Soil Mechanics and Geology
22CVB102

Semester 2 2023 | In-Person Exam Paper

This examination is to take place in-person at a central University venue under exam conditions. The standard length of time for this paper is **3 hours**.

You will not be able to leave the exam hall for the first 30 or final 15 minutes of your exam. Your invigilator will collect your exam paper when you have finished.

<u>Help during the exam</u>

Invigilators are not able to answer queries about the content of your exam paper. Instead, please make a note of your query in your answer script to be considered during the marking process.

If you feel unwell, please raise your hand so that an invigilator can assist you.

You may use a calculator for this exam. It must comply with the University's Calculator Policy for In-Person exams, in particular that it must not be able to transmit or receive information (e.g. mobile devices and smart watches are **not** allowed).

Answer **ALL EIGHT** questions from **Section A** and **TWO** questions from **Section B**. **Section A** is worth 40 marks and **Section B** is worth 60 marks.

A 5-page Formulae Sheet is provided.

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SECTION A
(Answer all EIGHT questions)

Students are advised to spend approximately 70 minutes on Section A

A1. A soil specimen is 38 mm in diameter, 76 mm long, with a bulk mass of 168.0 g. When dried completely in an oven, the specimen weighs 130.5 g. The value of the soil's specific gravity G_s is 2.73. What is the degree of saturation of the specimen?

[5 marks]

A2. A thick layer of saturated CLAY (γ_{sat} = 20.1 kN/m^3) with groundwater level at ground level will be subjected to a surcharge load following the rapid construction of a 4 m thick granular fill embankment (γ_{bulk} = 21.1 kN/m^3). Consider a point 4 m below the surface of the CLAY layer, calculate the total stress, effective stress and pore-water pressure immediately following construction of the embankment.

[5 marks]

A3. **Figure QA3** shows results recorded during direct shear tests on specimens of a SAND compacted to the same initial void ratio. Plot the Coulomb failure envelope and determine the peak friction angle for the SAND.

[5 marks]

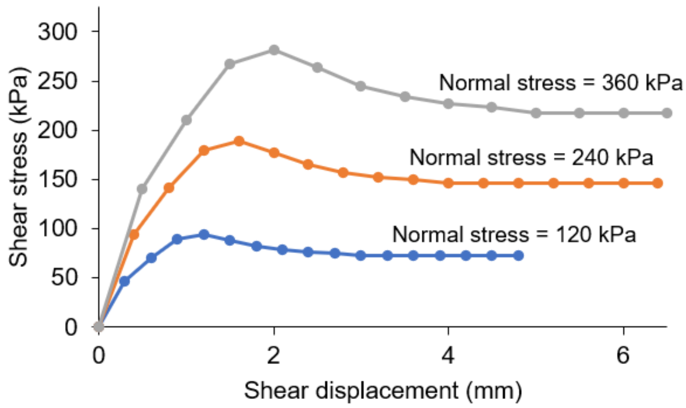

Figure QA3. Results from direct shear tests on the SAND specimens

Section A continues/…

A4. A canal runs above and parallel to a river around a hillside. The difference in their water levels is 15 m. The geological structure of the ground is such that a permeable stratum 0.1 m thick links the two waterways over a 375 m length. The slope distance between the canal and river is 180 m. The permeability of the permeable stratum is 0.002 m/s. Determine the discharge into the river in cubic metres per day.

[5 marks]

A5. The results of a compaction test for a soil having a specific gravity of 2.5 are shown in **Table QA5**. Using these measurements, plot the compaction curve and obtain the maximum dry unit weight and optimum moisture content.

[5 marks]

Table QA5. Compaction test data

Water content (%)	6.2	8.1	9.8	11.5	12.3	13.2
Unit weight (kN/m^3)	16.9	18.7	19.5	20.5	20.4	20.1

A6. a) A laboratory compression test performed on a CLAY sample showed that the maximum stress experienced by the CLAY was 380 kPa. The soil sample was obtained from a depth of 5 m below ground level in a CLAY deposit known to be overconsolidated. Results of the tests on other samples obtained from the CLAY layer indicate a representative soil unit weight of 18.5 kN/m^2. What is the overconsolidation ratio of this clay deposit?

[3 marks]

b) The virgin consolidation curve is the curve between which of the following?

i) voids ratio and pore pressure
ii) effective stress and total stress
iii) effective stress and pore pressure
iv) voids ratio and effective stress

[1 mark]

c) When the soil is laterally confined, the change in volume is which of the following?

i) proportional to change in thickness, ΔH
ii) inversely proportional to change in thickness, ΔH
iii) equal to change in thickness, ΔH
iv) does not depend upon the thickness

[1 mark]

A7. Explain in brief how ‘undisturbed’ and ‘disturbed’ samples are taken during borehole drilling in soils, and provide a comment for each type as to their use in testing for the soil properties.

[5 marks]

A8. Explain and illustrate the benefits of using a pattern of rock bolts for the strengthening of a rock face.

[5 marks]

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SECTION B
(Answer TWO questions, each question is worth 30 marks)
Students are advised to spend approximately 110 minutes on Section B

B1. A site underlain by CLAY is to be developed as part of a construction project (**Figure QB1**). Development of the site includes a cutting slope to be formed in a hillside, as well as foundations for industrial buildings.

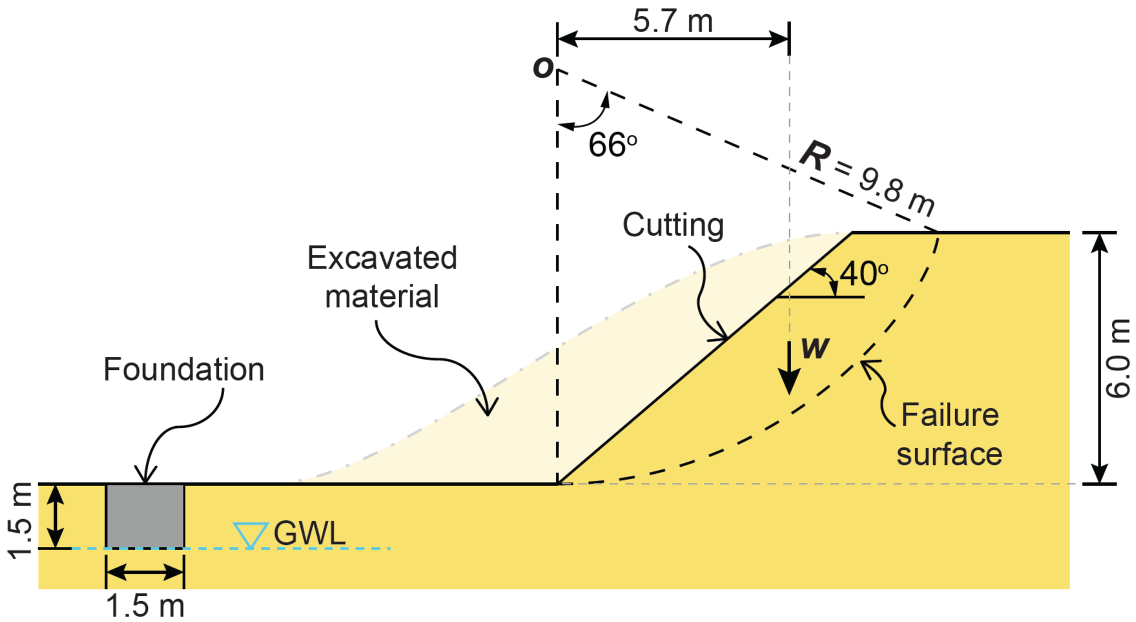

Figure QB1. Cross-section of the site comprising CLAY

a) Consolidated-undrained (CU) triaxial tests were performed on three specimens of CLAY taken from the site in **Figure QB1**. The results at failure are given in **Table QB1**.

Table QB1. Triaxial test data

Cell pressure (kPa)	200	400	800
Deviator stress at failure (kPa)	117	242	468
Pore pressure at failure (kPa)	110	227	455

i) Using the data in **Table QB1**, construct a table that shows values of major and minor principal stresses at failure in both total stress and effective stress terms. Show in full how you have calculated all answers.

[6 marks]

ii) Determine the effective stress shear strength parameters for the CLAY by plotting three Mohr circles.

[8 marks]

Question B1 continues/…

b) The foundation shown in **Figure QB1** is to support a vertical column load of 700 kN. Foundation level and ground water level are both 1.5 m below ground level. The foundation is square with a width of 1.5 m. Use the shear strength parameters for the CLAY you determined in Part (a). Assume the CLAY and foundation both have a unit weight of 21.5 kN/m^3. Determine the long-term factor of safety against bearing capacity failure, and comment on whether this is an appropriate factor of safety for foundations.

[12 marks]

c) The cutting slope shown in **Figure QB1** failed immediately after excavation along the circular slip surface as shown in the figure. Assume the weight of the sliding mass, ***W***, is 430 kN/m. Determine the average undrained shear strength along the failure surface.

[4 marks]

B2. A site underlain by SAND is to be developed as part of a construction project (**Figure QB2**). Development of the site includes a concrete dam to retain a body of water, as well as a wall to retain soil that will carry a surcharge load of 20 kN/m^2/m.

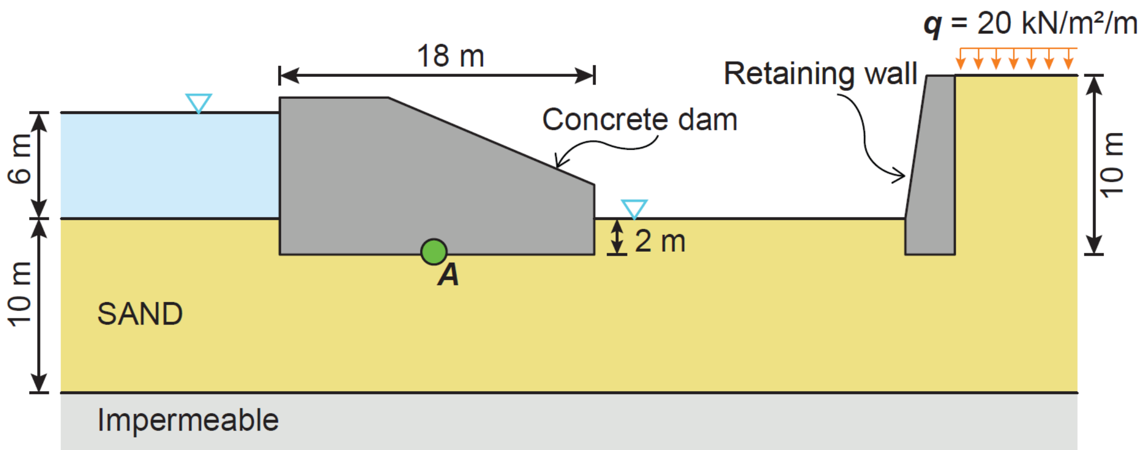

Figure QB2. Cross-section of the site comprising SAND

a) As part of an investigation into groundwater seepage at the site, the following must be carried out:

i) A falling head permeameter test was performed on a sample of SAND taken from the site. The sample had a diameter of 76 mm and a length of 152 mm. The standpipe had a diameter of 12.7 mm. The initial level in the standpipe was 504 mm, which dropped to 127 mm after 39 seconds. Determine the coefficient of permeability of the SAND.

[4 marks]

Question B2 continues/…

ii) Draw a flow net for seepage under the concrete dam in **Figure QB2**. [*Note: You must draw **Figure QB2** to scale to obtain a solution. Ignore the adjacent retaining wall for the purpose of drawing the flow net.*]

[10 marks]

iii) Calculate the flow rate in m^3/day per metre run under the dam.

[4 marks]

iv) Calculate the pore-water pressure under the dam at point A, which is located half-way along the base of the dam.

[5 marks]

b) The 10 m high retaining wall shown in **Figure QB2** supports SAND and carries a surcharge load of 20 kN/m^2/m. The SAND has an effective friction angle of 32° and a unit weight on 19 kN/m^3. Determine the total forces acting on the back of the wall (active thrust) per metre run. Assume the water table is below the base of the retaining wall in your analysis.

[7 marks]

B3. a) A standard oedometer test carried out on a fully saturated soft CLAY sample gave the results presented in **Table QB3**. The initial thickness of the oedometer sample was 20mm, with porous stones located above and below the sample to allow consolidation to occur. The initial water content was 24% and the specific gravity, G_s = 2.7.

Calculate the void ratio at the end of each pressure increment and plot the graph of log effective stress ($\log_{10} \sigma_v'$) against void ratio (e).

[10 marks]

Table QB3. Oedometer test data

Applied pressure (kPa)	Specimen thickness (mm)
0	20
25	19.806
50	19.733
100	19.600
200	19.357
400	18.835
800	18.167

Question B3 continues/…

…/question B3 continued

b) A layer of normally consolidated CLAY is 6-m-thick and underlain by impervious material. The CLAY has a unit weight of 19 kN/m^3, initial void ratio is 0.9 and the water table is at the top of the CLAY layer. A surface load causes an increase in total vertical stress of 150 kPa at the top and 50 kPa at the bottom of the CLAY layer respectively. If the compression index C_c for the CLAY is 0.2, estimate the ultimate primary consolidation settlement by splitting the CLAY layer into 3 sub-layers. Assume the unit weight of water is 9.81 kN/m^3.

[10 marks]

c) A layer of compressible CLAY 6-m-thick lies on an impervious bed of rock and carries an overburden of high permeability SAND. A large structure founded in the SAND causes the pressure on every horizontal section of the CLAY to increase to the same value. In a standard laboratory oedometer test, the void ratio of a sample of the CLAY (19-mm-thick) decreased from 0.765 to 0.760 under an increase in pressure corresponding to that experienced by the CLAY layer on site. Consolidation was 70% complete after 30 min.

i) Estimate the ultimate settlement of the structure sitting on the SAND.

[3 marks]

ii) Estimate the time elapsing before one half of the consolidation settlement calculated in part (i) has taken place.

[7 marks]

B4. A range of commercial buildings are to be constructed on a brownfield site, which is adjacent to a 30-m-high rock cliff.

a) Explain to your client why they should invest in a Site Investigation (SI) before constructing a new building on a brownfield site. In your answer, include any specific objectives of a SI, and implications if the SI is of poor quality or not carried out.

[12 marks]

b) **Figure QB4** represents a simplified stereoplot of the main features of the rock face.

i) List the dip angles and dip directions of the rock face and the four planes.

[5 marks]

ii) What is the characteristic frictional resistance for this slope?

[1 mark]

Question B4 continues/…

…/question B4 continued

c) Critically evaluating all observations from the section and the stereoplot (**Figure QB4**), describe and explain:

i) What types of rock you expect this face to comprise;
[2 marks]

ii) What type of failure you would expect to occur at this cliff face;
[3 marks]

iii) What options for mitigating rock slope failure can be applied here; and
[3 marks]

iv) What the main uncertainties are to assess the risk of slope failure in this case.
[4 marks]

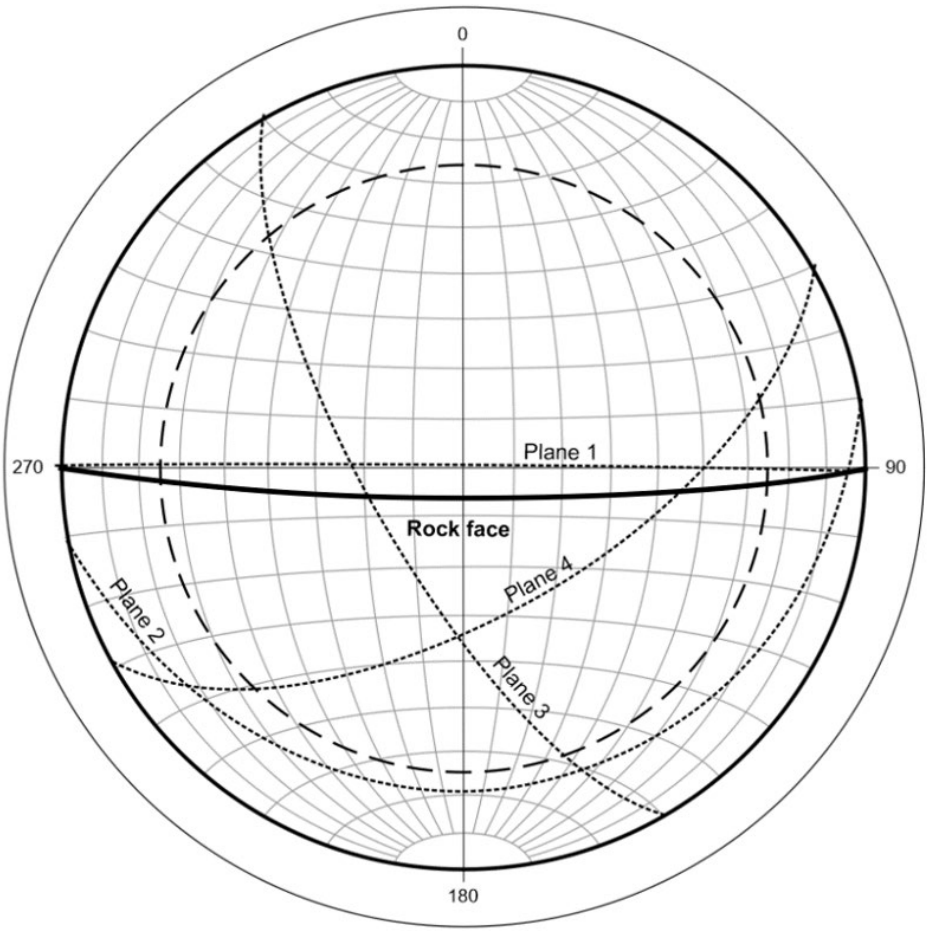

Figure QB4. A stereographic plot representing the rock face and its discontinuities

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LOUGHBOROUGH UNIVERSITY
School of Architecture, Building and Civil Engineering
Soil Mechanics & Geology (CVB102) - FORMULAE SHEET and CHARTS

Classification

Specific gravity	G_s	= density of solids/density of water = ρ_s/ρ_w = γ_s/γ_w
Bulk density	ρ	= overall mass of soil per unit volume = m/V
Bulk unit weight	γ	= overall weight of soil per unit volume = W/V
Unit weight of water	γ_w	= ρ_w g = 9.81 kN/m^3
Submerged (buoyant) density	ρ'	= $\rho - \rho_w$
Dry density (mass of solid particles per unit volume of soil)	ρ_d	= $\rho/(1 + w)$
Density of water	ρ_w	= 1000 kg/m^3 = 1.0 g/cm^3
Moisture content	w	= mass of water in soil/mass of solids = m_w/m_s
Total soil volume	V	= $V_s + V_v = V_w + V_s + V_a$
Air content	A_v	= volume of air/volume of soil = V_a/V
Degree of saturation	S_r	= V_w/V_v = volume of water/volume of voids
Void ratio	e	= V_v/V_s = volume of voids/volume of solids
Porosity	n	= $V_v/V = V_v/(V_s + V_v)$ = $e/(1 + e)$
Plasticity Index	PI	= LL - PL
Grading, Coefficient of Uniformity	C_u	= D_{60}/D_{10}
Grading, Coefficient of Curvature	C_c	= $\dfrac{(D_{30})^2}{D_{10}\,D_{60}}$

Phase relationships

Moisture content	w	= $S_r \,.\, e / G_s$	These are examples - you can derive any
Bulk density	ρ	= $\rho_w G_s(1 + w)/(1 + e)$	phase relationship required from the
Unit weight	γ	= $\gamma_w G_s(1 + w)/(1 + e)$	definitions above.

Seepage

Darcy's Law	v	= k.i , q = A.k.i
Bernoulli's Theorem	H	= $z + u/\gamma_w$ = $z + h_w$
Hazen's approximation	k	~ 0.01 d_{10}^2 (k in m/s, d in mm)

k from laboratory falling head tests $k = \dfrac{2.3aL}{A(t_2 - t_1)}\log\left(\dfrac{h_1}{h_2}\right)$

k from well pumping tests (unconfined flow) $k = \frac{2.3q \log(r_2 / r_1)}{\pi(h_2^2 - h_1^2)}$

k from well pumping tests (confined flow) $k = \frac{2.3q \log(r_2 / r_1)}{2\pi H(h_2 - h_1)}$

Stratified soils $k_h = \frac{\Sigma kH}{\Sigma H}$

$k_v = \frac{\Sigma H}{\Sigma (H/k)}$

Piping $i_c = \frac{\gamma'}{\gamma_w}$

Flow nets $q = k \left(\frac{N_f}{N_d}\right) H$

Anisotropic soil scale factor for x = $\sqrt{\frac{k_v}{k_h}}$ k' = $\sqrt{k_v k_h}$

Boundary condition $\frac{k_1}{k_2} = \frac{\tan\alpha_1}{\tan\alpha_2}$

Modification to position of exit phreatic surface in an embankment dam:

β	30°	60°	90°
Δa/a	0.36	0.3	0.26

Shear strength

Coulomb $\tau_f = c + \sigma \tan \phi$

$\tau_f = c' + \sigma' \tan \phi'$

Mohr's Circle $\sigma_1 - \sigma_3 = P/A$ (= deviator stress)

$\tau_{max} = (\sigma_1 - \sigma_3)/2$ (undrained)

$\theta = 45 + \varphi/2$

Pore Pressure parameters

$\Delta u = B\Delta\sigma_3 + A.B\,\Delta(\sigma_1 - \sigma_3)$

$A.B = \bar{A}$

$\bar{A}_f = u_f/(\sigma_1 - \sigma_3)_f$ (f refers to failure)

Consolidation and Compression

Coefficient of volume compressibility $m_v = -\frac{\Delta\varepsilon_v}{\Delta\sigma'} = \frac{\Delta e}{(1+e_0)(\Delta\sigma')} = \frac{e_0 - e_1}{(1+e_0)(\sigma'_1 - \sigma'_0)} = \frac{a_v}{(1+e_0)}$

Coefficient of compressibility $a_v = \frac{e_0 - e_1}{\Delta\sigma'}$

Volumetric strain $\Delta\varepsilon_v = \frac{\Delta H}{H_0} = -\frac{\Delta e}{1+e_0}$

$\Delta e = e_0 - e_1$

Voids ratio e = water content * specific gravity = $w.\ G_s$ (saturated)

Compression $\Delta H = s_{max} = H_0\ m_v\ \Delta\sigma'$

$$\frac{\Delta H}{H_0} = \frac{e_0 - e_1}{(1+e_0)} = \frac{c_c \log\left(\frac{\sigma'_1}{\sigma'_0}\right)}{(1+e_0)}$$

where e_0 = initial voids ratio, e_1=final voids ratio

σ'_0 = initial effective stress, σ'_1 = final effective stress

ΔH = primary consolidation settlement, H_0 = initial thickness

$\Delta\sigma'$= difference in effective stress

Compression Index $C_c = (e_0 - e_1) / \log(\sigma_1' / \sigma_0')$

Coefficient of Consolidation $c_v = \dfrac{k}{m_v\ .\ \gamma w}$

Overconsolidation Ratio $R = \sigma'_{max} / \sigma'_{current}$

Degree of consolidation $U_z = \dfrac{e_0 - e}{e_0 - e_1} = \dfrac{\sigma' - \sigma'_0}{\sigma'_1 - \sigma'_0} = 1 - \dfrac{u^e}{u^0} = \dfrac{s_t}{s_{max}}$

Time factor $T_v = \dfrac{c_v t}{d^2}$

$U_z = 0.9$ for $T_v = 0.848$; $U_z = 0.5$ for $T_v = 0.196$ Note: c_v in m^2/year

Finite difference calculation of excess pore pressure and settlement:

$$\bar{u}_{i,j+1} = \bar{u}_{i,j} + \frac{c_v \Delta t}{(\Delta z)^2}(\bar{u}_{i-1,j} + \bar{u}_{i+1,j} - 2\bar{u}_{i,j})$$

$$S_t = \sum_0^t m_v\ \Delta z\ \Delta\bar{u}$$

Correction for construction period:

For $0 \le t < t_c$: $s_t^{corrected} = s_{t/2}^{instant}\ (\Delta\sigma^t/\Delta\sigma^{net}) = s_{t/2}^{instant}\ (t/t_c)$

For $t = t_c$: $s_t^{corrected} = s_{tc/2}^{instant}$

For $t > t_c$: $s_t^{corrected} = s_{t-tc/2}^{instant}$

<u>Compaction of Earthworks</u>

Dry Density $\rho_d = \rho_b / (1+w)$ $\rho_d = (G_s / (1+e))\ .\ \rho_w$

ρ_b = Bulk Density

ρ_d = Dry density

$\rho_d = (1-A) / ((1/\rho_s) + (w/\rho_w))$

Note: w = moisture content

Lateral Earth Pressure and Retaining Walls

$K_0 = 1 - \sin\phi'$

$K_a = (1 - \sin\phi') / (1 + \sin\phi')$

$K_p = (1 + \sin\phi') / (1 - \sin\phi')$

$P_a = K_a.\sigma'_z - 2.c'\sqrt{K_a}$

$P_p = K_p.\sigma'_z + 2.c'\sqrt{K_p}$

Bearing Capacity

$Q_{ult} = c.N_c.S_c + p_0.N_q.S_q + ½.\gamma'.B.N_\gamma.S_\gamma$

Bearing capacity factors:

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

$N_c = \frac{N_q - 1}{\tan\phi'}$

$N_\gamma = 2(N_q - 1)\tan\phi'$

ϕ'	N_q	N_c	N_γ
0	1	5.14	0
5	1.6	6.9	0.1
10	2.5	8.5	0.5
15	3.9	10.8	1.6
20	6.4	14.8	3.9
25	10.7	20.8	9.0
30	18.4	30.1	20.1
35	33.3	46.1	45.2
40	64.2	75.3	106.1
45	134.9	133.9	267.8
50	319.1	266.9	758.2

Shape factors:

Shape	S_c	S_q	S_γ
Strip	1.0	1.0	1.0
Rectangle	$1 + \frac{B}{L}\frac{N_q}{N_c}$	$1 + \frac{B}{L}\tan\phi$	$1 - 0.4\frac{B}{L}$
Square, circle	$1 + \frac{N_q}{N_c}$	$1 + \tan\phi$	0.6

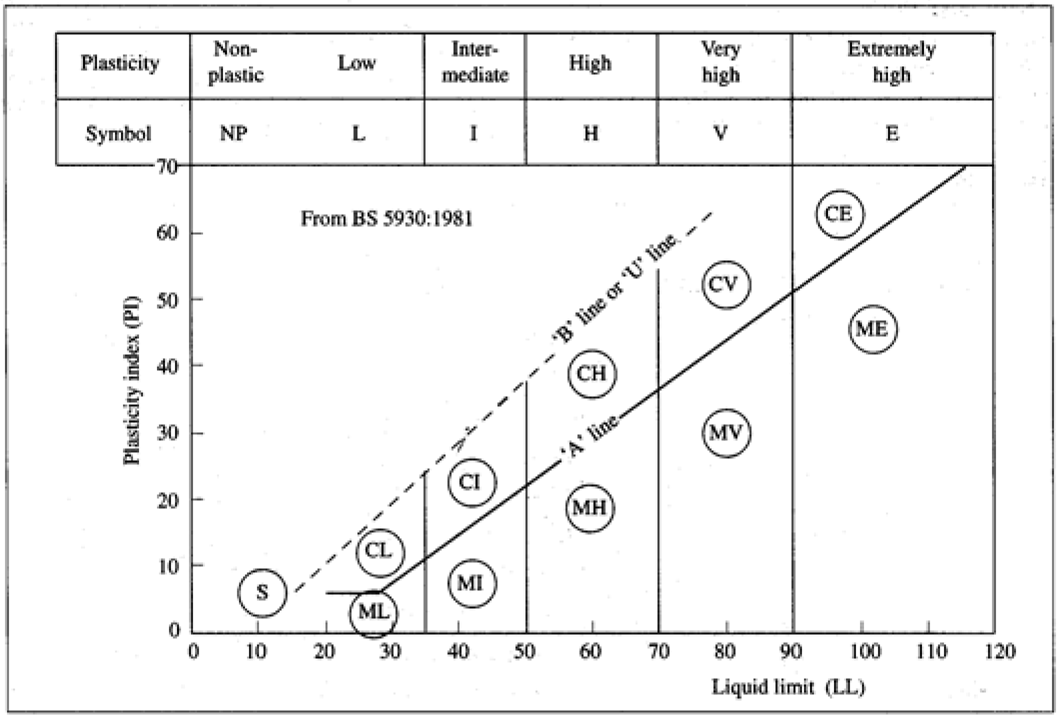
Slope Stability

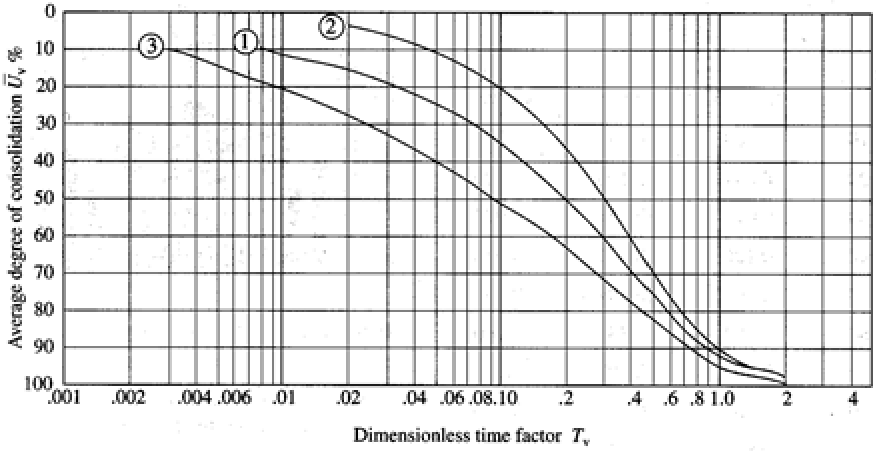
Translational slides:

$$\mathrm{FoS} = \frac{\tau_{\max}}{\tau} = \frac{c' + (\gamma z - \gamma_w m z)\cos^2\beta \tan\varphi'}{\gamma z \sin\beta \cos\beta}$$

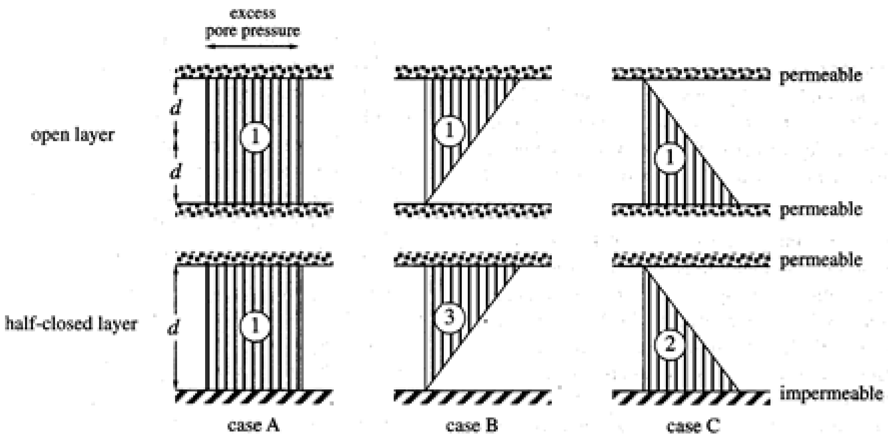
Circular slides:

$$\mathrm{FoS} = \frac{c_u r^2 \theta}{Wd}$$





a) $\overline{U}_v$ - T_v relationships



b) Variations of initial excess pore water pressure