HANDOUT

Geotechnics

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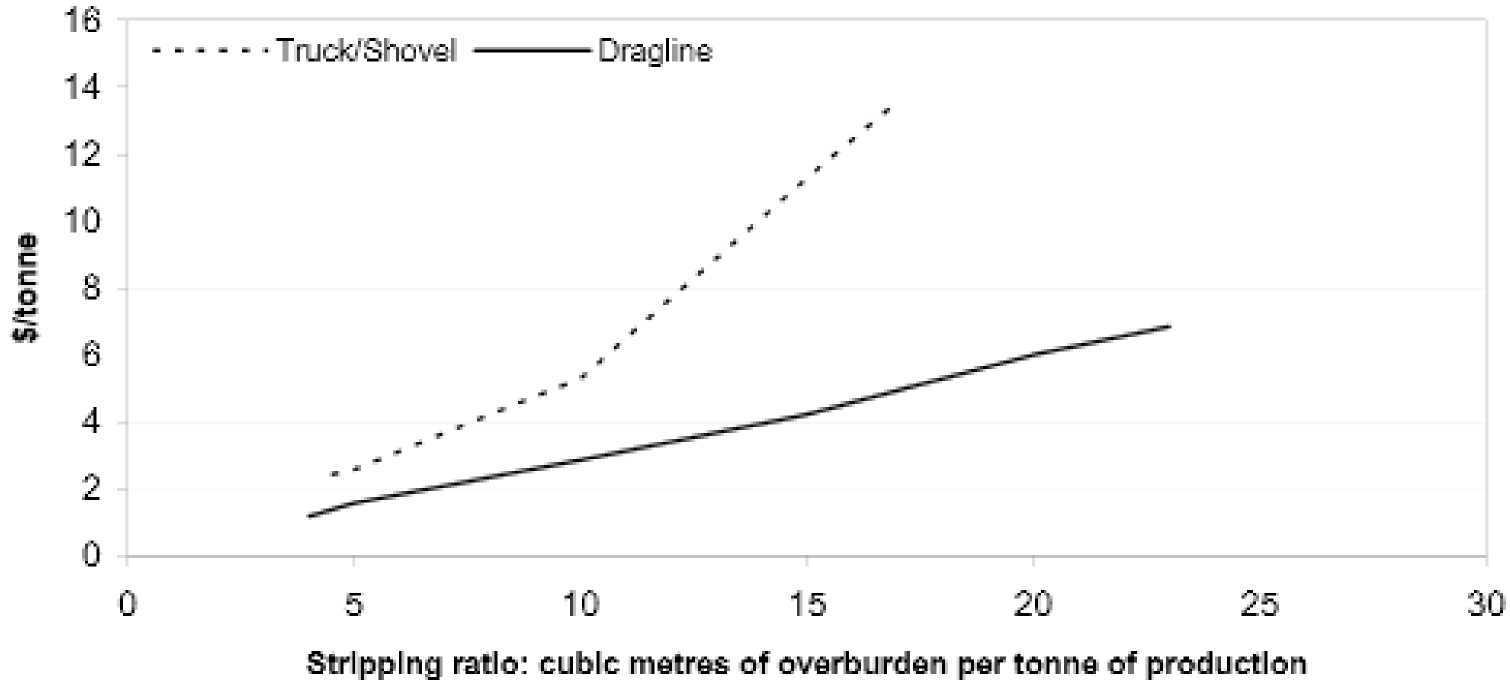
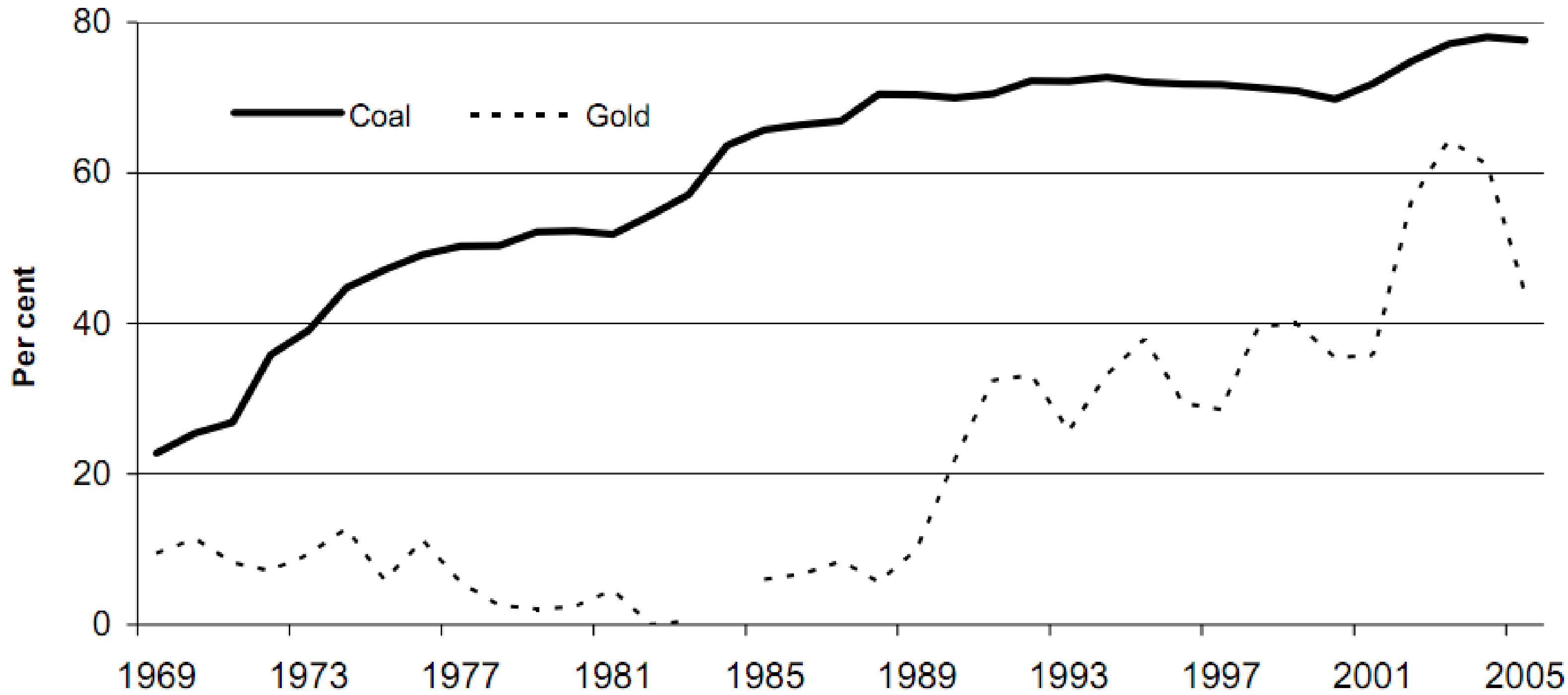
LESSON PART 1

Other Factors Influencing Mining

- Technology Change
- Work Practice
- Safety
- Poor Weather
- Infrastructure Constrains

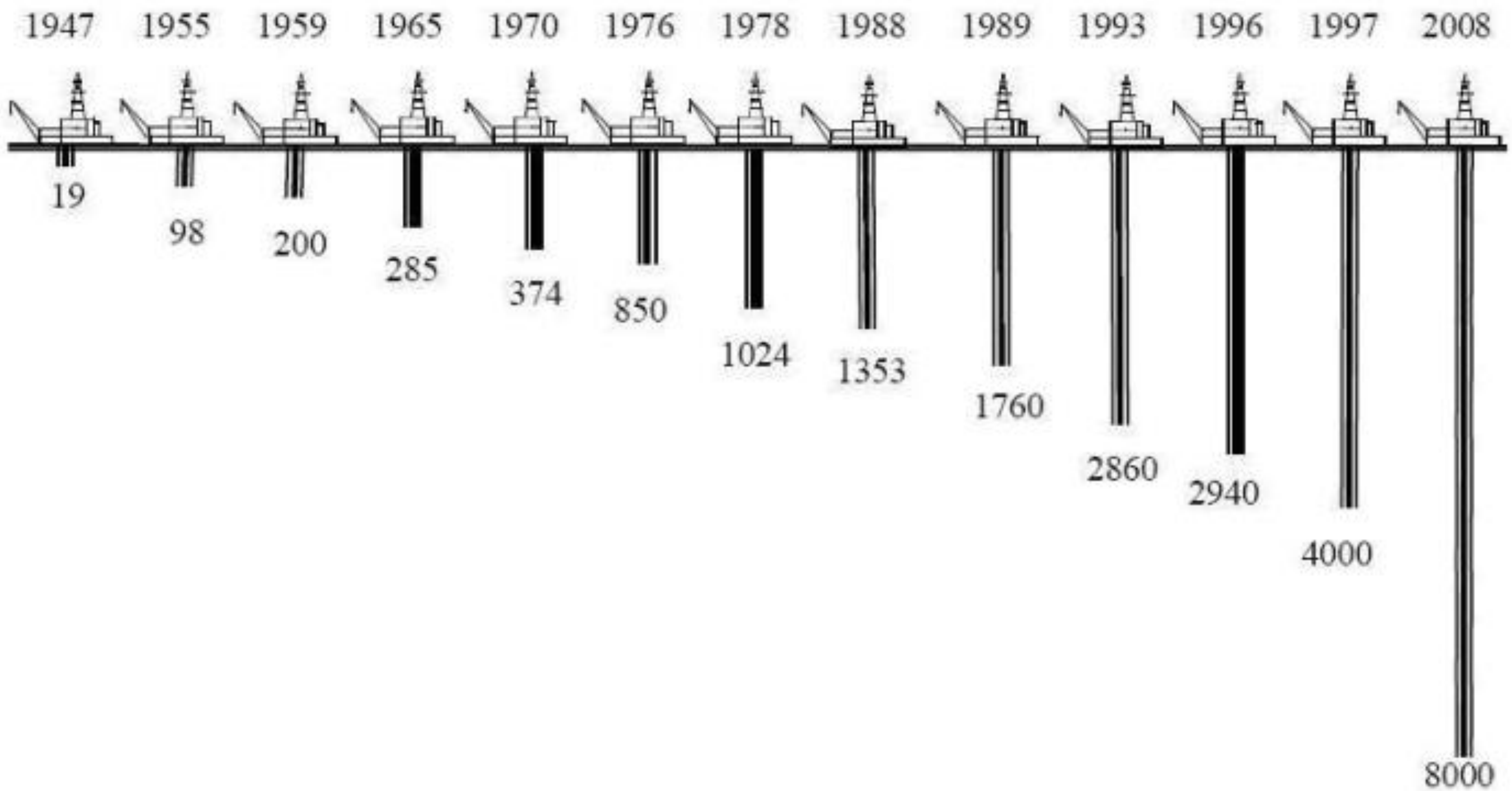


Data source: From Hartman and Mutmansky (2002).



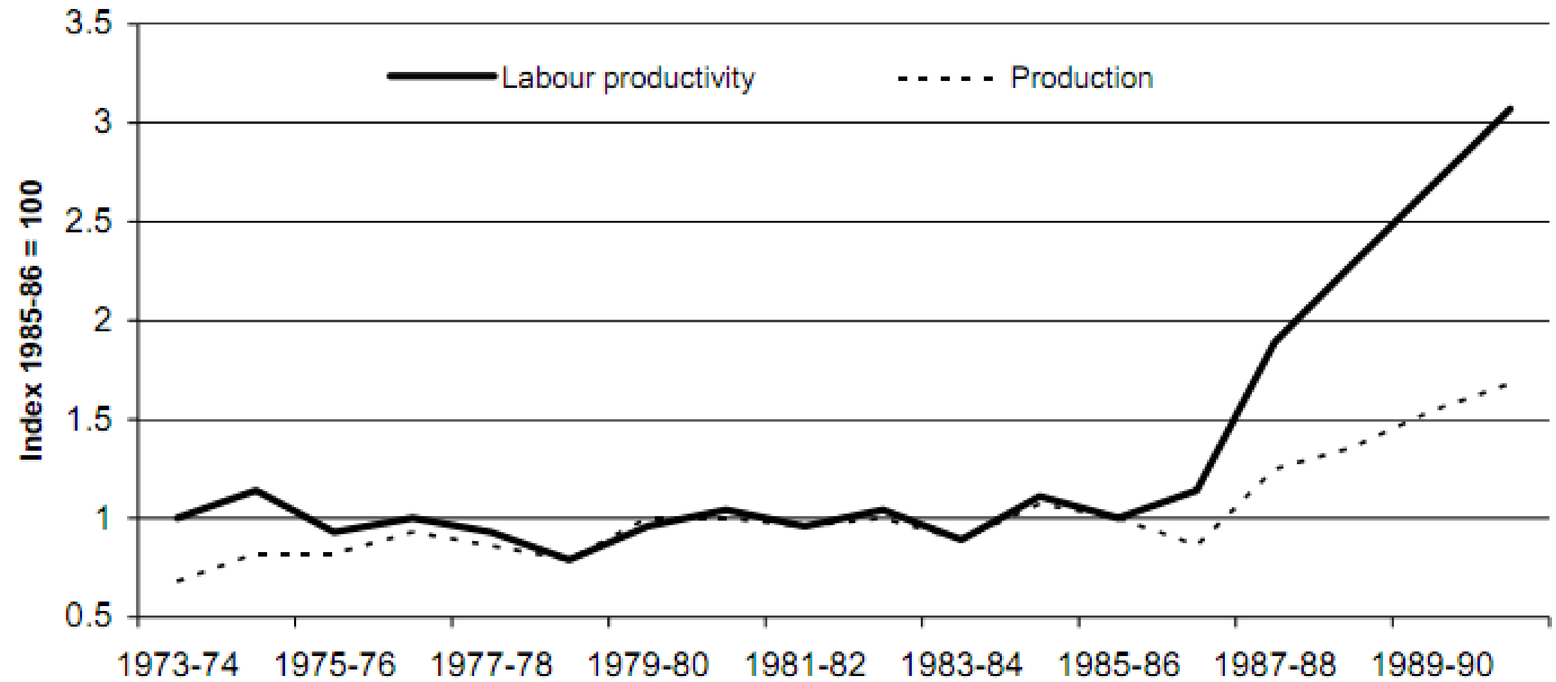
[a] The gold data represent a minimum of gold produced by open-cut mines. The proportion, especially in more recent years is likely to be higher.

Data source: Mudd (2007).



[a] Depth of water is given in feet.

Data sources: Bohi (1998) (in turn adapted from various Shell briefing notes). The data for 2008 added from Phillips (2008).



Data source: Schmitz (2005).

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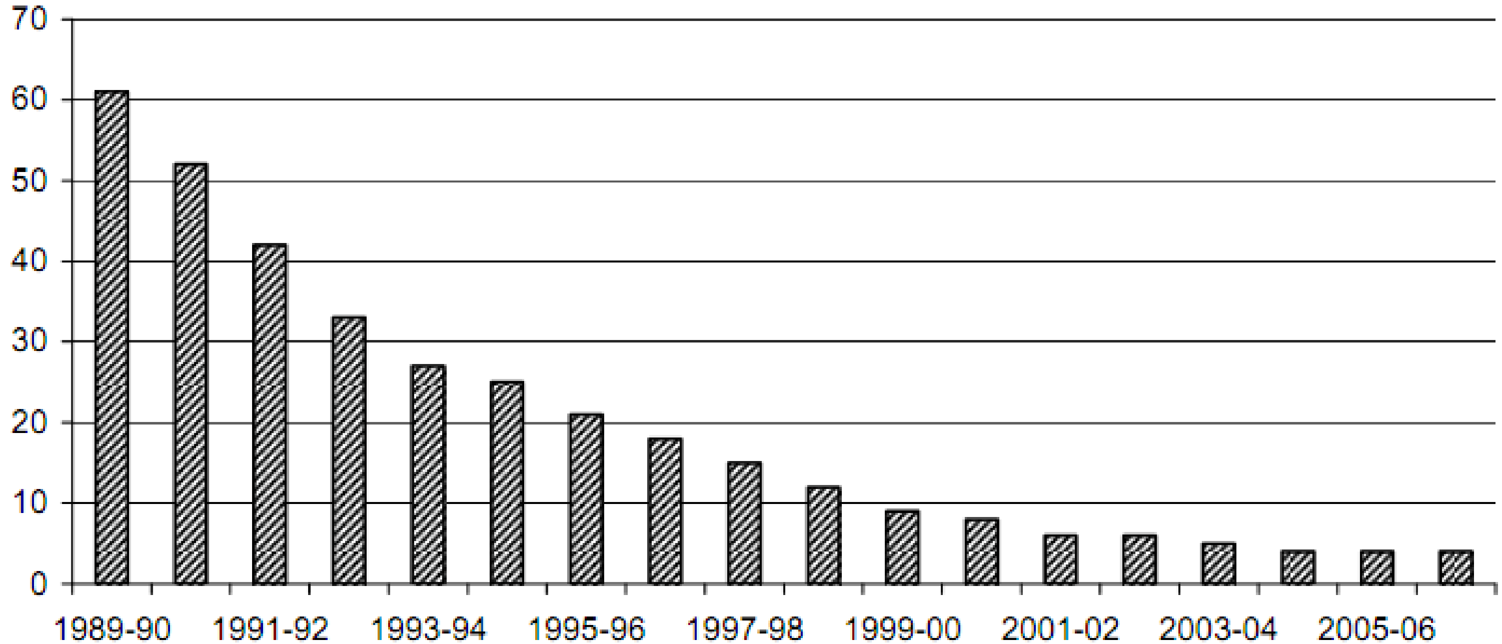
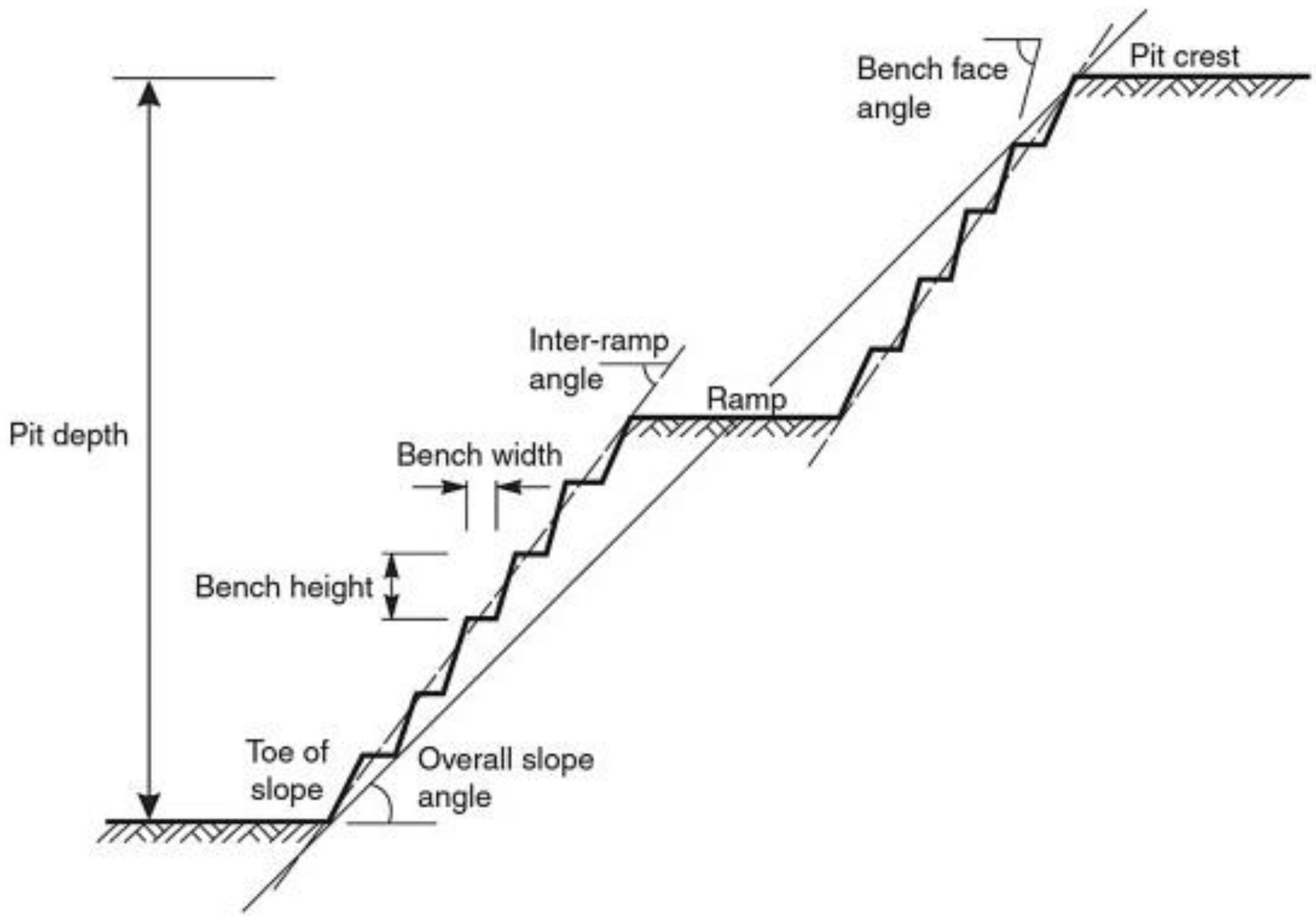
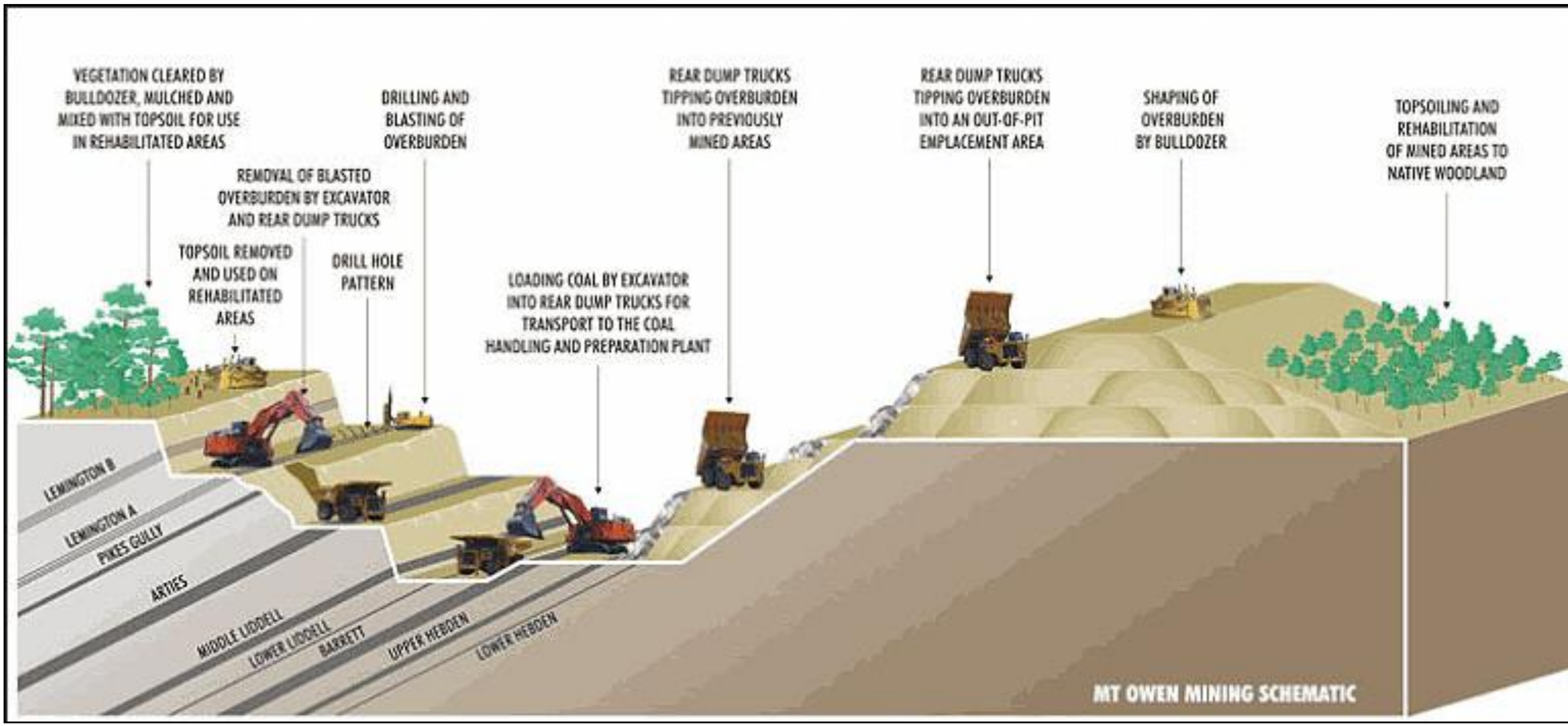


[a] LTIFR = The number of lost time injuries per one million hours of work.

Data sources: Minerals Council of Australia, (*Safety Performance Report of the Australian Minerals Industry*, 2007); Minerals Council of Australia, (*Safety & Health Performance Report of the Australian Minerals Industry*, 1999).

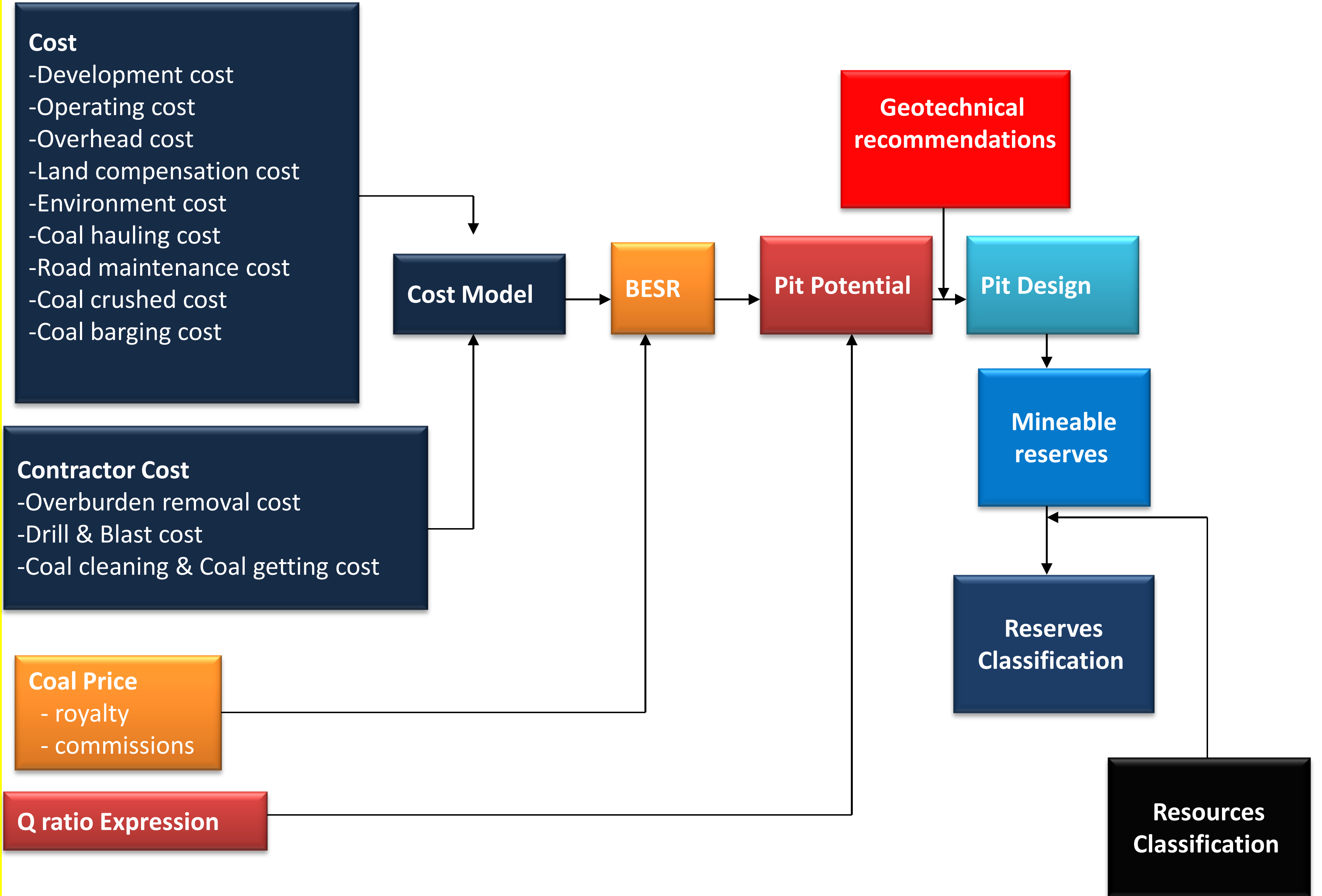
Open Pit Slopes Design Scales





VEGETATION CLEARED BY BULLDOZER, MULCHED AND MIXED WITH TOPSOIL FOR USE IN REHABILITATED AREAS
REMOVAL OF BLASTED OVERBURDEN BY EXCAVATOR AND REAR DUMP TRUCKS
TOPSOIL REMOVED AND USED ON REHABILITATED AREAS
DRILL HOLE PATTERN
DRILLING AND BLASTING OF OVERBURDEN
LOADING COAL BY EXCAVATOR INTO REAR DUMP TRUCKS FOR TRANSPORT TO THE COAL HANDLING AND PREPARATION PLANT
REAR DUMP TRUCKS TIPPING OVERBURDEN INTO PREVIOUSLY MINED AREAS
REAR DUMP TRUCKS TIPPING OVERBURDEN INTO AN OUT-OF-PIT EMPLACEMENT AREA
SHAPING OF OVERBURDEN BY BULLDOZER
TOPSOILING AND REHABILITATION OF MINED AREAS TO NATIVE WOODLAND
LEMINGTON B
LEMINGTON A
PIKES GULLY
ARTIES
MIDDLE LIDDELL
LOWER LIDDELL
BARRETT
UPPER HEBDEN
LOWER HEBDEN
MT OWEN MINING SCHEMATIC

RESERVES CALCULATION STEPS



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KEBIJAKAN DAN PEDOMAN PENGATURAN KEMANTAPAN LERENG PENAMBANGAN DI INDONESIA

Kepmen Pertambangan dan Energi No. 555. K/26/M.PE/1995

Kepmen Pertambangan dan Energi
No.555. K/26/M.PE/1995 tanggal 12 Mei 1995

- Tujuan dari dikeluarkan Kepmen tersebut adalah untuk melindungi tenaga kerja, peralatan, pelaksanaan kegiatan penambangan bisa berjalan dengan aman, terjadi efisiensi biaya, efektif dan produktivitas dari pekerja tinggi serta lancar tanpa terjadi atau seminimal mungkin kecelakaan kerja.
- Menyangkut kemantapan lereng, Kepmen Pertambangan dan Energi No. 555.K/26/M.PE/1995 dalam Bab VI pasal 240 sampai dengan pasal 242 berisi tentang peraturan mengenai tinggi jenjang, lebar jenjang, dan sudut lereng yang sangat tergantung pada ukuran peralatan, jenis batuan, sistem penambangan yang dipakai serta kondisi dari keadaan geologi tempat bekerja seperti rekahan, patahan, atau tanda-tanda tekanan atau tanda-tanda kelemahan lainnya.

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Pasal 240 Cara Kerja

1. Kepala Teknik Tambang (KTT) harus menjamin bahwa kemantapan lereng penambangan, penimbunan dan material lainnya telah diperhitungkan dalam perencanaan tambang
2. Penimbunan tanah penutup hanya dapat dilakukan pada jarak sekurang- kurangnya 7,5 m dari ujung teras penambangan
3. Dilarang melakukan penggalian potong bawah (*under cutting*) pada permuka kerja, teras atau galeri, kecuali mendapat persetujuan Kepala Pelaksana Inspeksi Tambang (KAPIT)
4. Permuka kerja harus aman dari batuan menggantung dan pada waktu pengguguran batuan, para pekerja pada tempat tersebut harus menyingkir
5. Permuka kerja tambang permukaan pada bagian atas daerah kegiatan tambang bawah tanah hanya dapat dibuat setelah mendapat persetujuan KAPIT

6. Dilarang bekerja atau berada di atas timbunan aktif batu pecah, kecuali:
   - berdasarkan perintah seorang pengawas tambang
   - curahan batu ke dan dari timbunan telah dihentikan
   - telah diperoleh kepastian bahwa corongan di bawah timbunan telah ditutup
   - pekerja menggunakan sabuk pengaman yang dihubungkan dengan tali yang sesuai dengan panjangnya, diikatkan secara kuat dan aman pada titik tetap diatasnya.

Pasal 241
Tinggi Permuka Kerja dan Lebar Teras Kerja

1. Kemiringan, tinggi, dan lebar teras harus dibuat dengan baik dan aman untuk keselamatan para pekerja agar terhindar dari material atau benda jatuh
2. Tinggi jenjang (*bench*) untuk pekerjaan yang dilakukan pada lapisan yang mengandung pasir, tanah liat, kerikil, dan material lepas lainnya harus:
   - tidak boleh lebih dari 2,5 m apabila dilakukan secara manual
   - tidak boleh lebih dari 6 m apabila dilakukan secara mekanis
   - tidak boleh lebih dari 20 m apabila dilakukan dengan menggunakan clamsheel, dragline, bucket wheel excavator atau alat sejenis, kecuali mendapat persetujuan KAPIT
3. Tinggi jenjang untuk pekerjaan yang dilakukan pada material kompak tidak boleh lebih dari 6 m apabila dilakukan secara manual

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4. Dalam hal penggalian dilakukan sepenuhnya dengan alat mekanis yang dilengkapi dengan kabin pengaman yang kuat, maka tinggi jenjang maksimum untuk jenis material kompak 15 m, kecuali mendapat persetujuan KAPIT
5. Studi kemantapan lereng harus dibuat apabila:
   - tinggi jenjang keseluruhan pada sistem penambangan berjenjang lebih dari 15 m
   - tinggi setiap jenjang lebih dari 15 m
6. Lebar lantai teras kerja sekurang-kurangnya 1,5 kali tinggi jenjang atau disesuaikan dengan alat-alat yang digunakan sehingga dapat bekerja dengan aman dan harus dilengkapi dengan tanggul pengaman (*safety berm*) pada tebing yang terbuka dan diperiksa pada setiap gilir kerjadari kemungkinan adanya rekahan atau tanda-tanda tekanan atau tanda-tanda kelemahan lainnya.

Pasal 242

1. Pada waktu membuat sumuran, parit, atau pekerjaan sejenis yang dinding bukaannya mencapai tinggi lebih dari 1,2 m, harus diberi penyangga atau dibuat miring dengan sudut yang aman
2. Pembuatan tanggul atau bendungan air yang bersifat sementara atau tetap harus cukup kuat dan memenuhi persyaratan yang berlaku.

Surfece Mining FMI - Mineral

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Surface Mining Newmont - Mineral

Surface Mining Palabora - Mineral

Surface Mining KPC - Coal

Adaro Coal Mine

Surface Mining Adaro - Coal

Surface Mining Satui - Coal

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Surface Mining Senakin - Coal

Slope Failure in Copper Mine

Joint In Sediment Rock

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Joint in Igneous Rock

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A large scale slope failure in an open pit mine

Bingham Canyon mine slope failure

Slope failure in which some structural control by faults is evident at the top of the failure but where the mechanisms involved in the lower part of the failure are unclear.

A large scale slope failure in an open pit mine

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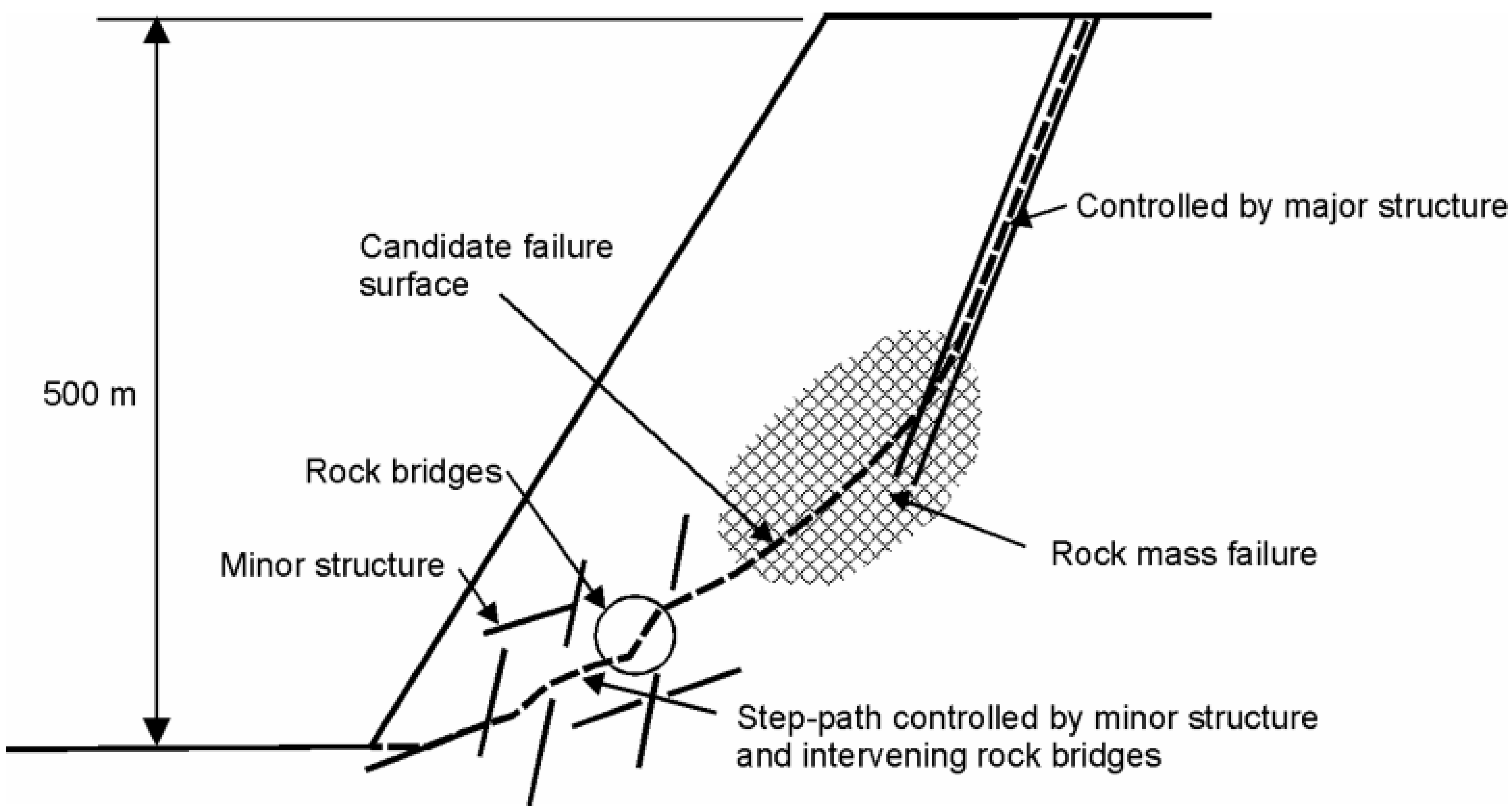
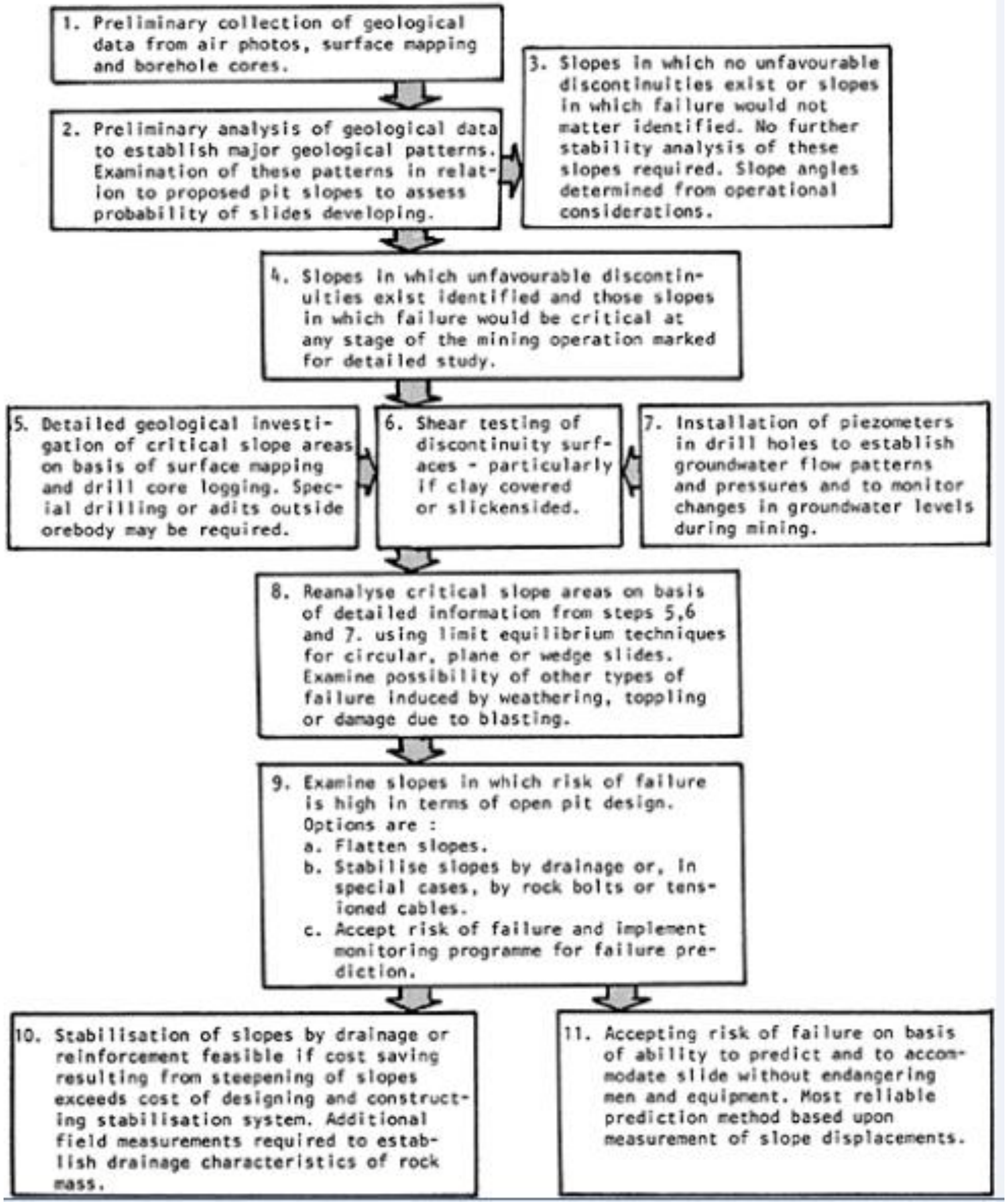
Candidate Failure Surface Involving A Number Of Different Shear Failure Mechanisms



PLANNING A SLOPE STABILITY PROGRAMME



LESSON PART 2

Soil and Rock

Rock definition

- In geology, rock or stone is a naturally occurring solid aggregate of one or more minerals or mineraloids
- Talobre (1948)
- The man who first introduced the Rock Mechanics in France in 1948, is a rock material that makes up the earth's crust, including the fluid therein (such as water, oil, etc.).
- ASTM
- Rock is a material that consists of solid minerals (solid) form a large mass, or in the form of fragments.

Classification of rock and soil strengths (ISRM, 1981)

Class	Description	Unconfined Compressive Strength (MPa)	Examples
S1	Very soft soil - Easily penetrated several inches by fist.	<0,025	
S2	Soft clay - Easily penetrated several inches by thumb.	0,025–0,05	
S3	Firm clay - Can be penetrated several inches by thumb with moderate effort.	0,05–0,1	
S4	Stiff clay - Readily indented by thumb but penetrated only with great difficulty.	0,1–0,25	
S5	Very stiff clay - Readily indented by thumbnail.	0,25–0,5	
S6	Hard clay - Indented with difficulty by thumbnail.	>0,5	

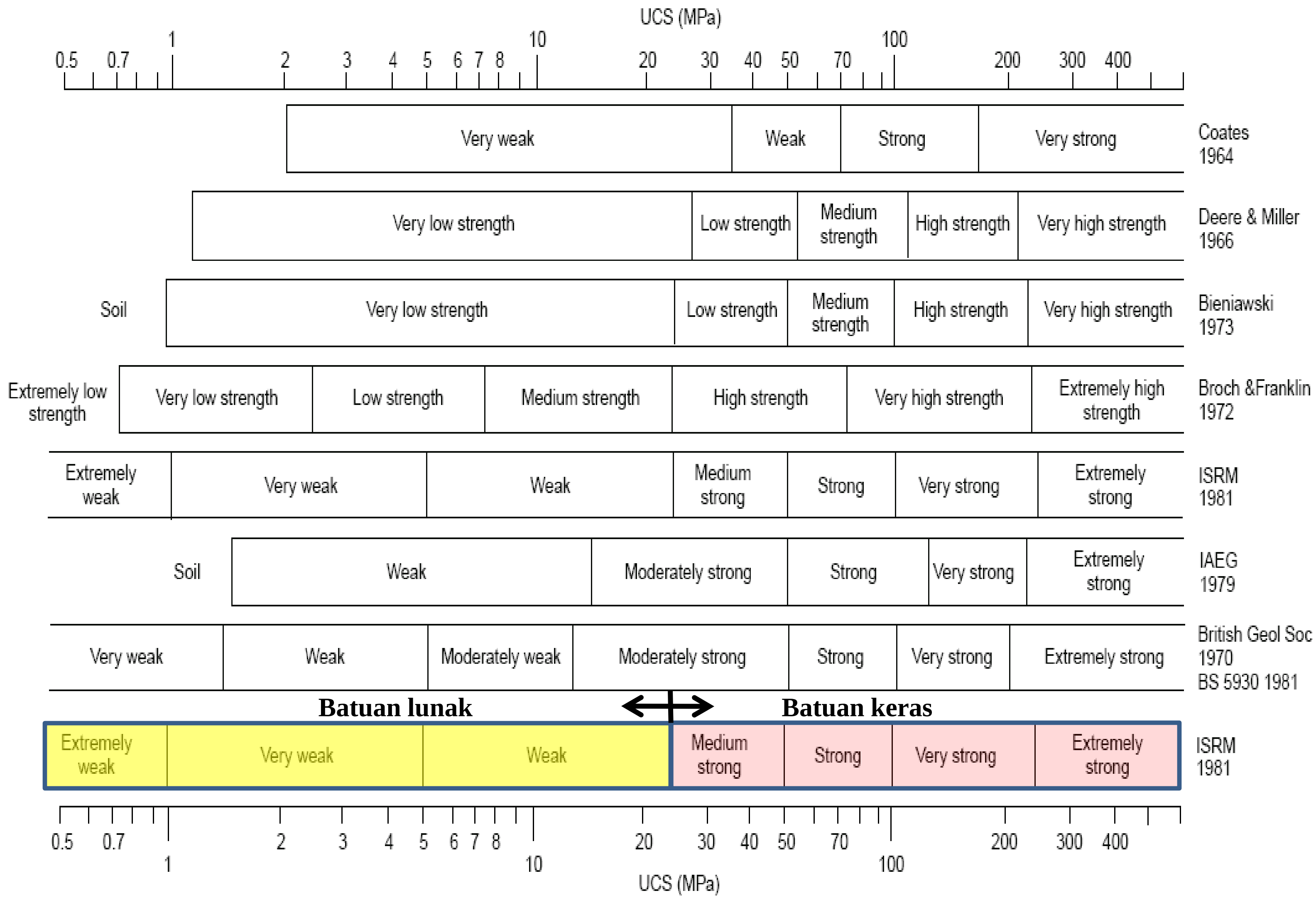
Classification of rock and soil strengths (ISRM, 1981)

Class	Description	Unconfined Compressive Strength (MPa)	Examples
R0	Extremely weak rock - Indented by thumbnail.	0,25–1,0	
R1	Very weak rock - Crumbles under firm blows with point of geological hammer and can be peeled by a pocket knife	1,0–5,0	Chalk, Rocksalt
R2	Weak rock - Can be peeled by a pocket knife with difficulty, shallow indentations made by firm blow with point of geological hammer.	5,0–25	Coal, Schist, Siltstone
R3	Medium strong rock - Cannot be scraped or peeled with a pocket knife, specimen can be fractured with single firm blow of geological hammer.	25–50	Sandstone Slate

Classification of rock and soil strengths (ISRM, 1981)

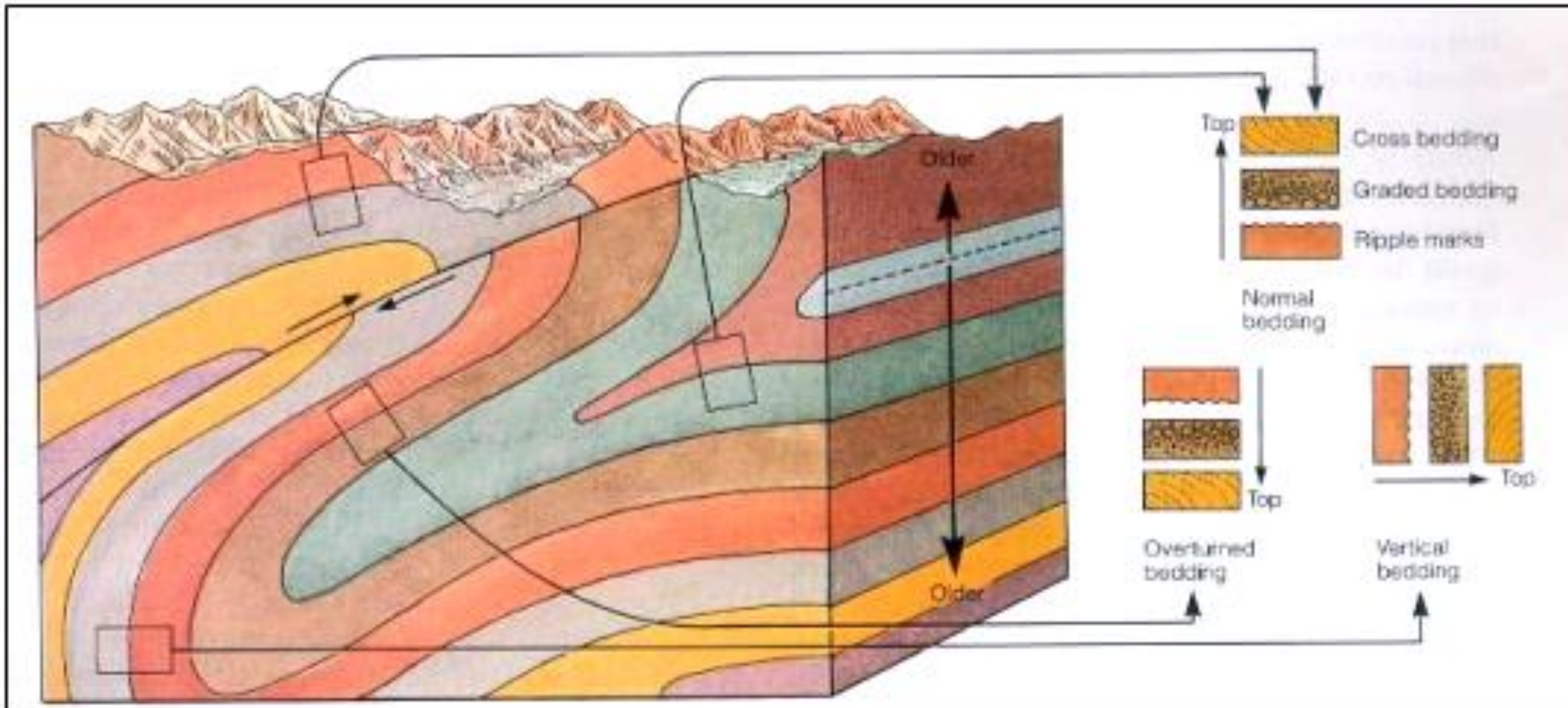
Class	Description	Unconfined Compressive Strength (MPa)	Examples
R4	Strong rock - Specimen requires more than one blow of geological hammer to fracture it.	50–100	Gneiss
R5	Very strong rock - Specimen requires many blows of geological hammer to fracture it.	100–250	Marble, Granite
R6	Extremely strong rock - Specimen can only be chipped with geological hammer.	>250	Quartzite, dolerite, Gabbro, Basalt

Rock Classification (Bieniawski, 1989)



Rock Mass

Geology Structure



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Joint

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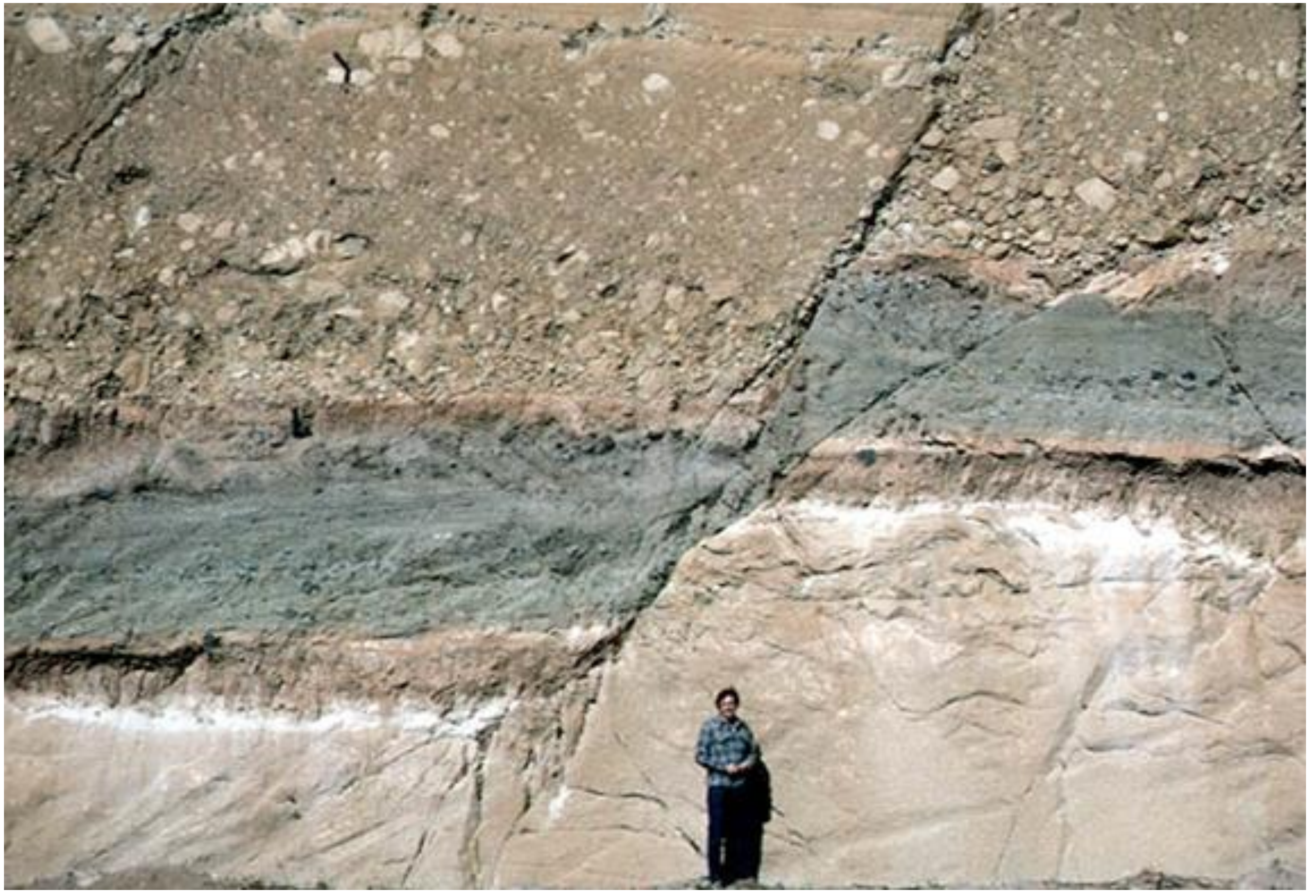
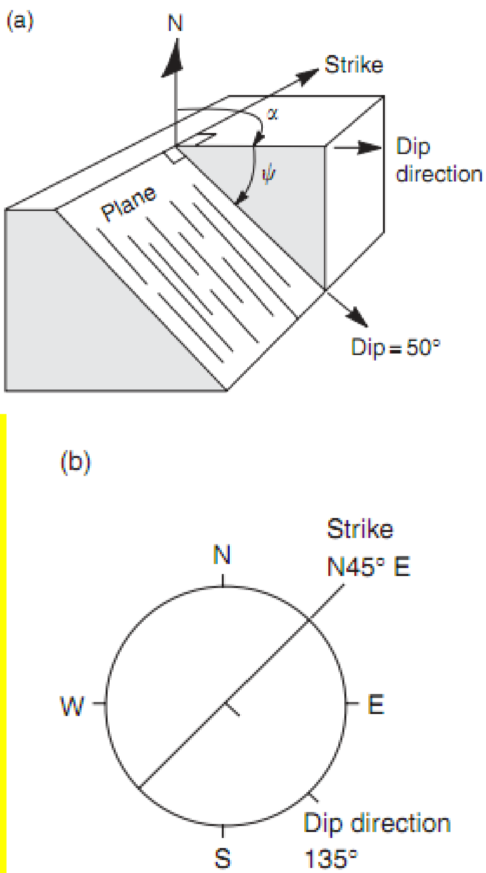
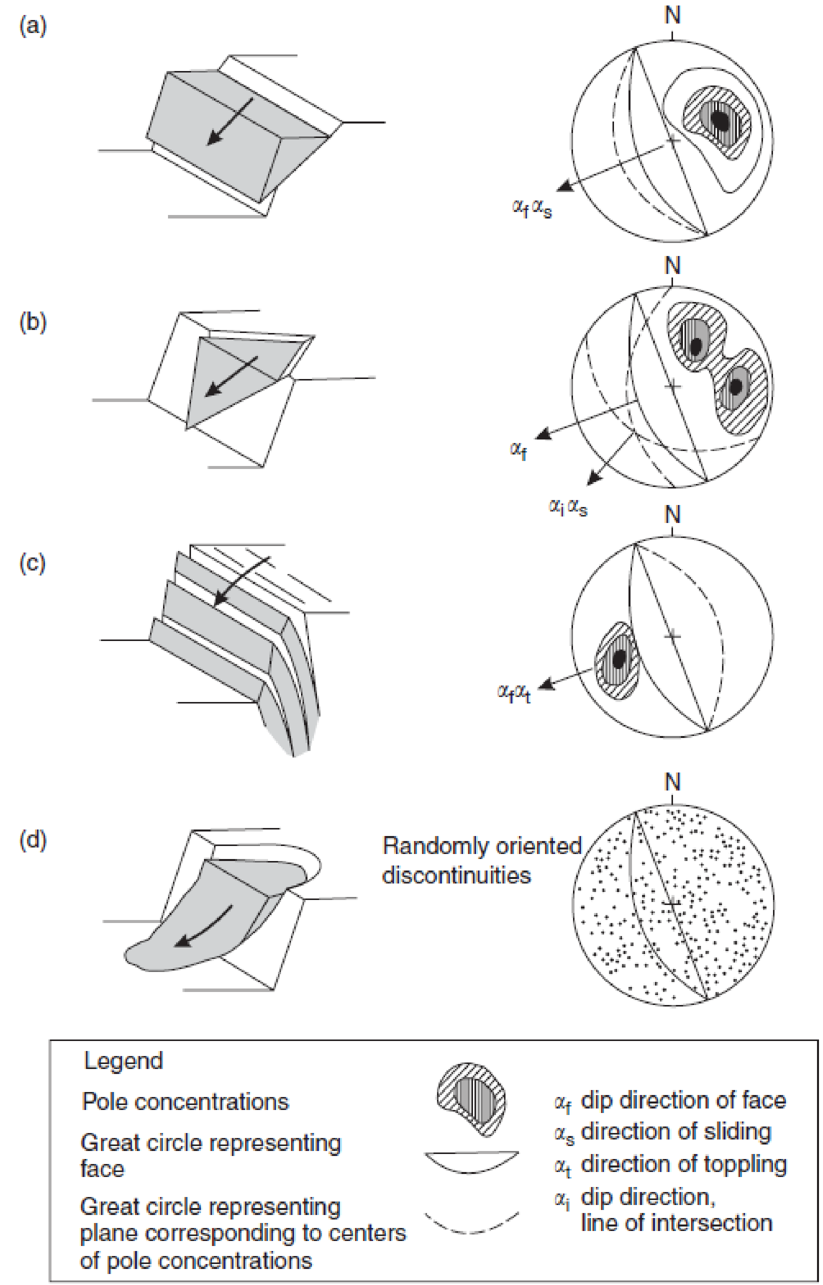
Fault



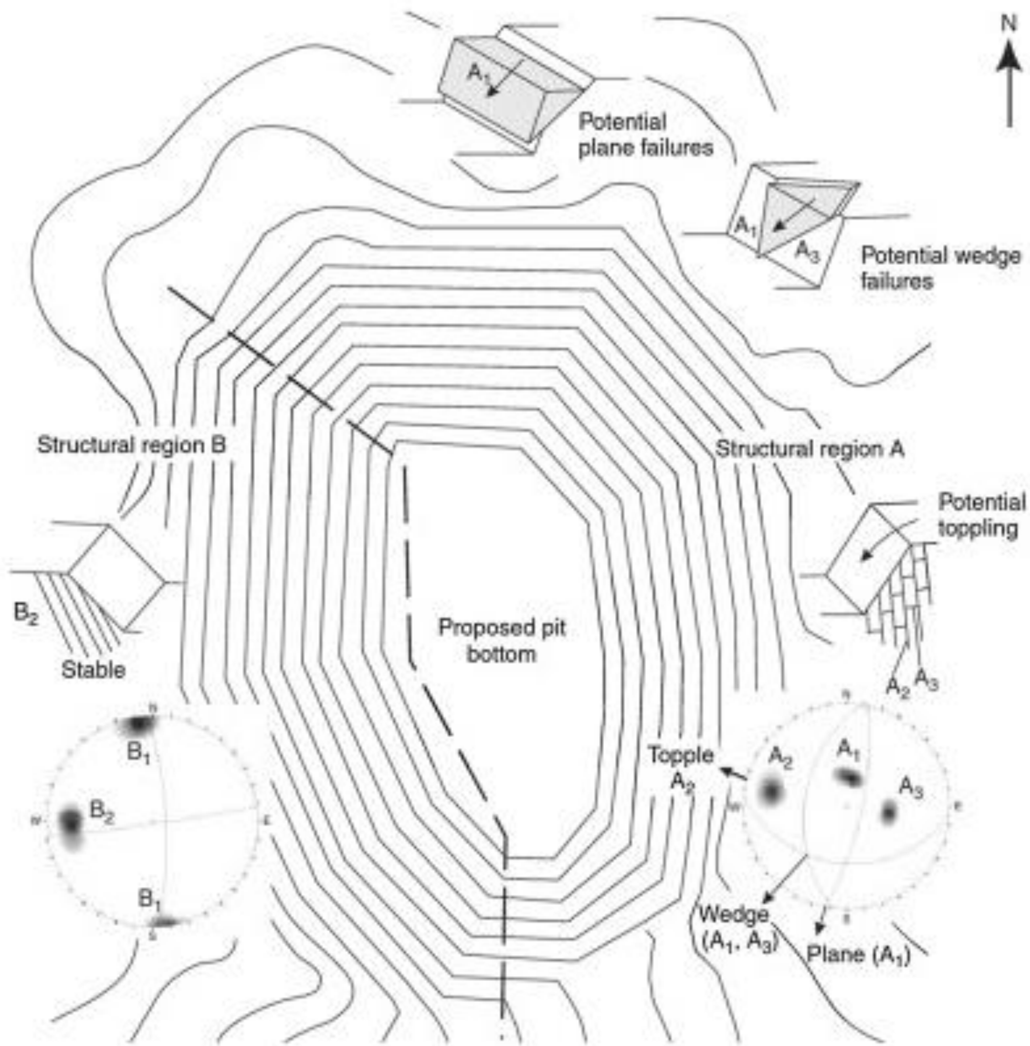
Stereographic analysis



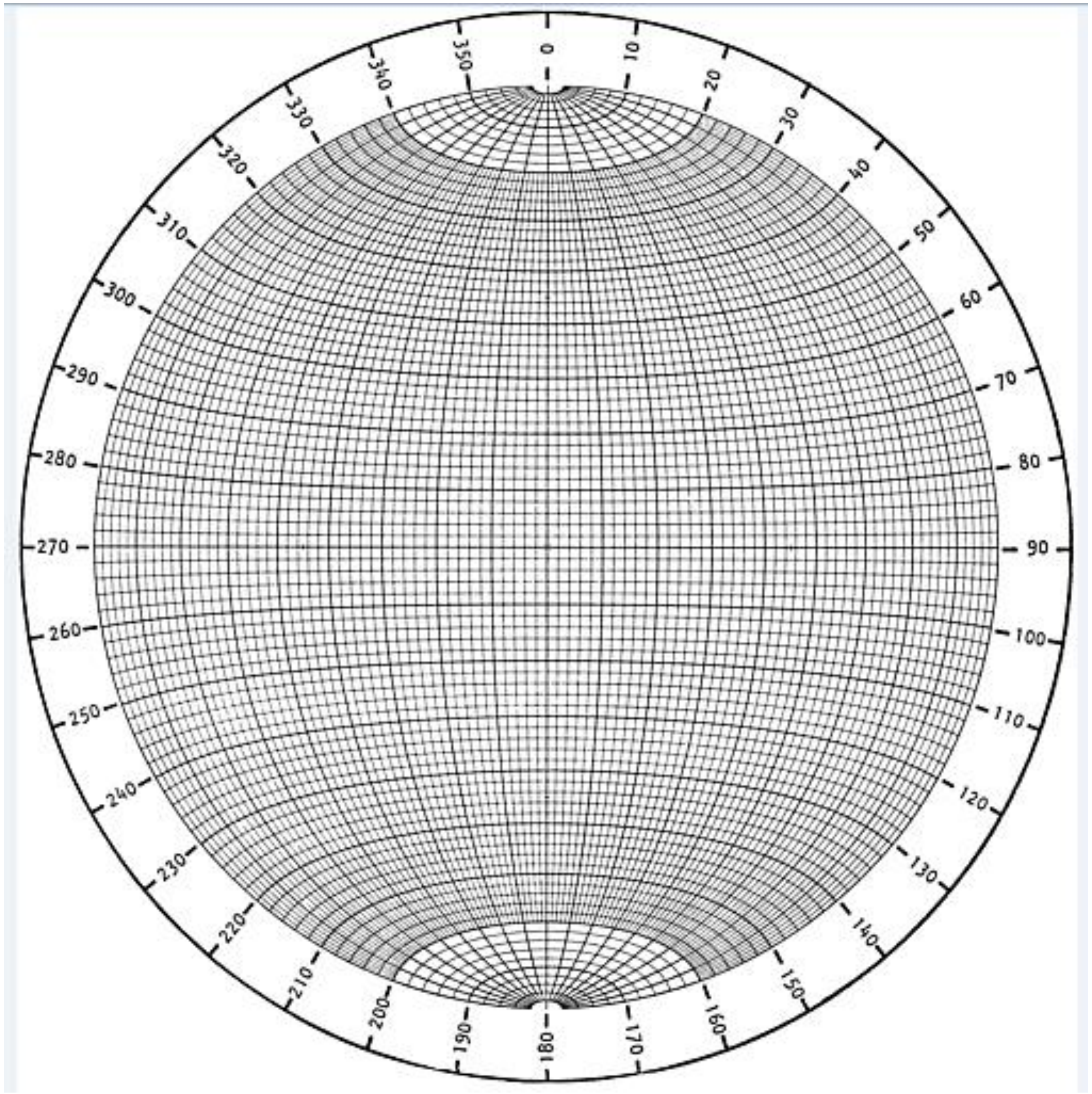


(Hoek & Bray, 1981)

Preliminary evaluation of slope stability of proposed open pit mine



Schimdt Net



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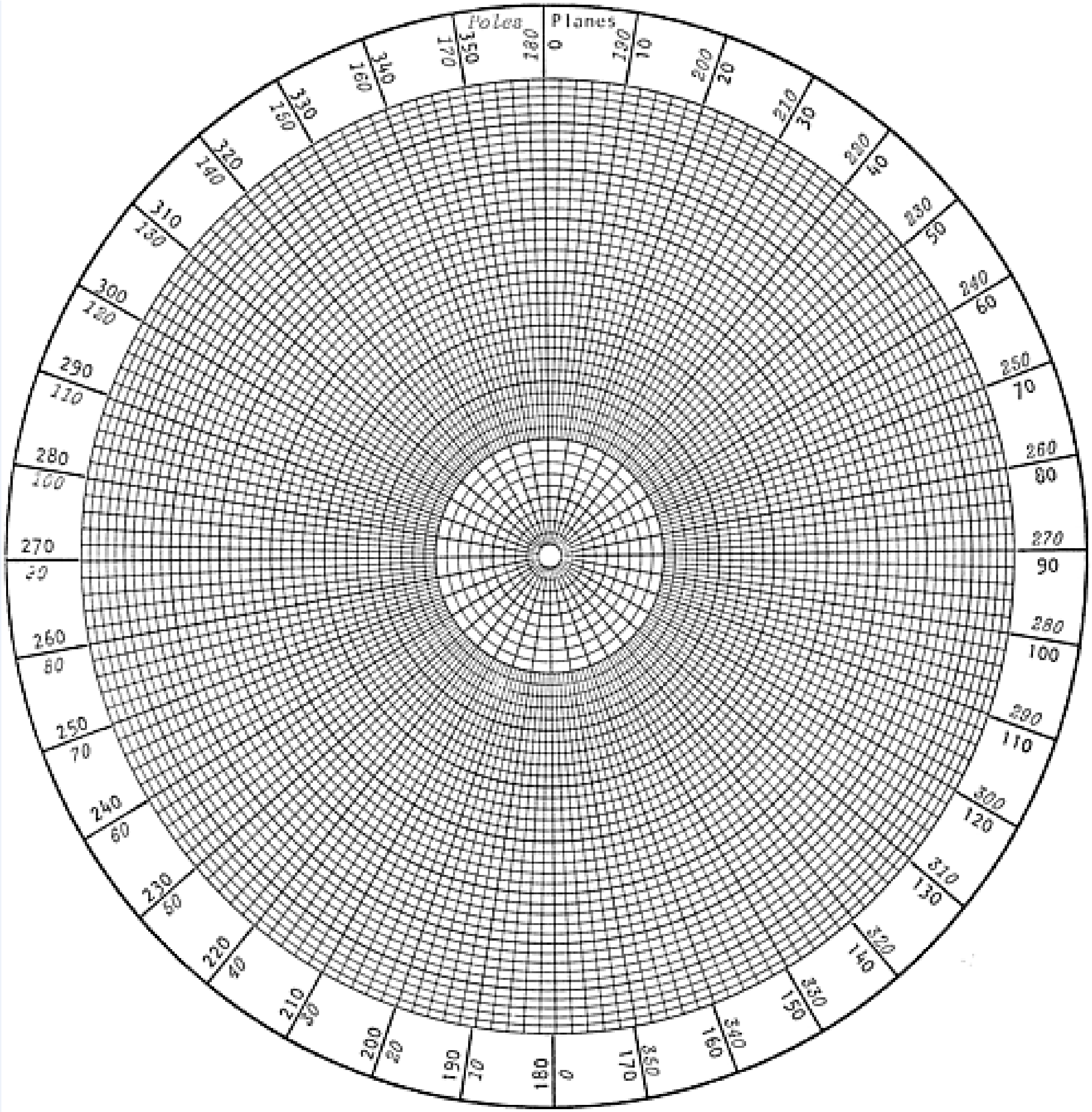
Wulff Net



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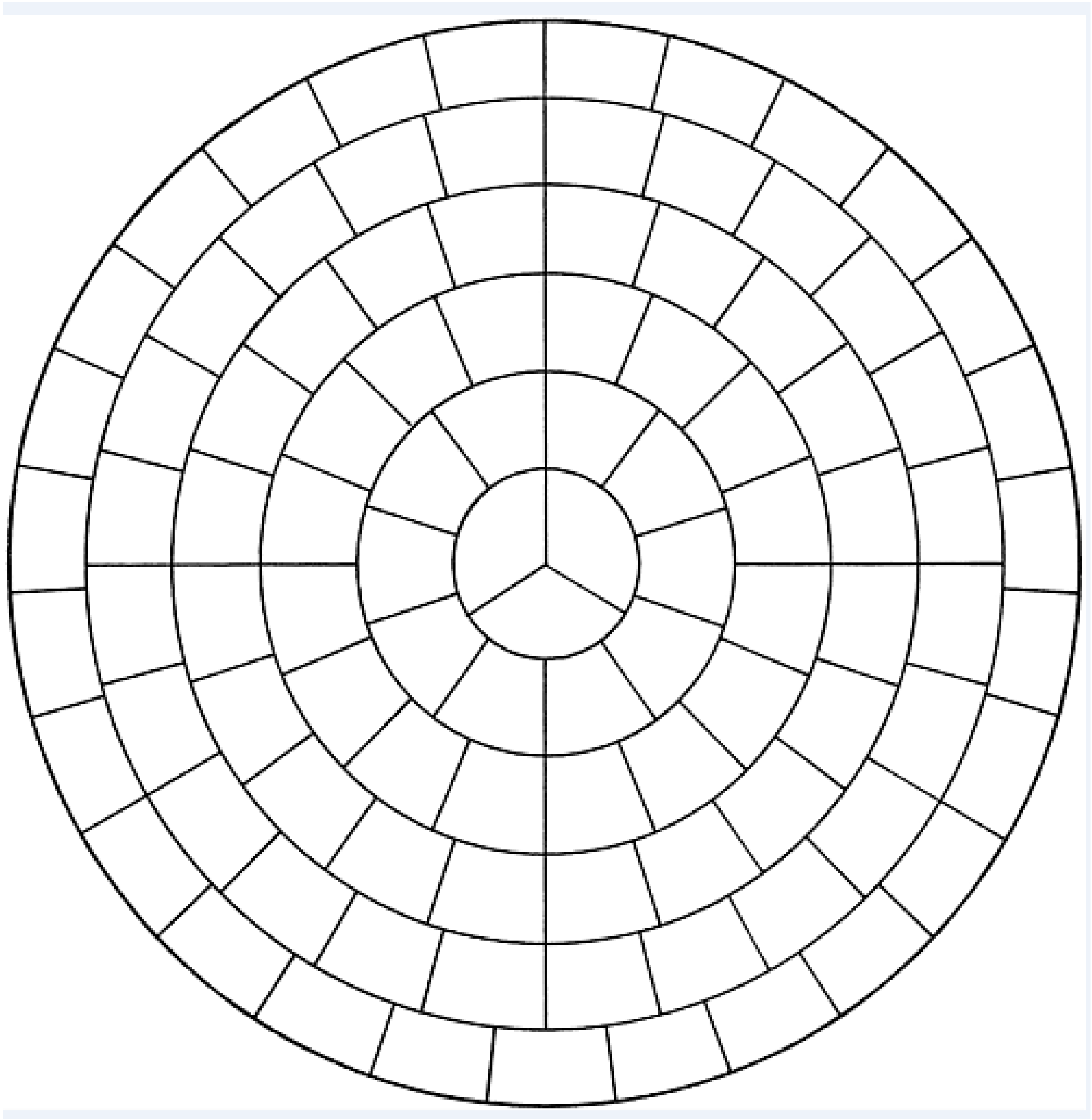
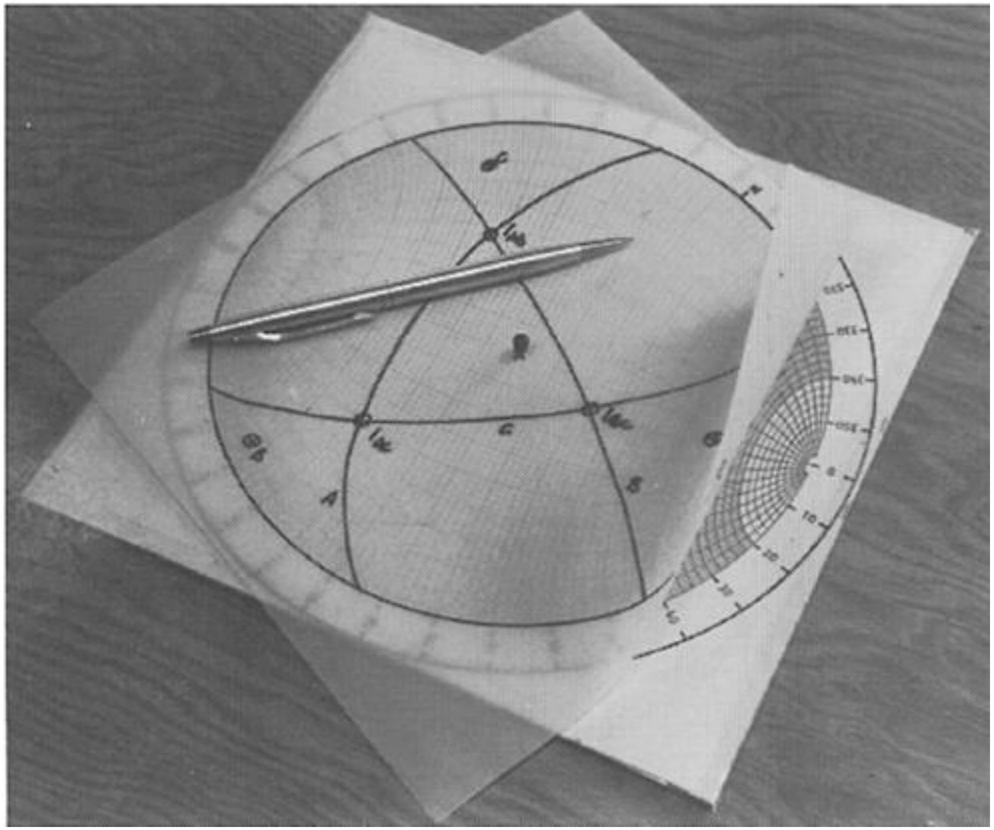
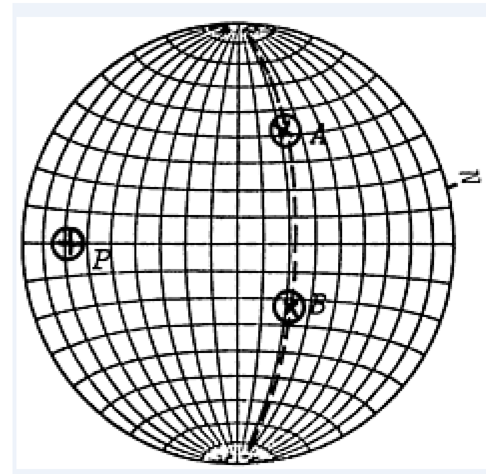
Kalsberg

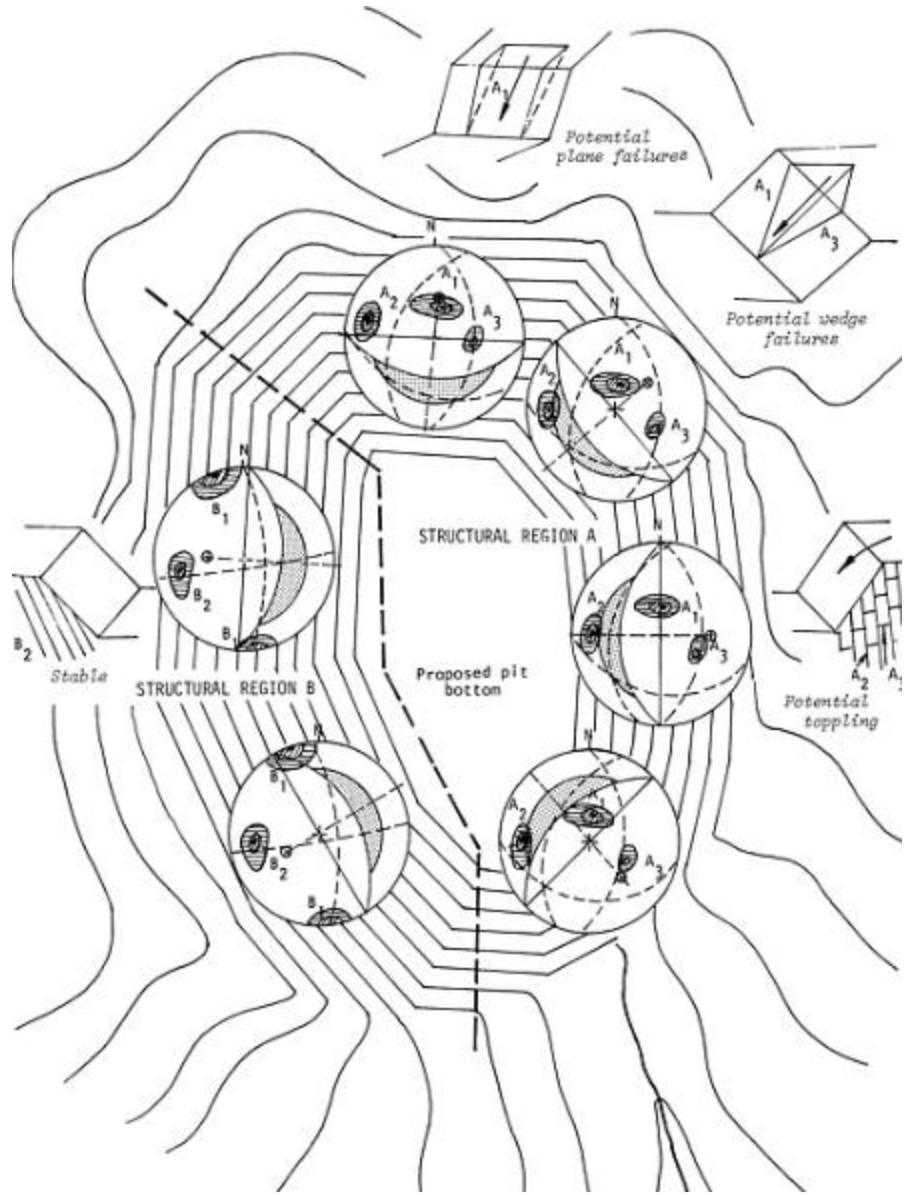


Plotting





Presentation of structural geology on stereonets, and preliminary evaluation of slope stability of proposed open pit mine.



LESSON PART 3

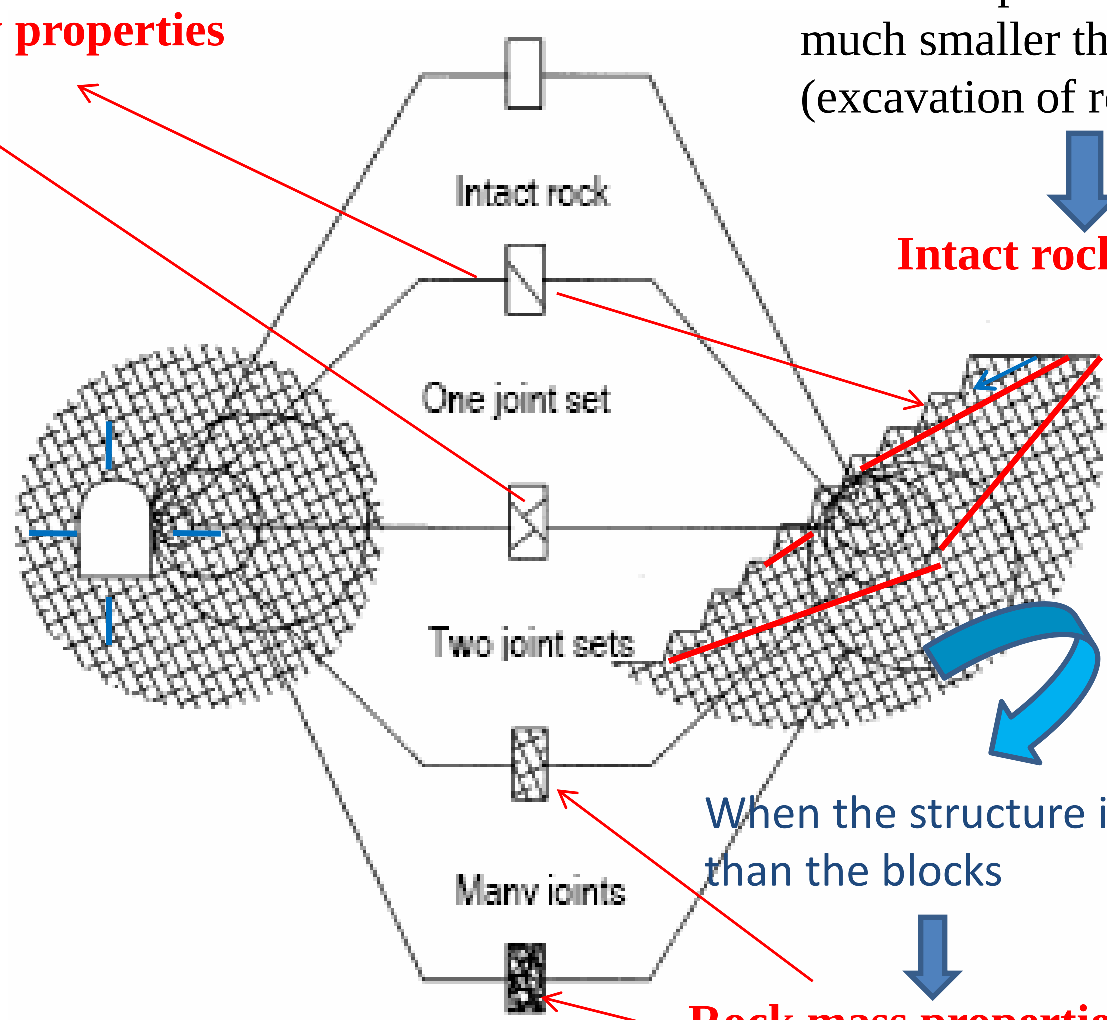
Uncertainty of Rocks

Relation of Discontinuity Spacing and Size of The Problem

When the problem domain is much smaller than rock blocks (excavation of rock by drilling)

Intact rock material

Discontinuity properties govern



When the structure is much larger than the blocks

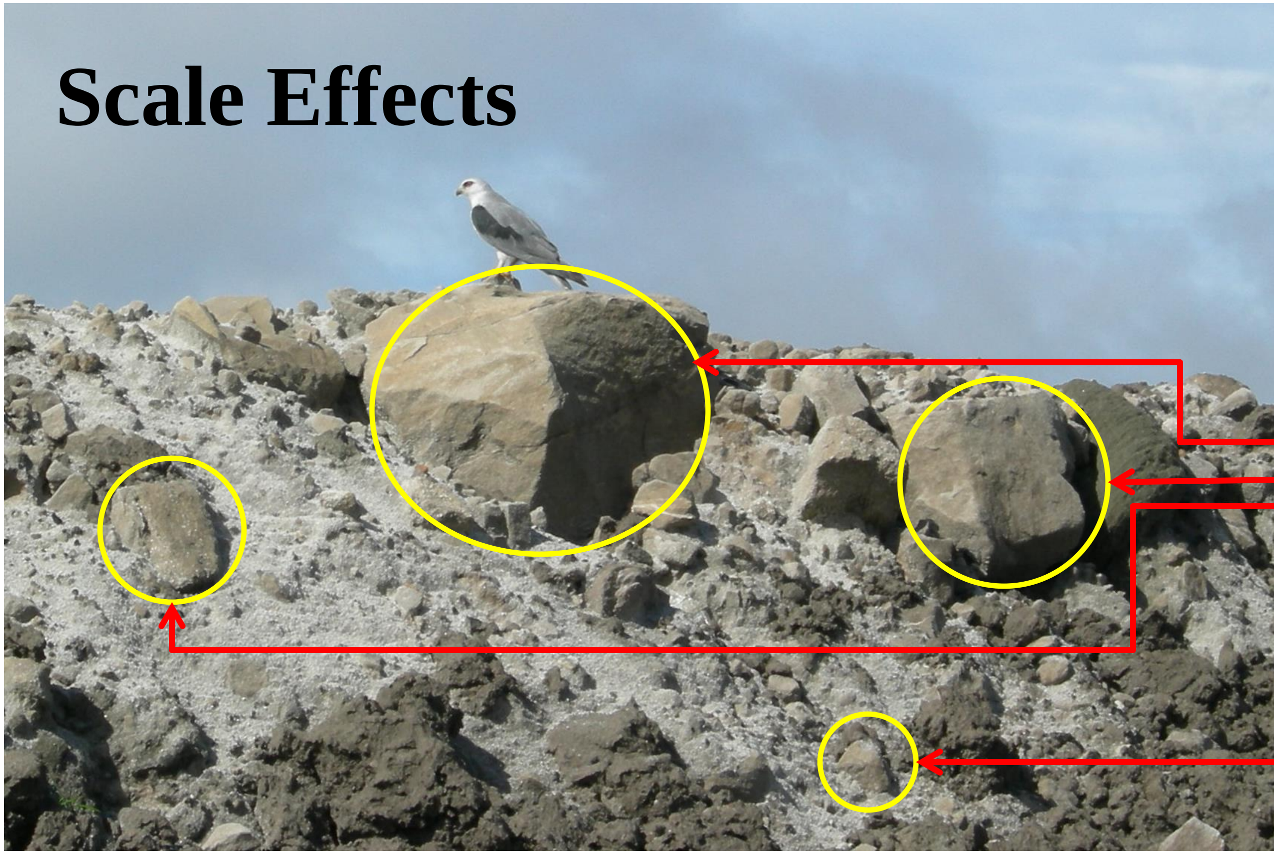
Rock mass properties

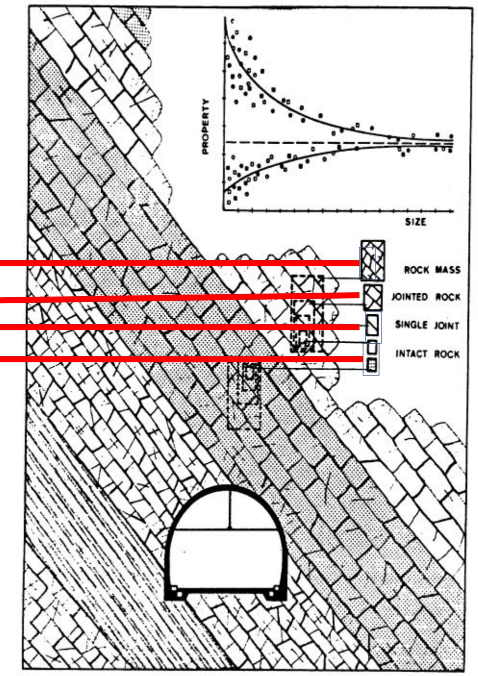
Uncertainty of Rocks

Intact rock

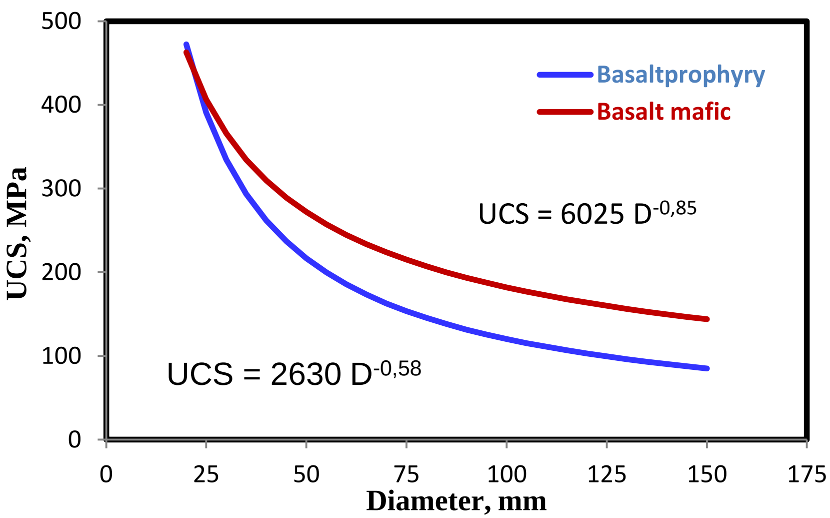
Uncertainty of Rocks

Scale Effects





Scale Effect (Cunha, 1990)



Influence of rock scale on igneous rock strength (Kramadibrata & Jones, 1993)

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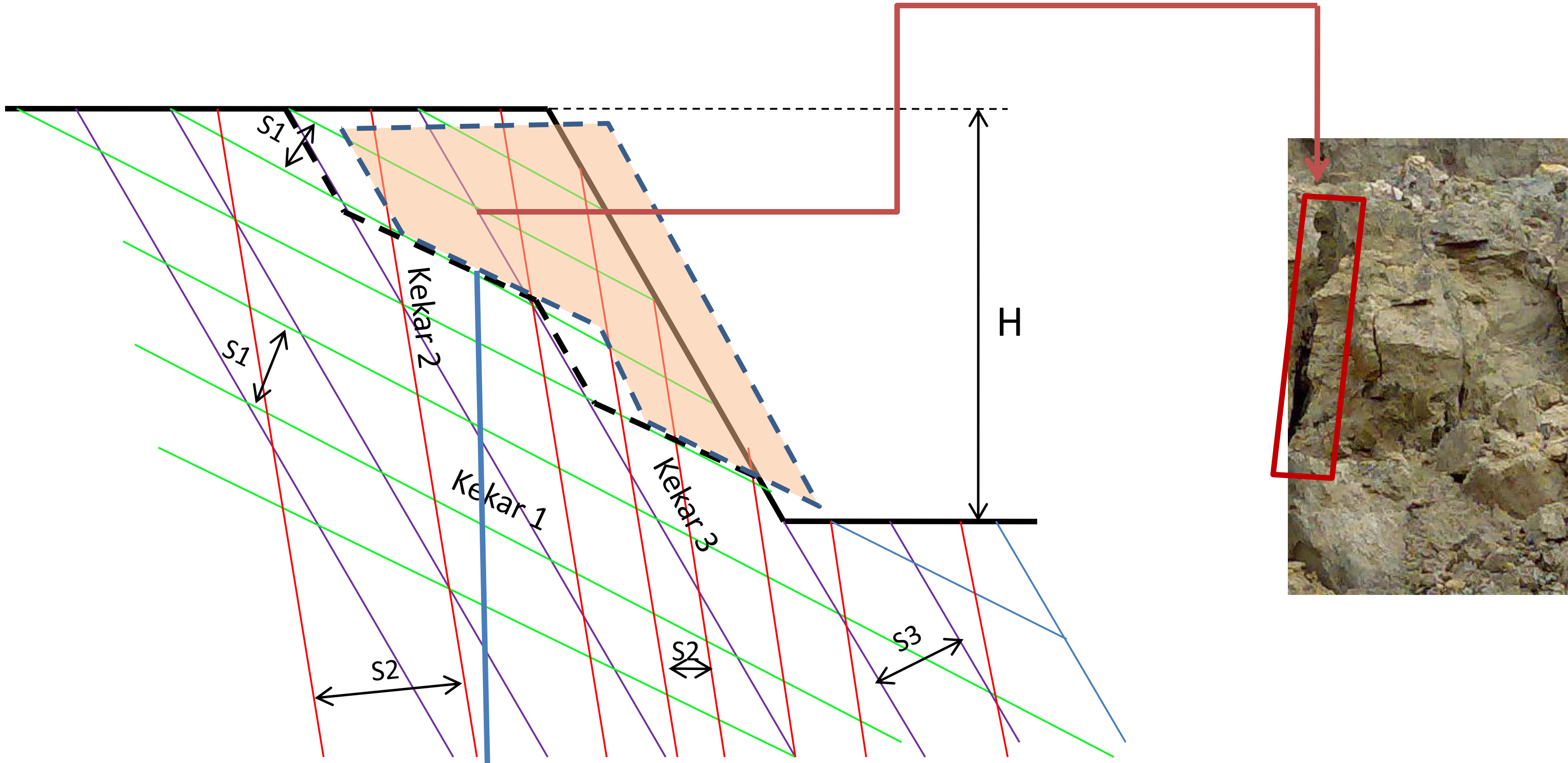
Individual slope failure

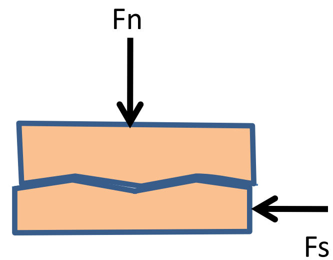
Individual slope rock mass failure due to joint and weather factors.

Individual slope mudstone failure on 22 Maret 2010 in Lowwall PIT RA , Height of slope = 12 m , α = 48^{o}
Some boulder exists between failures .

Influence of joint on failure mechanicsm



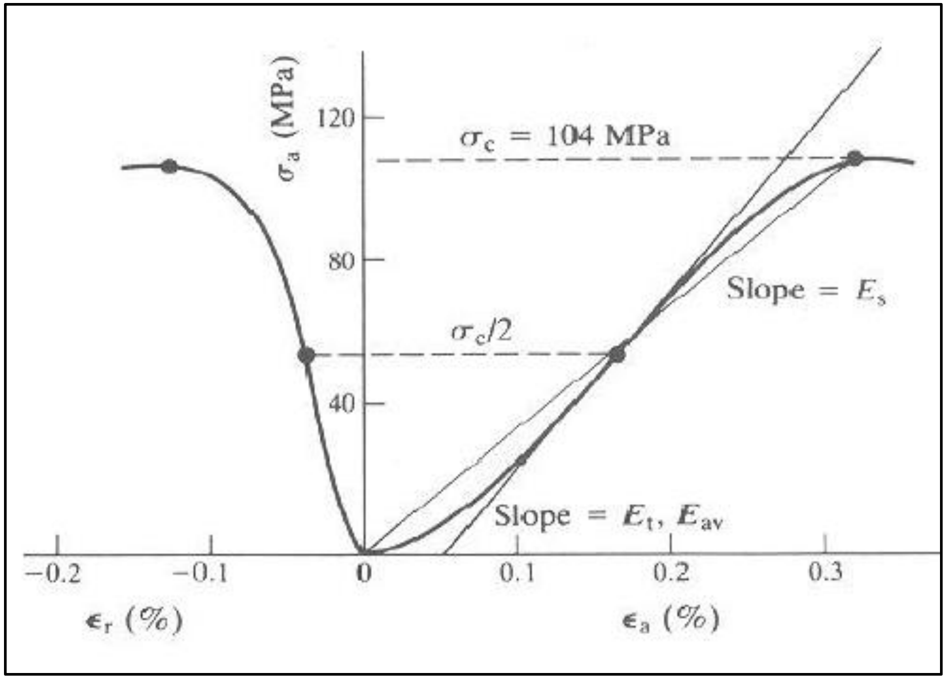
Where
S1 = Joint space 1
S2 = Joint space 2
S3 = Joint space 3



LESSON PART 4

Laboratory activity

UCS test



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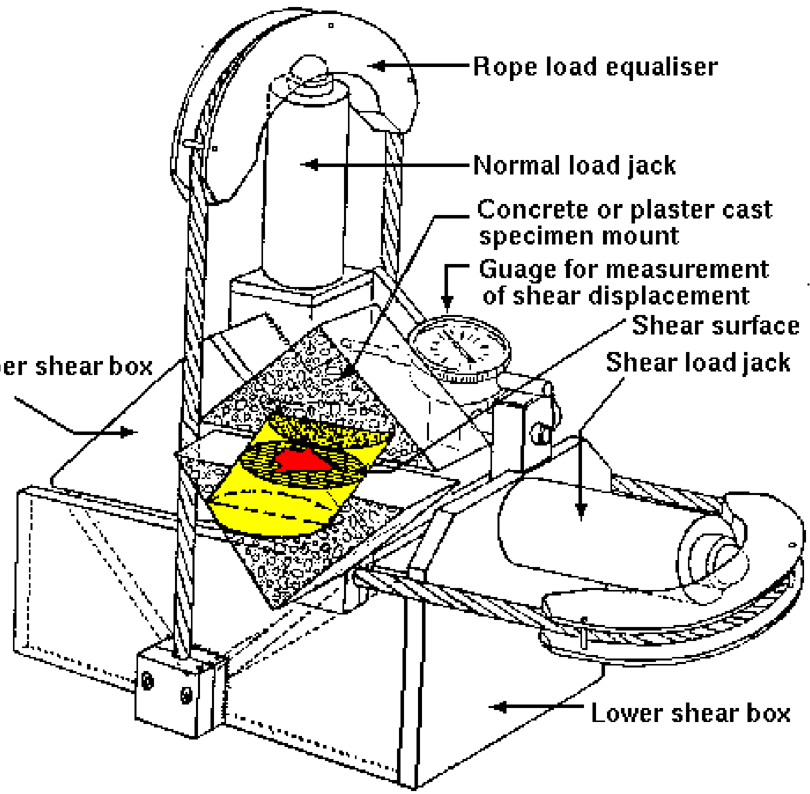
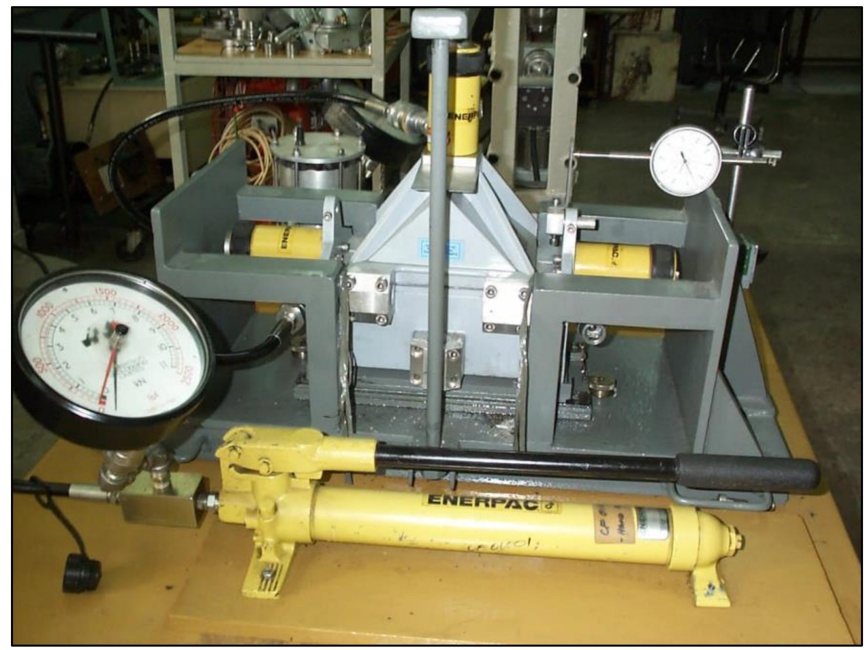
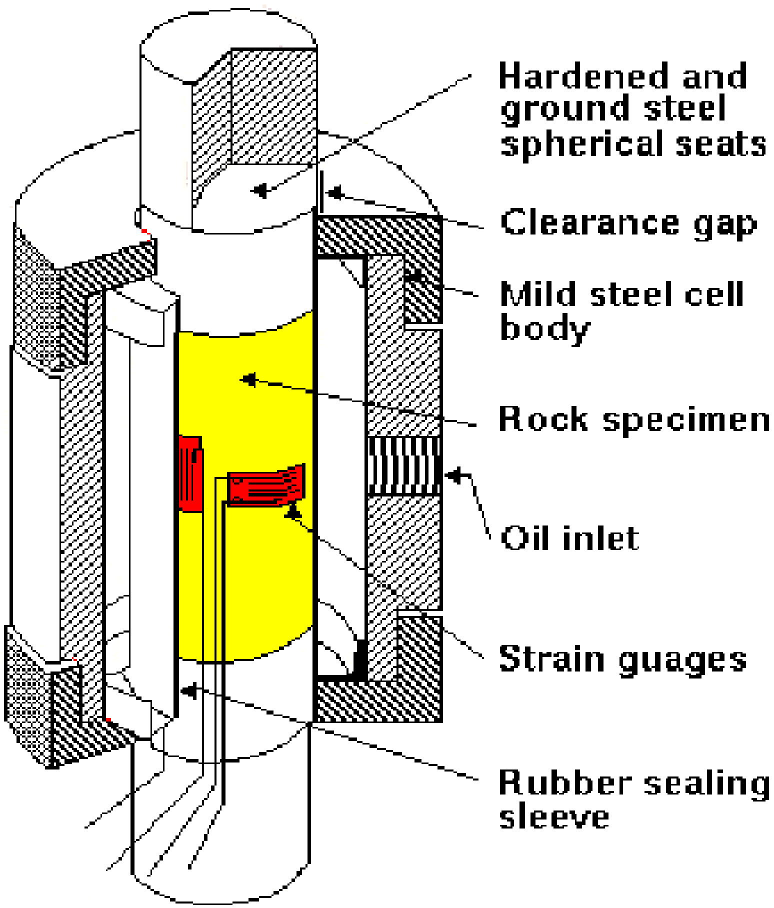
Direct Shear Test





Triaxial Test

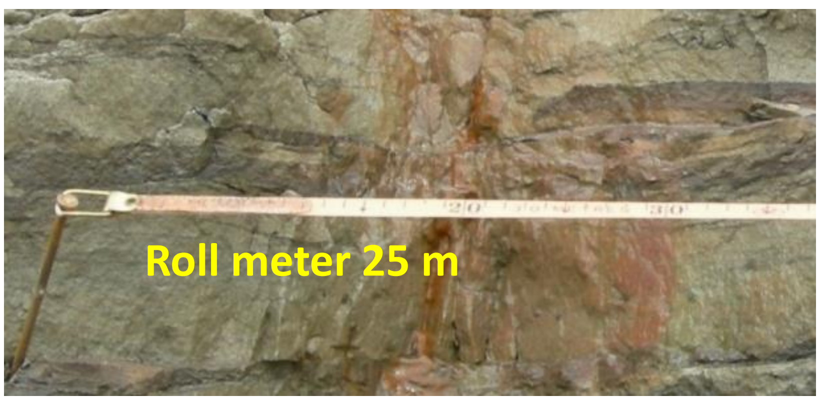


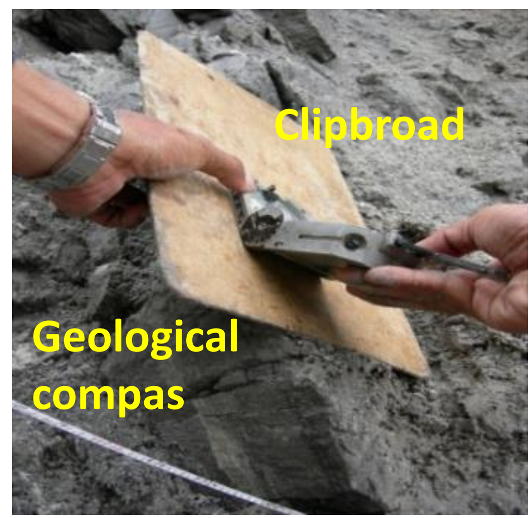
Triaxial test

Direct shear test for soil

Site Investigation

Joint Mapping Equipments

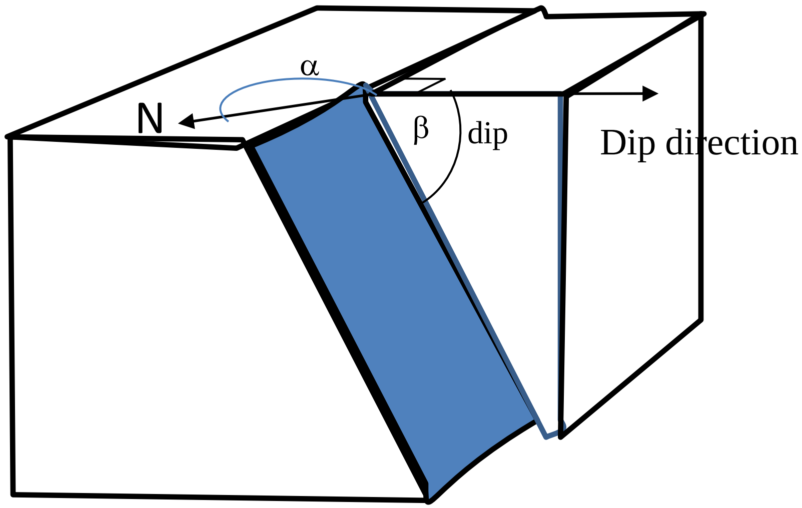




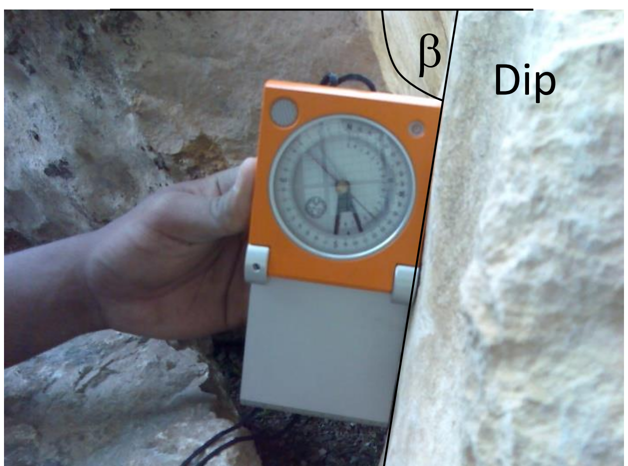
Pengukuran karakterisasi massa batuan

- Measurement of joint orientation using the compass geology and measured is the dip and dip direction,
- Measurements of the joint spacing use scanline method.
- Joint spacing procedure using a weighting system at the normal angle.

Determination of dip and dip direction



Dip direction
$\alpha + 90^{o}$



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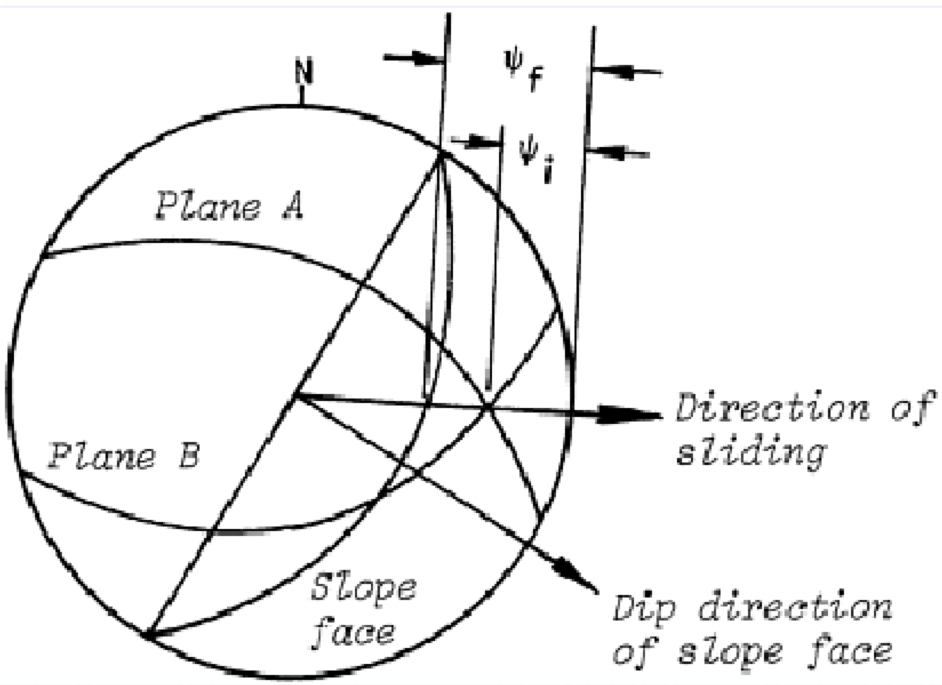
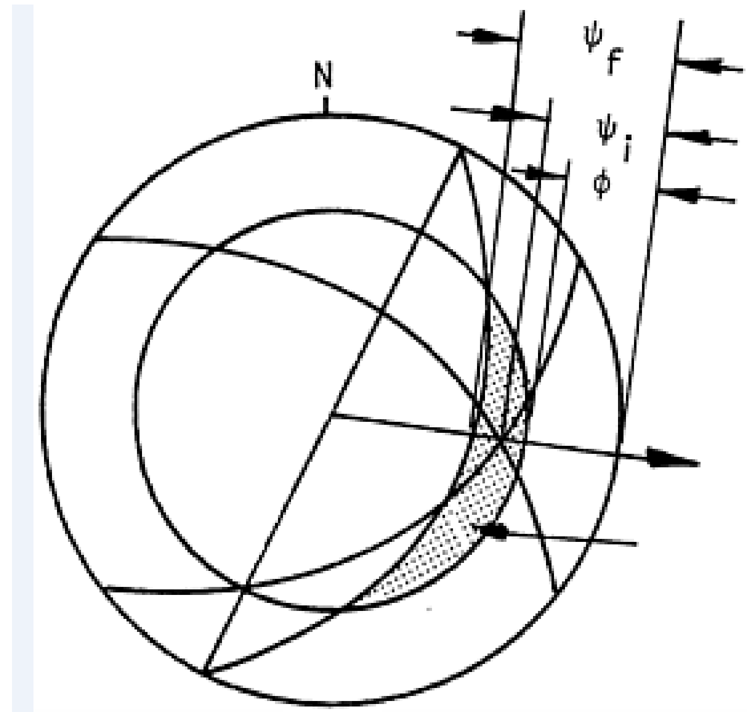
Slope Analysis of Joint orientation

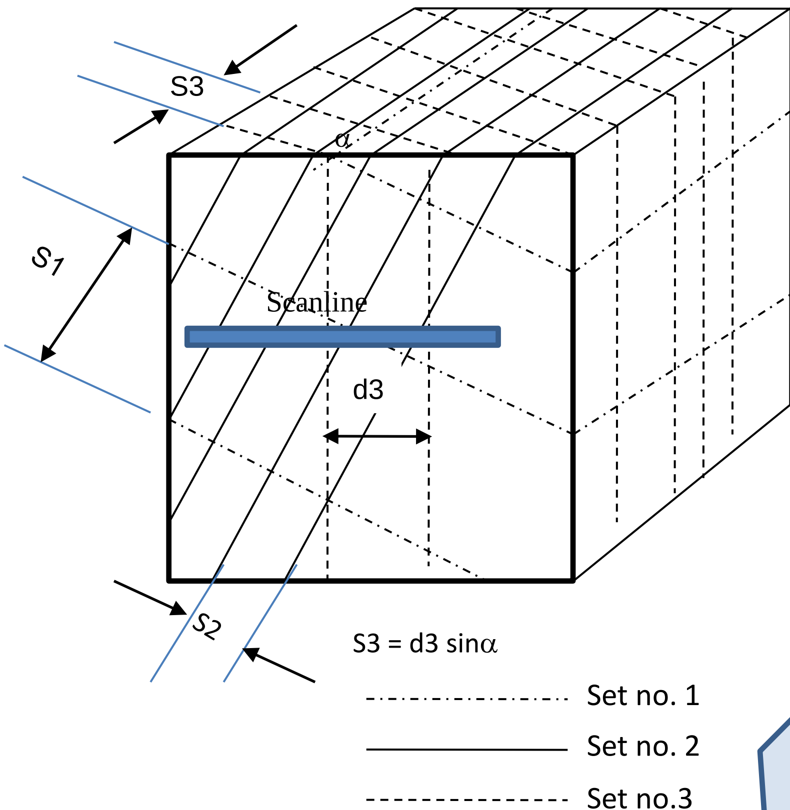


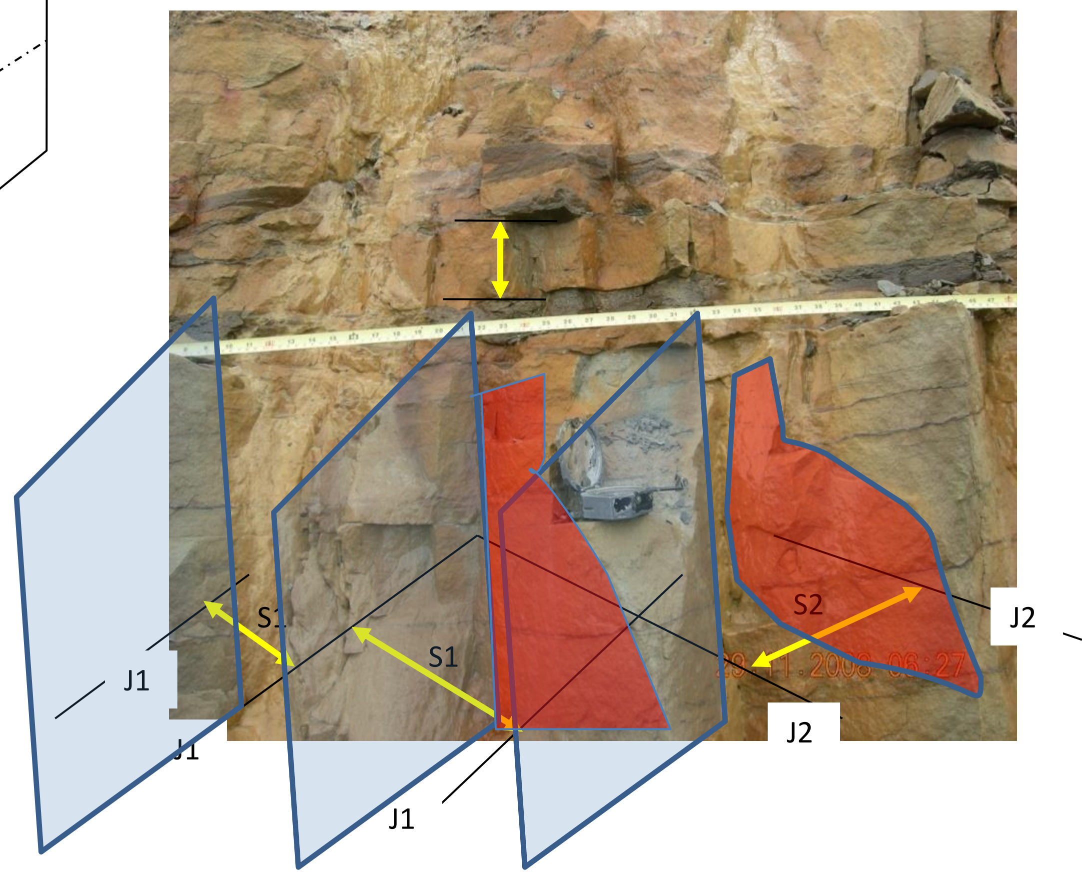


Procedure of joint mapping

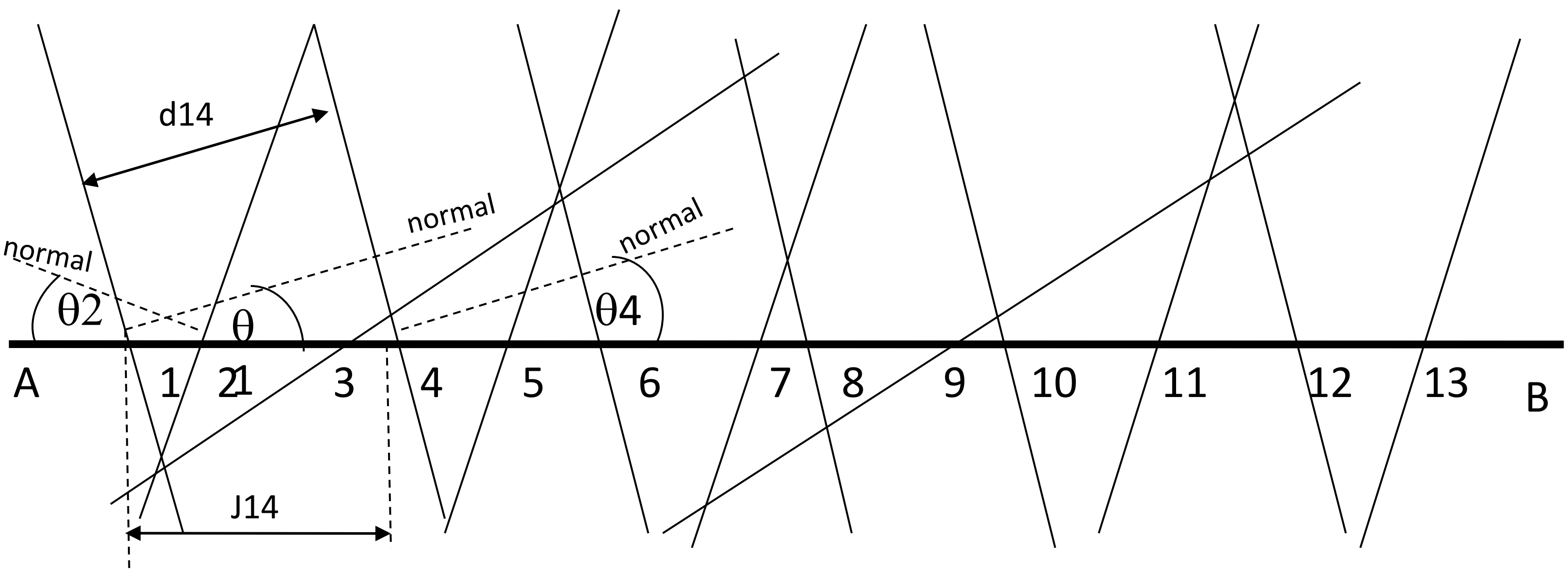
- Scanline have slope and direction
- Observer at eye level
- 10 times average joint spacing or minimum 30 m of length
- Variation of joint family
- Flatness of surface outcrops of rock masses
- Type of litology
- Seepage (Ground water condition)
- weathered
- Available of equipments

Spacing (ISRM, 1981)





Determine of joint spacing



SCANLINE

Correction factor on determination of joint spacing

- $\alpha f/\beta f$ = dip direction and dip of face
- $\alpha s/\beta s$ = dip direction and dip of scan line
- $\alpha d/\beta d$ = dip direction and dip of joint
- $\alpha n/\beta n$ = the normal of dip direction and dip of joint
- θ = normal angle of joint with scan line
- $\theta - \alpha$ = average of θ of familty joint A
- W = scoreTerzaghi factor = $1/\cos \theta$
- i-m = Number joints
- Ji-m = apparent of joint spacing for number of joint, im
- d(im)= joint spacing prediction or true joint spacing
- dxw = joint spacing average of family joint respectively
- sw = score of true joint sapcing average

Example, determine of average true joint spacing

		αf =195	βf =50		αs =285		βs =2										
bid diskont	Joint no.	αd o	βd o	Jarak Joint terukur, m	αn αd + 180	βn 90 - βd	cos(αn-αs)	cos βn	cos βs	sin βn	sin βs	abs[cos θ]	θ (o)	i-m	j_{i-m} m	$d_{(im)}$ m	d_{xw} m
A	1	75	61		255	29	0.87	0.87	1.00	0.48	0.03	0.77	39.29				
A	2	40	54	0.15	220	36	0.42	0.81	1.00	0.59	0.03	0.36	68.76	1 - 2	0.15	0.09	
A	3	18	32	0.22	198	58	0.05	0.53	1.00	0.85	0.03	0.06	86.71	2 - 3	0.22	0.05	
A	4	50	80	0.50	230	10	0.57	0.98	1.00	0.17	0.03	0.57	55.21	3 - 4	0.50	0.16	
A	5	45	89	0.13	225	1	0.50	1.00	1.00	0.02	0.03	0.50	59.98	4 - 5	0.13	0.07	
B	48	136	75		316	15	0.86	0.97	1.00	0.26	0.03	0.84	33.23			A	0.18
B	49	152	85	0.30	332	5	0.68	1.00	1.00	0.09	0.03	0.68	47.00	48 - 49	0.30	0.23	
B	50	145	58	0.25	325	32	0.77	0.85	1.00	0.53	0.03	0.67	48.11	49 - 50	0.25	0.17	
B	51	150	60	0.20	330	30	0.71	0.87	1.00	0.50	0.03	0.63	50.99	50 - 51	0.20	0.13	
B	52	105	80	0.20	285	10	1.00	0.98	1.00	0.17	0.03	0.99	8.00	51 - 52	0.20	0.17	
C	78	215	63		35	27	-0.34	0.89	1.00	0.45	0.03	0.29	73.22			B	0.31
C	79	232	82	0.50	52	8	-0.60	0.99	1.00	0.14	0.03	0.59	53.79	78 - 79	0.50	0.22	
C	80	208	66	0.15	28	24	-0.22	0.91	1.00	0.41	0.03	0.19	78.98	79 - 80	0.15	0.06	
C	81	221	56	0.42	41	34	-0.44	0.83	1.00	0.56	0.03	0.34	69.90	80 - 81	0.42	0.11	
C	82	196	47	0.27	16	43	-0.02	0.73	1.00	0.68	0.03	0.01	89.37	81 - 82	0.27	0.05	
D	116	274	50		94	40	-0.98	0.77	1.00	0.64	0.03	0.73	43.19			C	0.21
D	117	320	48	0.20	140	42	-0.82	0.74	1.00	0.67	0.03	0.59	54.20	116 - 117	0.20	0.13	
D	118	334	60	0.16	154	30	-0.66	0.87	1.00	0.50	0.03	0.55	56.61	117 - 118	0.16	0.09	
D	119	334	38	0.40	154	52	-0.66	0.62	1.00	0.79	0.03	0.38	67.90	118 - 119	0.40	0.19	
																C	0.27
		teta-A =	63.33		w-A =	2.23											
		teta-B =	45.27		w-B =	1.42									0.44	dsw	0.24
		teta-C =	63.01		w-C =	2.20											
		teta-D =	48.80		w-D =	1.52											

where :

$\cos\theta$ = abs $[\cos(\alpha n - \alpha s)\cos\beta n \cos\beta s + \sin\beta n \sin\beta s]$

αs = dip direction of scanline

βs = dip of scanline

αd = dip direction of joint

βd = dip of joint

$\alpha d < 180$, $\alpha n = \alpha d + 180$

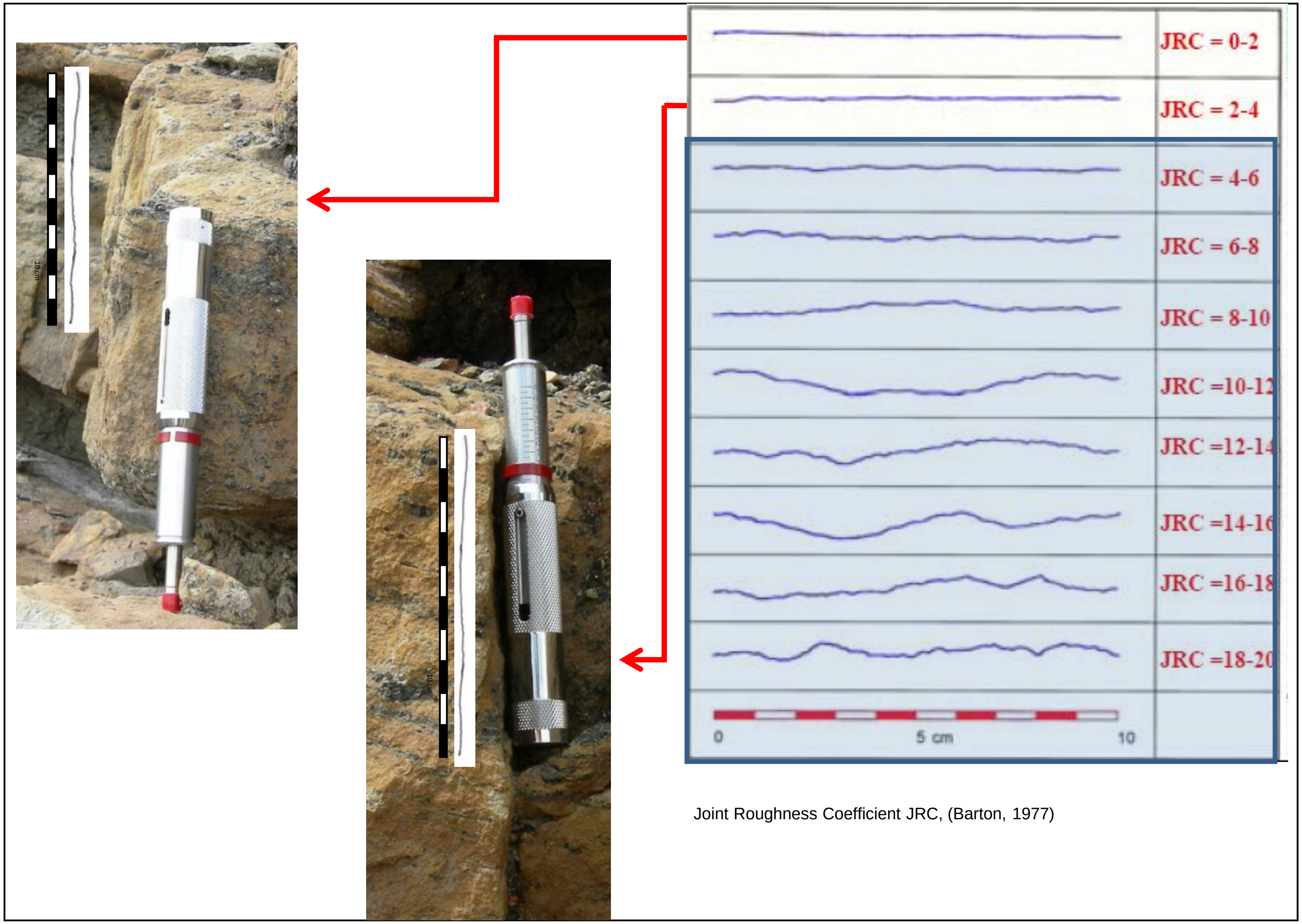
$\alpha d > 180$, $\alpha n = \alpha d - 180$

βn , $\beta n = 90 - \beta d$

RQD of joint mapping from scanline method is

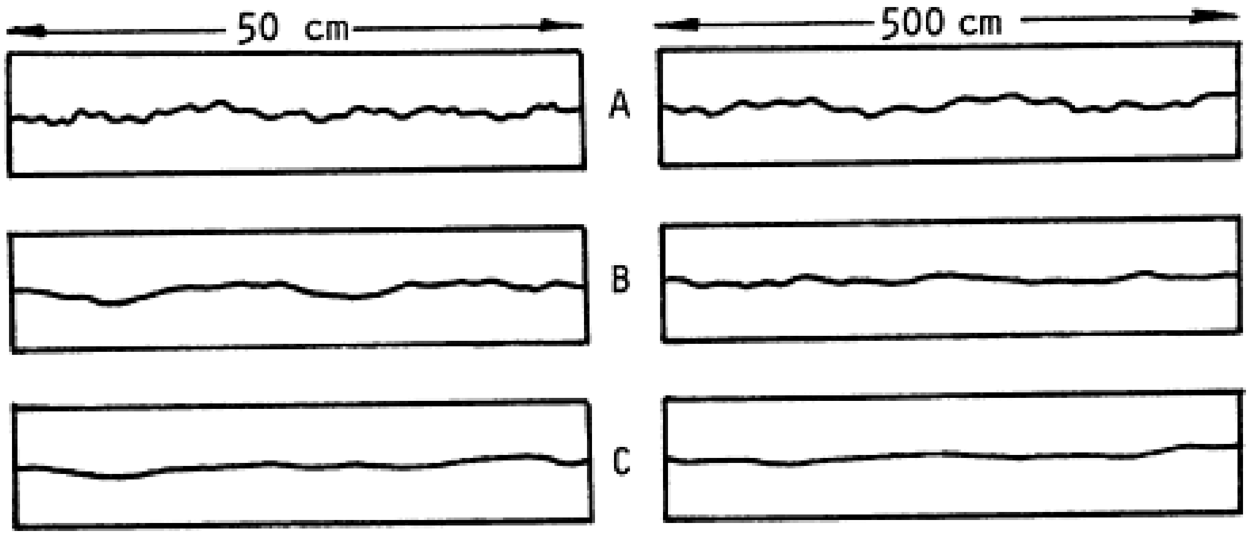
Joint spacing family A	= 0.18 m
Joint spacing family B	= 0.31 m
Joint spacing family C	= 0.21 m
Joint spacing family D	= 0.27 m
True joint spacing	= 0.24 m
frequency of joint, λ= 1/spacing	= 4.17 joints/m
RQD, $RQD = 100\, e^{-0.1\lambda}(0.1\lambda + 1)$	= 93.38%

Method of joint roughness (JRC)



Joint Roughness Coefficient JRC, (Barton, 1977)

EXAMPLES OF ROUGHNESS PROFILES



A.	Rough undulating - tension joints, rough sheeting, rough bedding.	JRC = 20
B.	Smooth undulating - smooth sheeting, non-planar foliation, undulating bedding.	JRC = 10
C.	Smooth nearly planar - planar shear joints, planar foliation, planar bedding.	JRC = 5

The equipment of Joint Compressive Strength

Persistence

- Persistence – discontinuity trace lengtg as observed in an exposure. May gave a crude measure of the areal extent or penetration length of a dicontinuity.

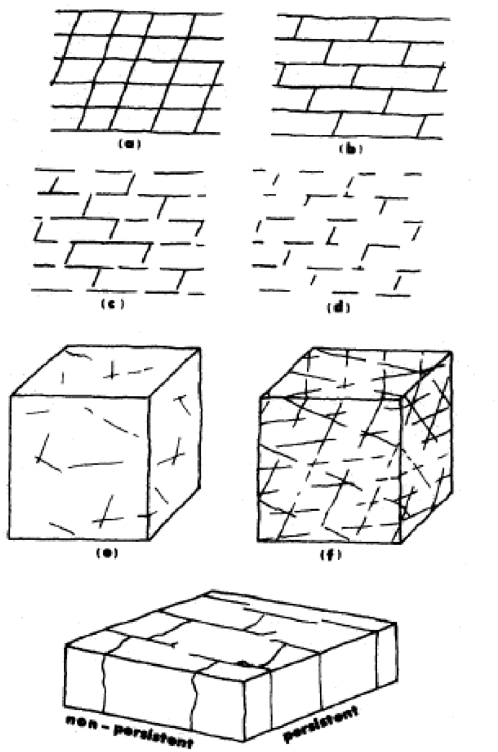
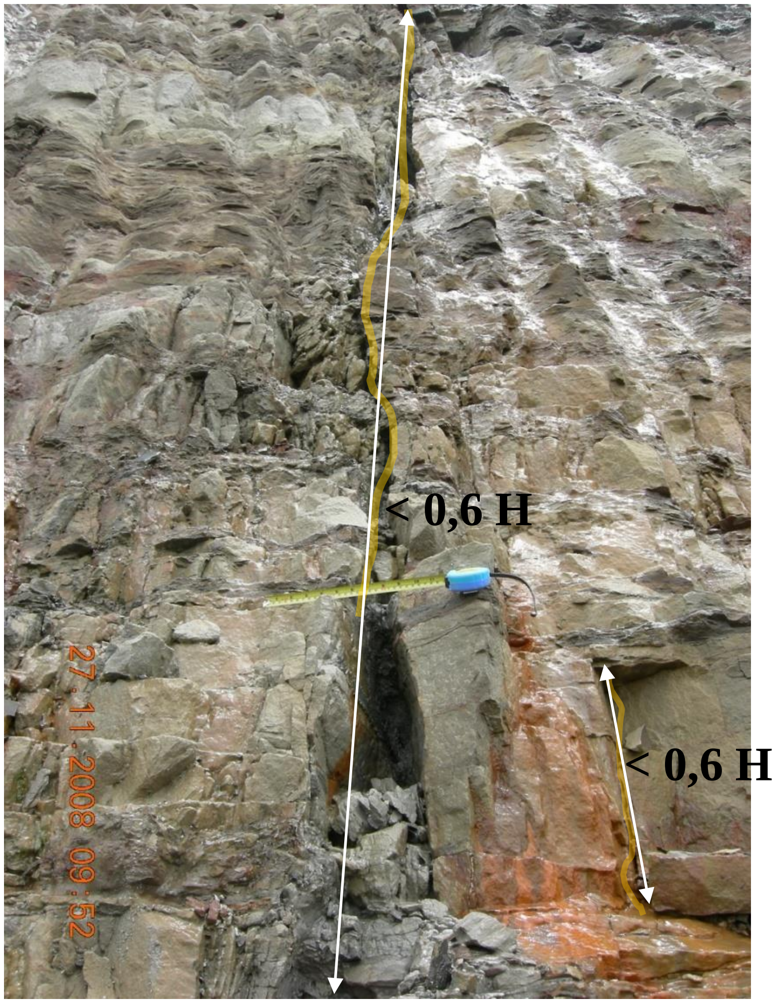


Fig. 12. Simple sketches and block diagrams help to indicate the relative *persistence* of the various sets of discontinuities. Examples adapted from [1] and [2].



Weathering

- Determined of weathering with metode Manual index test, yaitu (ISRM, 1981; Hencer and Martin, 1982)

  - Fresh
  - Slightly weathered (Schmidt Rebound “N” > 45)
  - Moderately weathered (25 < “N” < 45)
  - Highly weathered (“N” < 25)
  - Completed weathered (< 250 kPa)
  - Residual soil

Apperture of joint

- Aperture - perpendicular distance between adjacent rock walls of a discontinuity, in which the interbeing sapce is air or water filled.

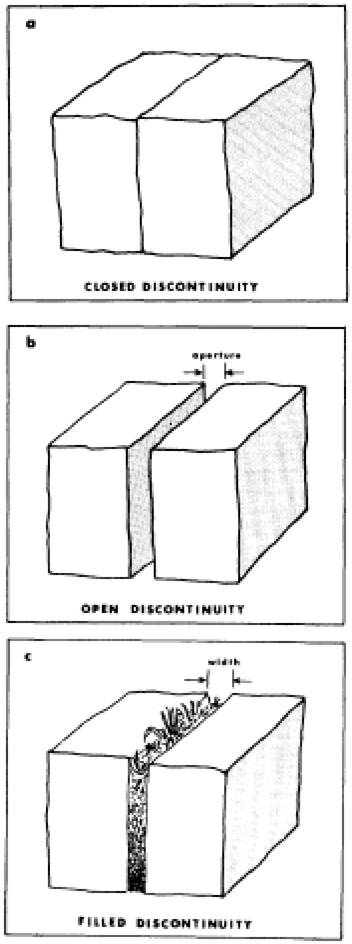
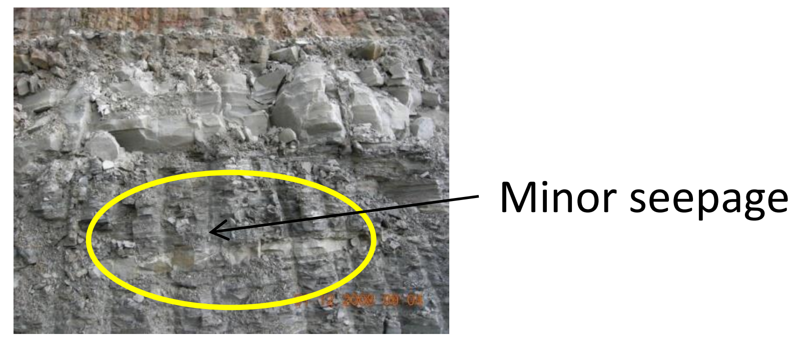


Fig. 21. Diagrams showing the suggested definitions of the aperture of open discontinuities and the width of filled discontinuities.

Seepage condition

Condition	Description
I	Dry walls and roof
II	Minor seepage
III	Medium inflow
IV	Mayor inflow
V	Exceptionally high inflow



LESSON PART 5

Slope Stability Analysis

Plane Failure

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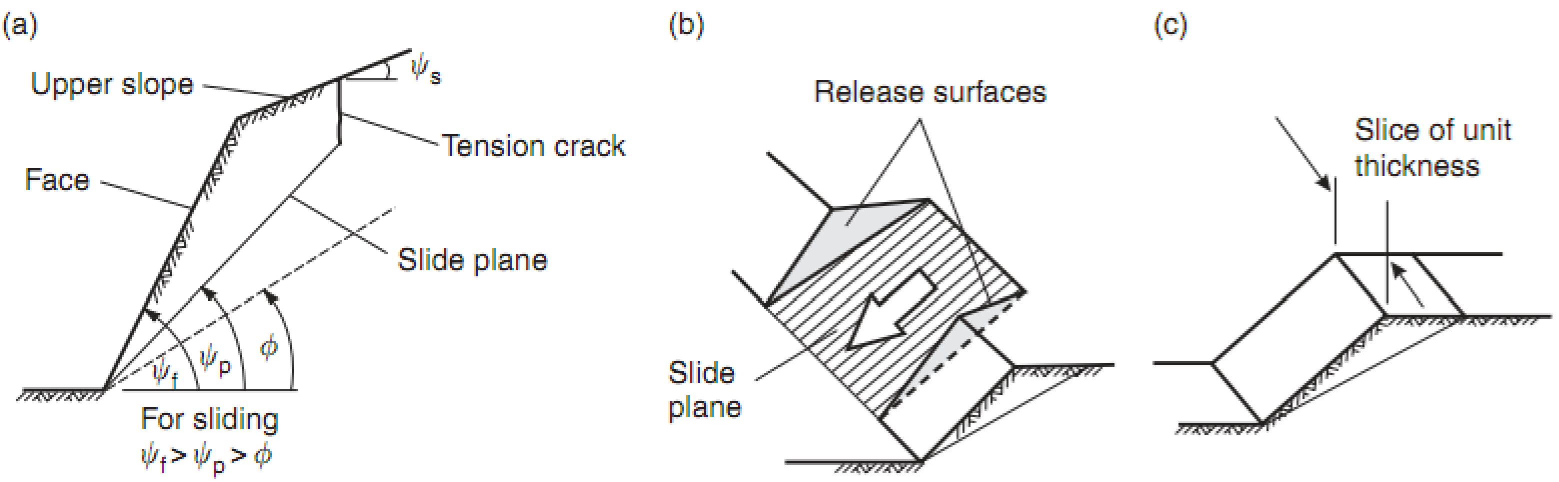

Figure 6.2 Geometry of slope exhibiting plane failure: (a) cross-section showing planes forming a plane failure; (b) release surfaces at ends of plane failure; (c) unit thickness slide used in stability analysis.

The following assumptions are made in plane failure analysis:

1. Both sliding surface and tension crack strike parallel to the slope.
2. The tension crack is vertical and is filled with water to a depth zw.
3. Water enters the sliding surface along the base of the tension crack and seeps along the sliding surface, escaping at atmospheric pressure where the sliding surface daylights in the slope face. The pressure distributions induced by the presence of water in the tension crack and along the sliding surface are illustrated in Figure.
4. The forces W (the weight of the sliding block), U (uplift force due to water pressure on the sliding surface) and V (force due to water pressure in the tension crack) all act through the centroid of the sliding mass. In other words, it is assumed that there are no moments that would tend to cause rotation of the block, and hence failure is by sliding only. While this assumption may no be strictly true for actual slopes, the errors introduced by ignoring moments are small enough to neglect. However, in steep slopes with steeply dipping discontinuities, the possibility of toppling failure should be kept in mind.

5. The shear strength τ of the sliding surface is defined by cohesion c and friction angle ϕ that are related by the equation

   $\tau = c + \sigma \tan \phi$. In the case of a rough surface or a rock mass having a curvilinear shear strength envelope, the apparent cohesion and apparent friction angle are defined by a tangent that takes into account the normal stress acting on the sliding surface. The normal stress σ acting on a sliding surface can be determined from the curves given in Figure. It is assumed that release surfaces are present so that there is no resistance to sliding at the lateral boundaries of the failing rock mass (Figure (b)).
5. In analyzing two-dimensional slope problems, it is usual to consider a slice of unit thickness taken at right angles to the slope face. This means that on a vertical section through the slope, the area of the sliding surface can be represented by the length of the surface, and the volume of the sliding block is represented by the cross-section area of the block (Figure (c)).

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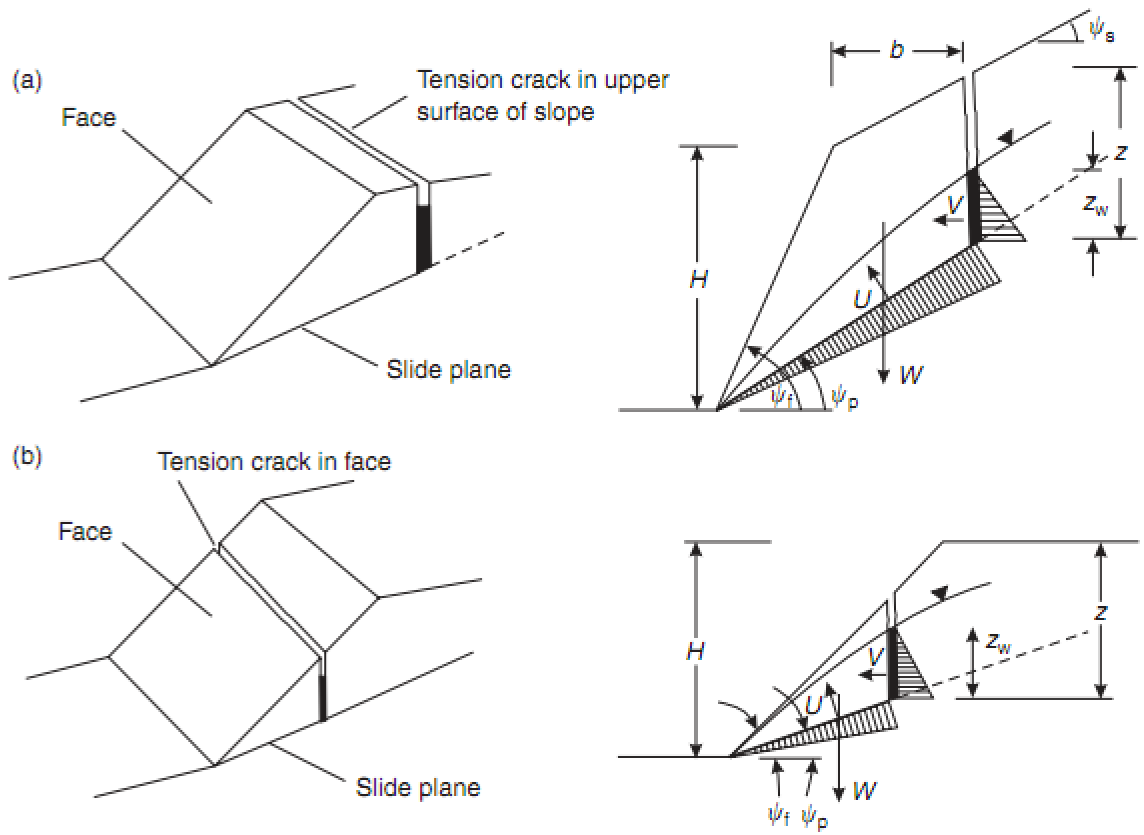
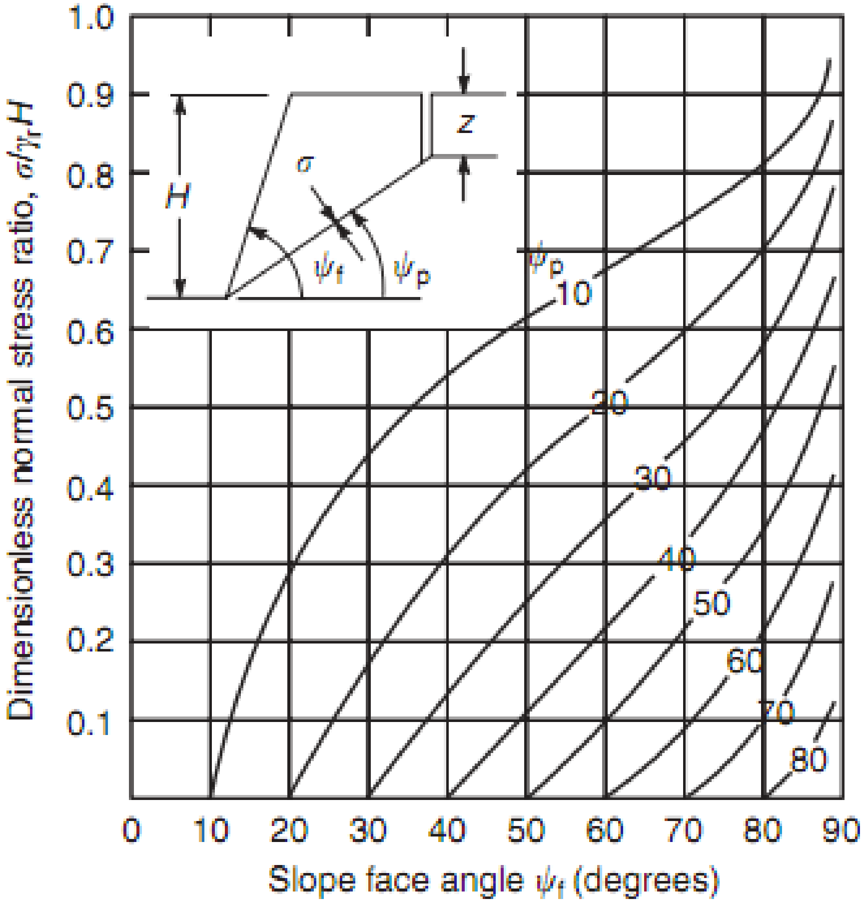
Geometries of plane slope failure: (a) tension crack in the upper slope; (b) tension crack in the face





$$\frac{\sigma}{\gamma_r H} = \frac{[(1-(z/H)^2)\cot\psi_p - \cot\psi_f]\sin\psi_p}{2(1-z/H)}$$

where $z/H = 1-(\cot\psi_f \tan\psi_p)^{1/2}$, and $\psi_s = 0$

$$\mathrm{FS} = \frac{\text{Resisting force}}{\text{Driving force}} = \frac{cA + \sum N \tan\phi}{\sum S}$$

$$\mathrm{FS} = \frac{cA + (W\cos\psi_p - U - V\sin\psi_p)\tan\phi}{W\sin\psi_p + V\cos\psi_p}$$

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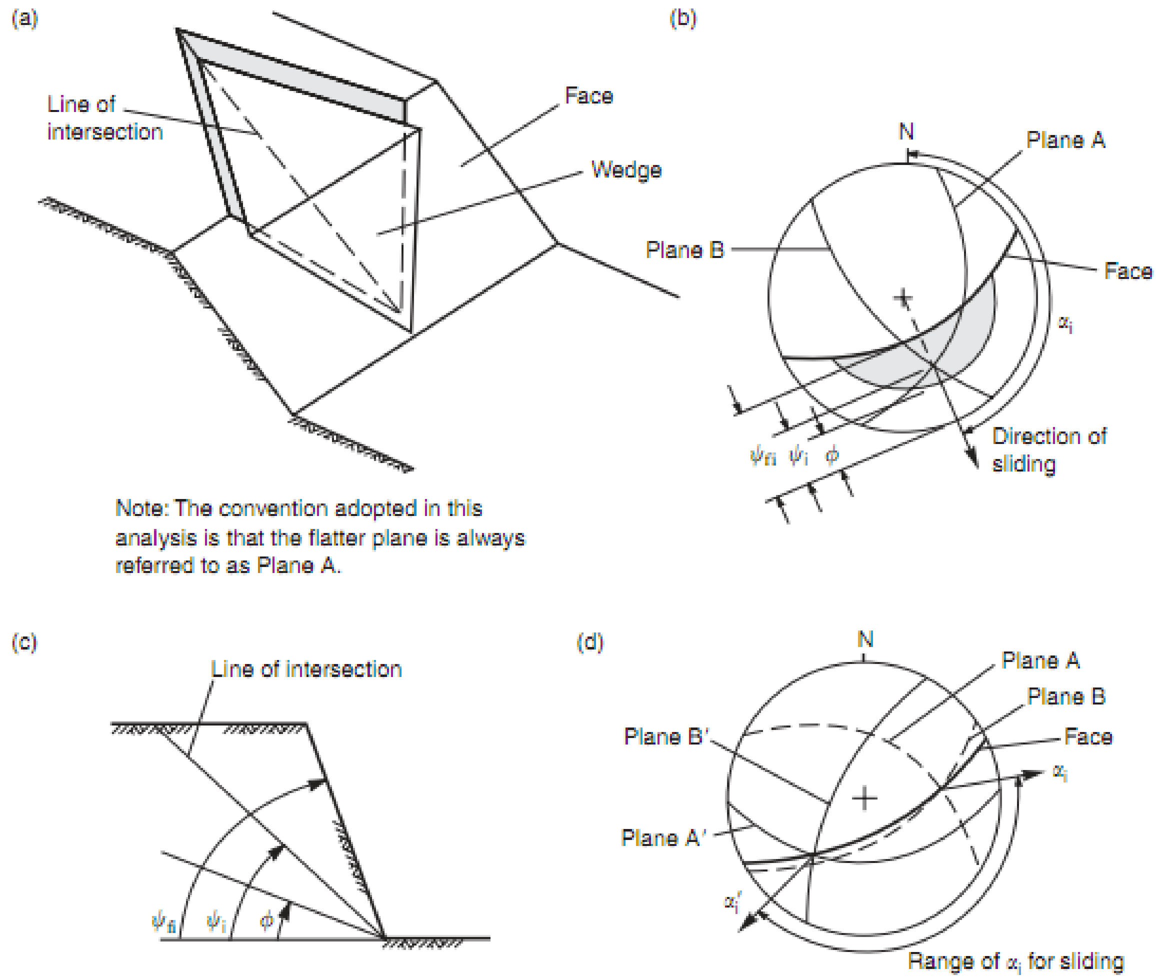
Wedge failure


(a)
Line of intersection
Face
Wedge
Note: The convention adopted in this analysis is that the flatter plane is always referred to as Plane A.
(b)
N
Plane A
Plane B
Face
α_i
ψ_{fi} ψ_i ϕ
Direction of sliding
(c)
Line of intersection
ψ_{fi}
ψ_i
ϕ
(d)
N
Plane A
Plane B
Face
Plane B′
Plane A′
α_i
α_i'
Range of α_i for sliding

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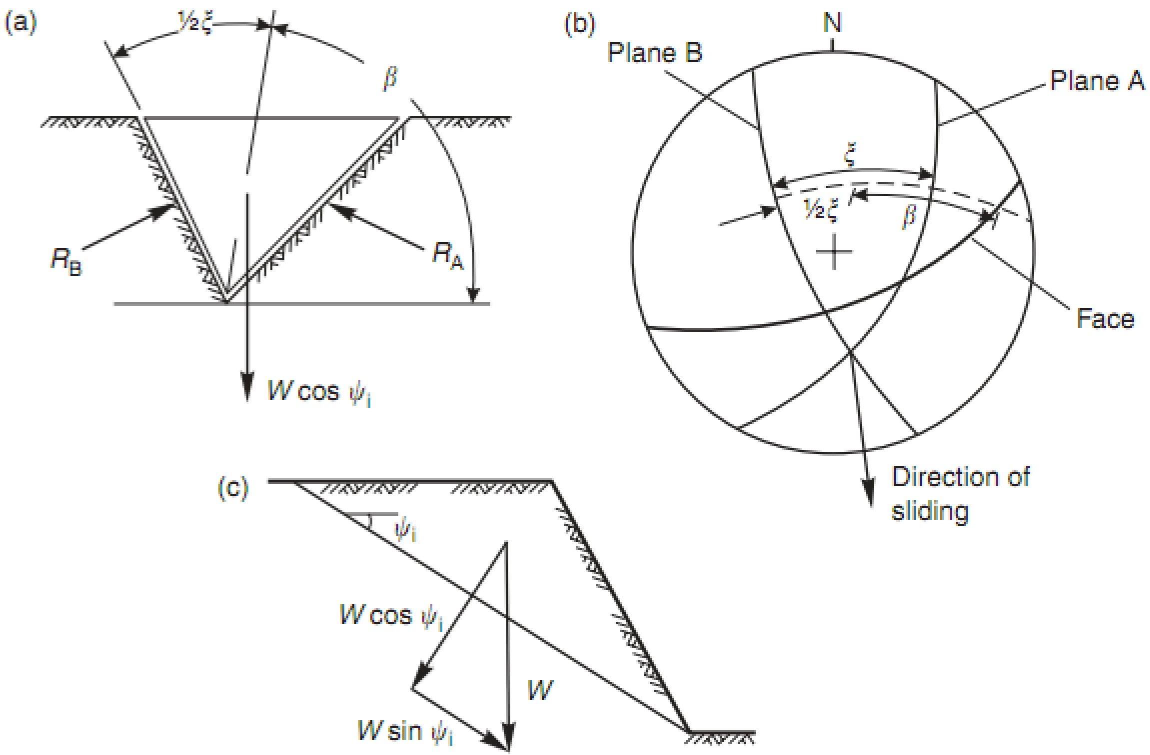


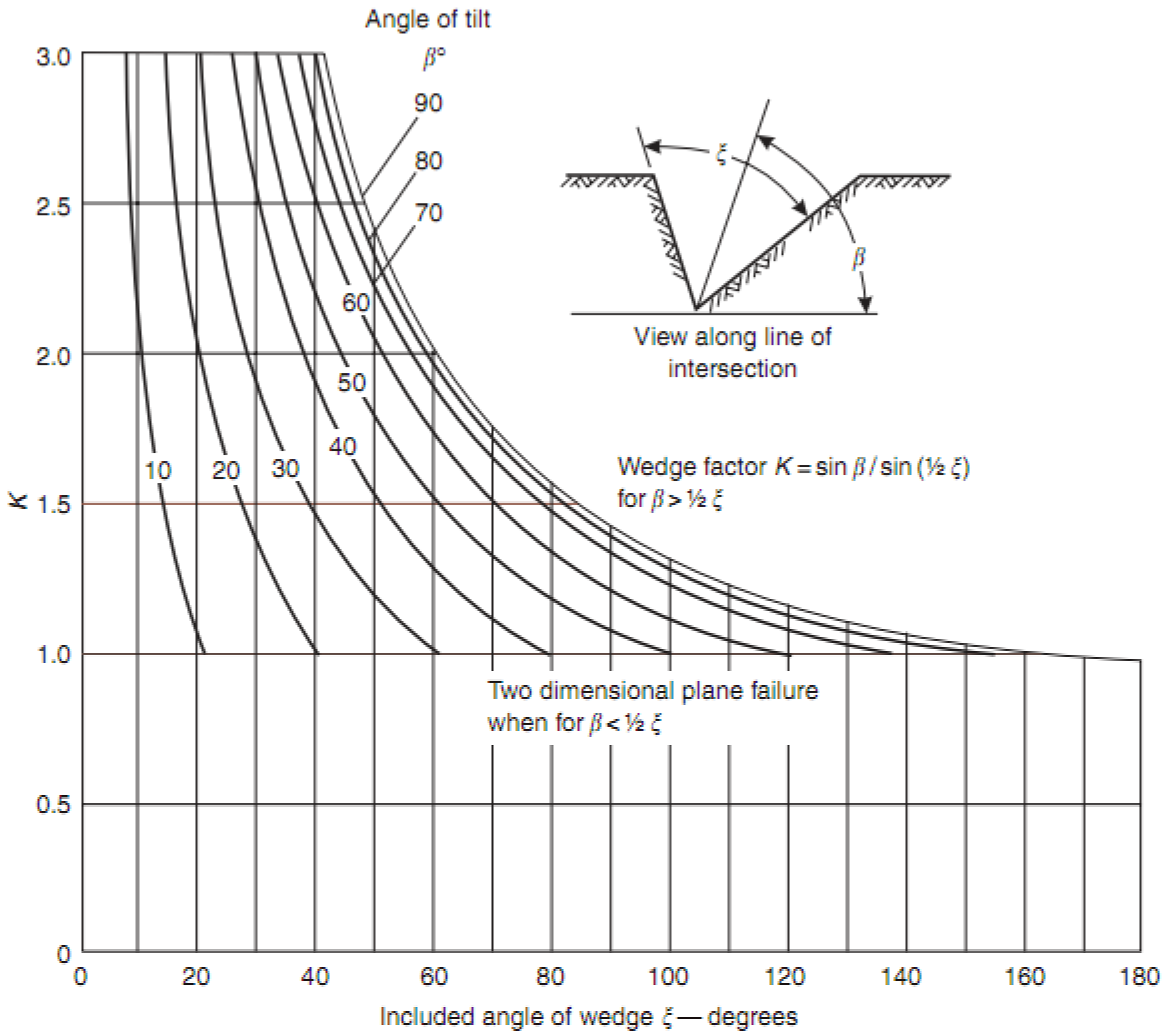
$$FS = \frac{(R_A + R_B)\tan\phi}{W\sin\psi_i}$$

$$R_A + R_B = \frac{W\cos\psi_i\sin\beta}{\sin(\xi/2)}$$

$$FS = \frac{\sin\beta}{\sin(\xi/2)} \cdot \frac{\tan\phi}{\tan\psi_i}$$

$$FS_W = KFS_P$$

Wedge factor K as a function of wedge geometry



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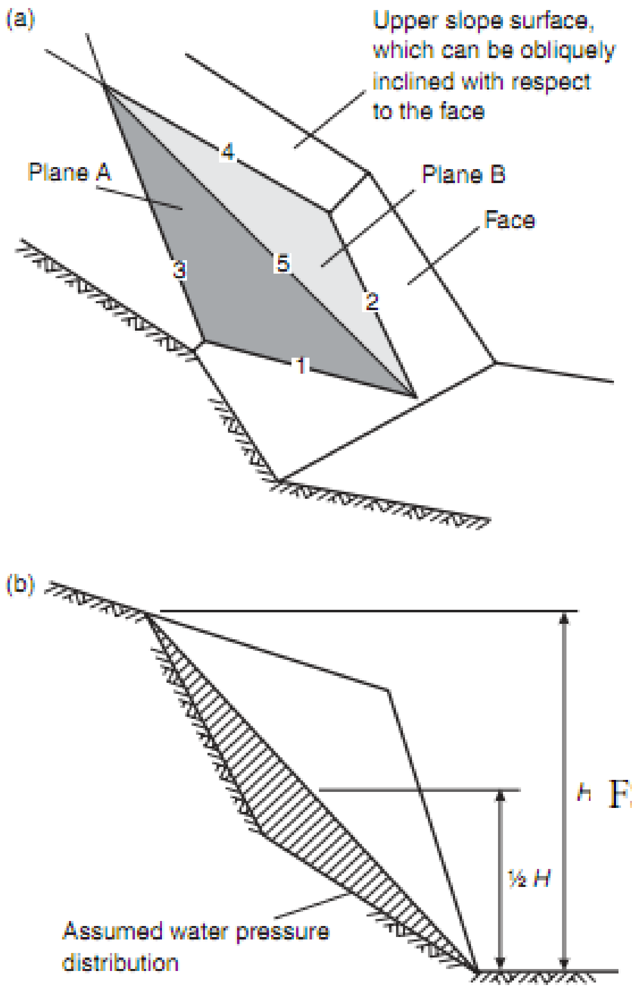


$$X = \frac{\sin \theta_{24}}{\sin \theta_{45} \cos \theta_{2.na}}$$

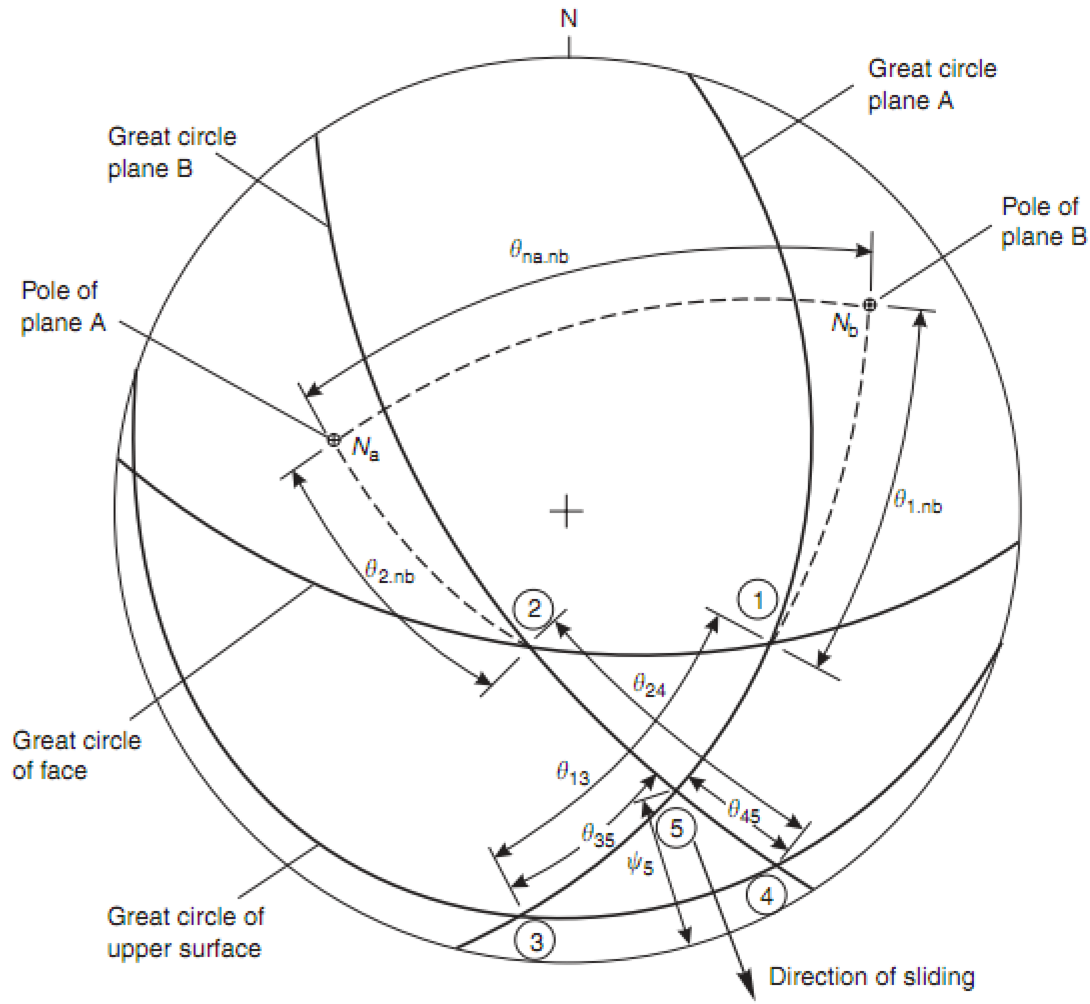
$$Y = \frac{\sin \theta_{13}}{\sin \theta_{35} \cos \theta_{1.nb}}$$

$$A = \frac{\cos \psi_a - \cos \psi_b \cos \theta_{na.nb}}{\sin \psi_5 \sin^2 \theta_{na.nb}}$$

$$B = \frac{\cos \psi_b - \cos \psi_a \cos \theta_{na.nb}}{\sin \psi_5 \sin^2 \theta_{na.nb}}$$

$$\text{FS} = \frac{3}{\gamma_r \text{H}}(c_A X + c_B Y) + \left(A - \frac{\gamma_w}{2\gamma_r} X\right) \tan \phi_A + \left(B - \frac{\gamma_w}{2\gamma_r} Y\right) \tan \phi_B$$

Stereoplot of data required for wedge stability analysis



LESSON PART 6

Circular failure

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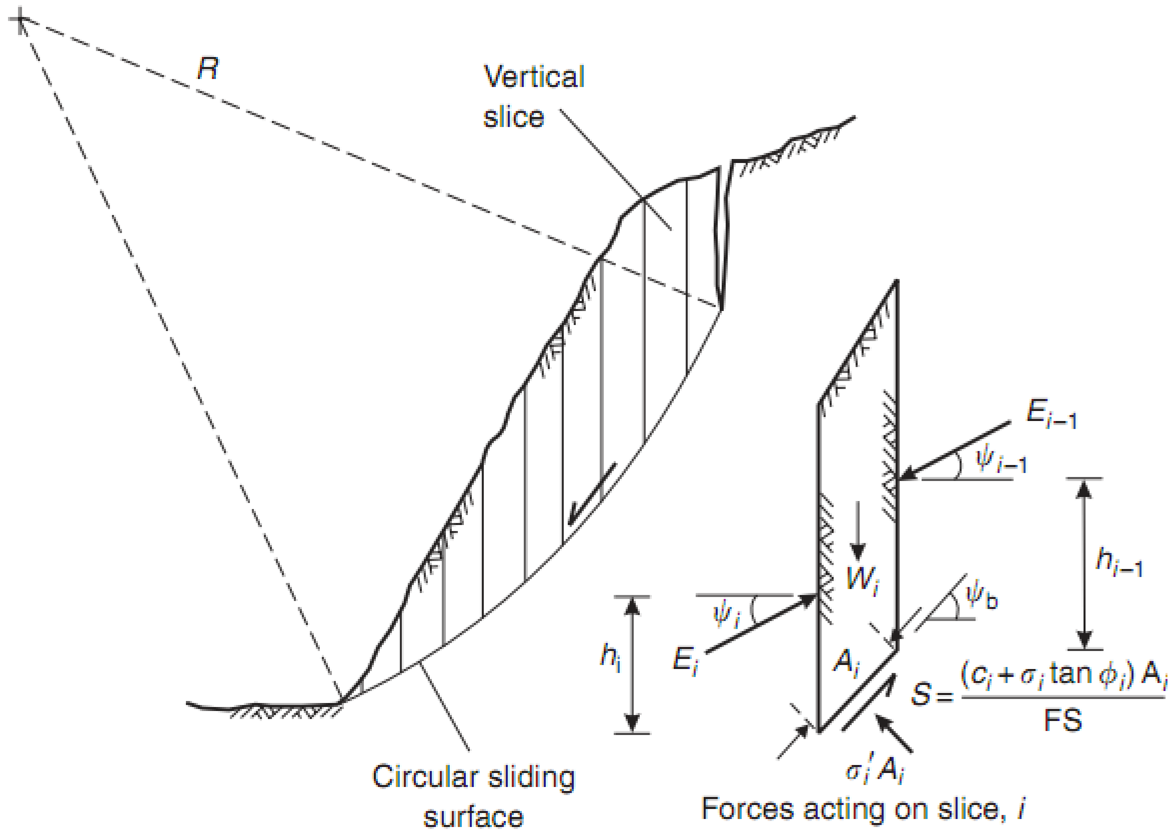
The shape of typical sliding surfaces

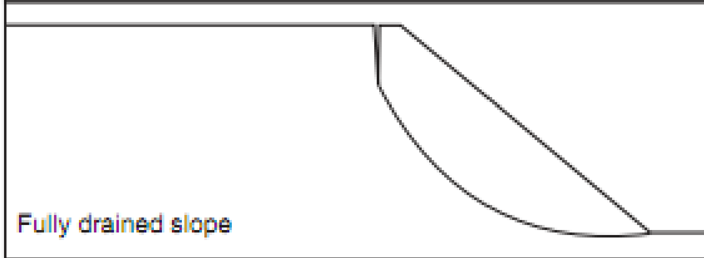
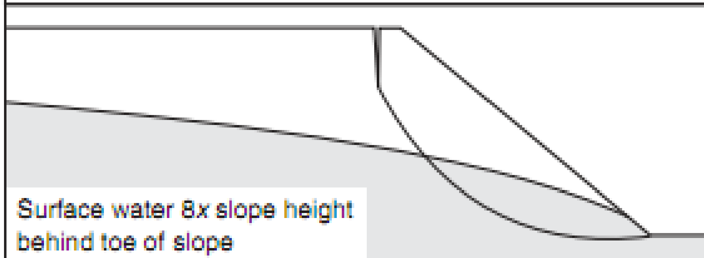
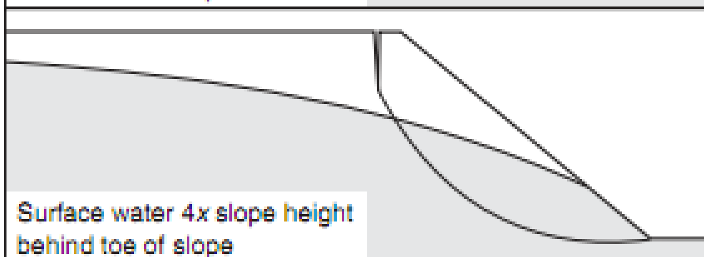
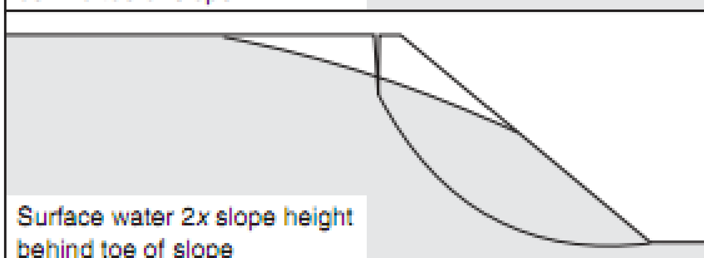
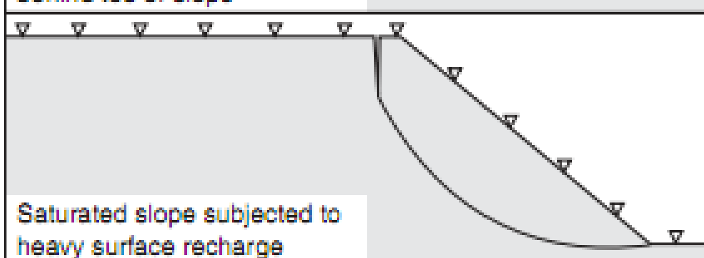


$$\mathrm{FS} = \frac{\text{shear strength available to resist sliding } (c + \sigma \tan \phi)}{\text{shear stress required for equilibrium on slip surface} (\tau_e)}$$

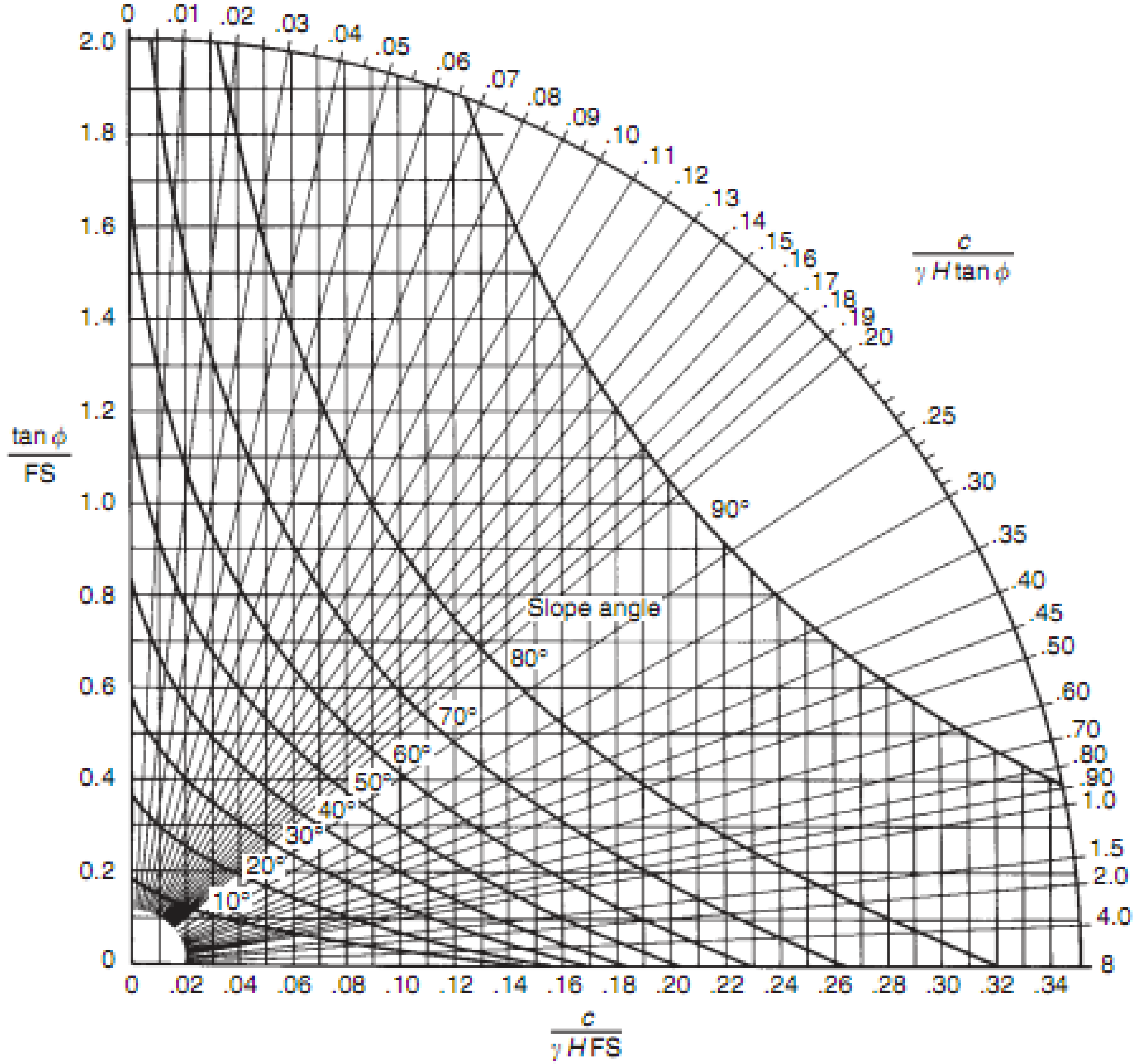
$$\tau_e = \frac{c + \sigma \tan \phi}{\mathrm{FS}}$$

Use of the stability charts presented requires that the conditions in the slope meet the following assumptions:

1. The material forming the slope is homogeneous, with uniform shear strength properties along the slide surface.
2. The shear strength τ of the material is characterized by cohesion: c and a friction angle ϕ, that are related by the equation $\tau = c + \sigma \tan \phi$
3. Failure occurs on a circular slide surface, which passes through the toe of the slope.
4. A vertical tension crack occurs in the upper surface or in the face of the slope.

Ground water flow conditions	Chart number
 Fully drained slope	1
 Surface water 8*x* slope height behind toe of slope	2
 Surface water 4*x* slope height behind toe of slope	3
 Surface water 2*x* slope height behind toe of slope	4
 Saturated slope subjected to heavy surface recharge	5

Ground water flow models used with circular failure analysis chart.



Circular failure chart number 1—fully drained slope.

Use of the circular failure charts

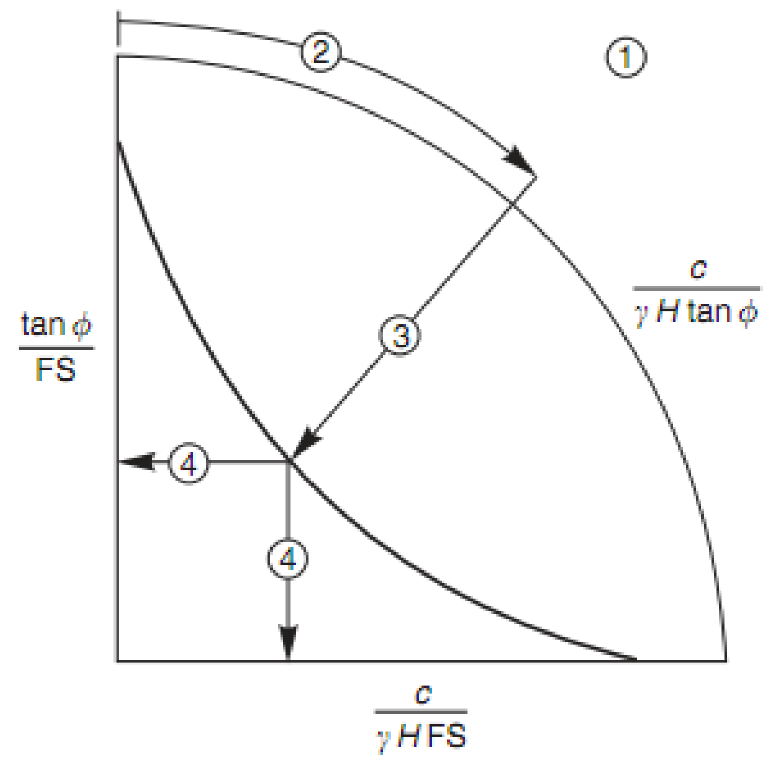
Step 1: Decide upon the ground water conditions which are believed to exist in the slope and choose the chart which is closest to these conditions, using Figure.

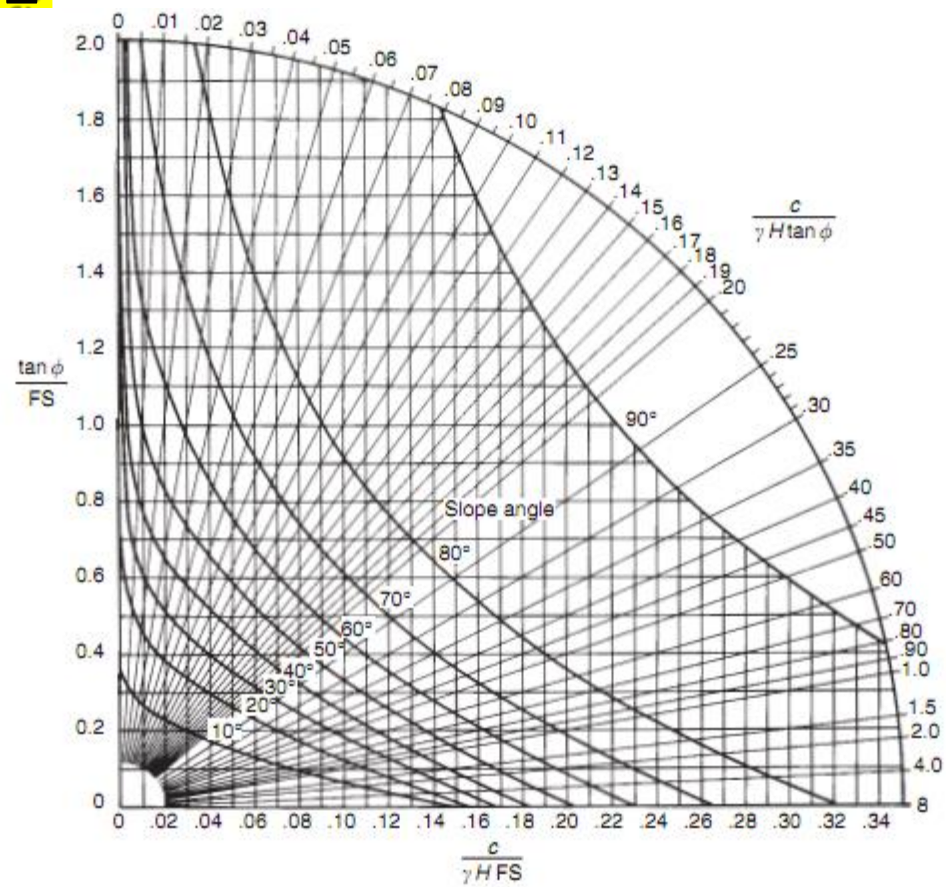
Step 2: Select rock strength parameters applicable to the material forming the slope.

Step 3: Calculate the value of the dimensionless ratio c/(γ H tan ϕ) and find this value on the outer circular scale of the chart.

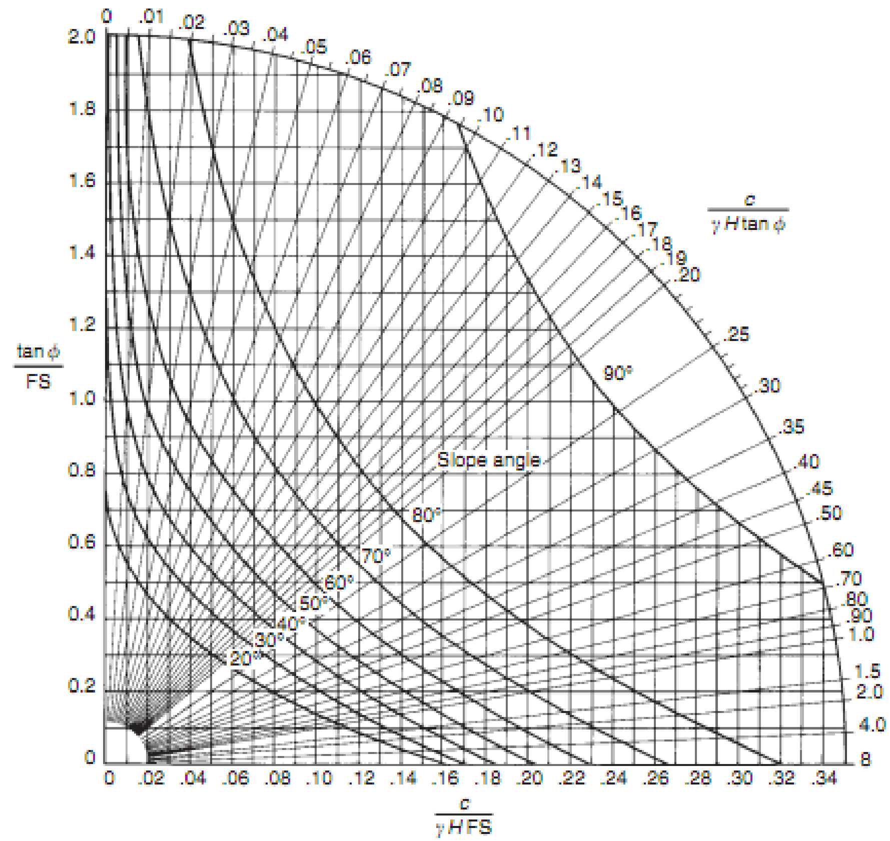
Step 4: Follow the radial line from the value found in step to its intersection with the curve which corresponds to the slope angle.

Step 5: Find the corresponding value of tan ϕ/FS or c/(γ H FS), depending upon which is more convenient, and calculate the factor of safety.

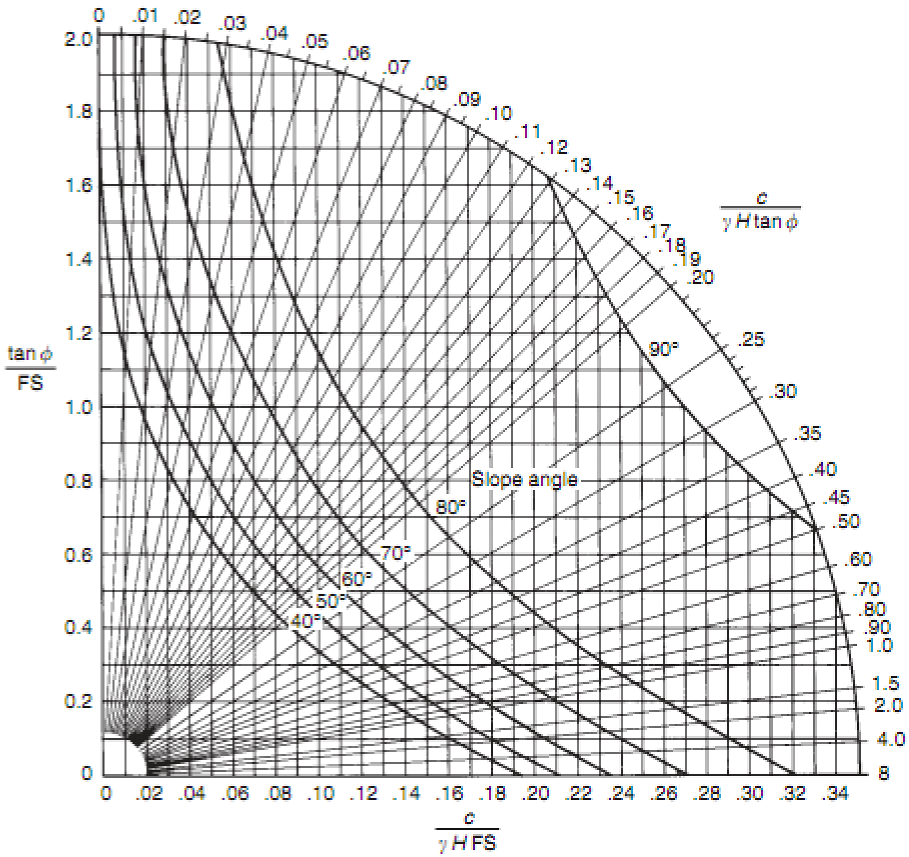




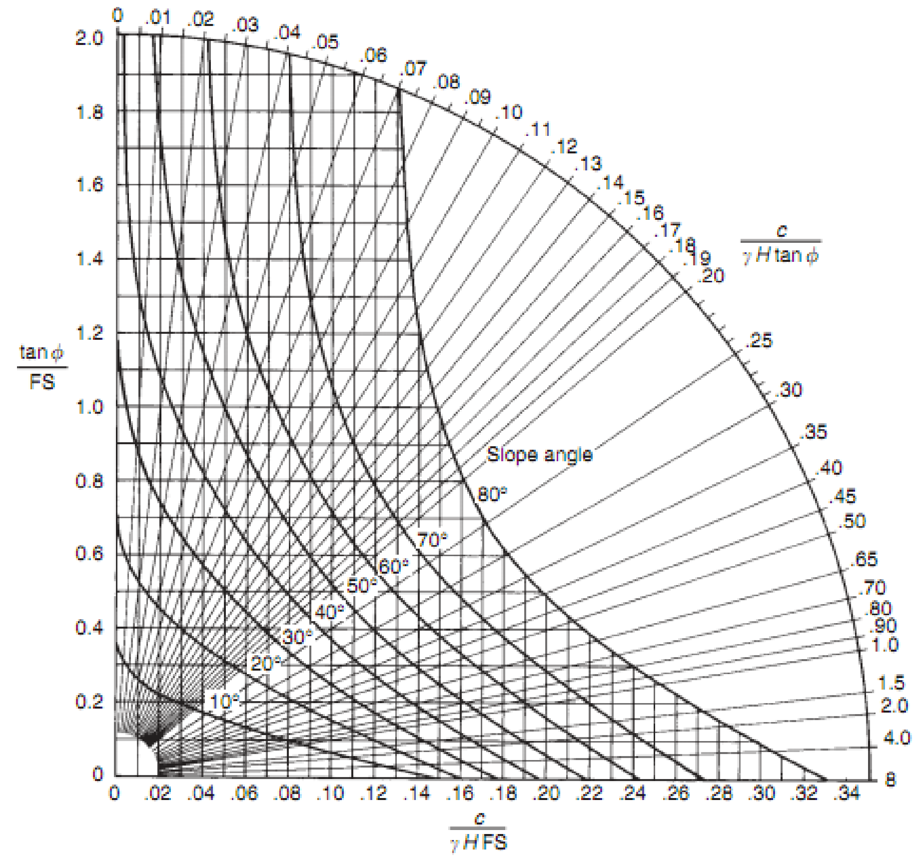
Circular failure chart number 2—
ground water condition 2



Circular failure chart number 3—
ground water condition 3

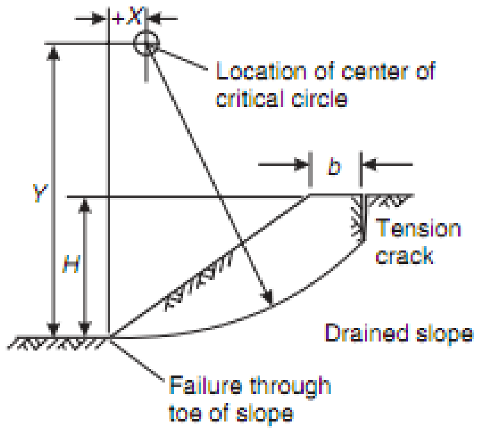


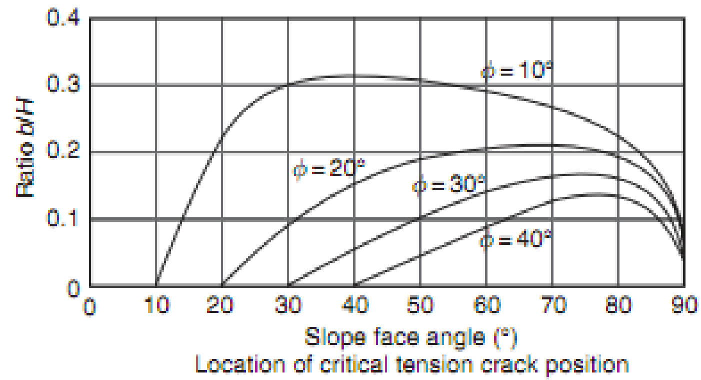
Circular failure chart number 4—ground water condition 4

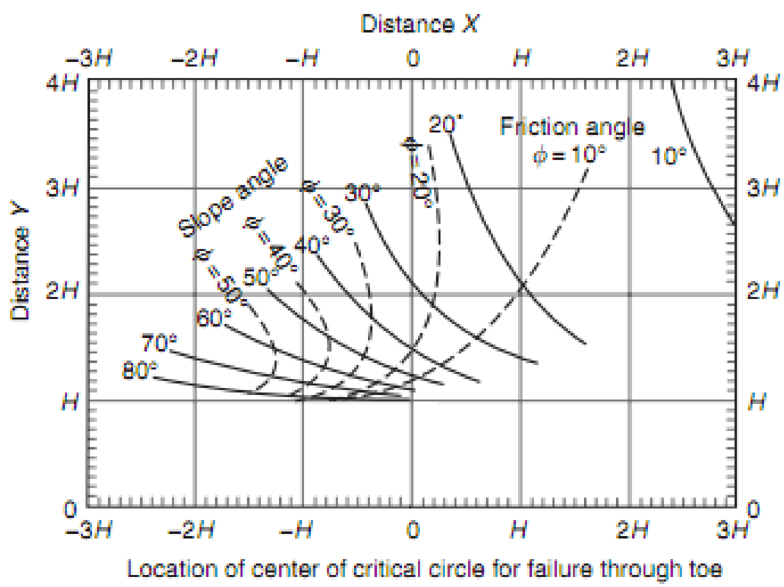


Circular failure chart number 5—fully saturated slope.

Location of critical sliding surface and critical tension crack for drained slopes







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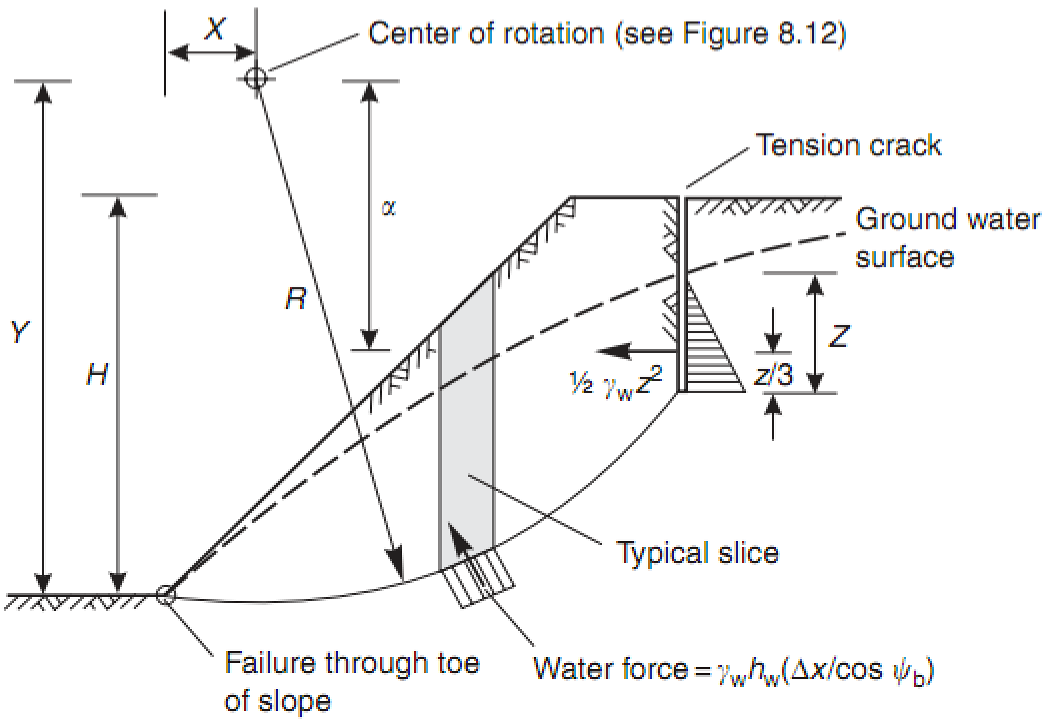
Bishop's simplified method of slices for the analysis of non-circular failure in slopes cut into materials in which failure is defined by the Mohr–Coulomb failure criterion



Factor of safety:

$$FS = \frac{\sum x/(1 + Y/FS)}{\sum Z + Q}$$

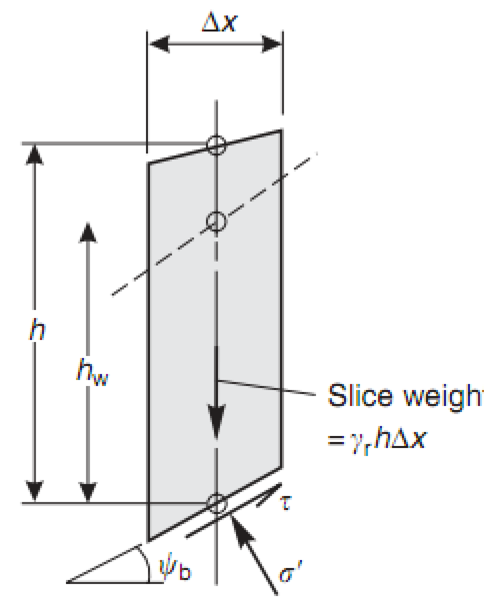
where

$$X = [c + (\gamma_r h - \gamma_w h_w) \tan\phi] (\Delta x / \cos\psi_b)$$

$$Y = \tan\psi_b \tan\phi$$

$$Z = \gamma_r h \,\Delta x \sin\psi_b$$

$$Q = ½\, \gamma_w z^2 (\alpha/R)$$



Li dkk (2002)

Stability charts for rock slopes based on the Hoek–Brown failure criterion

A.J. Li[a,*], R.S. Merifield[a], A.V. Lyamin[b]

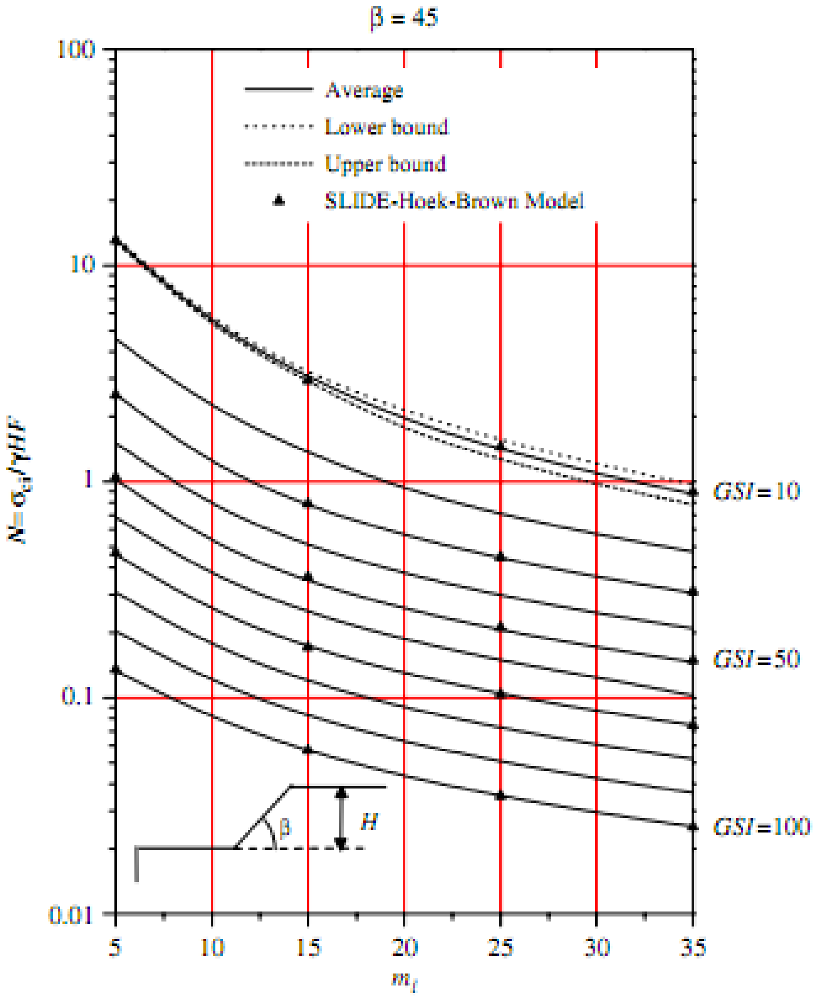


Fig. 4. Average finite element limit analysis solutions of stability numbers ($\beta = 45°$).

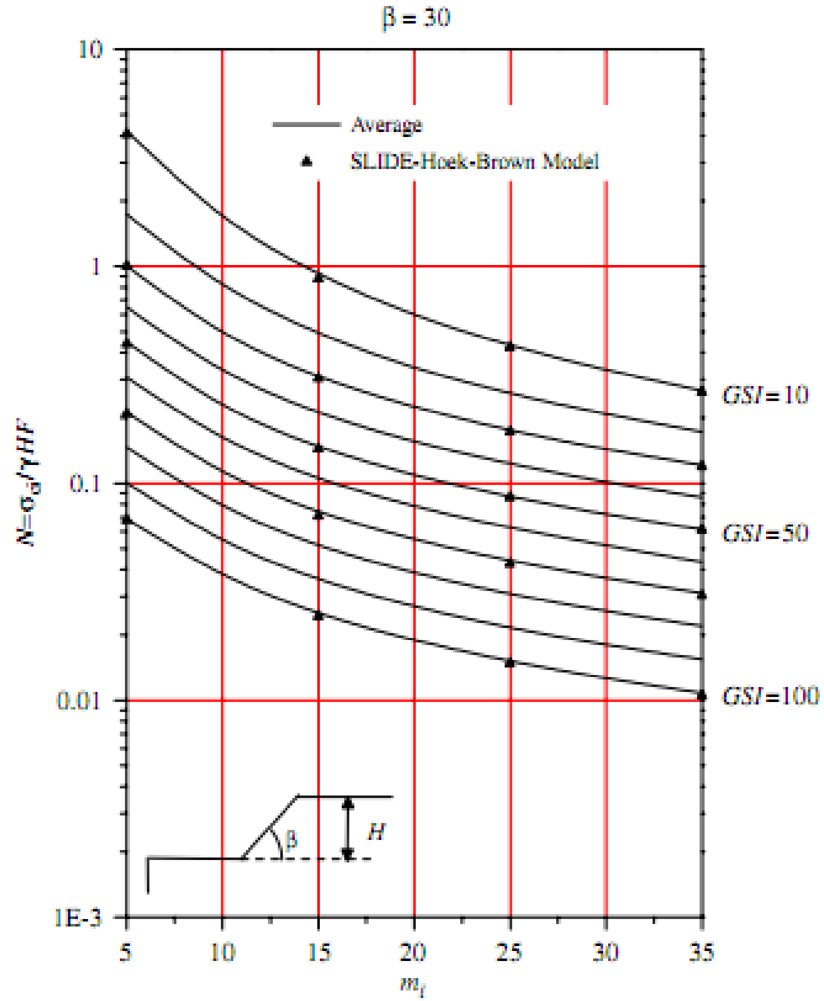
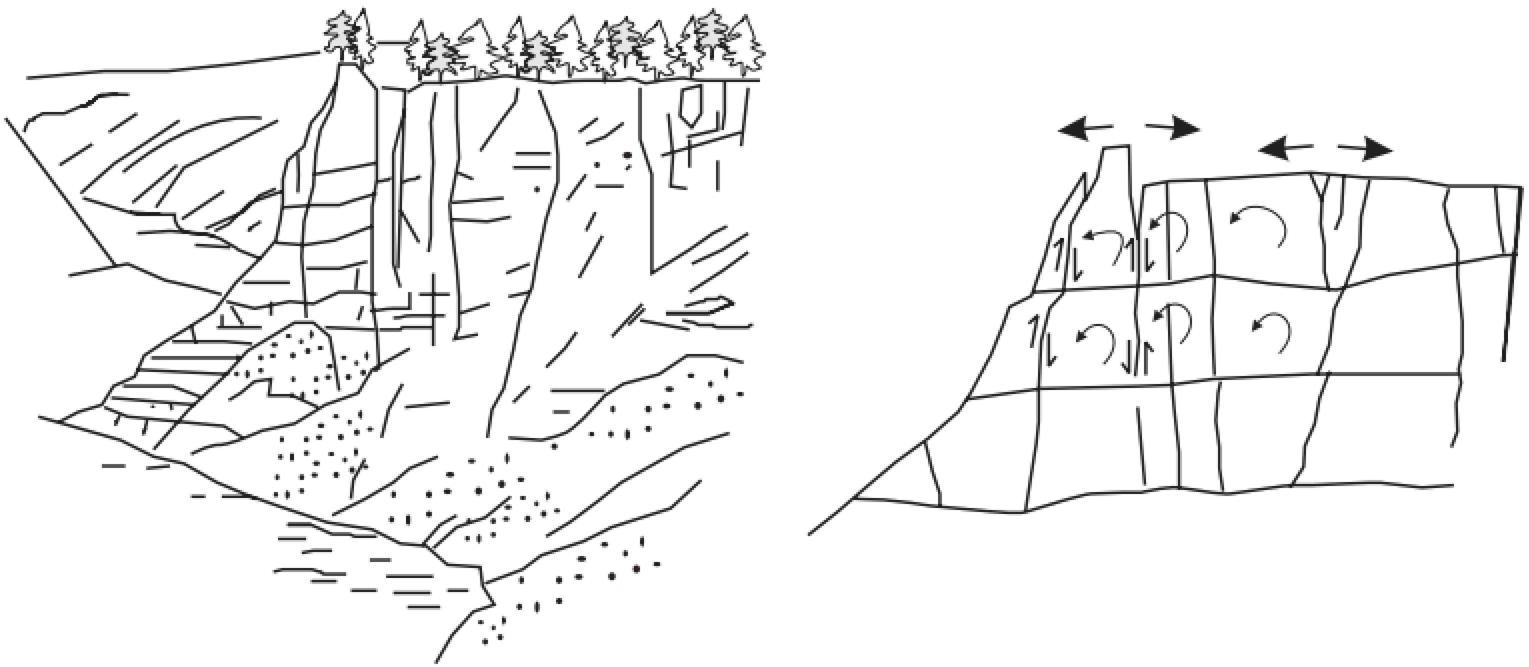


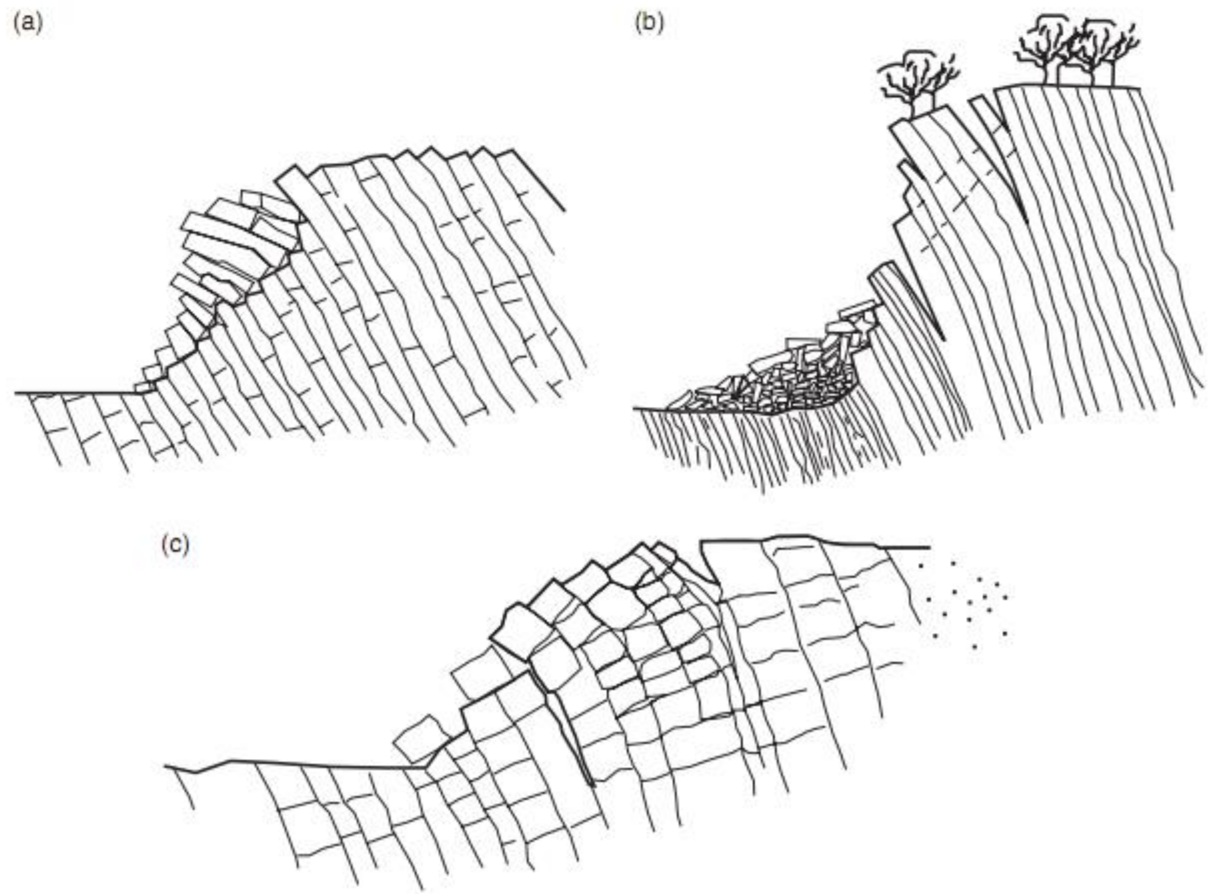
Fig. 6. Average finite element limit analysis solutions of stability numbers ($\beta = 30°$).

LESSON PART 7

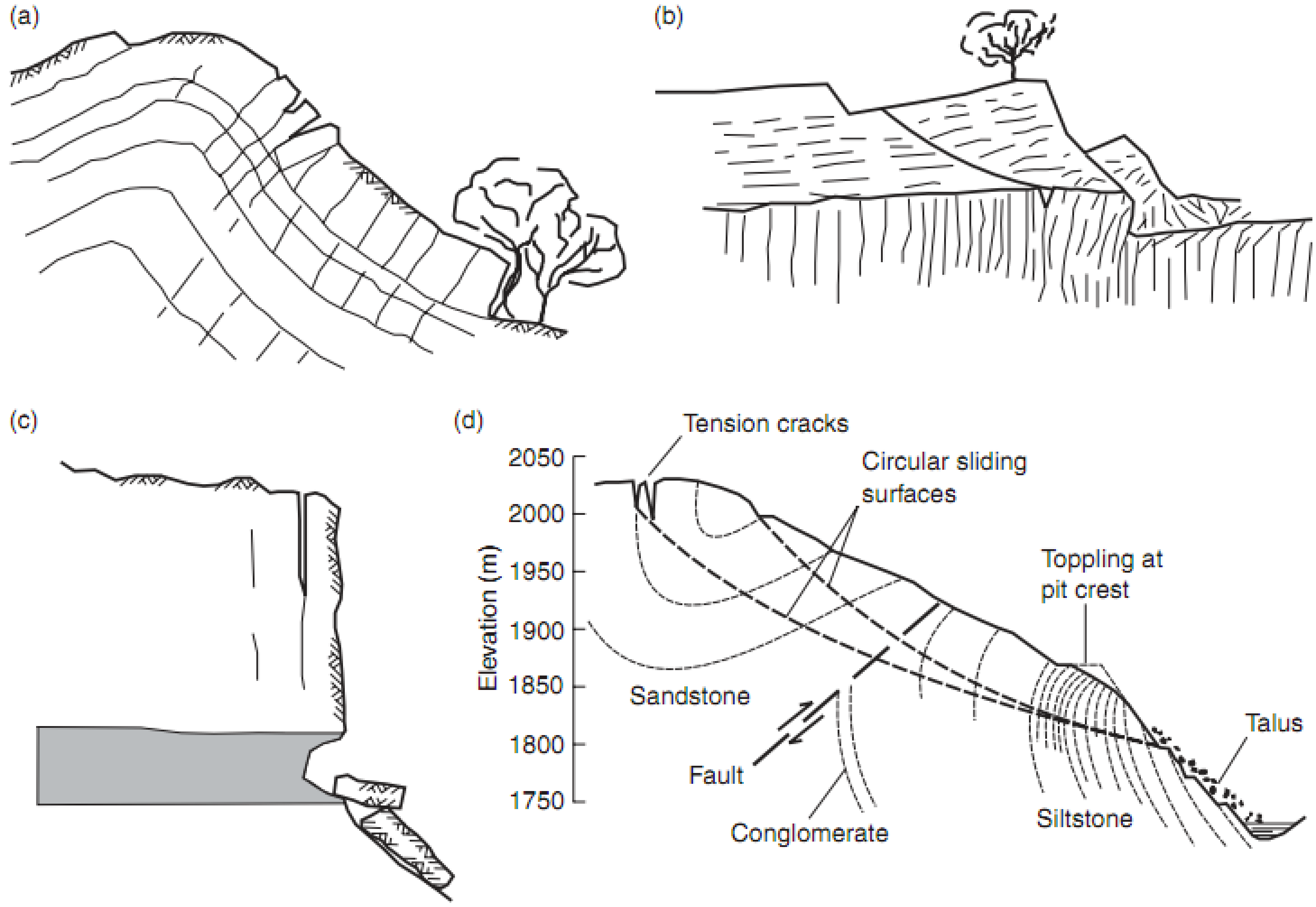
Toppling failure



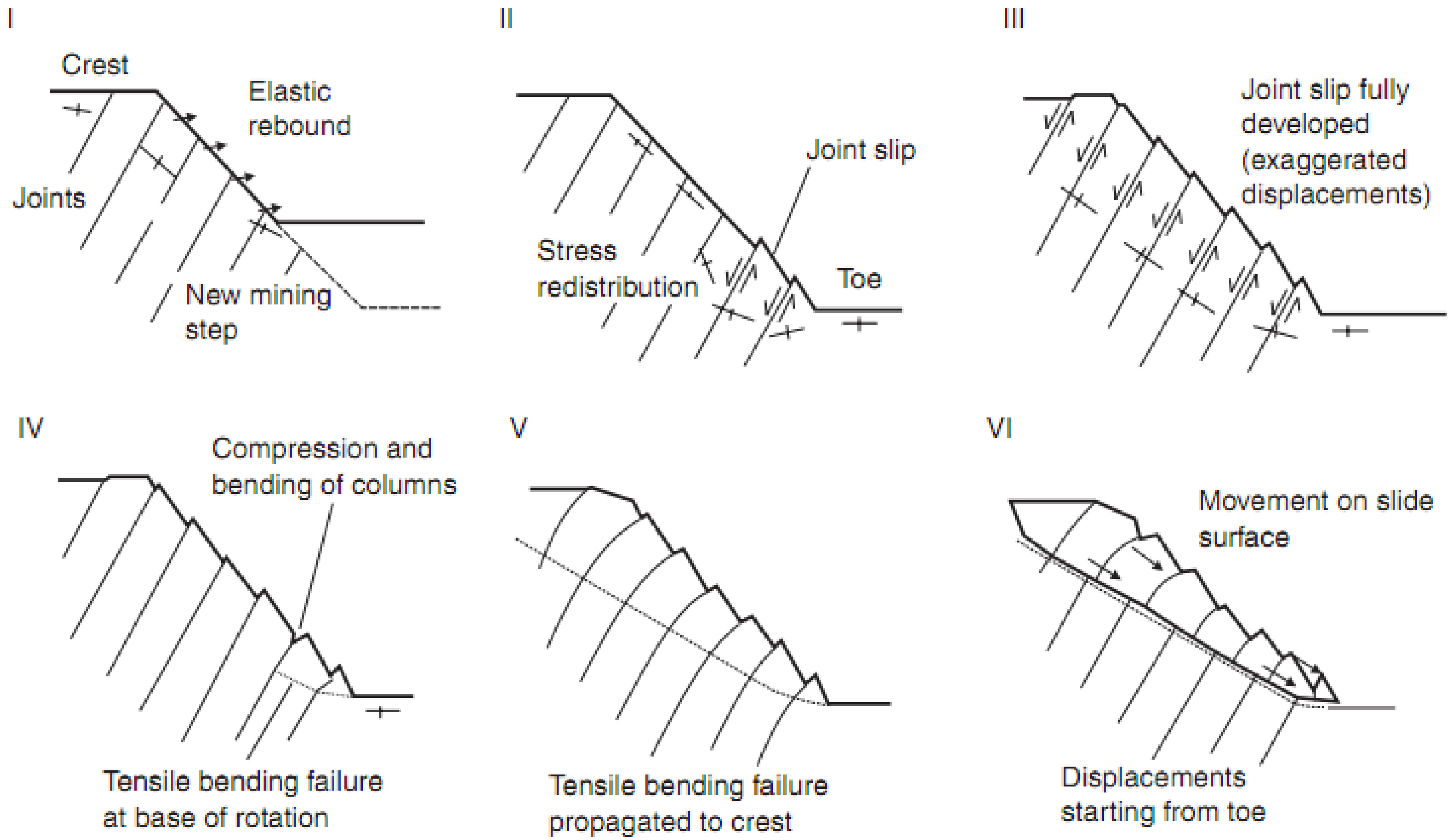
Suggested toppling mechanism of the north face of Vaiont slide (Muller, 1968)



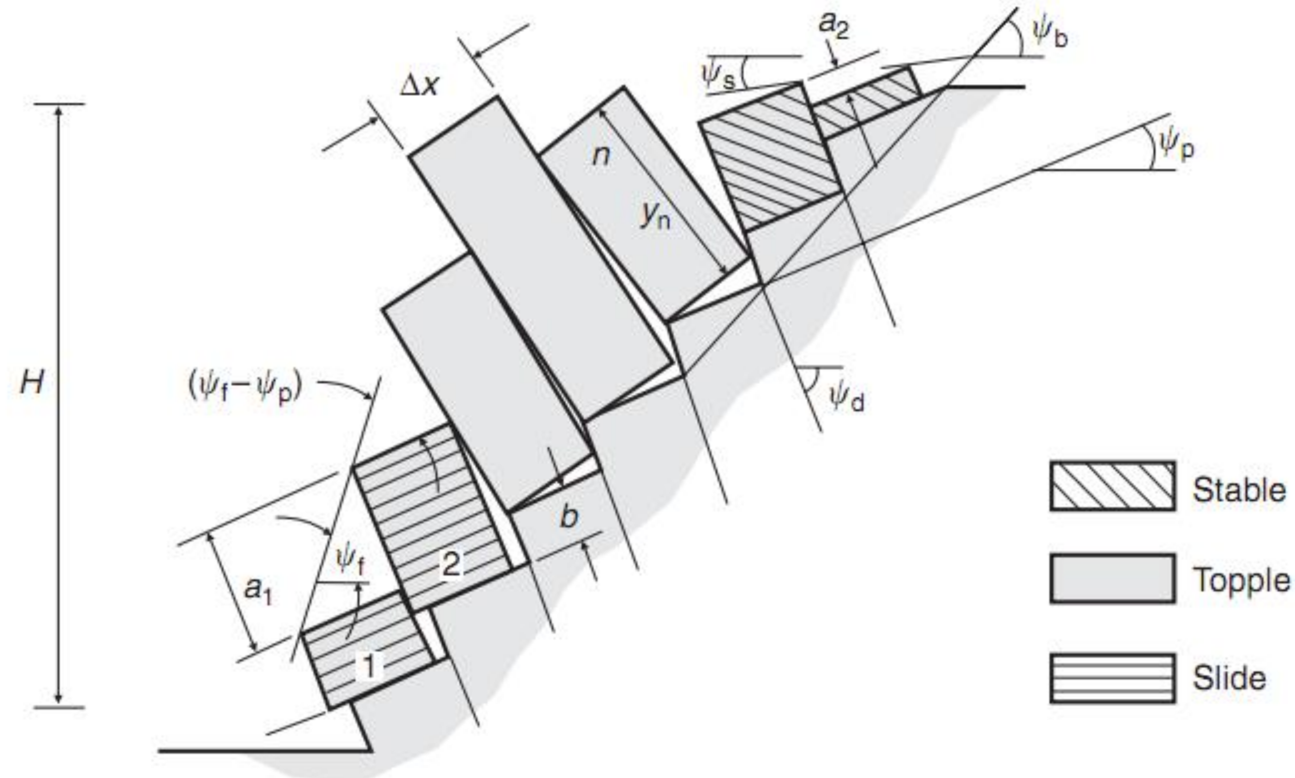
Common classes of toppling failures: (a) block toppling of columns of rock containing widely spaced orthogonal joints; (b) flexural toppling of slabs of rock dipping steeply into face; (c) block flexure toppling characterized by pseudo-continuous flexure of long columns through accumulated motions along numerous cross-joints (Goodman and Bray 1976).



Secondary toppling modes: (a) toppling at head of slide; (b) toppling at toe of slide with shear movement of upper slope (Goodman and Bray, 1976); (c) toppling of columns in strong upper material due to weathering of underlying weak material; (d) toppling at pit crest resulting in circular failure of upper slope (Wyllie and Munn, 1978).



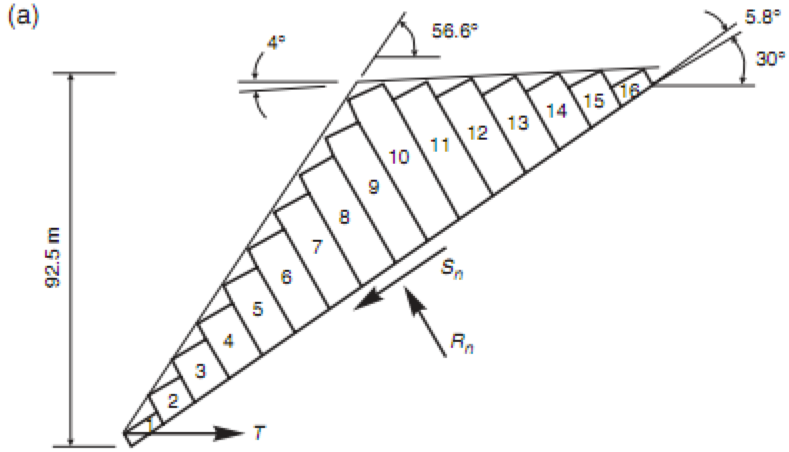
Failure stages for large-scale toppling failure in a slope (Sjöberg, 2000)

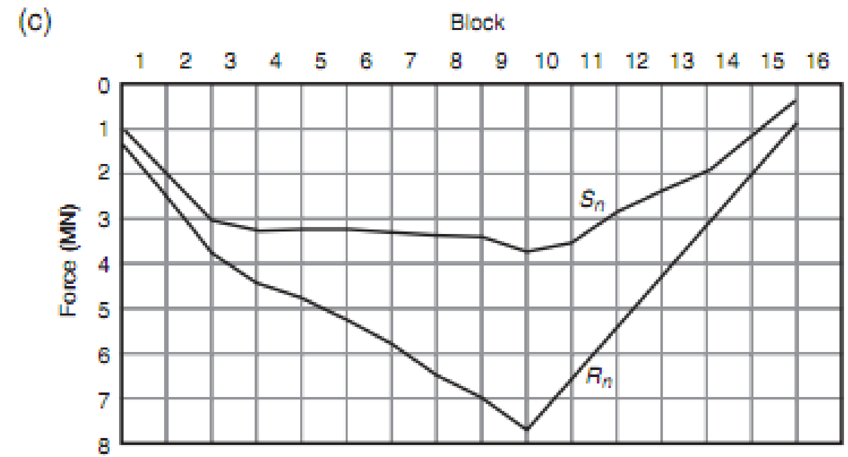


Model for limiting equilibrium analysis of toppling on a stepped base (Goodman and Bray, 1976).

Toppling Analysis

- The first step in toppling analysis is to calculate the dimensions of each block. Consider the regular system of blocks shown in above which the blocks are rectangular with width x and height yn. The dip of the base of the blocks is ψp and the dip of the orthogonal planes forming the faces of the blocks is ψd($\psi d = 90 - \psi p$). The slope height is H, and the face is excavated at angle ψf while the upper slope above the crest is at angle ψs.





(b)

n	y_n	$y_n/\Delta x$	M_n	L_n	$P_{n,t}$	$P_{n,s}$	P_n	R_n	S_n	S_n/R_n	Mode
16	4.0	0.4			0	0	0	866	500	0.577	
15	10.0	1.0			0	0	0	2165	1250	0.577	STABLE
14	16.0	1.6			0	0	0	3463	2000	0.577	--------
13	22.0	2.2	17	22	0	0	0	4533.4	2457.5	0.542	
12	28.0	2.8	23	28	292.5	−2588.7	292.5	5643.3	2966.8	0.526	T
11	34.0	3.4	29	34	825.7	−3003.2	825.7	6787.6	3520.0	0.519	O
10	40.0	4.0	35	35	1556.0	−3175.0	1556.0	7662.1	3729.3	0.487	P
9	36.0	3.6	36	31	2826.7	−3150.8	2826.7	6933.8	3404.6	0.491	P
8	32.0	3.2	32	27	3922.1	−1409.4	3922.1	6399.8	3327.3	0.520	L
7	28.0	2.8	28	23	4594.8	156.8	4594.8	5872.0	3257.8	0.555	I
6	24.0	2.4	24	19	4837.0	1300.1	4837.0	5352.9	3199.5	0.598	N
5	20.0	2.0	20	15	4637.5	2013.0	4637.5	4848.1	3159.4	0.652	G
4	16.0	1.6	16	11	3978.1	2284.1	3978.1	4369.4	3152.5	0.722	
3	12.0	1.2	12	7	2825.6	2095.4	2825.6	3707.3	2912.1	0.7855	--------
2	8.0	0.8	8	3	1103.1	1413.5	1413.5	2471.4	1941.3	0.7855	SLIDING
1	4.0	0.4	4	–	−1485.1	472.2	472.2	1237.1	971.8	0.7855	

Limited equilibrium analysis of a toppling slope: (a) slope geometry; (b) table listing block dimensions, calculated forces and stability mode; (c) distribution of normal (R) and shear (S) forces on base of blocks (Goodman and Bray, 1976).

LESSON PART 8

Rock Mass Classification

Rock Mass Rating Classification (Bieniawski, 1989)

<table>
<tr><td colspan="10">A. PARAMETER KLASIFIKASI DAN PEMBOBOTANNYA</td></tr>
<tr><td colspan="3">Parameter</td><td colspan="7">Selang Nilai</td></tr>
<tr><td rowspan="3">1.</td><td rowspan="2">Kekuatan Batuan Utuh</td><td>Indeks Kekuatan Point Load (MPa)</td><td>>10</td><td>4 - 10</td><td>2 - 4</td><td>1 - 2</td><td colspan="3">Untuk nilai yang kecil dipakai hasil UCS</td></tr>
<tr><td>Kuat Tekan Tekan Uniaksial (MPa)</td><td>>250</td><td>100 - 250</td><td>50 - 100</td><td>25 - 50</td><td>5 - 25</td><td>1 - 5</td><td><1</td></tr>
<tr><td colspan="2">Pembobotan</td><td>15</td><td>12</td><td>7</td><td>4</td><td>2</td><td>1</td><td>0</td></tr>
<tr><td rowspan="2">2.</td><td colspan="2">Rock Quality Designation (%)</td><td>90 - 100</td><td>75 - 90</td><td>50 - 75</td><td>25 - 50</td><td colspan="3"><25</td></tr>
<tr><td colspan="2">Pembobotan</td><td>20</td><td>17</td><td>13</td><td>5</td><td colspan="3">3</td></tr>
<tr><td rowspan="2">3.</td><td colspan="2">Spasi Rekahan</td><td>>2m</td><td>0.6 - 2m</td><td>0.2 - 0.6m</td><td>60 - 200mm</td><td colspan="3"><60mm</td></tr>
<tr><td colspan="2">Pembobotan</td><td>20</td><td>15</td><td>10</td><td>8</td><td colspan="3">5</td></tr>
<tr><td rowspan="2">4.</td><td colspan="2">Kondisi Rekahan</td><td>Permukaan sangat kasar, tidak menerus tidak reng-gang dan tidak lapuk</td><td>Agak kasar, rengangan <1mm, agak lapuk</td><td>Agak kasar , renggangan <1mm, sangat lapuk</td><td>Slickensides/gouge <5mm, renggangan 1 - 5mm, menerus</td><td colspan="3">Gouge lemah, tebal >5mm atau renggangan 5mm, menerus</td></tr>
<tr><td colspan="2">Pembobotan</td><td>30</td><td>25</td><td>20</td><td>10</td><td colspan="3">0</td></tr>
<tr><td rowspan="4">5.</td><td rowspan="3">Air Tanah</td><td>Aliran /10m panjang terowongan (L/min.)</td><td>Tidak ada</td><td><10</td><td>10 - 25</td><td>25 - 125</td><td colspan="3">>125</td></tr>
<tr><td>Tek. Pori/Teg. Utama Max.</td><td>0</td><td><0.1</td><td>0.1 - 0.2</td><td>0.2 - 0.5</td><td colspan="3">>0.5</td></tr>
<tr><td>Keadaan Umum</td><td>kering</td><td>lembab</td><td>basah</td><td>menetes</td><td colspan="3">mengalir</td></tr>
<tr><td colspan="2">Pembobotan</td><td>15</td><td>10</td><td>7</td><td>4</td><td colspan="3">0</td></tr>
</table>

B. PENGARUH ORIENTASI JURUS DAN KEMIRINGAN PADA PEMBUATAN TEROWONGAN						
Arah jurus tegak lurus sumbu terowongan				Arah jurus sejajar sumbu terowongan		Kemiringan 0°-20° tidak memperhatikan kemiringan
Maju searah kemiringan		Maju melawan kemiringan				
45° - 90°	20° - 45°	45° - 90°	20° - 45°	45° - 90°	20° - 45°	
Sangat menguntung-kan	Menguntung-kan	Sedang	Tidak menguntung-kan	Sangat tidak menguntung-kan	Sedang	Tidak menguntungkan

C. PENYESUAIAN PEMBOBOTAN UNTUK ORIENTASI KEKAR						
Orientasi Jurus dan Kemiringan		Sangat menguntungkan	Menguntungkan	Sedang	Tidak menguntungkan	Sangat tidak menguntungkan
Pembobotan	Terowongan	0	-2	-5	-10	-12
	Pondasi	0	-2	-7	-15	-25
	Lereng	0	-2	-25	-50	-60

D. KELAS MASSA BATUAN DARI PEMBOBOTAN TOTAL

Pembobotan	100 - 81	80 - 61	60 - 41	40 - 21	<21
Nomor kelas	I	II	III	IV	V
Pemerian	Sangat Baik	Baik	Sedang	Buruk	Sangat Buruk
Kohesi (kPa)	>400	300 - 400	200 - 300	100 - 200	<100
Sudut Gesek Dalam (°)	>45	35 – 45	25 – 35	15 – 25	<15

Guide of joint condition and rating					
Persistensi	< 1 m	1 – 3 m	3 – 10 m	10 – 20 m	> 20 m
rating	**6**	**4**	**2**	**1**	**0**
aperture	none	< 0.1 mm	0.1 – 1.0 mm	1 – 5 mm	> 5 mm
rating	**6**	**5**	**4**	**1**	**0**
roughness	Very rough	Rough	Slightly rough	Smooth	Slickensided
rating	**6**	**5**	**3**	**1**	**0**
Filling (gauge)	none	Hard filling < 5mm	Hard filling > 5 mm	Soft filling < 5mm	Soft filling > 5mm
rating	**6**	**4**	**2**	**2**	**1**
weathering	Unweathered	Slightly weathered	Moderately weathered	Highly weathered	Decomposed
rating	**6**	**5**	**3**	**1**	**0**

Slope Mass Rating (Romana,1985)

A. PARAMETER KLASIFIKASI DAN PEMBOBOTANNYA

Parameter			Selang Nilai						
1.	Kekuatan Batuan Utuh	Indeks Kekuatan Point Load (MPa)	>10	4 - 10	2 - 4	1 - 2	Untuk nilai yang kecil dipakai hasil UCS		
		Kuat Tekan Tekan Uniaksial (MPa)	>250	100 - 250	50 - 100	25 - 50	5 - 25	1 - 5	<1
	Pembobotan		15	12	7	4	2	1	0
2.	Rock Quality Designation (%)		90 - 100	75 - 90	50 - 75	25 - 50	<25		
	Pembobotan		20	17	13	5	3		
3.	Spasi Rekahan		>2m	0.6 - 2m	0.2 - 0.6m	60 - 200mm	<60mm		
	Pembobotan		20	15	10	8	5		
4.	Kondisi Rekahan		Permukaan sangat kasar, tidak menerus tidak reng-gang dan tidak lapuk	Agak kasar, rengangan <1mm, agak lapuk	Agak kasar , renggangan <1mm, sangat lapuk	Slickensides/gouge <5mm, renggangan 1 - 5mm, menerus	Gouge lemah, tebal >5mm atau renggangan 5mm, menerus		
	Pembobotan		30	25	20	10	0		
5.	Air Tanah	Aliran /10m panjang terowongan (L/min.)	Tidak ada	<10	10 - 25	25 - 125	>125		
		Tek. Pori/Teg. Utama Max.	0	<0.1	0.1 - 0.2	0.2 - 0.5	>0.5		
		Keadaan Umum	kering	lembab	basah	menetes	mengalir		
	Pembobotan		15	10	7	4	0		

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Adjustment Rating for Joints

Case		Very favorable	Favorable	Fair	Unfavorable	Very unfavorable
P	$\lvert \alpha_j - \alpha_s \rvert$	> 30°	30-20°	20-10°	10-5°	5°
T	$\lvert (\alpha_j - \alpha_s) - 180° \rvert$					
P/T	F_1	0.15	0.40	0.70	0.85	1.00
P	$\lvert \beta_j \rvert$	< 20°	20-30°	30-35°	35-45°	45°
P	F_2	0.15	0.40	0.70	0.85	1.00
T	F_2	1	1	1	1	1
P	$\beta_j - \beta_s$	> 10°	10-0°	0°	0° to 10°	< -10°
T	$\beta_j - \beta_s$	< 110°	110-120°	> 120°	-	-
P/T	F_3	0	-6	- 25	-50	- 60

P, plane failure; T, toppling failure; α_j, joint dip direction; α_s slope dip direction; β_j, joint dip; β_s, slope dip

Adjustment Rating for Methods of Excavation of Slopes

Method	Natural Slope	Presplitting	Smooth blasting	Blasting or mechanical	Deficient blasting
F_4	+ 15	+ 10	+ 8	0	- 8

Tentative Description of SMR Classes

Class	SMR	Description	Stability	Failures	Support
I	81-100	Very good	Completely stable	None	None
II	61-80	Good	Stable	Some blocks	Occasional
III	41-60	Normal	Partially stable	Some joints or many wedges	Systematic
IV	21-40	Bad	Unstable	Planar or big wedges	Important/corrective
V	0-20	Very bad	Completely unstable	Big planar or soil-like	Reexcavation

Description of SMR and Failure probability

Description SMR Class

<table>
<tr><td>Class N</td><td>Vb</td><td>Va</td><td>IVb</td><td>IVa</td><td>IIIb</td><td>IIIa</td><td>IIb</td><td>IIa</td><td>Ib</td><td>Ia</td></tr>
<tr><td>Description</td><td colspan="2">Very bad</td><td colspan="2">Bad</td><td colspan="2">Fair</td><td colspan="2">Good</td><td colspan="2">Very good</td></tr>
<tr><td>Stability</td><td colspan="2">Completely unstable</td><td colspan="2">unstable</td><td colspan="2">Partially stable</td><td colspan="2">stable</td><td colspan="2">Completely stable</td></tr>
<tr><td>failures</td><td colspan="2">Big planar or soil like</td><td colspan="2">Planar or Big Wedges</td><td colspan="2">Some joint or many wedges</td><td colspan="2">Some blocks</td><td colspan="2">None</td></tr>
<tr><td>Support</td><td colspan="2">Reexcavtion</td><td colspan="2">Important corrective</td><td colspan="2">Systematic</td><td colspan="2">Occasional</td><td colspan="2">None</td></tr>
</table>

Probable Failure According SMR Values

<table>
<tr><td>Plane Failure</td><td colspan="2"></td><td colspan="4">Very big</td><td colspan="4">Major</td><td colspan="6">None</td></tr>
<tr><td>Wedge Failure</td><td colspan="6"></td><td colspan="2">Many</td><td colspan="4">Some</td><td colspan="3">Very Few</td><td>None</td></tr>
<tr><td>Toppling</td><td colspan="5"></td><td>Major</td><td colspan="2"></td><td colspan="3">Minor</td><td colspan="5">None</td></tr>
<tr><td>Mass Faulure</td><td></td><td colspan="5">Possible</td><td colspan="10">None</td></tr>
<tr><td>SMR</td><td>10</td><td>15</td><td>15</td><td>20</td><td>30</td><td>40</td><td>45</td><td>50</td><td>55</td><td>60</td><td>65</td><td>70</td><td>75</td><td>80</td><td>90</td><td>100</td></tr>
</table>

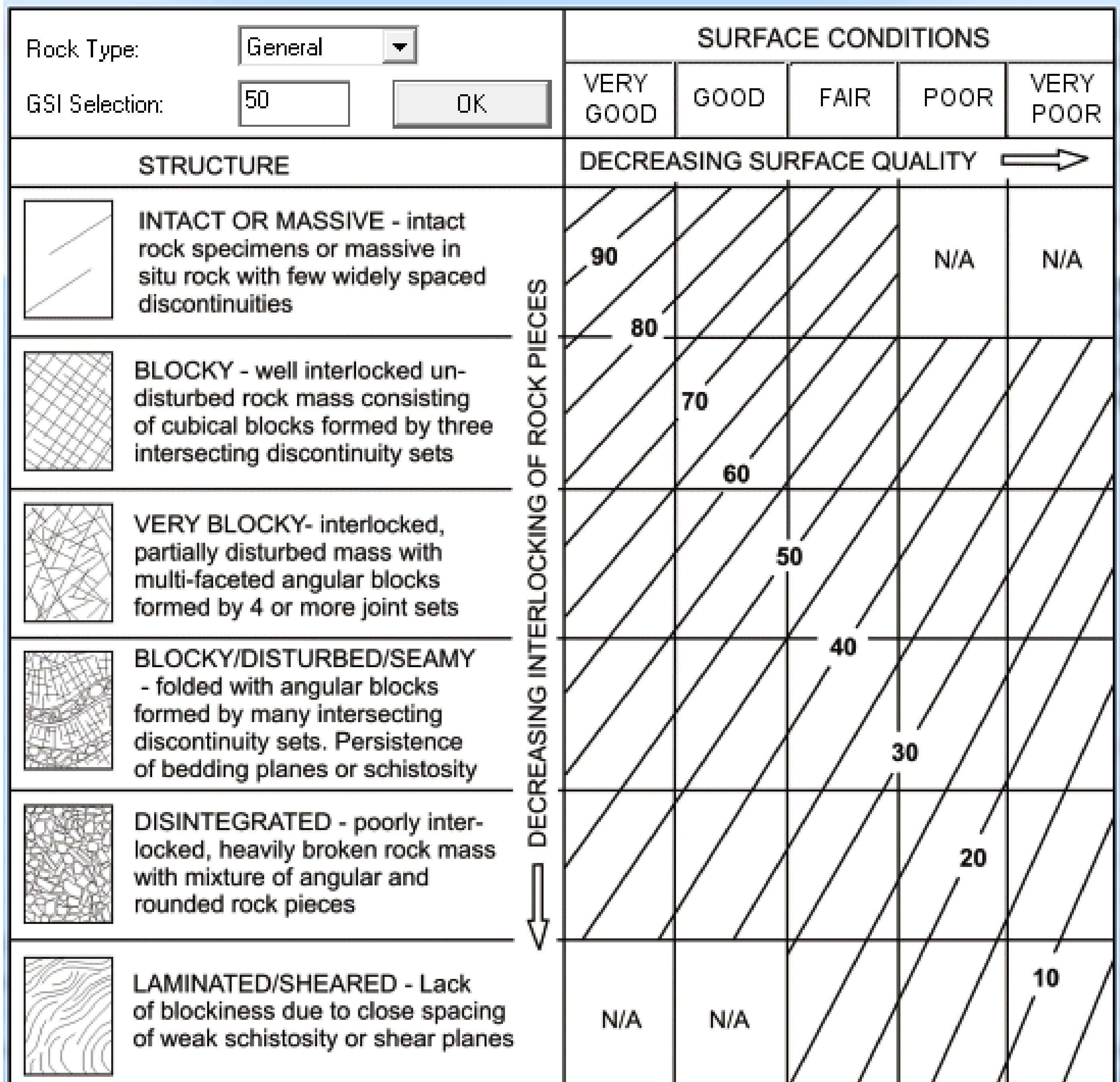
LESSON PART 9

ROCK MASS STRENGTH

Geological Strength Index (Hoek,1995)

A. PARAMETER KLASIFIKASI DAN PEMBOBOTANNYA									
Parameter			Selang Nilai						
1.	Kekuatan Batuan Utuh	Indeks Kekuatan Point Load (MPa)	>10	4 - 10	2 - 4	1 - 2	Untuk nilai yang kecil dipakai hasil UCS		
		Kuat Tekan Tekan Uniaksial (MPa)	>250	100 - 250	50 - 100	25 - 50	5 - 25	1 - 5	<1
	Pembobotan		15	12	7	4	2	1	0
2.	Rock Quality Designation (%)		90 - 100	75 - 90	50 - 75	25 - 50	<25		
	Pembobotan		20	17	13	5	3		
3.	Spasi Rekahan		>2m	0.6 - 2m	0.2 - 0.6m	60 - 200mm	<60mm		
	Pembobotan		20	15	10	8	5		
4.	Kondisi Rekahan		Permukaan sangat kasar, tidak menerus tidak renggang dan tidak lapuk	Agak kasar, rengangan <1mm, agak lapuk	Agak kasar , renggangan <1mm, sangat lapuk	Slickensides/ gouge <5mm, renggangan 1 - 5mm, menerus	Gouge lemah, tebal >5mm atau renggangan 5mm, menerus		
	Pembobotan		25	20	12	6	0		

Estimate of Geological Strength Index GSI based on geological descriptions



Rock type	Class	Group	Texture			
			Coarse	Medium	Fine	Very fine
SEDIMENTARY	Clastic		Conglomerate (22)	Sandstone 19	Siltstone 9	Claystone 4
				— Greywacke (18) —		
	Non-Clastic	Organic		— Chalk 7 —		
				— Coal (8-21) —		
		Carbonate	Breccia (20)	Sparitic Limestone (10)	Micritic Limestone 8	
		Chemical		Gypstone 16	Anhydrite 13	
METAMORPHIC	Non Foliated		Marble 9	Hornfels (19)	Quartzite 24	
	Slightly foliated		Migmatite (30)	Amphibolite 25 - 31	Mylonites (6)	
	Foliated*		Gneiss 33	Schists 4 - 8	Phyllites (10)	Slate 9
IGNEOUS	Light		Granite 33		Rhyolite (16)	Obsidian (19)
			Granodiorite (30)		Dacite (17)	
	Dark		Diorite (28)		Andesite 19	
			Gabbro 27	Dolerite (19)	Basalt (17)	
			Norite 22			
	Extrusive pyroclastic type		Agglomerate (20)	Breccia (18)	Tuff (15)	

Values of the constant mi for intact rock, by rock group

Determine of cohesion and friction angle rock with Hoek & Brown criterion

$$c' = \frac{\sigma_{ci}[(1+2\alpha)s + (1-\alpha)m_b\sigma'_{3n}](s + m_b\sigma'_{3n})^{\alpha-1}}{(1+\alpha)(2+\alpha)\sqrt{1+(6\alpha m_b(s+m_b\sigma'_{3n})^{\alpha-1}/(1+\alpha)(2+\alpha)}}$$

$$\phi' = \sin^{-1}\left[\frac{6\alpha m_b(s+m_b\sigma'_{3n})^{\alpha-1}}{2(1+\alpha)(2+\alpha)+6\alpha m_b(s+m_b\sigma'_{3n})^{\alpha-1}}\right]$$

where:

c' : effective coheson

ϕ' : effective friction angle

σ_1' & σ_3' : effective principla stress

σ_{ci} : UCS intact rock

m_b , s and α : constanta rock massa Hoek & Brown

Hoek, Carranza-Torres and Corkum, 2002

$$\sigma_1' = \sigma_3' + \sigma_{ci}\left(m_b\,\sigma_3'/\sigma_{ci} + s\right)^a$$

$$m_b = m_i \exp\left(GSI - 100/28 - 14D\right)$$

$$s = \exp\left(GSI - 100/9 - 3D\right)$$

$$a = \frac{1}{2} + \frac{1}{6}\left(e^{-GSI/15} - e^{-20/3}\right)$$

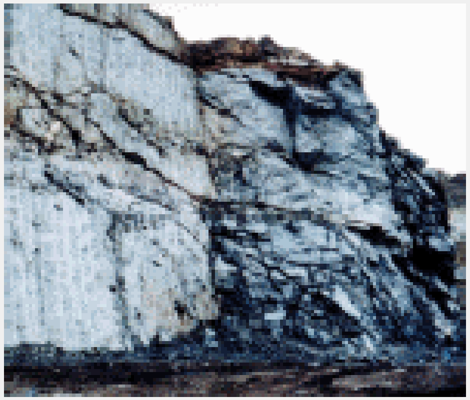
$$E_m(GPa) = \left(1 - \frac{D}{2}\right)\sqrt{\frac{\sigma_{ci}}{100}} \cdot 10^{((GSI-10)/40)}$$

$$\phi' = \sin^{-1}\left[\frac{6am_b(s + m_b\sigma'_{3n})^{a-1}}{2(1+a)(2+a) + 6am_b(s + m_b\sigma'_{3n})^{a-1}}\right]$$

$$c' = \frac{\sigma_{ci}\left[(1+2a)s + (1-a)m_b\sigma'_{3n}\right](s + m_b\sigma'_{3n})^{a-1}}{(1+a)(2+a)\sqrt{1 + \left(6am_b(s + m_b\sigma'_{3n})^{a-1}\right)/\left((1+a)(2+a)\right)}}$$

A disturbance factor (D)

Application: ○ Tunnels ◉ Slopes



Small scale blasting in civil engineering slopes results in modest rock mass damage, particularly if controlled blasting is used as shown on the left hand side of the photograph. However, stress relief results in some disturbance.

D=0.7
Good Blasting

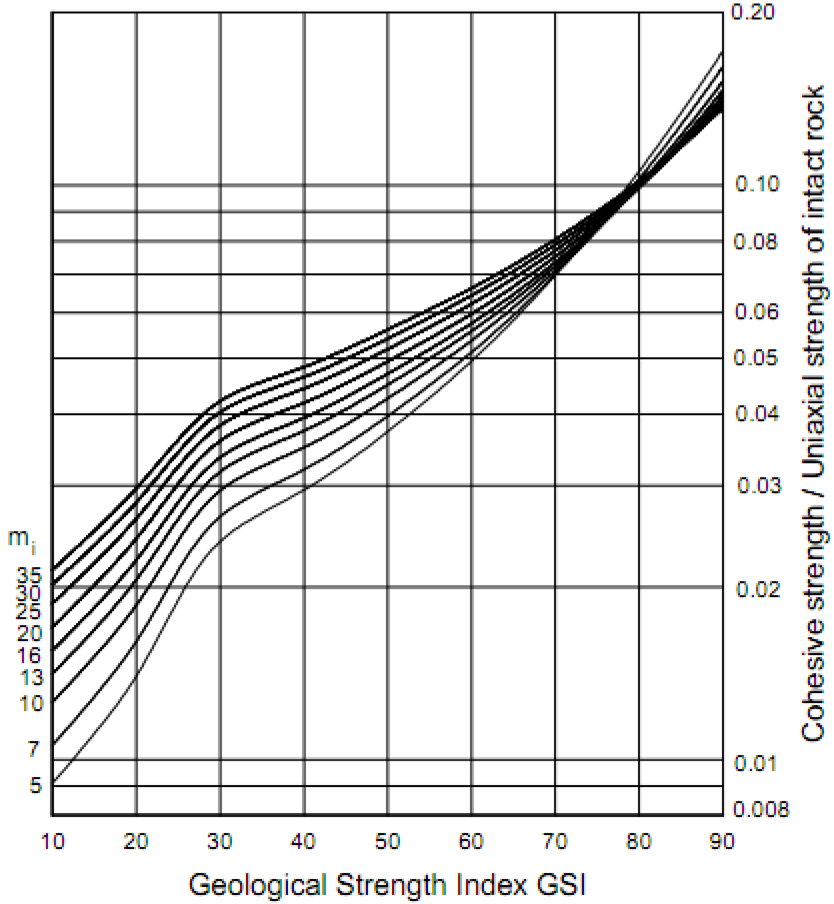
D=1.0
Poor Blasting

Very large open pit mine slopes suffer significant disturbance due to heavy production blasting and also due to stress relief from overburden removal.

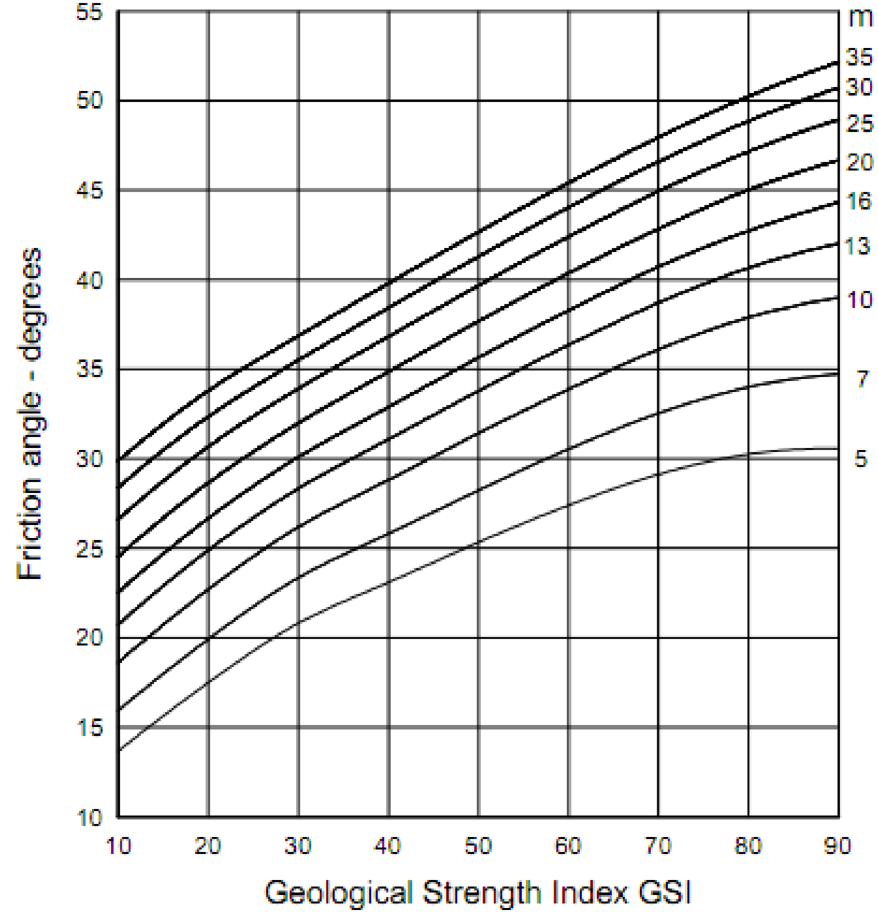
In some softer rocks excavation can be carried out by ripping and dozing and the degree of damage to the slopes is less.

D=1.0
Production
Blasting

D=0.7
Mechanical
Excavation



a. Plot of ratio of cohesive strength c′ to uniaxial compressive strength σci .



b. Plot of friction angle ϕ′

(Hoek-Brown, 1997)

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Intact rock properties

$$\sigma_1' = \sigma_3' + \sigma_{ci}\left(m_i \frac{\sigma_3'}{\sigma_{ci}} + 1\right)^{0.5}$$

- The relationship between the principal stresses at failure for a given rock is defined by two constants, $\boldsymbol{\sigma_{ci}}$ *and* $\mathbf{m_i}$.
- Wherever possible the values of these constants should be determined by statistical analysis of the results of a set of triaxial tests on carefully prepared core samples.

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Intact rock properties

- The range of minor principal stress (σ_3') values over which these tests are carried out is critical in determining reliable values for the two constants.
- In deriving the original values of σ_{ci} and m_i, Hoek and Brown (1980) used a range of **$0 < \sigma_3' < 0.5\sigma_{ci}$**.
- In order to be consistent, it is essential that the same range be used in any laboratory triaxial tests on intact rock specimens.

Intact rock properties

- At least five data points should be included in the analysis.
- Once the five or more triaxial test results have been obtained, they can be analysed to determine the σ_{ci} and the m_i as described by Hoek and Brown (1980).

Intact rock properties

$$\sigma_1' = \sigma_3' + \sigma_{ci}\left(m_i \frac{\sigma_3'}{\sigma_{ci}} + 1\right)^{0.5}$$

$$\Downarrow$$

$$y = m\sigma_{ci}x + s\sigma_{ci}$$

$$x = \sigma_3'$$

$$y = (\sigma_1' - \sigma_3')^2$$

$$\sigma_{ci}^2 = \frac{\sum y}{n}\left[\frac{\sum xy - \sum x \sum y / n}{\sum x^2 - (\sum x)^2 / n}\right]\frac{\sum x}{n}$$

$$m_i = \frac{1}{\sigma_{ci}}\left[\frac{\sum xy - \sum x \sum y / n}{\sum x^2 - (\sum x)^2 / n}\right]$$

$$r^2 = \frac{\sum xy - \sum x \sum y / n}{(\sum x^2 - (\sum x)^2 / n)\,(\sum y^2 - (\sum y)^2 / n)}$$

Intact rock properties

Triaxial test data

x		y	xy	xsq	ysq
sig3	sig1				
0	38.3	1466.89	0.0	0.0	2151766
5	72.4	4542.76	22713.8	25.0	20636668
7.5	80.5	5329.00	39967.5	56.3	28398241
15	115.6	10120.36	151805.4	225.0	102421687
20	134.3	13064.49	261289.8	400.0	170680899
47.5	441.1	34523.50	475776.5	706.3	324289261
sumx		sumy	sumxy	sumxsq	sumysq

Calculation results

Number of tests	n =	5
Uniaxial strength	sigci =	37.4
Hoek-Brown constant	mi =	15.50
Hoek-Brown constant	s =	1.00
Coefficient of determination	r2 =	0.997

Cell formulae

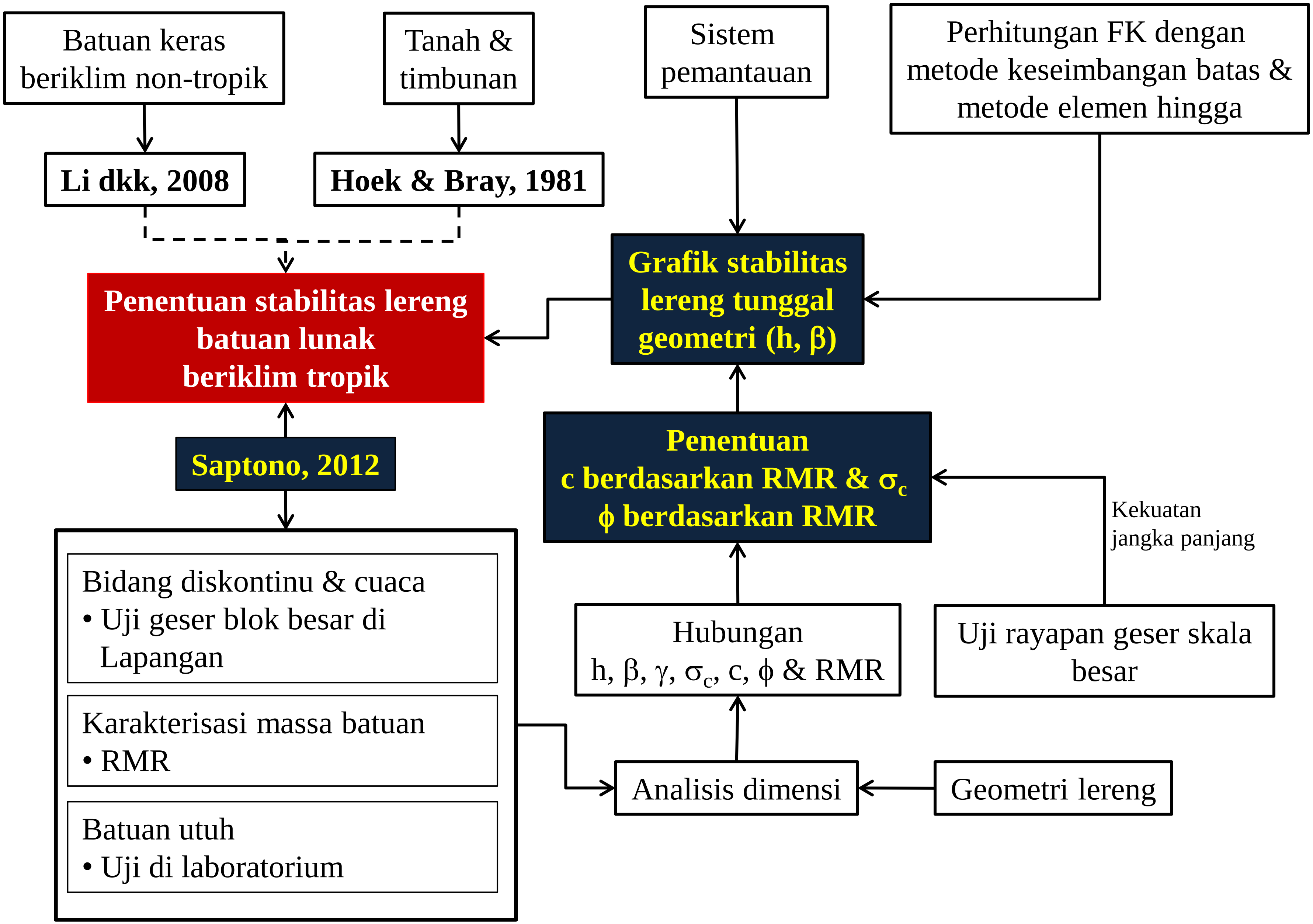
y = (sig1-sig3)^2

sigci = SQRT(sumy/n - (sumxy-sumx*sumy/n)/(sumxsq-(sumx^2)/n)*sumx/n)

mi = (1/sigci)*((sumxy-sumx*sumy/n)/(sumxsq-(sumx^2)/n))

r2 = ((sumxy-(sumx*sumy/n))^2)/((sumxsq-(sumx^2)/n)*(sumysq-(sumy^2)/n))

Development of rock slope stability in sof rock (Saptono, 2012)



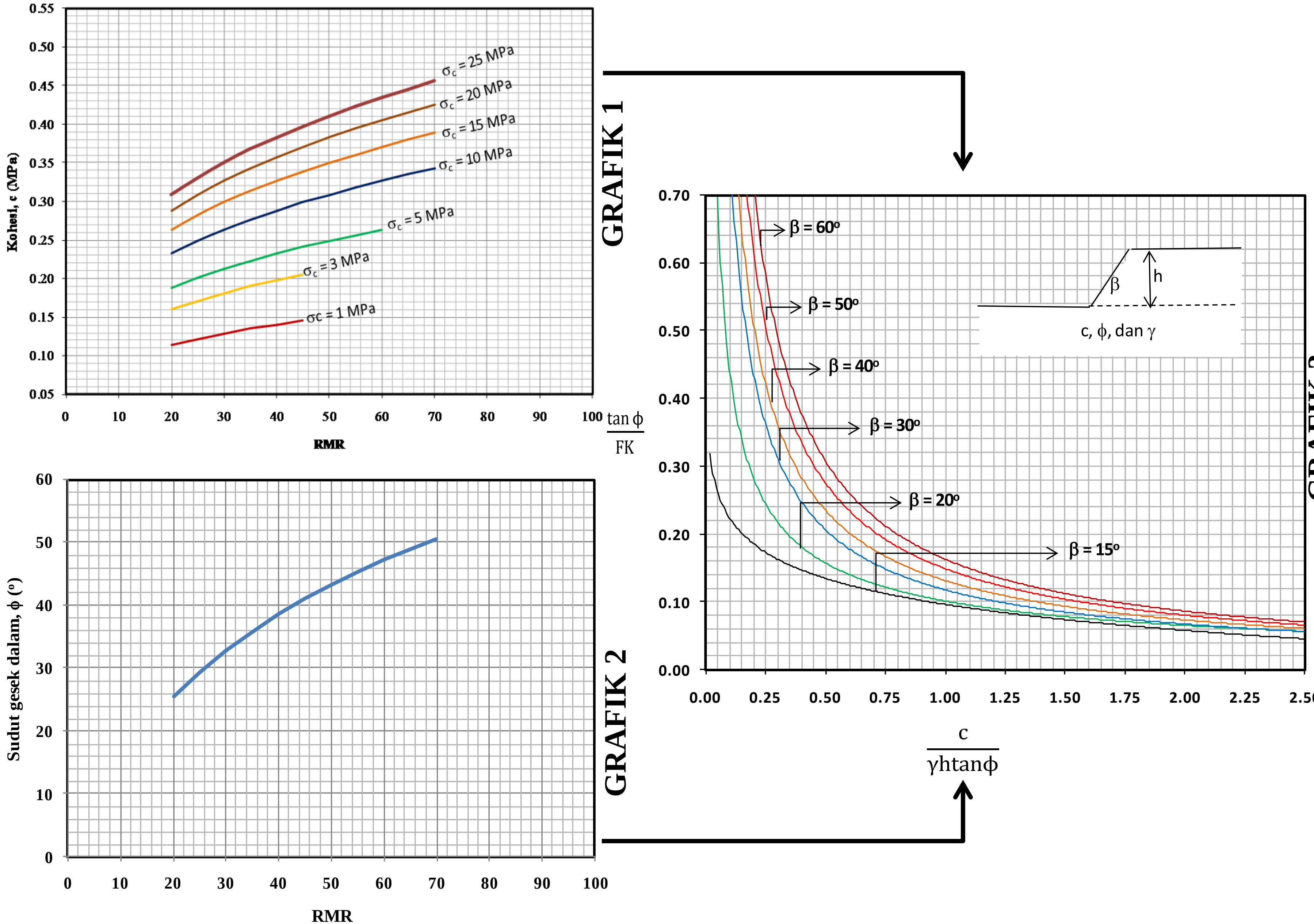
Paremeter of development slope stability on soft rock

Peneliti	Parameter Kekuatan									Pengaruh Skala			Klasifikasi		Uji
	c	ϕ	σ_c	m_i	s	m_b	a	GSI	D	σ_c	c	ϕ	RMR	GSI	
Hoek & Bray (1981)	√	√	-	-	-	-	-	-	-	-	-	-	-	-	-
Hoek & Brown (1980)	-	-	√	√	√	-	-	-	-	√	√	√	-	-	TX
Hoek & Brown (1988)	√	√	√	√	√	-	-	-	-	√	√	√	-	-	TX
Hoek & Brown (1995)	√	√	√	√	√	√	√	√	-	√	√	√	-	√	TX
Hoek & Brown (2002)	√	√	√	√	√	√	√	√	√	√	√	√	-	√	TX
Saptono (2008 – 2012)	√	√	-	-	-	-	-	-	-	-	√	√	√	-	GL

Peneliti	Jenis Batuan			Iklim		Tingkat Pelapukan		Kelas Batuan
	Beku	Sedimen	Metamorf	Tropik	Non - tropik	Tinggi	Rendah	
Hoek & Bray (1981)	-	-	-	-	√	-	√	Tanah & Timbunan
Hoek & Brown (1980)	√	-	-	-	√	-	√	Batuan
Hoek & Brown (1988)	√	-	-	-	√	-	√	Batuan
Hoek & Brown (1995)	√	-	-	-	√	-	√	Batuan
Hoek & Brown (2002)	√	-	-	-	√	-	√	Batuan
Saptono (2008 – 2012)	-	√	-	√	-	√	-	Batuan Lunak

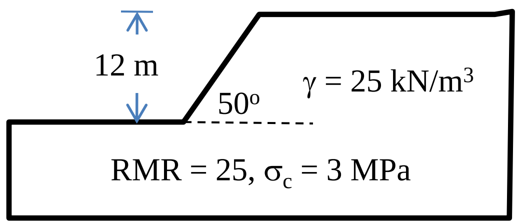
Peneliti	Bentuk Penentuan Stabilitas	Parameter penentuan FK lereng								
		c	ϕ	σ_c	m_i	GSI	RMR	γ	h	β
Hoek & Bray (1981)	Grafik	√	√	-	-	-	-	√	√	√
Hoek & Brown (2002)	Grafik Li dkk. (2008)	-	-	√	√	√	-	√	√	√
Saptono (2008 – 2012)	Grafik	√	√	√	-	-	√	√	√	√

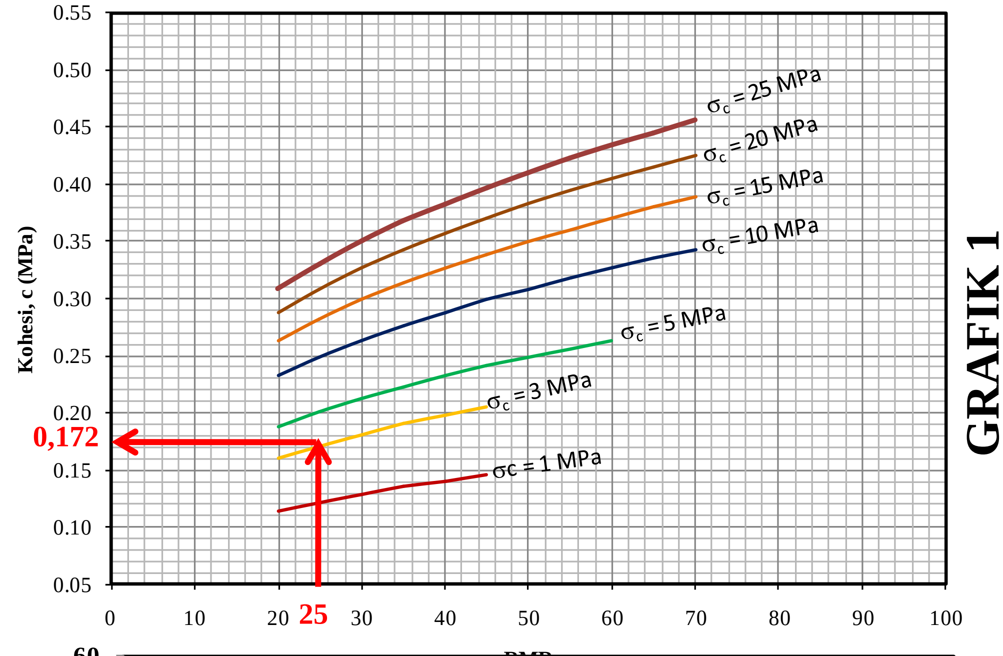
Slope stability curve (Saptono, 2012)



Example of use of stability curve (Saptono, 2012)

Example case :



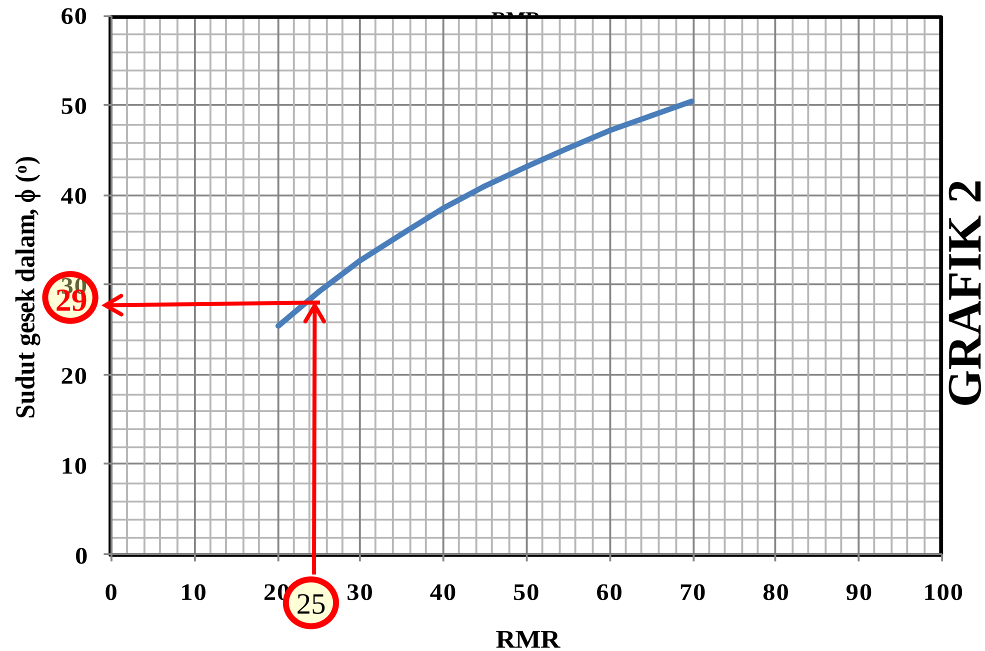


Phase 1:

Curve 1:

RMR = 25 and σ_c = 3 MPa

c = 0,172 MPa,



Phase 2:

Curve 2:

RMR = 25

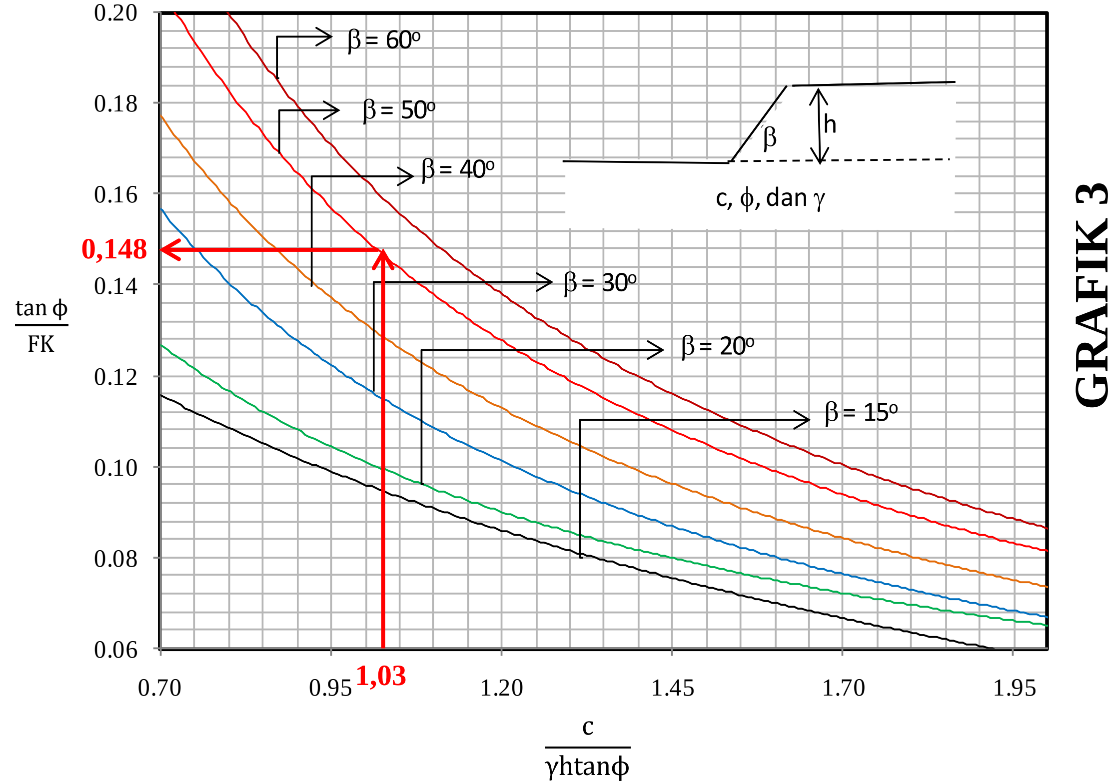
ϕ = 29º.

Example of use of stability curve (Saptono, 2012)

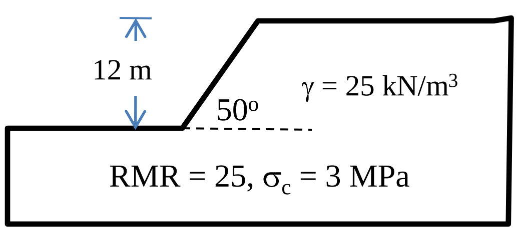
Phase 3:

Curve 3:

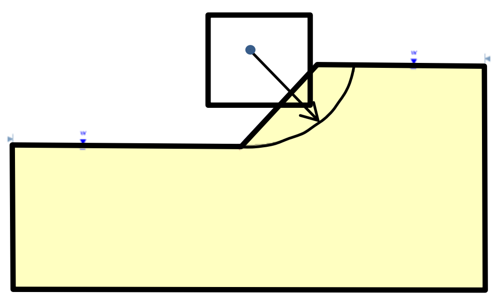
- $\beta = 50^o$
- $(c/\ \gamma h \tan \phi) = 1{,}03$
- $(\tan \phi / FK) = 0{,}148$
- $FK = (\tan \phi / 0{,}148) = 3{,}74$



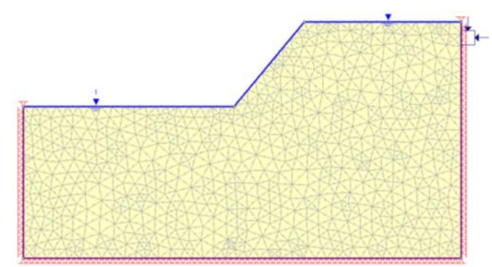
FK Grafik *)	FK KB **)	FK EH ***)
3,74	4,19	3,69



*) Grafik



**)   KB (Keseimbangan batas)



***) EH (Elemen hingga)

LESSON PART 10 & 11

FAILURE CRITERIA

Types of Failure

- **Fracture** via crack development and propagation (brittle, ductile, low- and high-cycle fatigue, etc.)
- **Yielding via plastic** (permanent) deformation of ductile materials
- **Low (High) Stiffness** due to softening (hardening) caused by aging (cyclic loading, cold work, environmental effects, etc.)
- **Instability via buckling** (abrupt decrease in stiffness with loading)
- **Creep slow increase of deformation (mostly at high temperature)**

A variety of rock failure criteria

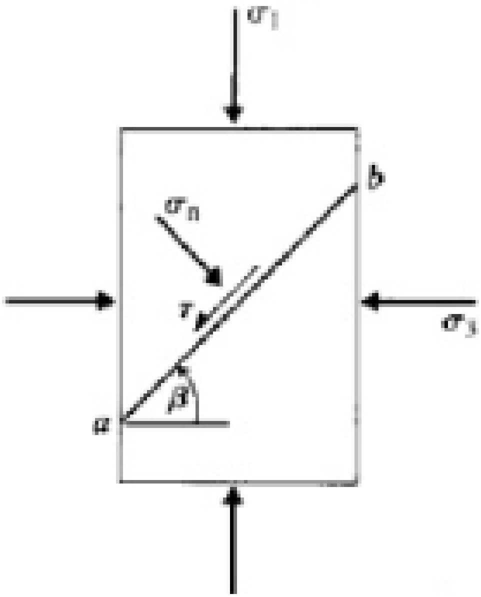
- A variety of rock failure criteria and rock constitutive models are developed based on experimental and theoretical efforts and concepts. Like, Plane Griffith Crack Theory (Griffith, 1921), Mohr- Coulomb Criterion (Coulomb, 1776) and Hoek and Brown Failure Criterion (Hoek et al., 2002)

Mohr–Coulomb failure criterion

- **The Mohr–Coulomb failure criterion represents the linear envelope that is obtained from a plot of the shear strength of a material versus the applied normal stress.**

$$\tau = \sigma \tan(\phi) + c$$

where τ is the shear strength, σ is the normal stress, c is the intercept of the failure envelope with the τ axis, and ϕ is the slope of the failure envelope.



$$\sigma_n = \frac{1}{2}(\sigma_1 + \sigma_3) + \frac{1}{2}(\sigma_1 - \sigma_3)\cos 2\beta$$

$$\tau_f = \frac{1}{2}(\sigma_1 - \sigma_3)\sin 2\beta$$

$$\sigma_1 = \frac{2c + \sigma_3[\sin 2\beta + \tan\varphi(1 - \cos 2\beta)]}{\sin 2\beta - \tan\varphi(1 + \cos 2\beta)}$$

$$\sigma_1 = \frac{2c\cos\varphi + \sigma_3(1 + \sin\varphi)}{1 - \sin\varphi}$$

$$\sigma_c = \frac{2c\cos\varphi}{1 - \sin\varphi}$$

$$\sigma_T = \frac{2c\cos\varphi}{1 + \sin\varphi}$$

Hoek and brown criterion (2002)

- **This criterion which is one of the most important rock failure criteria widely applied by rock mechanics specialists can be used for both intact rocks and rock masses.**

$$\sigma_1' = \sigma_3' + \sigma_{ci}\left(m\frac{\sigma_3'}{\sigma_{ci}} + s\right)^{0.5}$$

Where σ_1‘ and σ_3‘ are the major and minor effective principal stresses at failure σ_{ci} is the uniaxial compressive strength of the intact rock material and m and s are material constants, where s = 1 for intact rock.

Hoek and brown criterion (2002)

$$\sigma_1' = \sigma_3' + \sigma_{ci}\left(m_b \frac{\sigma_3'}{\sigma_{ci}} + s\right)^a$$

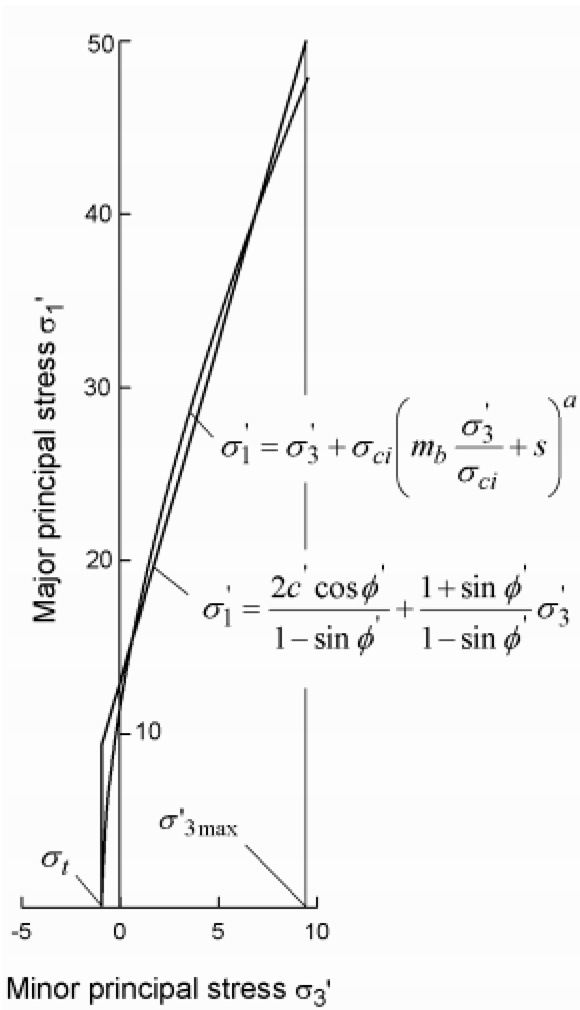
$$s = \exp\left(\frac{GSI - 100}{9 - 3D}\right)$$

$$m_b = m_i \exp\left(\frac{GSI - 100}{28 - 14D}\right)$$

$$a = \frac{1}{2} + \frac{1}{6}\left(e^{-GSI/15} - e^{-20/3}\right)$$

In which, σ_{ci} and D are uniaxial compressive strength of intact rock and disturbance factor, respectively. Also m_i, s and a are material constants which depend on material quality. And, GSI is Geological Strength Index (Hoek et al.,2002).

MOHR-COULOMB CRITERION



$$\phi' = \sin^{-1}\left[\frac{6am_b(s+m_b\sigma'_{3n})^{a-1}}{2(1+a)(2+a)+6am_b(s+m_b\sigma'_{3n})^{a-1}}\right]$$

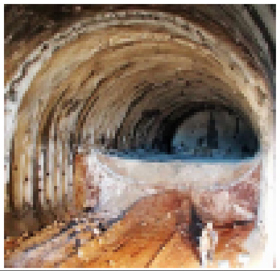
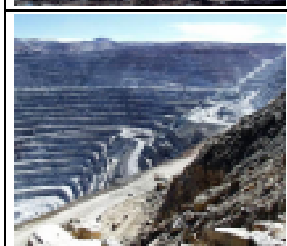
$$c' = \frac{\sigma_{ci}\left[(1+2a)s+(1-a)m_b\sigma'_{3n}\right](s+m_b\sigma'_{3n})^{a-1}}{(1+a)(2+a)\sqrt{1+\left(6am_b(s+m_b\sigma'_{3n})^{a-1}\right)/\left((1+a)(2+a)\right)}}$$

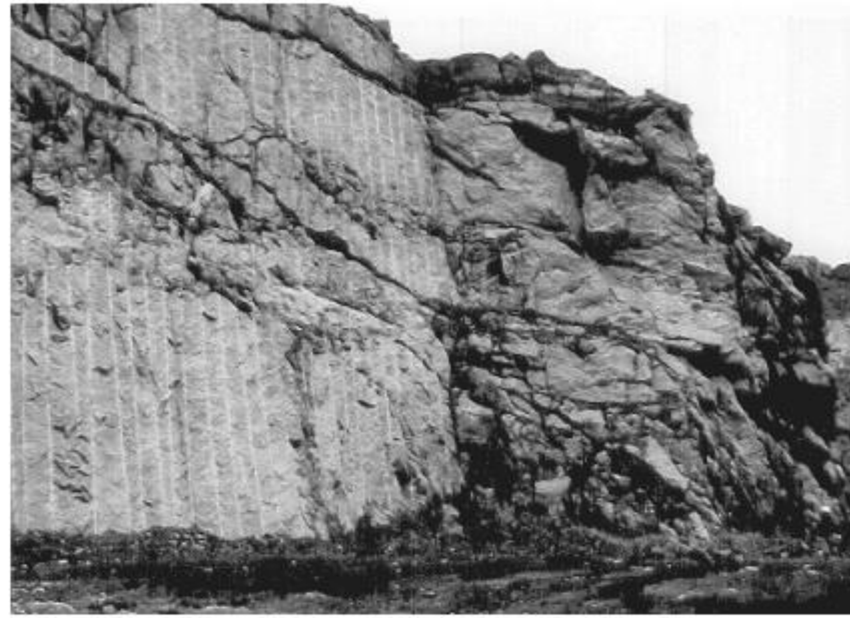
Table 2. Values of the constant m_i for intact rock, by rock group. Note that values in parenthesis are estimates.

Rock type	Class	Group	Texture: Coarse	Texture: Medium	Texture: Fine	Texture: Very fine
SEDIMENTARY	Clastic		Conglomerate (22)	Sandstone 19	Siltstone 9	Claystone 4
				——— Greywacke (18) ———		
	Non-Clastic	Organic		——— Chalk 7 ———		
				——— Coal (8-21) ———		
		Carbonate	Breccia (20)	Sparitic Limestone (10)	Micritic Limestone 8	
		Chemical		Gypstone 16	Anhydrite 13	
METAMORPHIC	Non Foliated		Marble 9	Hornfels (19)	Quartzite 24	
	Slightly foliated		Migmatite (30)	Amphibolite 25 - 31	Mylonites (6)	
	Foliated*		Gneiss 33	Schists 4 - 8	Phyllites (10)	Slate 9
IGNEOUS	Light		Granite 33		Rhyolite (16)	Obsidian (19)
			Granodiorite (30)		Dacite (17)	
			Diorite (28)		Andesite 19	
	Dark		Gabbro 27	Dolerite (19)	Basalt (17)	
			Norite 22			
	Extrusive pyroclastic type		Agglomerate (20)	Breccia (18)	Tuff (15)	

* These values are for intact rock specimens tested normal to bedding or foliation. The value of m_i will be significantly different if failure occurs along a weakness plane.

Table 1: Guidelines for estimating disturbance factor D

Appearance of rock mass	Description of rock mass	Suggested value of D
	Excellent quality controlled blasting or excavation by Tunnel Boring Machine results in minimal disturbance to the confined rock mass surrounding a tunnel.	$D = 0$
	Mechanical or hand excavation in poor quality rock masses (no blasting) results in minimal disturbance to the surrounding rock mass. Where squeezing problems result in significant floor heave, disturbance can be severe unless a temporary invert, as shown in the photograph, is placed.	$D = 0$ $D = 0.5$ No invert
	Very poor quality blasting in a hard rock tunnel results in severe local damage, extending 2 or 3 m, in the surrounding rock mass.	$D = 0.8$
	Small scale blasting in civil engineering slopes results in modest rock mass damage, particularly if controlled blasting is used as shown on the left hand side of the photograph. However, stress relief results in some disturbance.	$D = 0.7$ Good blasting $D = 1.0$ Poor blasting
	Very large open pit mine slopes suffer significant disturbance due to heavy production blasting and also due to stress relief from overburden removal. In some softer rocks excavation can be carried out by ripping and dozing and the degree of damage to the slopes is less.	$D = 1.0$ Production blasting $D = 0.7$ Mechanical excavation



Comparison between the results achieved by controlled blasting (on the left) and normal bulk blasting for a surface excavation in gneiss.

Table 5. Estimate of Geological Strength Index GSI based on geological descriptions.

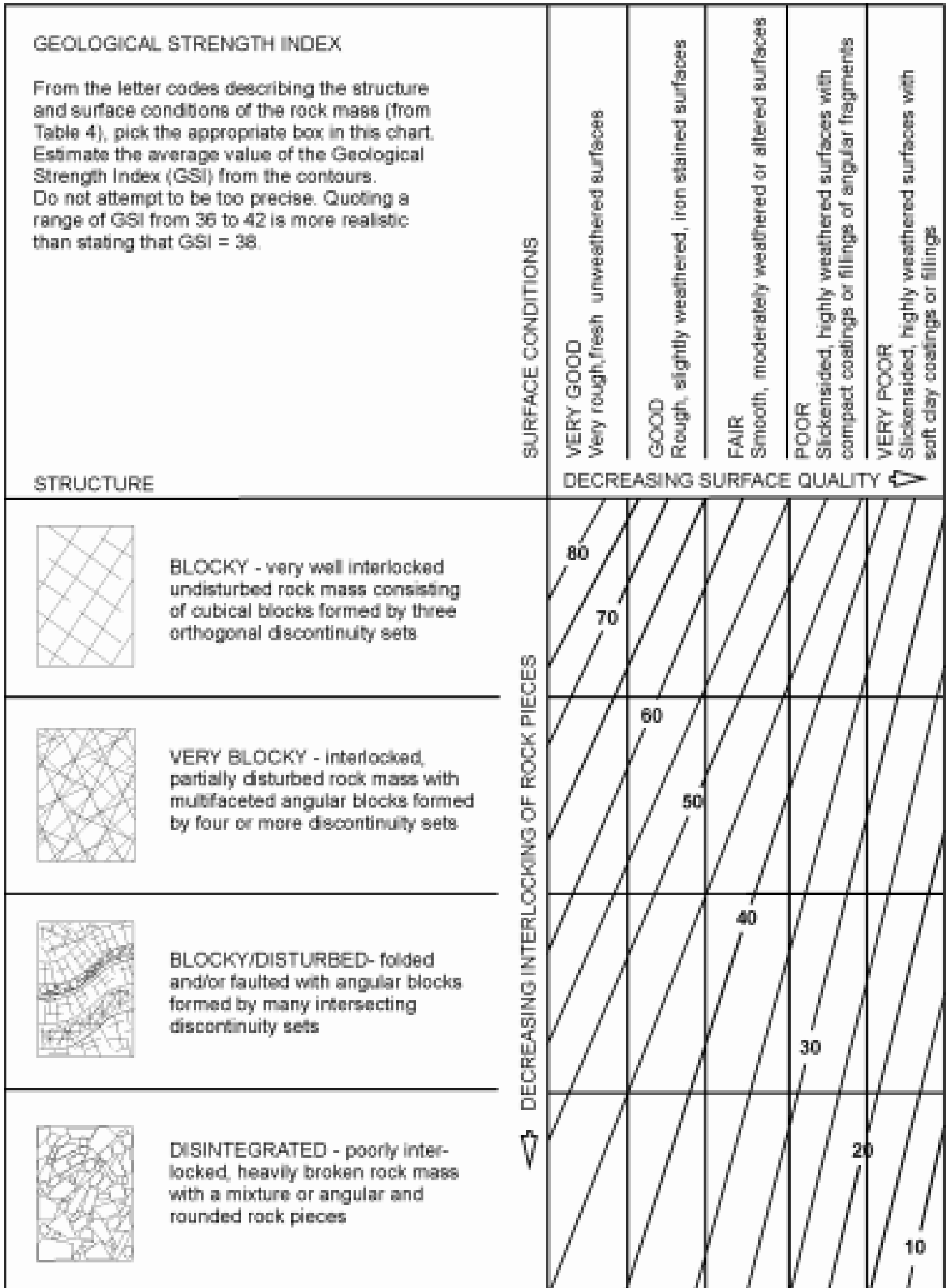


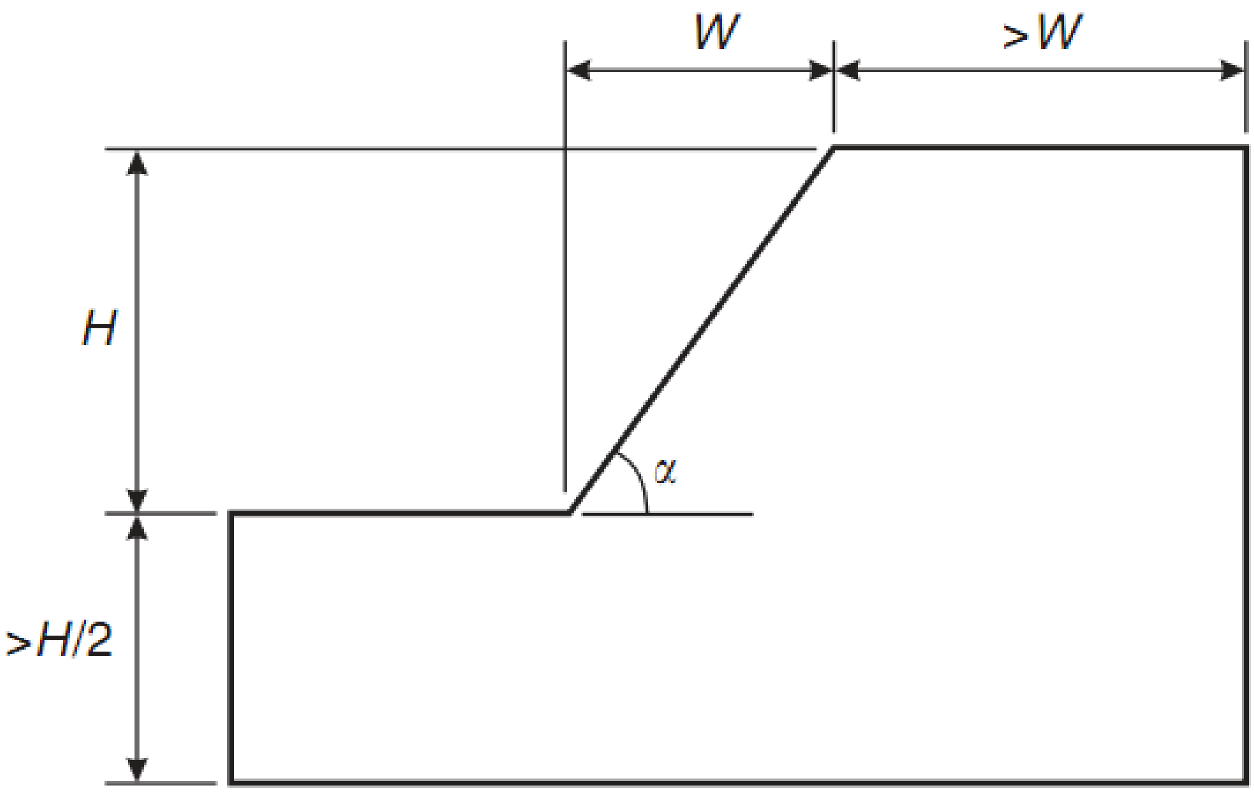
Fig. 23. Structurally controlled failure in the face of a steep bench in a heavily jointed rock mass.

LESSON PART 12

Numerical analysis

Analysis result	*Numerical solution*	*Limit equilibrium*
Equilibrium	Satisfied everywhere	Satisfied only for specific objects, such as slices
Stresses	Computed everywhere using field equations	Computed approximately on certain surfaces
Deformation	Part of the solution	Not considered
Failure	Yield condition satisfied everywhere; slide surfaces develop "automatically" as conditions dictate	Failure allowed only on certain pre-defined surfaces; no check on yield condition elsewhere
Kinematics	The "mechanisms" that develop satisfy kinematic constraints	A single kinematic condition is specified according to the particular geologic conditions

Boundary conditions

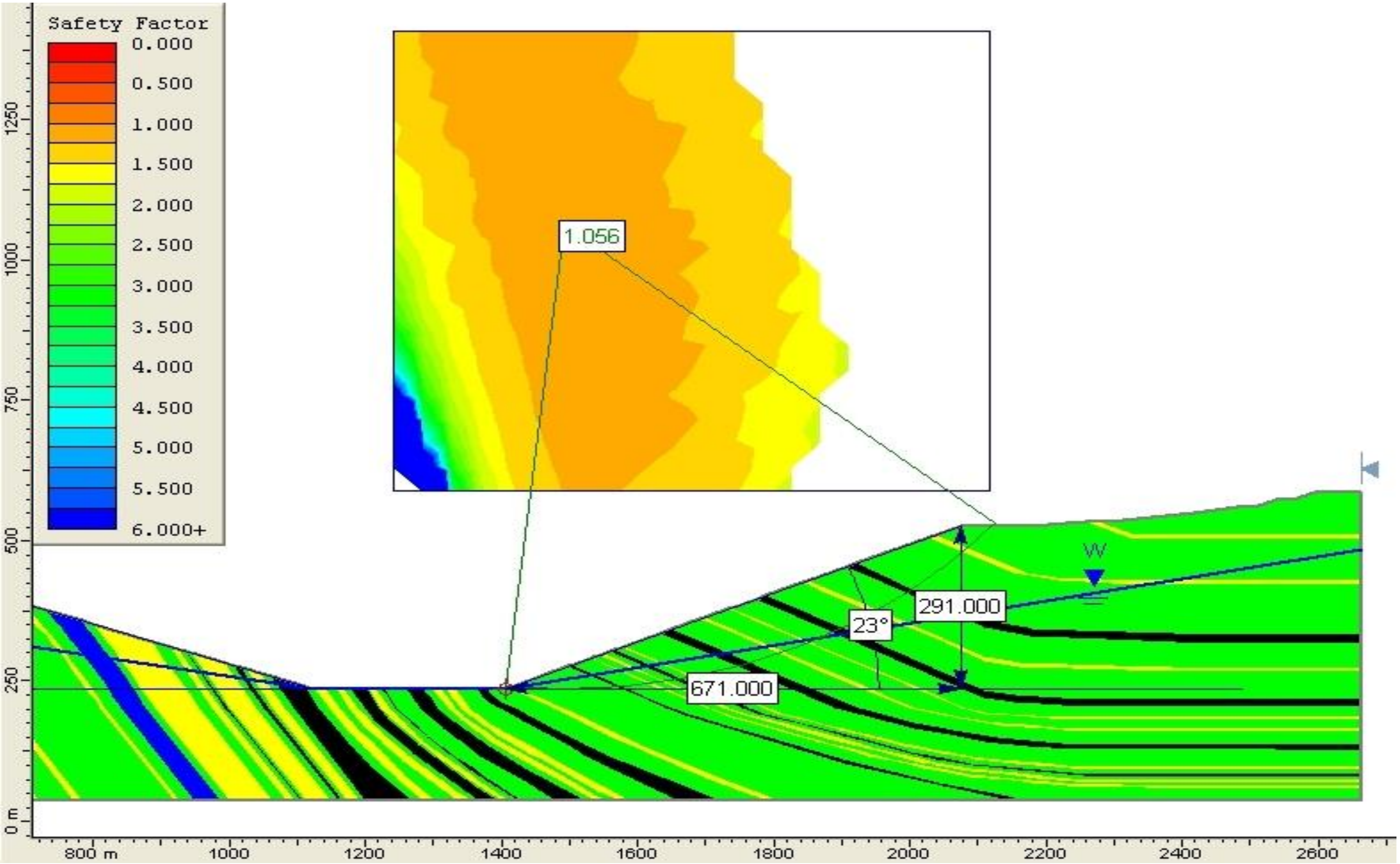


Typical recommendations for locations of artificial far-field boundaries in slope stability analyses

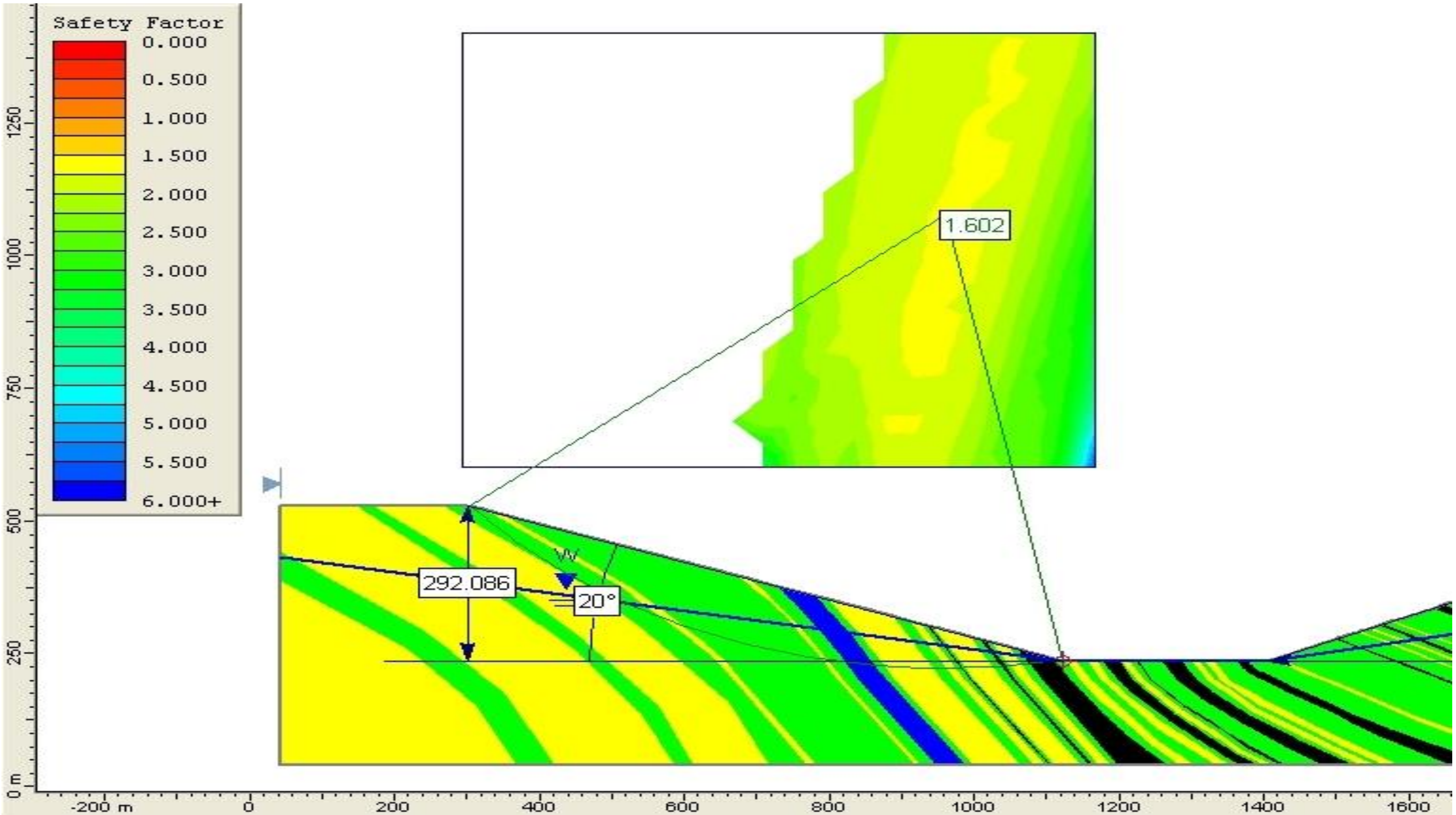
Slope Rock Mass Classification

- RMR - Rock mass rating (Bieniawski, 1976 & 1989)
- MRMR - Mining rock mass rating (Laubscher, 1977 & 1990)
- RMS - Rock mass strength (Sleby, 1980)
- SMR - Slope mass rating (Romana, 1985)
- SRMS - Slope rock mass rating (Robertson, 1988)
- CSMR - Chinese system for SMR (Chen, 1995)
- GSI - Geological strength index (Hoek et al, 1995)
- M-RMR - Modified rock mass classification (Unal, 1996)
- BQ - Index of rock mass basic quality (Lin, 1998)

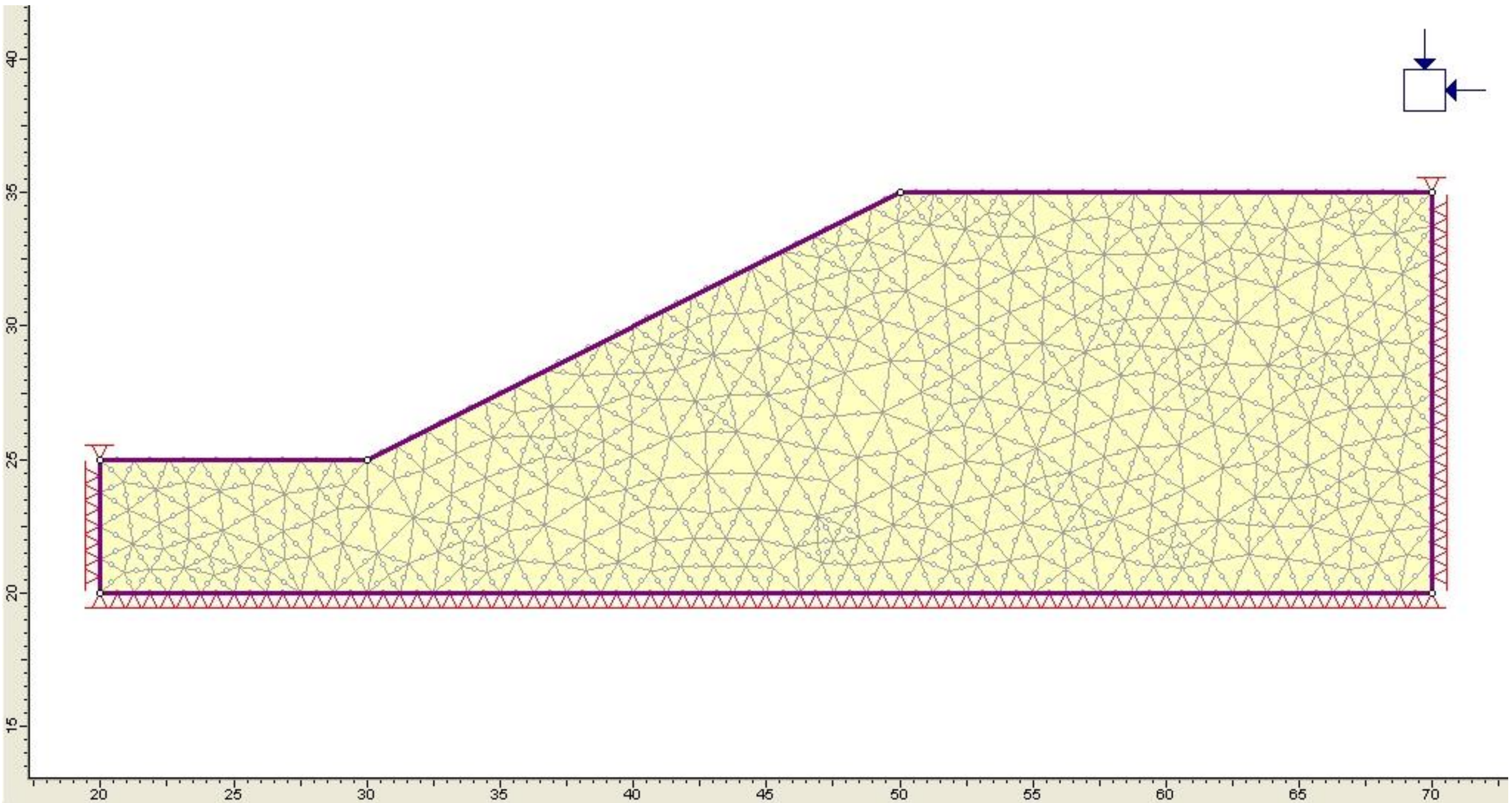
Equilibrium method for analysis stability



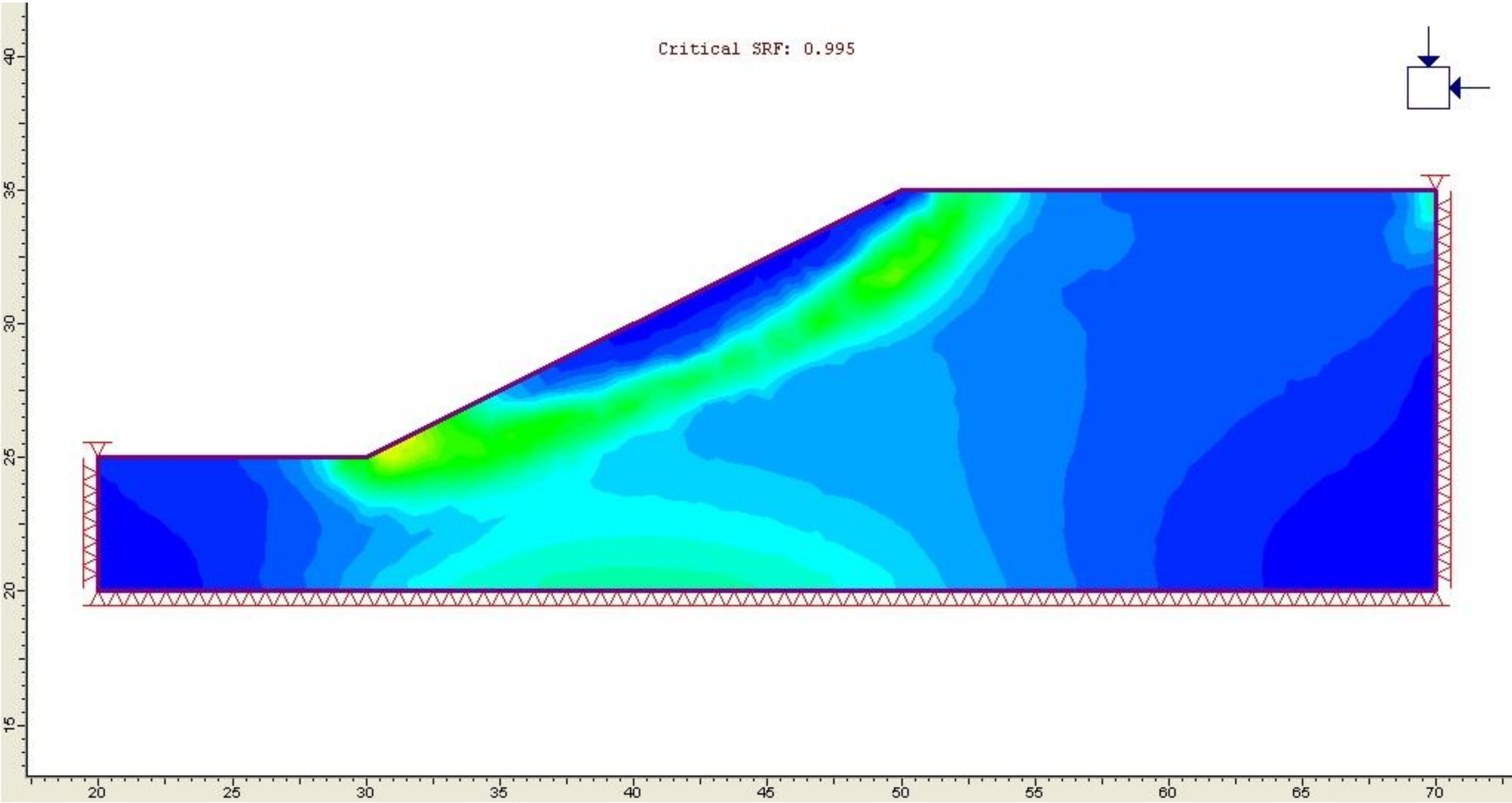
Equilibrium method for analysis stability on low wall surface coal mining



Slope model, analysis with numerical method for single slope



Slope model, the result of analysis with numerical method for single slope



LESSON PART 13

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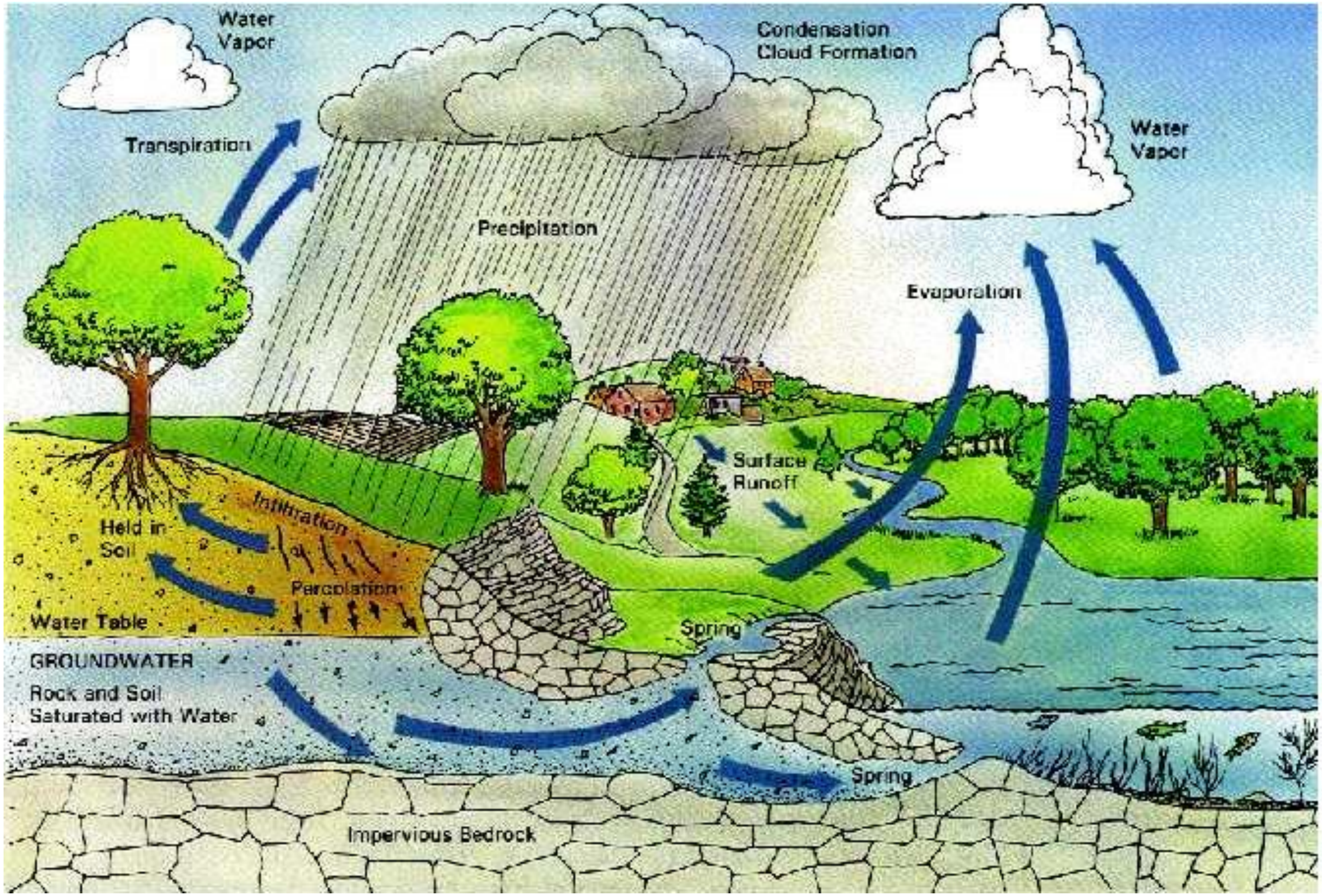
The hydrological cycle

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Vertical Drain Hole

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Drain Hole

Mine Water Management

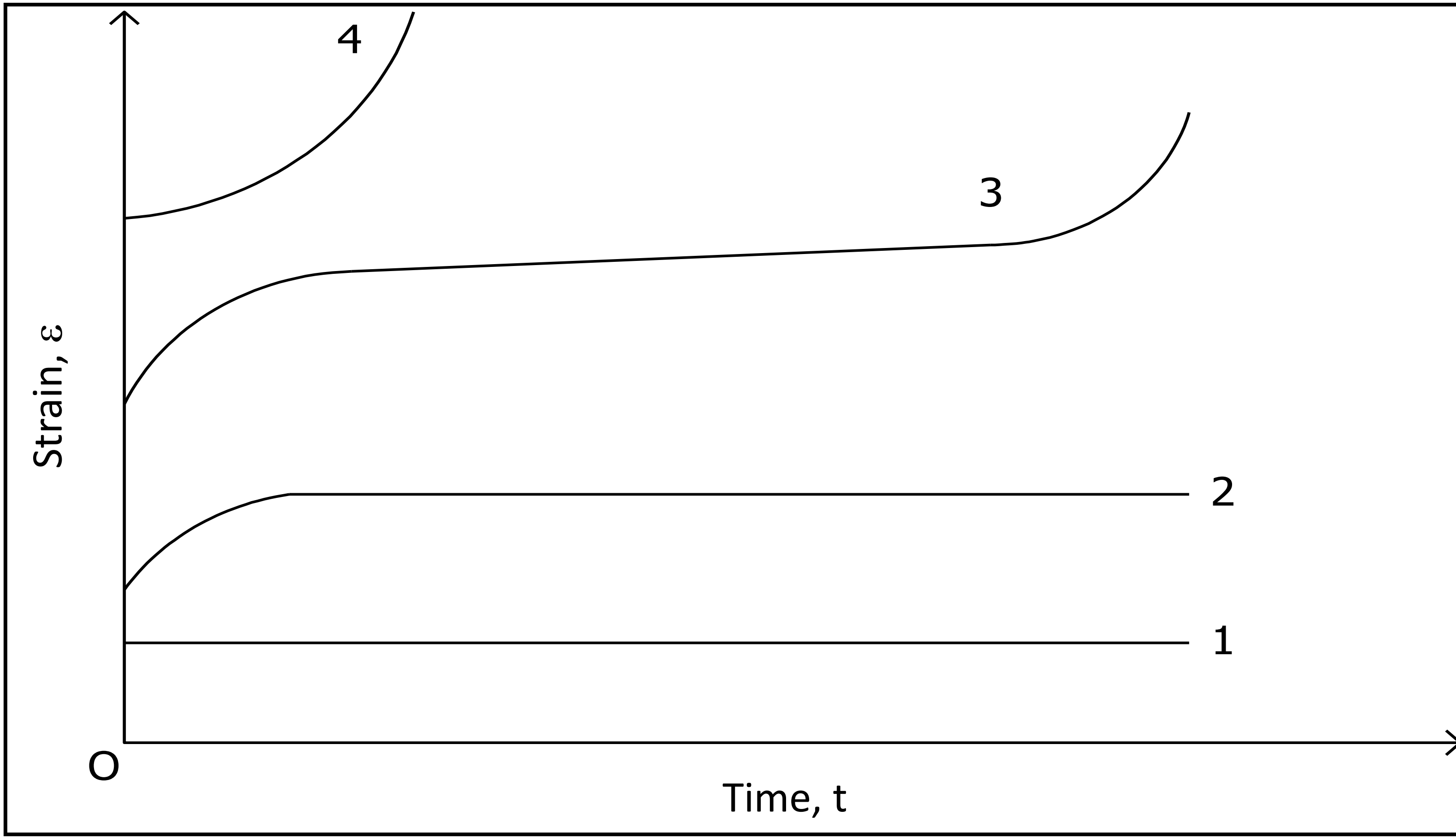
LESSON PART 14

Monitoring System

Monitoring (Brady & Brown, 1985)

a) to record the natural values of, and variations in, geotechnical parameters such as water table level, ground levels and seismic events before the initiation of an engineering project;
b) to ensure safety during construction and operation by giving warning of the development of excess ground deformations, groundwater pressures and loads in support and reinforcement elements, for example;
c) to check the validity of the assumptions, conceptual models and values of soil or rock mass properties used in design calculations;
d) to control the implementation of ground treatment and remedial works such as ground freezing during shaft sinking or tunnelling throughwater-bearing ground, grouting, drainage or the provision of support and reinforcement.

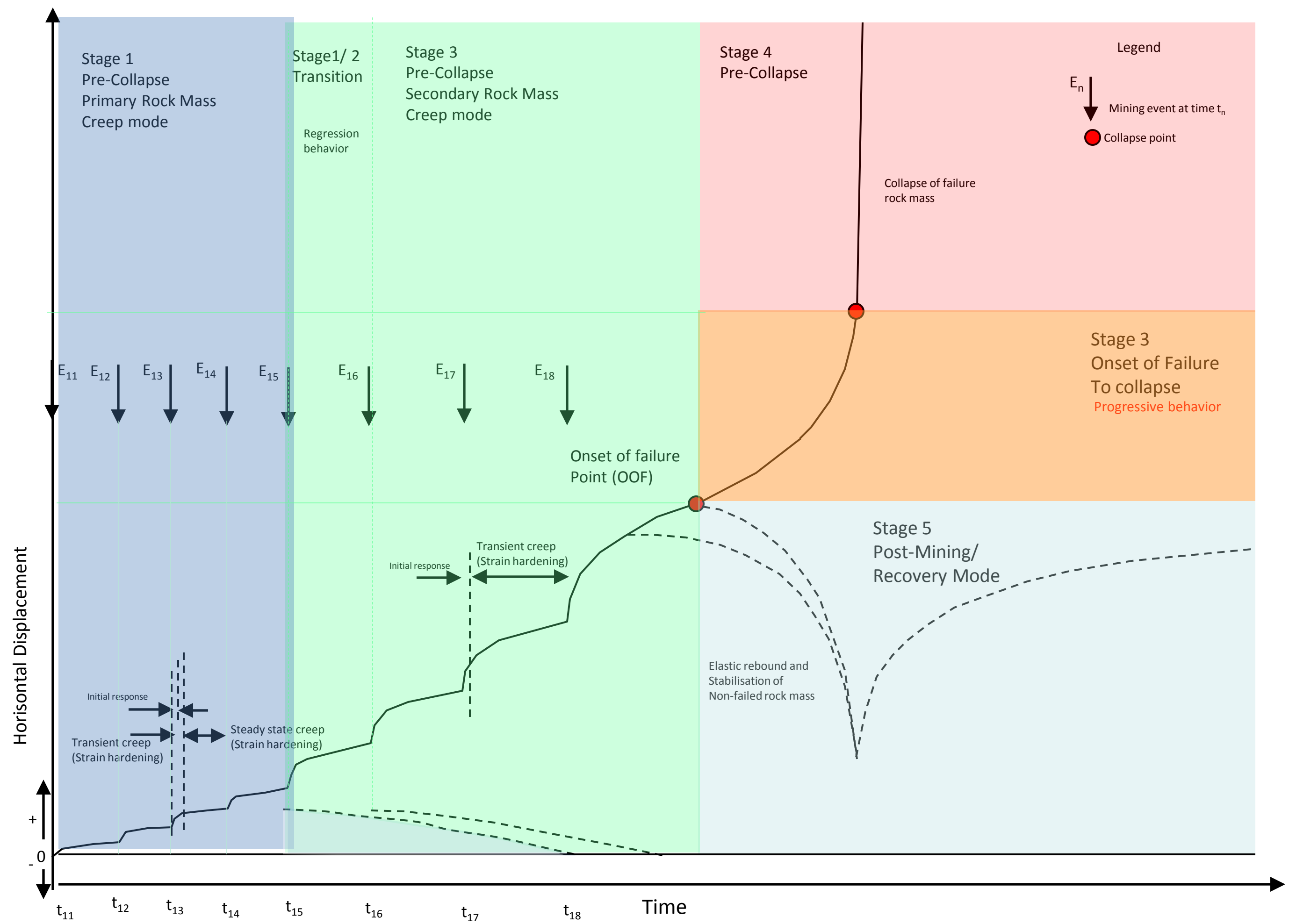
Effect of normal stress level of the process creep (Rai, 1993)



Criterion:

- Curve 1 : There is no creep
- Curve 2 : Stable (no failure)
- Curve 3 : The pseudo-stability, because a failure can occur once upon a time
- Curve 4 : Soon failure

The pattern of displacement for horizontal displacement behavior (Mercer and Stacey, 2008)



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Displacement monitoring

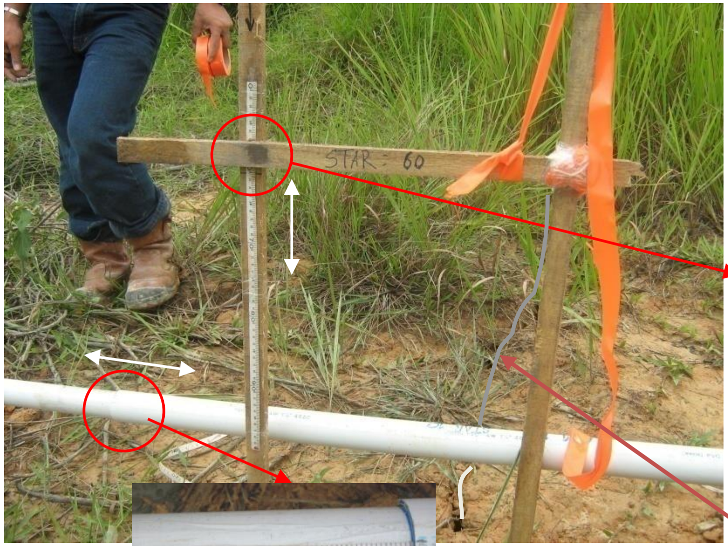
- “Total Station”: Electronic Distance Measurement (EDM) + Theodolite
- “DGPS” Different Global Positioning System: Base station + measuring stations

Slope Stability Radar

Slope Stability Radar

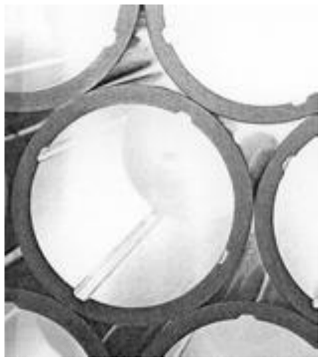
Surface rod extensometer (Crackmeter)

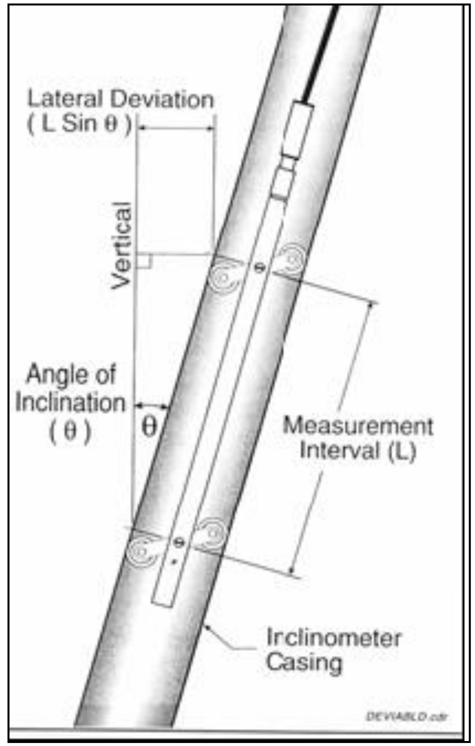
Vibrating wire displacement gauge (or a vernier for manual readings or a linier transducer) accuracy < 1 mm

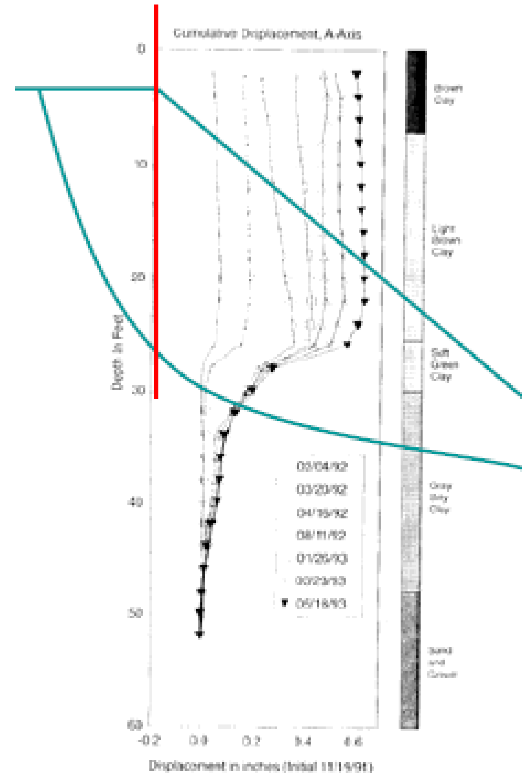


Tension crack

Borehole Inclinometer (Slope indicator)







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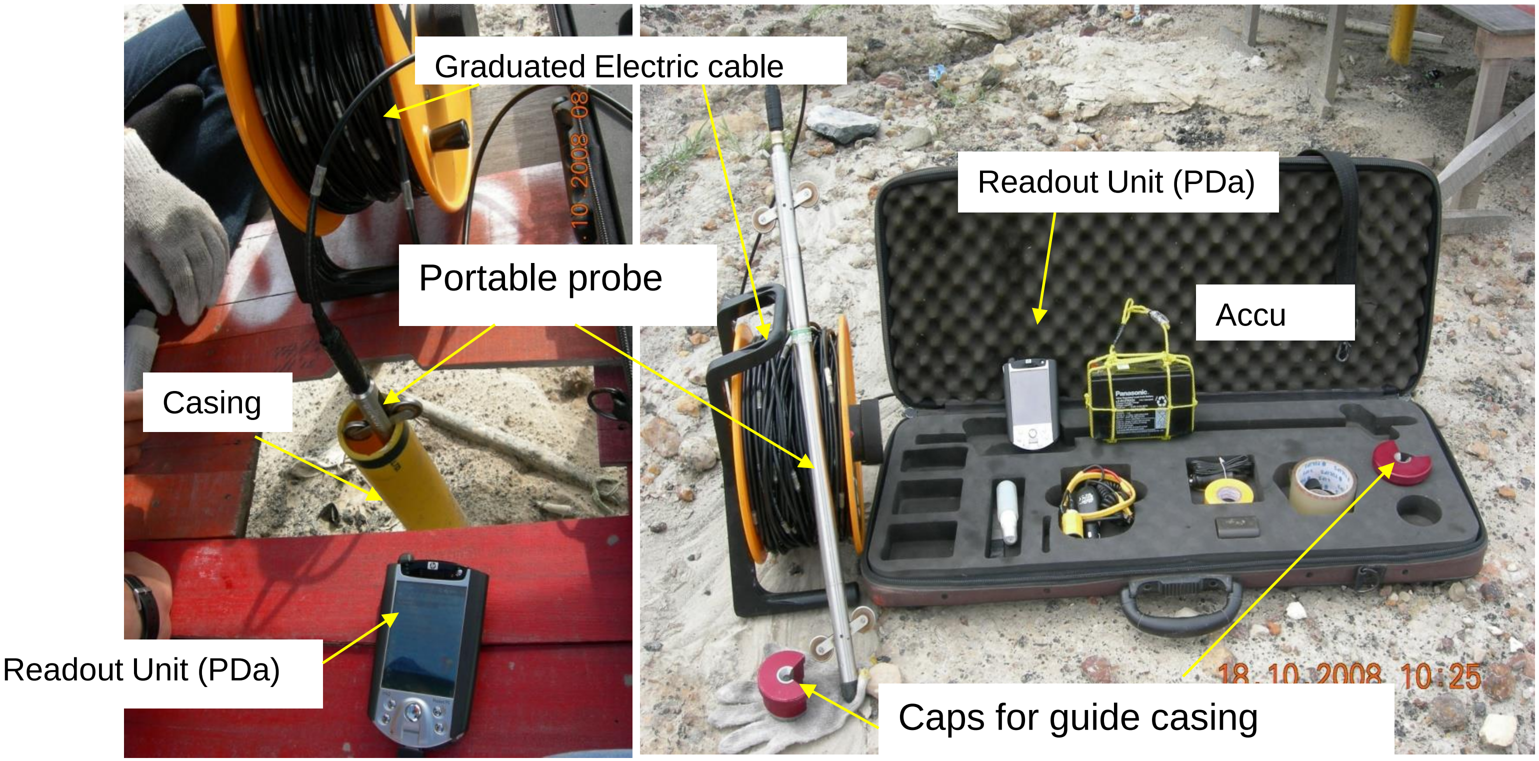
Borehole Inclinometer (Slope indicator)



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