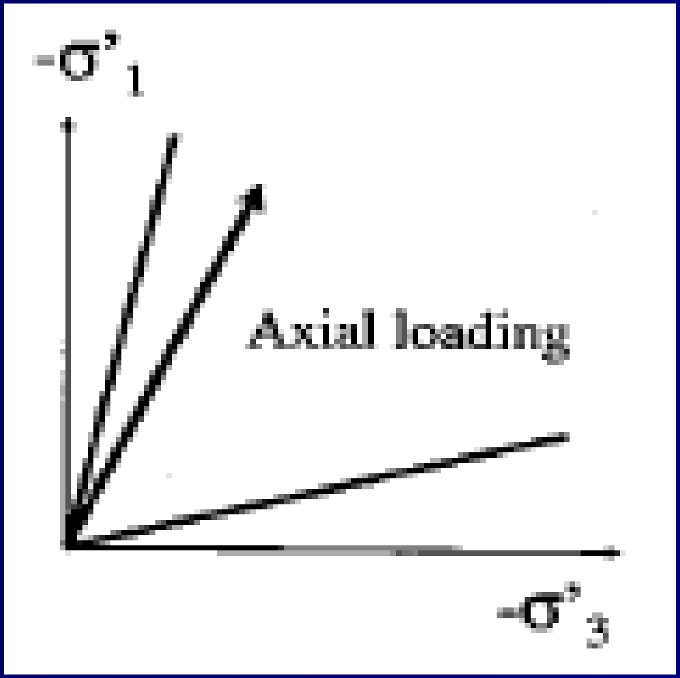


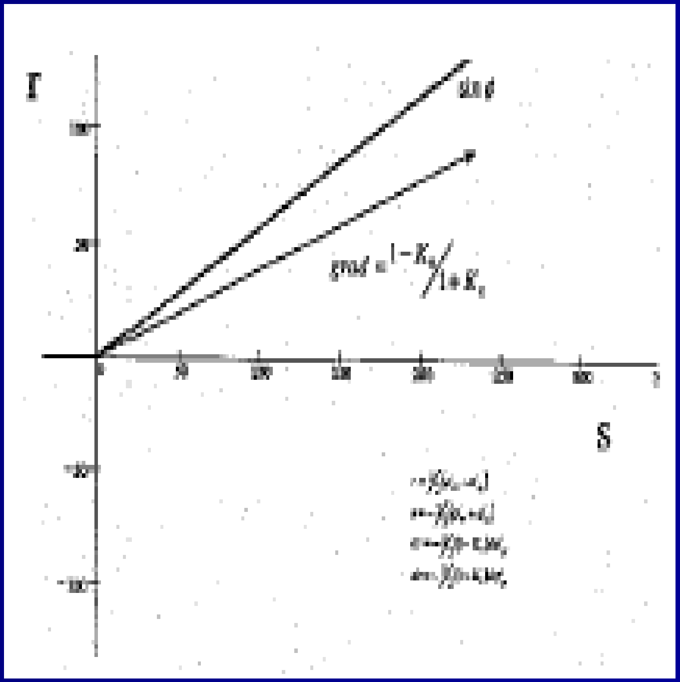


Stress – strain diagram

Stress Paths in Standard Soil Tests

- Oedometer Loading Test

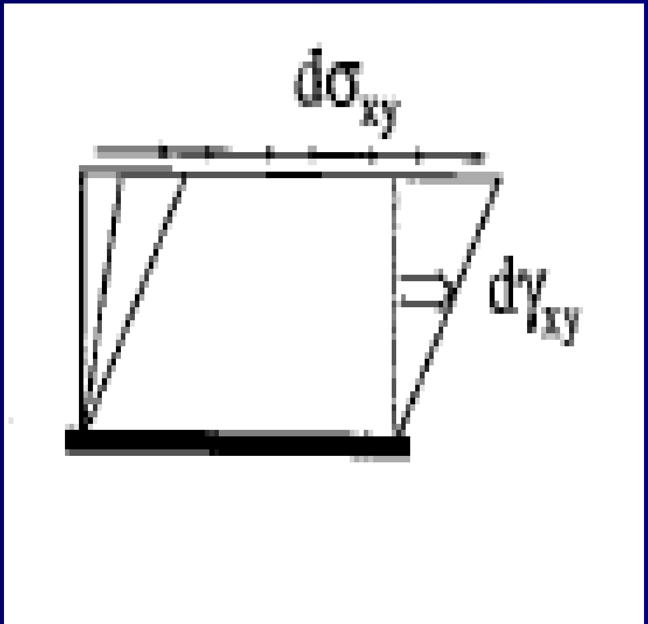


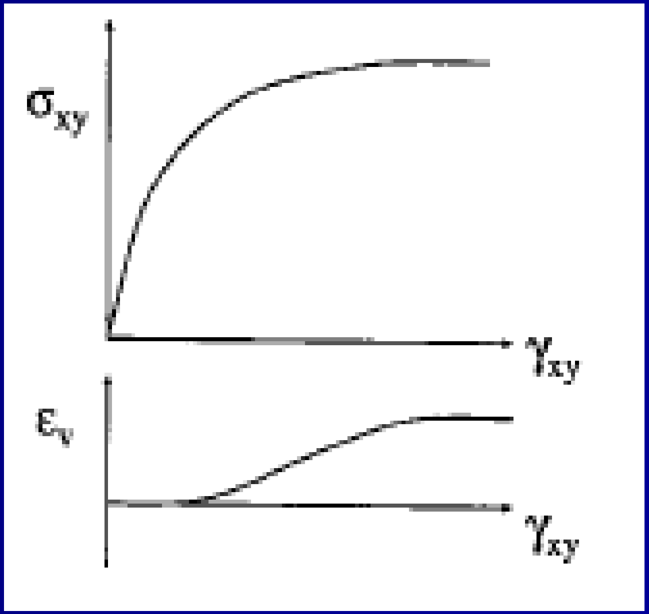


Stress paths

Stress Paths in Standard Soil Tests

- Simple shear test

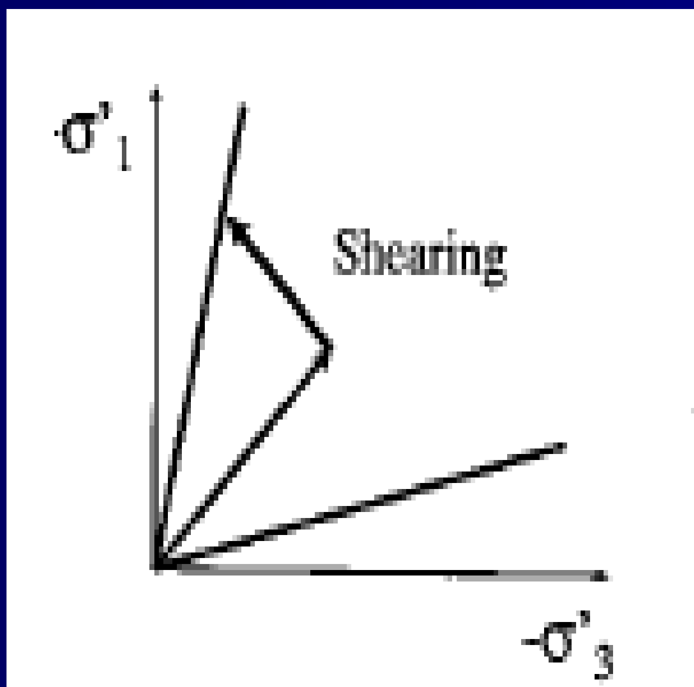


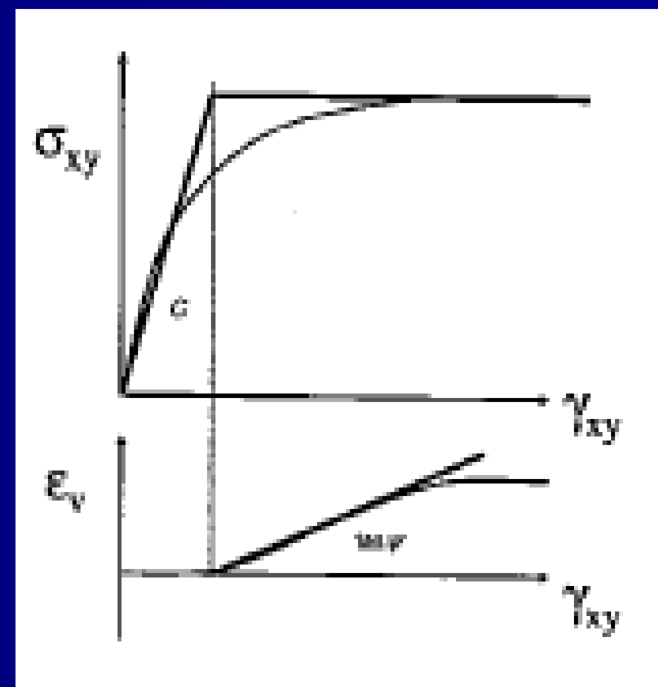


Stress – strain diagram

Stress Paths in Standard Soil Tests

- Simple shear test





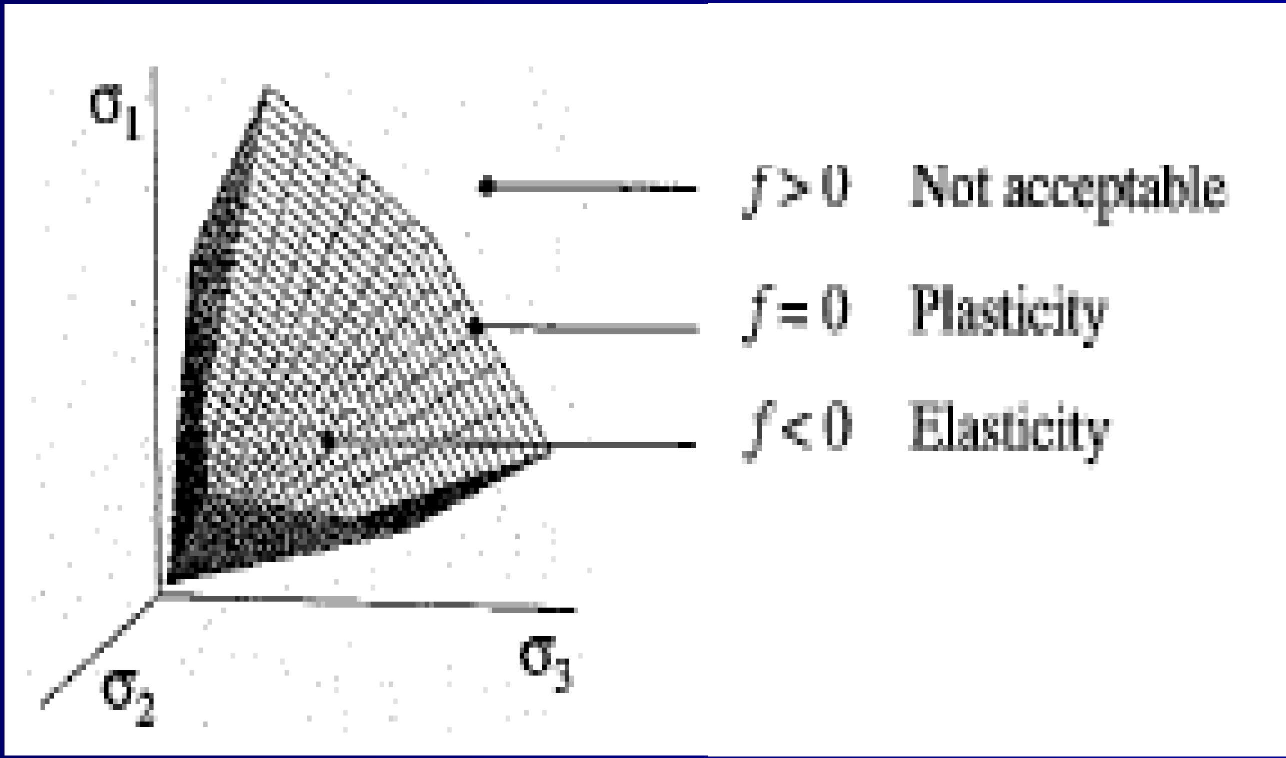
Stress paths

MOHR – COULOMB MODEL

Basic concepts of the M-C model

- Yield function

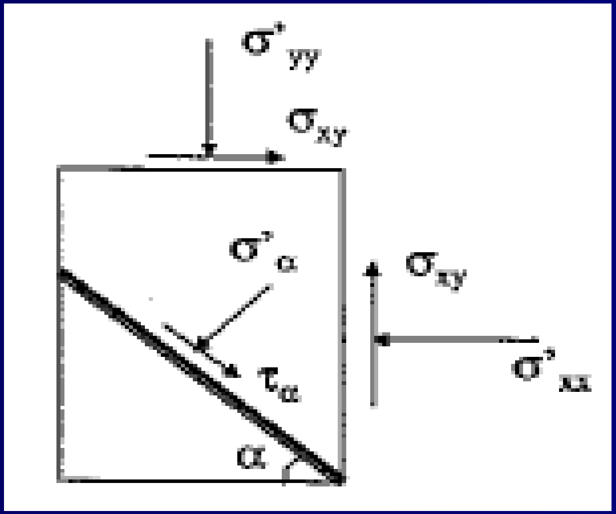
Can be represented as a contour in (principal) stress space

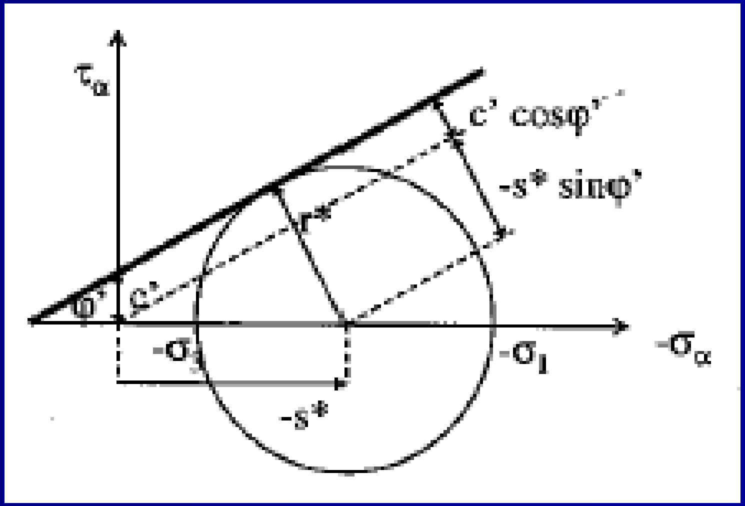


Basic concepts of the M-C model

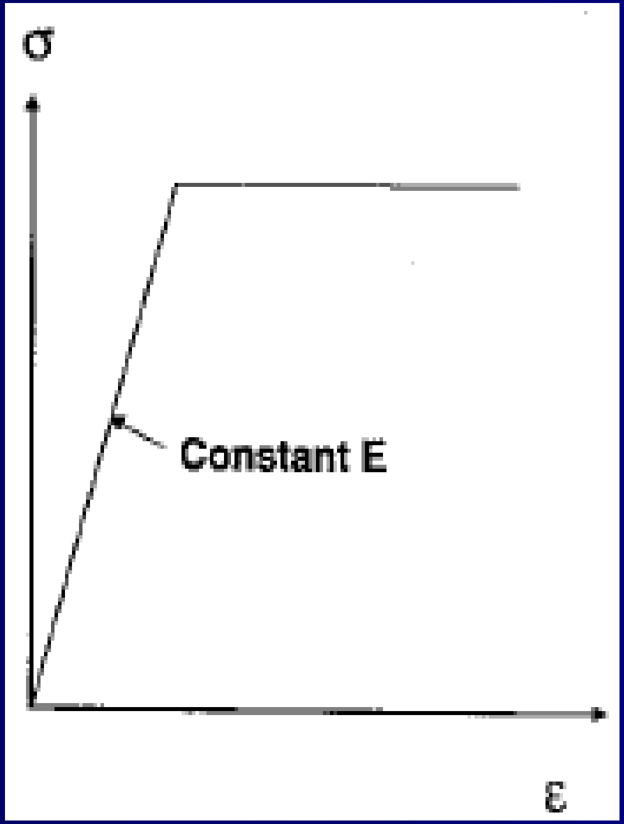
- Mohr-Coulomb yield criterion:

Can be represented as a contour in (principal) stress space

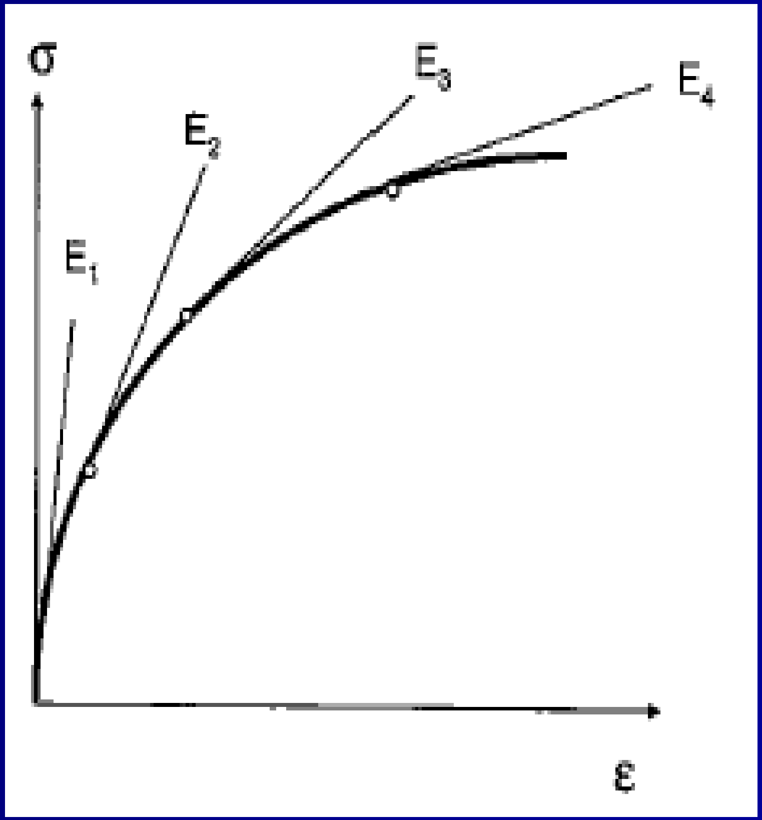




Simulation of Soil Behavior using Mohr-Coulomb Model



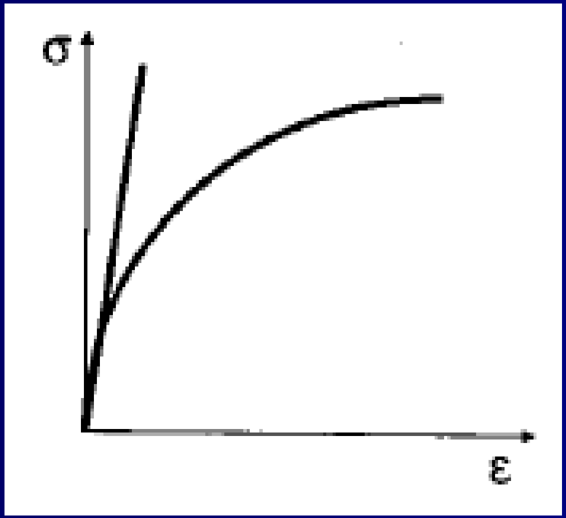
Mohr-Coulomb Model



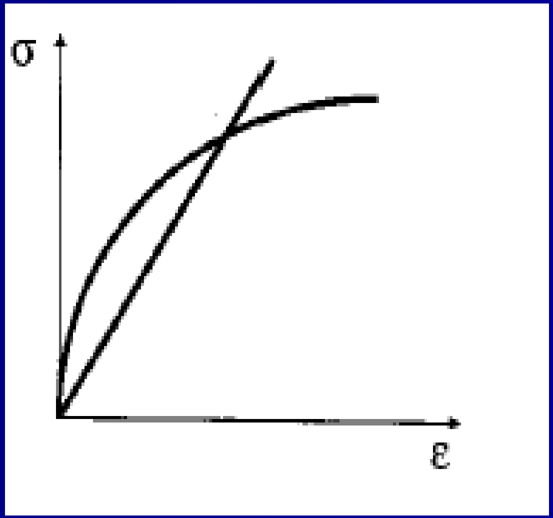
Real Soil Behavior

What are the implications?

Early Stage



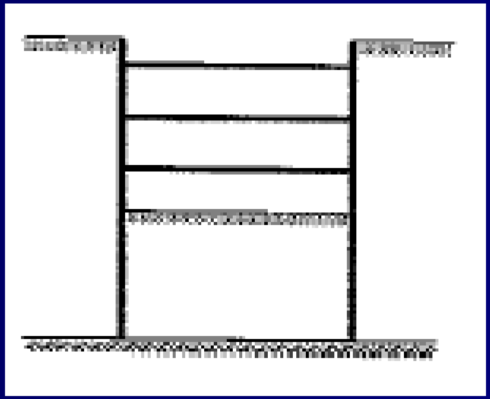
Final Stage

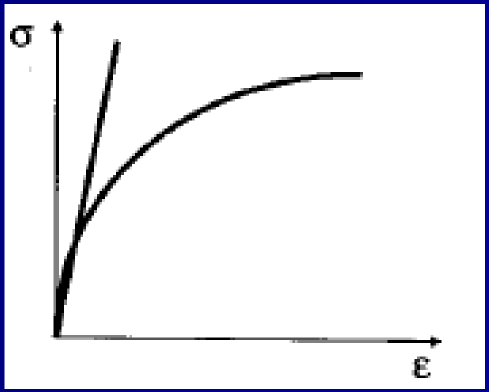


1. The M-C model cannot provide good matches at all stages of excavation in soft clay.

2. If we choose "E" to match δ_H at the final stage, we will over-estimate δ_H at the early stages.

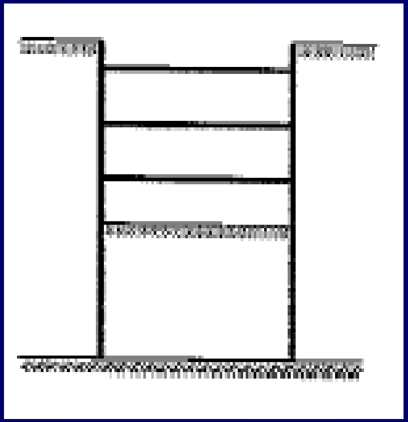
What are the implications?



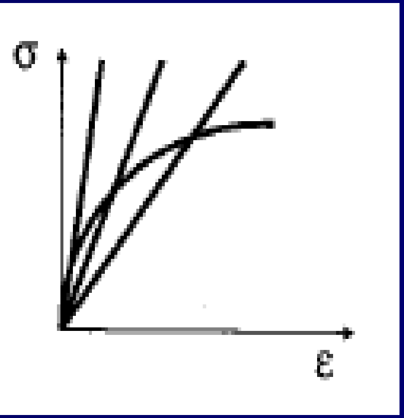


3. The M-C model cannot provide good matches at all stages for deep excavation in stiff clay under undrained condition.

What are the implications?



Case	E_u/c_u
Lavender Station	500
Syed Alwi Project	350
Rachor Complex	275
MOE Building	190
Vaterland I	75



4. It may be difficult to decide what "Eu" to use.

5. The M-C model may not produce the correct response even in undrained analysis.

Possibilities and Limitations of M-C

- Possibilities and advantages

  - Simple and clear model (elastic perfectly-plastic model)
  - First order approach of soil behavior in general
  - Suitable for many practical applications
  - Limited number and clear parameters
  - Good representation of failure behavior (drained)
  - Dilatancy can be included

What about other soil models?

<u>Plaxis</u>

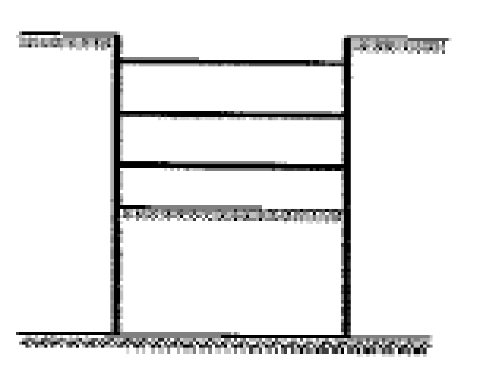
Soft Soil Model

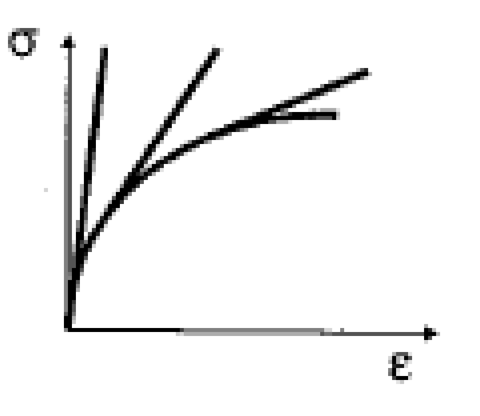
Hardening Soil Model

<u>Sage Crisp</u>

Modified Cam-Clay Model

Better Luck with Nonlinear Model?



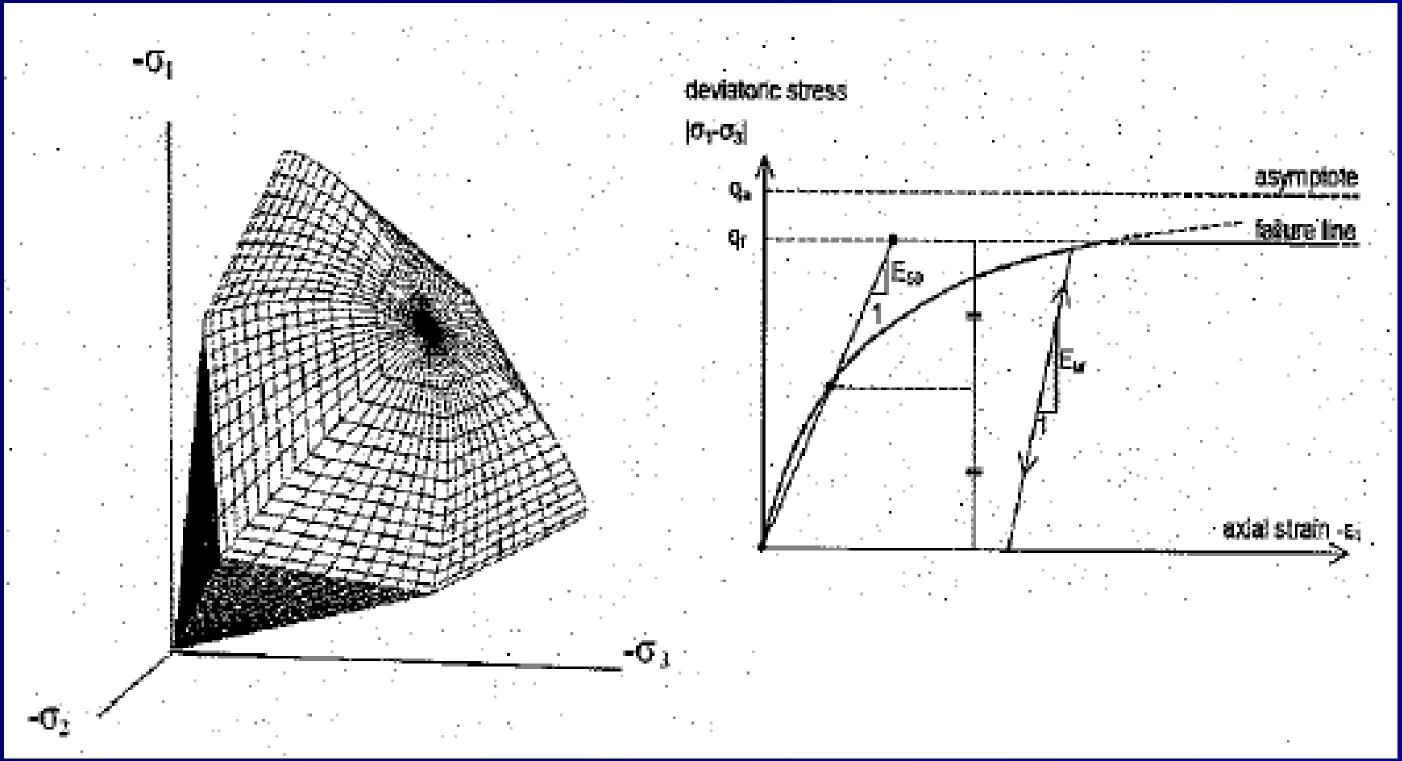


Hyperbolic Model

Case	E_i/c_u
Lavender Station	200
Syed Alwi Project	200
Rachor Complex	200
MOE Building	200
Vaterland I	200

Soil Model

- Hardening Soil Model



Soil Parameters

Soft clayey silt with Sand Coarse Gravel			
Unit Weight, g	19 kPa	E_{oed}^{ref}	12 Mpa
Permeability, k	$1x10^{-8}$ m/s	E_{50}^{ref}	12 Mpa
Friction angle, f'	30^o	E_{ur}^{ref}	36 Mpa
Cohesion,c'	10 kPa	m	1
Stiff clayey silt			
Unit Weight, g	20 kPa	E_{oed}^{ref}	38 Mpa
Permeability, k	$1x10^{-8}$ m/s	E_{50}^{ref}	38 Mpa
Friction angle, f'	30^o	E_{ur}^{ref}	104 Mpa
Cohesion,c'	20 kPa	m	0.5
Weathered Bukit Timah Granite			
Unit Weight, g	24 kPa	E_{oed}^{ref}	160 Mpa
Permeability, k	$1x10^{-8}$ m/s	E_{50}^{ref}	160 Mpa
Friction angle, f'	42^o	E_{ur}^{ref}	480 Mpa
Cohesion,c'	40 kPa	m	0.5

ANALYSIS IN PLAXIS

Undrained Behaviour					
Method	Plaxis Material Setting	Material Model	Parameters		Computed Stresses
			Strength	Stiffness	
A	Undrained	Mohr-Coulomb	C' , ϕ' (Effective)	E' , υ' (Effective)	Effective stress and pore pressure
B	Undrained	Mohr-Coulomb	Cu , ϕ_u=0 (Total)	E' , υ' (Effective)	Effective stress and pore pressure
C	Non-porous	Mohr-Coulomb	Cu , ϕ_u=0 (Total)	E_u , υ_u=0.495 (Total)	Total stress
D	As in Method A, for other soil models(HS,SS,SSC)				
Drained Behaviour					
	Drained	Mohr-Coulomb , other models	C' , ϕ' (Effective)	E' , υ' (Effective)	Effective stress, Pore pressure specified by user

EX. Compare H-S and M-C model

Table 1 : Parameter for wall and anchor

	EI [GNm^2/m]	EA [GN/m]	υ [–]	w [kN/m^2]	pre-load [kN/m]
wall	1.5	80	0	8	N/A
anchor	N/A	0.2	N/A		300

Table 2: Parameter used for the Hard Soil Model

	γ dry / γ wet [kN/m3]	E_{ur} [MPa]	V_{ur} [-]	E_{50} [Mpa]	ϕ [^{0}]	Ψ [^{0}]	C' [kPa]	R_{inter} [-]	K_o [-]
Soil	18	60	0.1	20	35	5	1	0.67	0.43

Mohr-Coulomb Model consider 2 cases:

Case 1 Use E50 equivalent

Case 2 Use Eur equivalent where Eur=3*E50

M-C Equivalent Parameters

Case 1 Use Equivalent E50

ID	Name	Type	g_unsat	g_sat	k_x	k_y	nu	E_ref	c_ref	phi	psi	R_inter
			[kN/m^3]	[kN/m^3]	[m/day]	[m/day]	[-]	[kN/m^2]	[kN/m^2]	[º]	[º]	[-]
1	Sand 1	Drained	18	18	1	1	0.3	15000	1	35	5	0.67
2	Sand 2	Drained	18	18	1	1	0.3	25000	1	35	5	0.67
3	Sand 3	Drained	18	18	1	1	0.3	32000	1	35	5	0.67

Ex. Sand at 7.5m depth, Eref=20 MPa

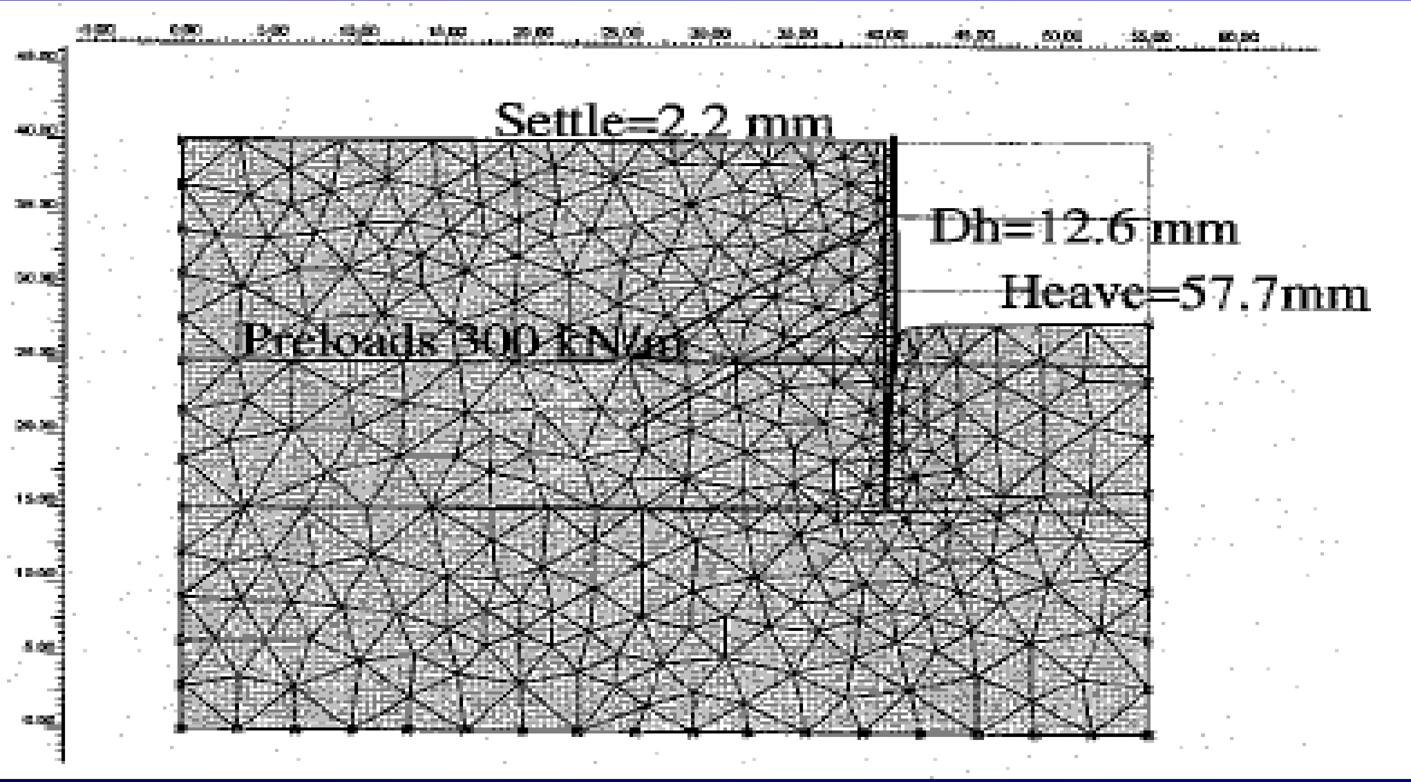
Sigv’=135 kPa, Sigh’=KoSigv’=58 kPa

E50=Eref(Sigh’/100)^0.5 = 15 MPa

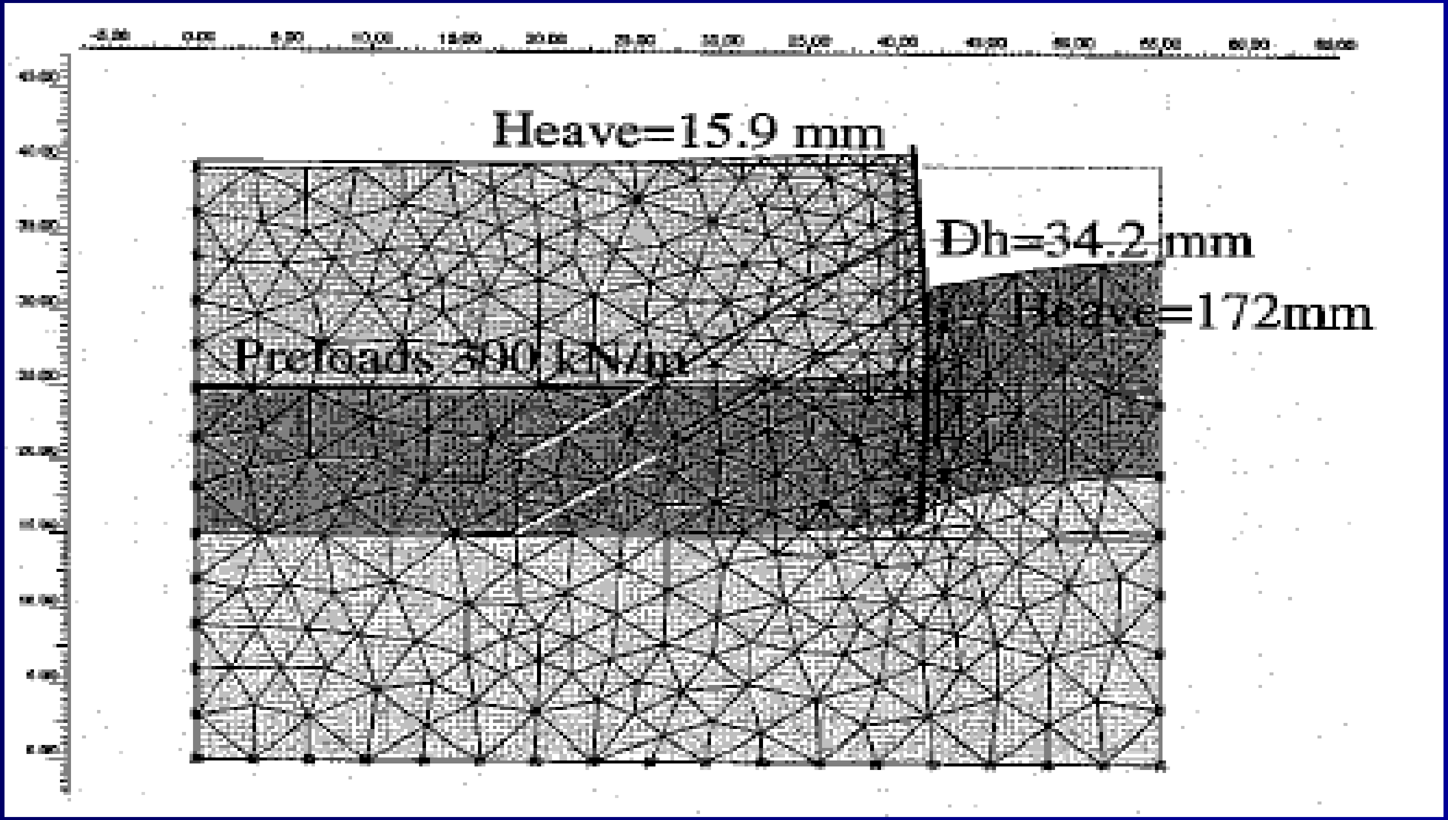
Case 2 Use Equivalent Eur

ID	Name	Type	g_unsat	g_sat	k_x	k_y	nu	E_ref	c_ref	phi	psi	R_inter
			[kN/m^3]	[kN/m^3]	[m/day]	[m/day]	[-]	[kN/m^2]	[kN/m^2]	[º]	[º]	[-]
1	Sand 1	Drained	18	18	1	1	0.1	45000	1	35	5	0.67
2	Sand 2	Drained	18	18	1	1	0.1	75000	1	35	5	0.67
3	Sand 3	Drained	18	18	1	1	0.1	96000	1	35	5	0.67

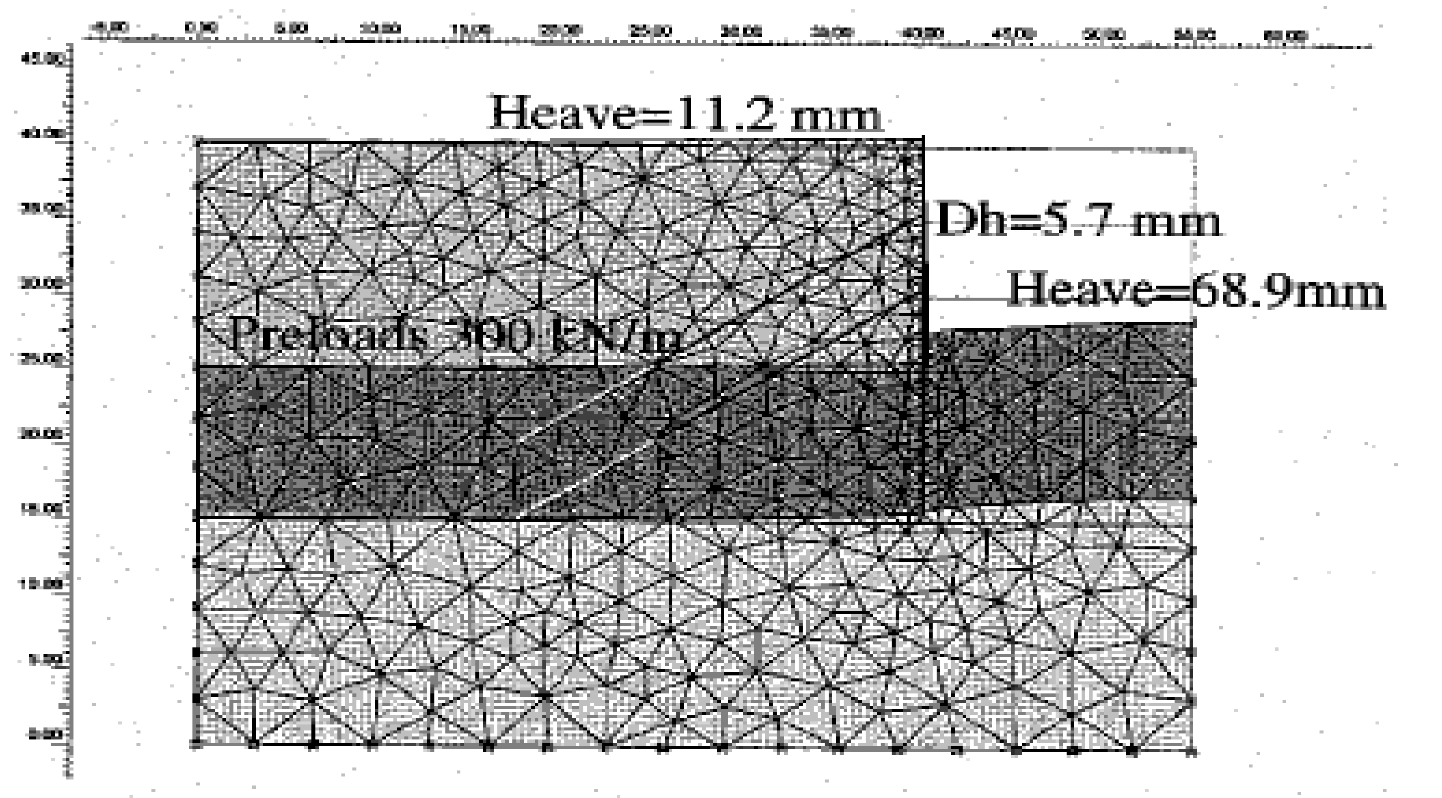
Deformed Mesh for H-S model



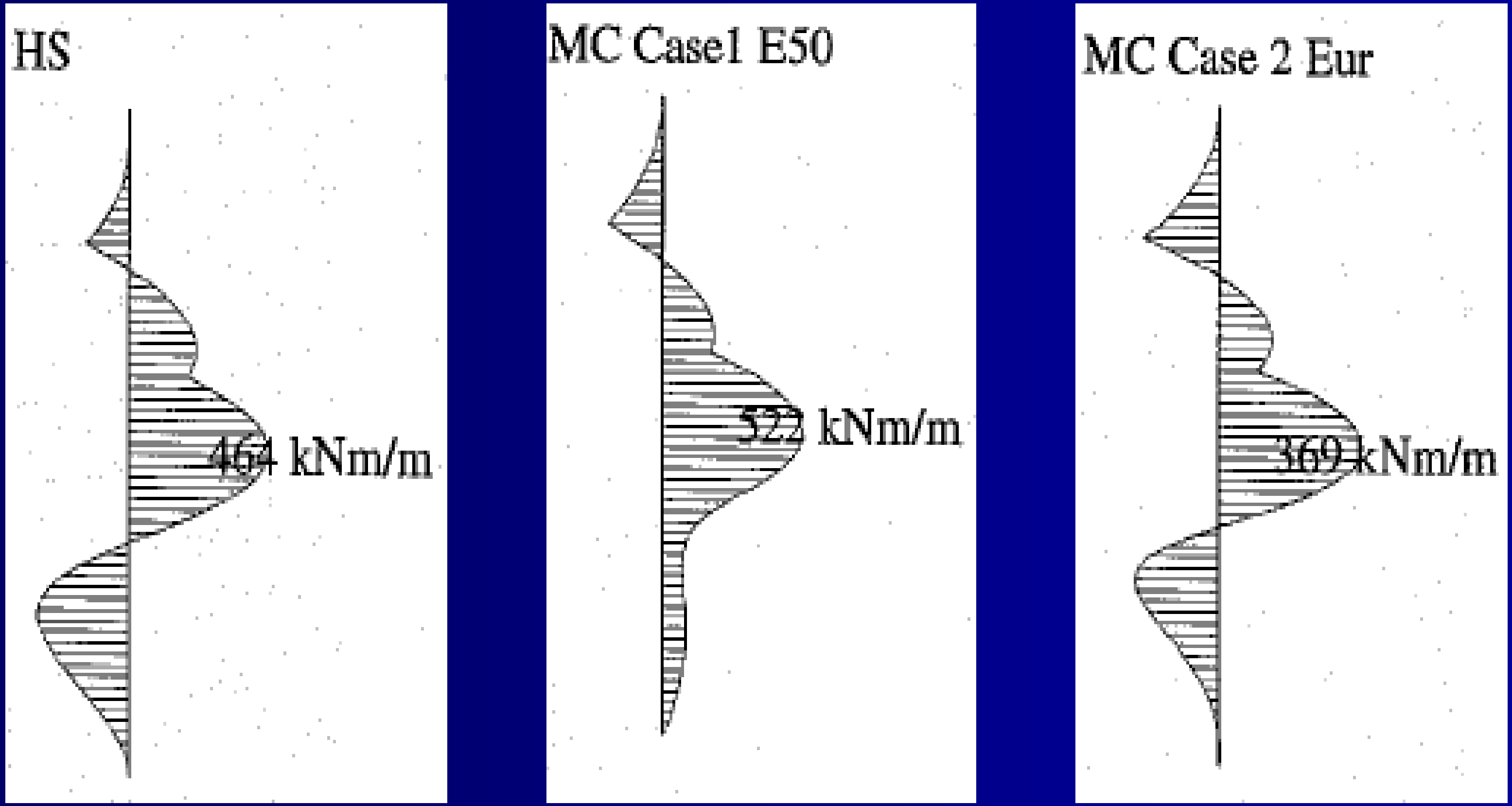
Deformed Mesh for M-C Case 1 model



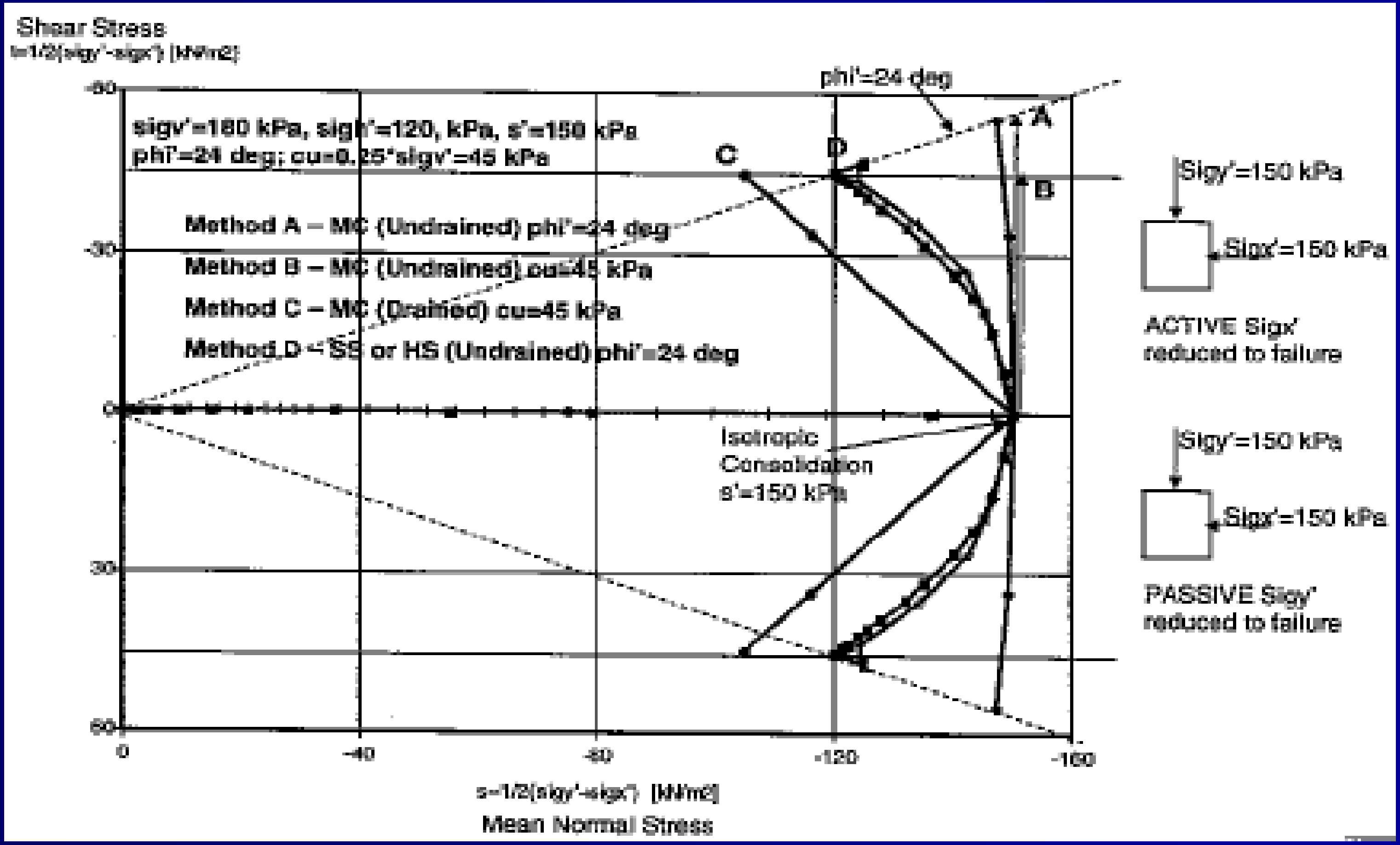
Deformed Mesh for M-C Case 2 model



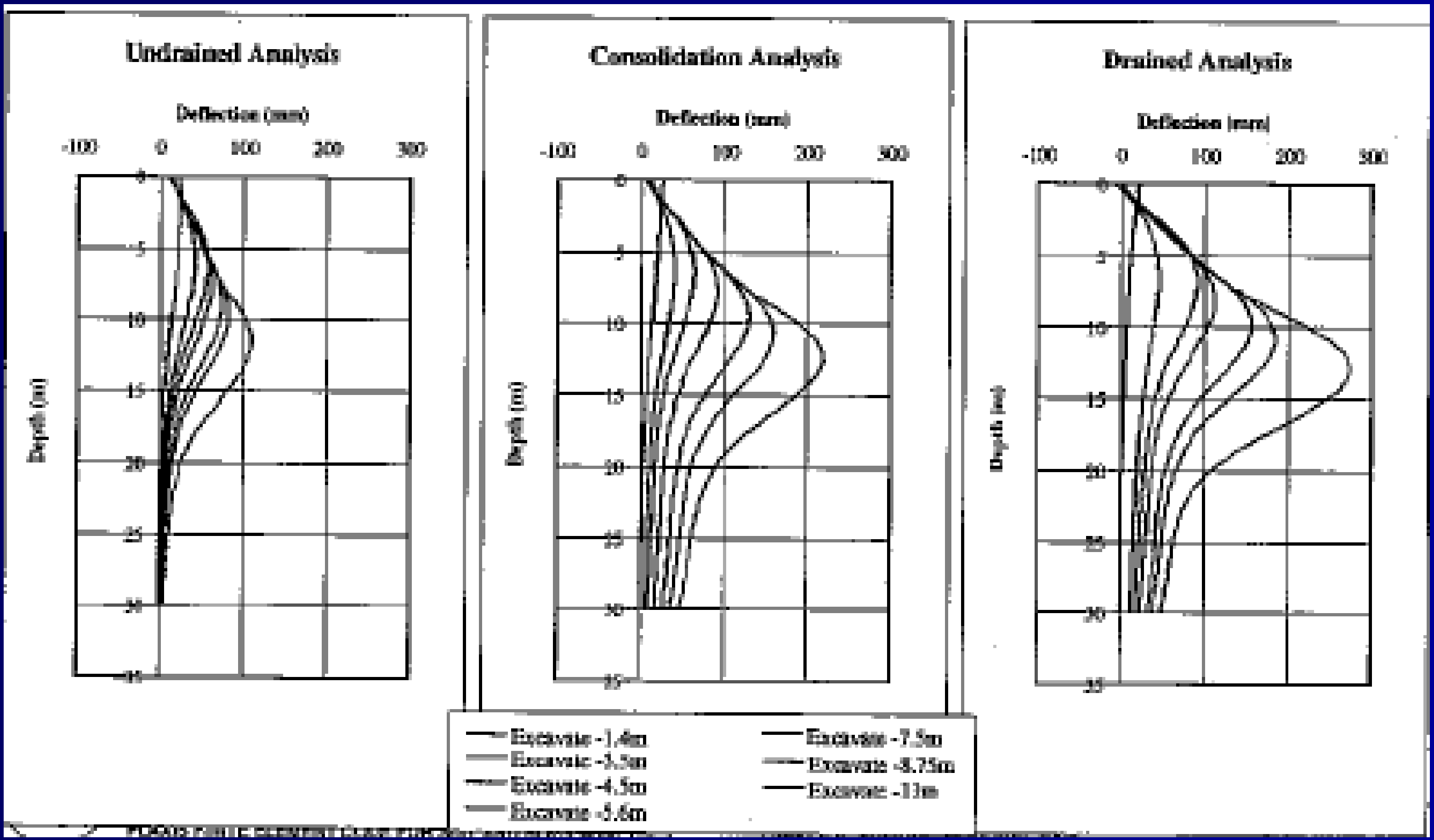
Compare BMs



Effects of Method A/B/C/D on Undrained Strength (Plain Strain)



Consolidation vs Drained and Undrained Analysis

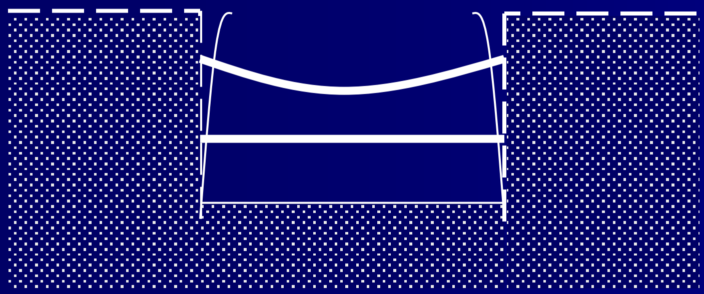


Stability Checks

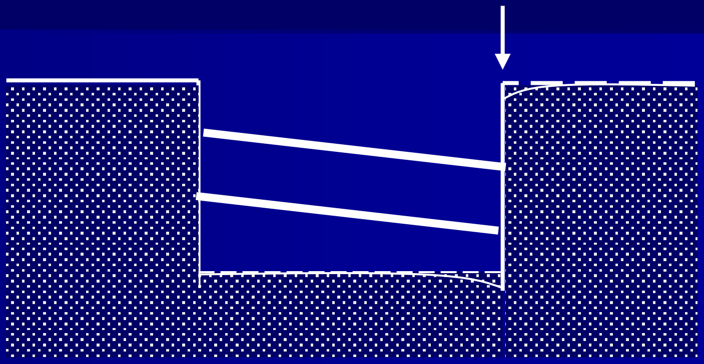
- Basal Stability
- Hydraulic Uplift
- Stability of Soil at Vertical Openings

Introduction into Deep Excavations

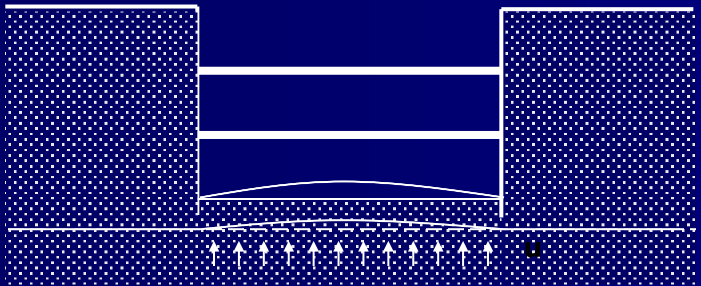
Stability and ULS



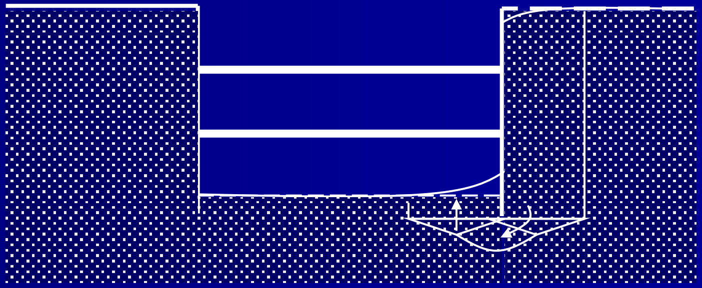
Horizontal stability of walls. Need FOS on penetration as well as wall BM, strut and anchor capacity



Vertical stability of walls. Need FOS on vertical bearing capacity of wall

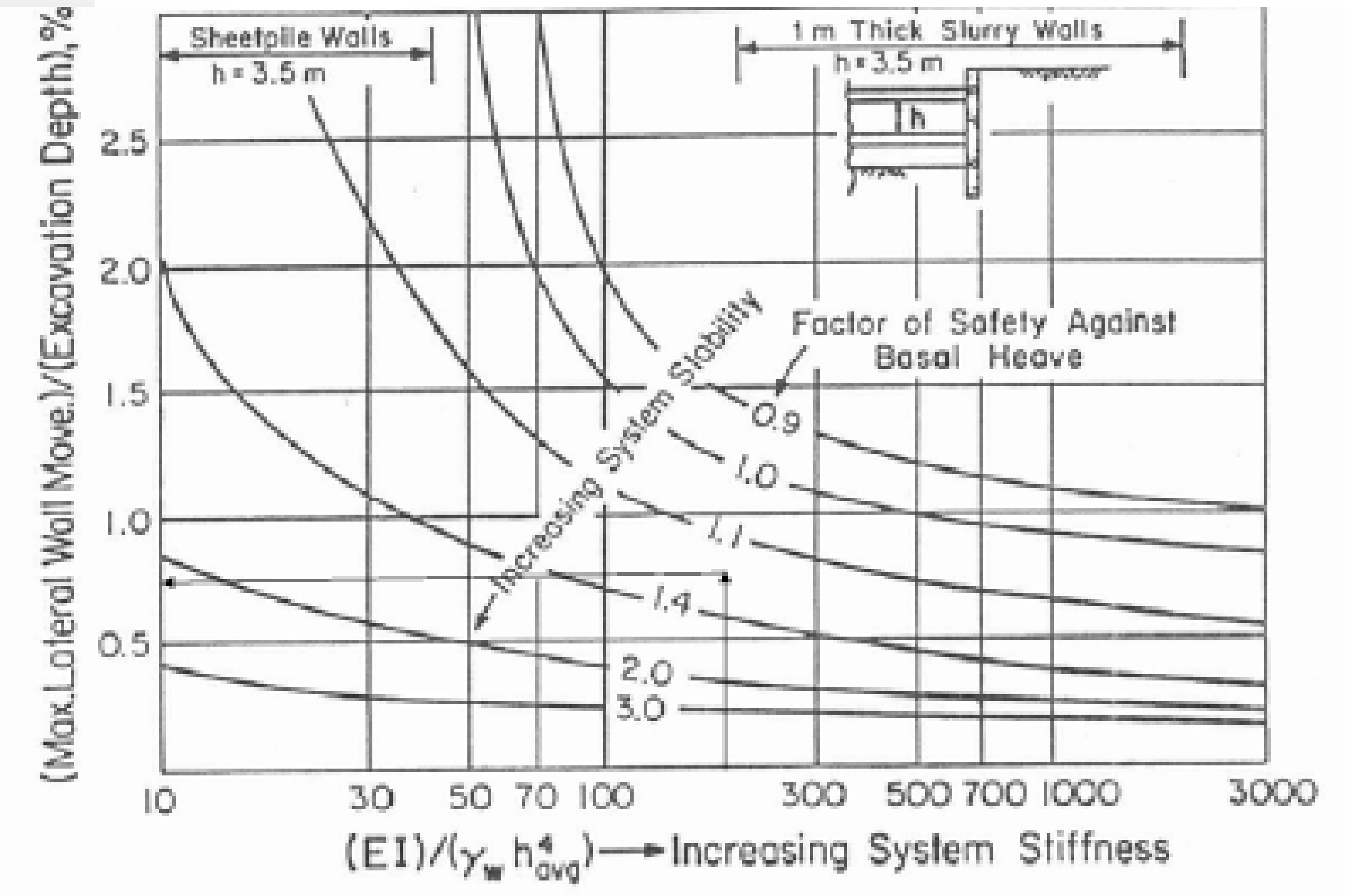


Base stability by Hydraulic Uplift



Base stability by Basal Heaving of Soft Soil

Basal Stability FOS Chart



CASE STUDY

CASE - A

- **1.0 m thick Diaphragm wall**
- **20 m deep excavation**
- **6 layers of struts**
- **Max wall movement is 45 mm**

Bird View of the Project

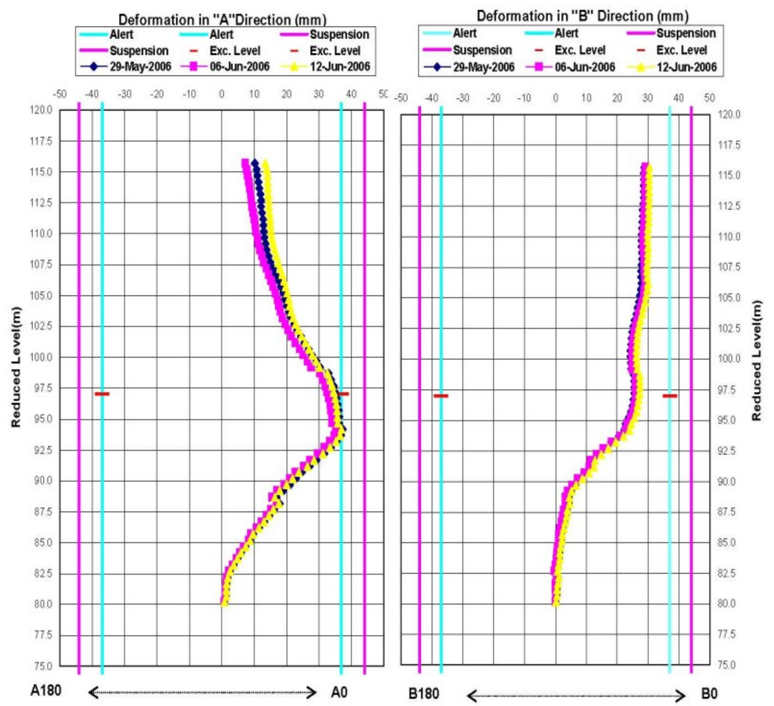
Over View of TERS

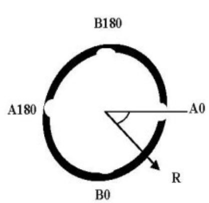
New Station TERS

Station Wall Movement

Report no: 422

Project:	Instrumentation	Installation Depth:	36 m	
Inclinometer No.:	I-3012	Ground E.L:	115.686 m	
Location:	Station Box	Coordinates:	N:36993.839	E:32338.4
Date of Reading:	12-Jun-2006	Elapsed time:	597	days



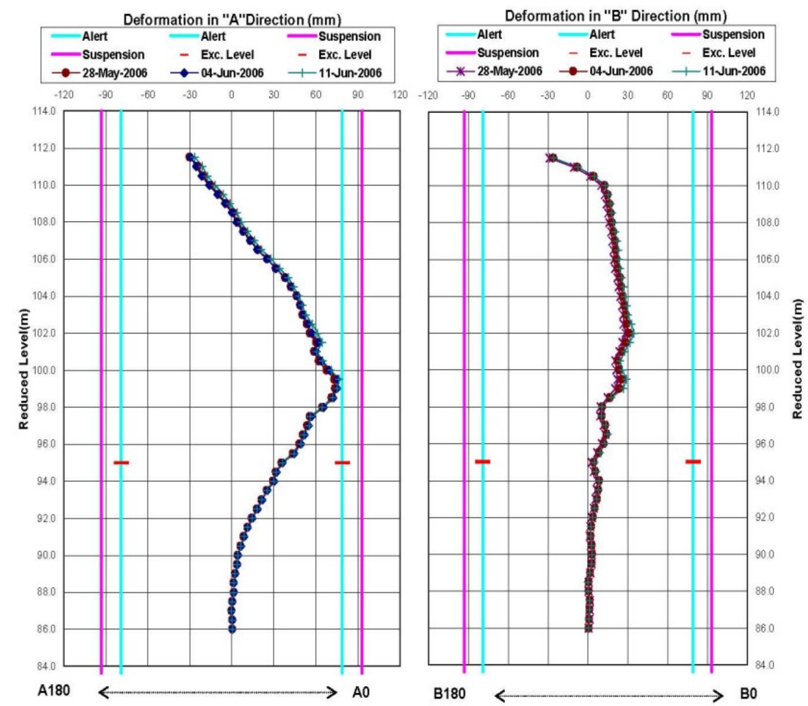


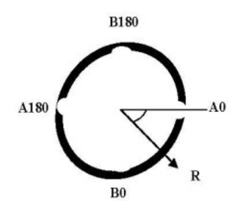
DATE	12-Jun-2006	
DEPTH	96.19	m of R.L
MAX. Defn.	44.26	mm
DEGREE	36.97	Degree

C&C Tunnel Wall Movement

Report no: 263

Project:	Instrumentation	Installation Depth:	26 m	
Inclinometer No.:	I-3005	Ground E.L:	111.496 m	
Location:	C&C Tunnel Area	Coordinates:	N36998.15 : E32216.484	
Date of Reading:	11-Jun-2006	Elapsed time:	661	days





DATE	11-Jun-2006	
DEPTH	99.496	m of R.L
MAX. Defn.	81.63	mm
DEGREE	20.67	Degree

Link Way TERS

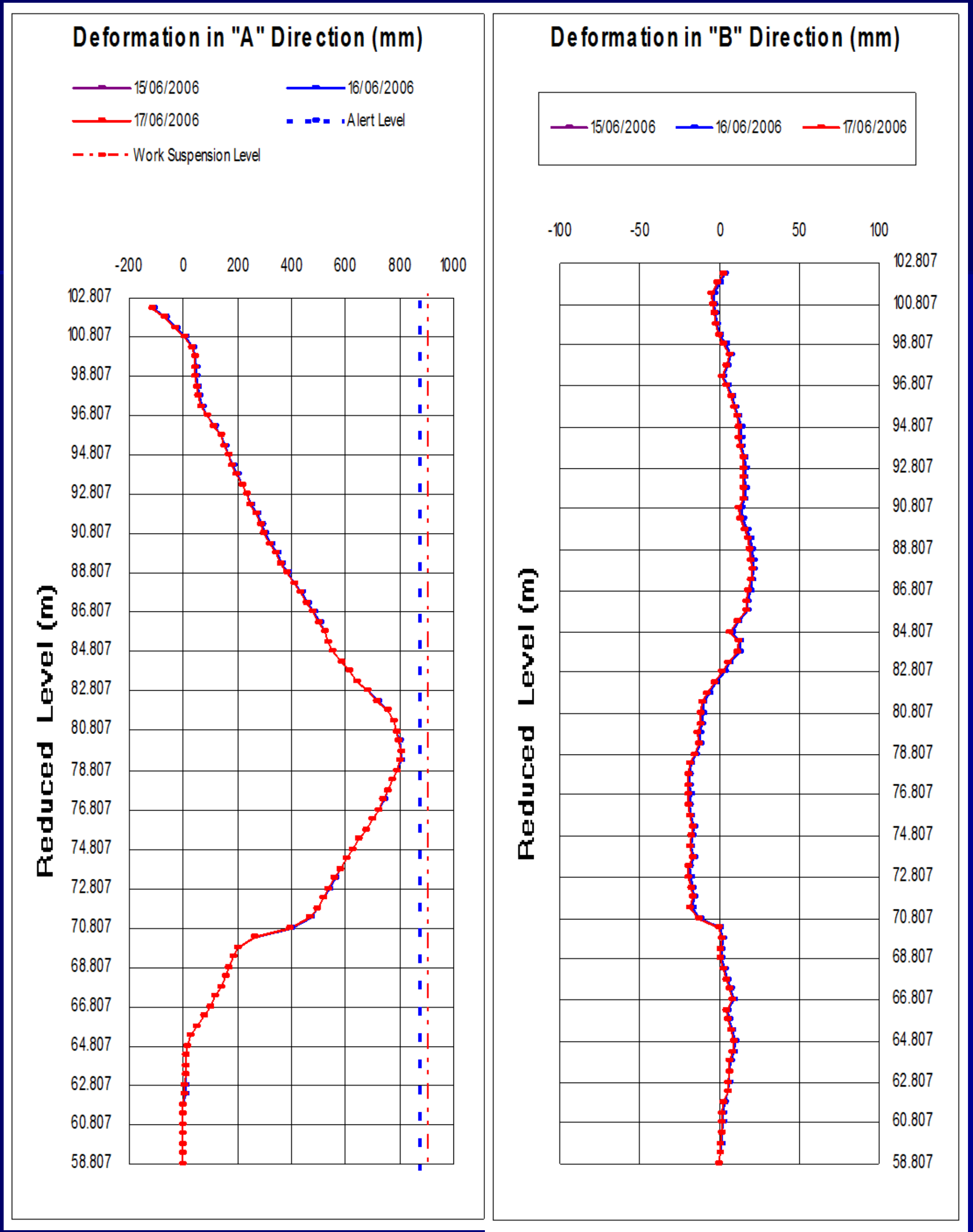
C&C Tunnel Roof Slab

CASE - B

- 1.0 m thick Diaphragm wall
- 22 m deep excavation
- 7 layers of struts
- Max Dwall movement 1000 mm towards excavation


TOMEN G

D Wall Movement




Dancing King Post


Another Dancing King Post
25
2.5


52

Base Heave Failure,
8m Deep Excavation in Marine Clay

Conclusion

&

Recommendation

Conclusions

- BMs and displacement depends on wall stiffness and soil stiffness
- For cantilever retaining wall, LEM and FEM can give similar results
- For propped walls, it is very difficult for LEM and FEM to agree for flexible walls due to soil arching

- The total earth pressure and strut loads is not significantly different between Method A and B
- The error in using Method A vs Method B will lead to serious under-estimation of wall deflection and BMs
- Both ULS and SLS are important and must be address in design

Use of Unloading Stiffness for more realistic deformation

- Removal of the soil in front of the retaining wall results in a reduction of lateral stress in the retained soil behind the wall
- Removal of vertical stress is experienced by the soil below the excavation
- Excavation is an unloading problem

- MC model is not appropriate for NC soils in Undrained analysis
- Mohr-Coulomb model using c’ and phi’ is not appropriate for modeling undrained strength of these soft clays
- MC-model realistic surface settlements difficult to achieve but wall deflection may be reasonable

- HS model with the logarithmic compression law will produce more realistic results in modeling of soft soils
- HS-Model is superior to MC-Model for these types of problems
- Proper excavation analysis requires advanced constitutive model like Hardening Soil Model

- In general strut forces are not significantly effected by the method and modeling in the geotechnical analysis but the structural details are important for the stability of the TERS.
- Wall deflection sensitively effected by the method of geotechnical analysis and soil modeling, therefore during construction stage the monitoring of the wall deflections have to be done stringently and carefully
- Base heave due to Hydraulic Uplift or Basal Stability is sensitively effected by the geotechnical analysis method and soil modeling, therefore the monitoring at the construction stage is important and the TERS collapse due to base heave frequently happen in a sudden rupture mode therefore the effort to minimize the base heave is essential.