6. Some empirical approaches to evaluating bimrocks

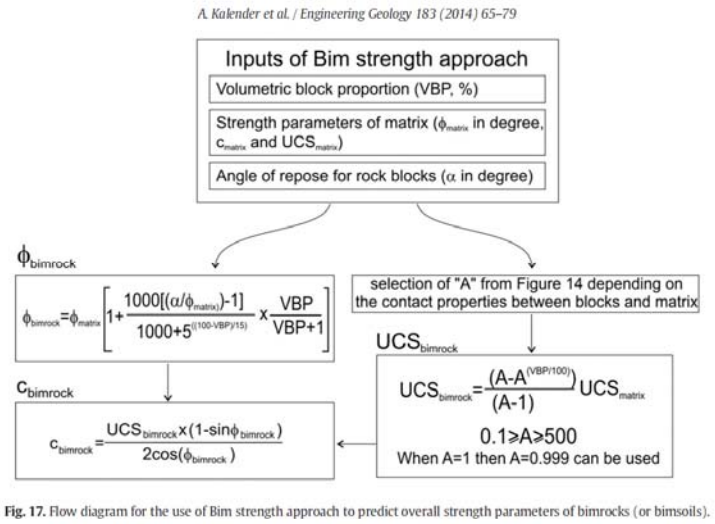

Fig. 17. Flow diagram for the use of Bim strength approach to predict overall strength parameters of bimrocks (or bimsoils).

Geotechnical and Geological Engineering with Melanges, Fault Rocks and Other Bimrocks

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Aula Máxima Facultad de Minas
Sept 18 -22 2017

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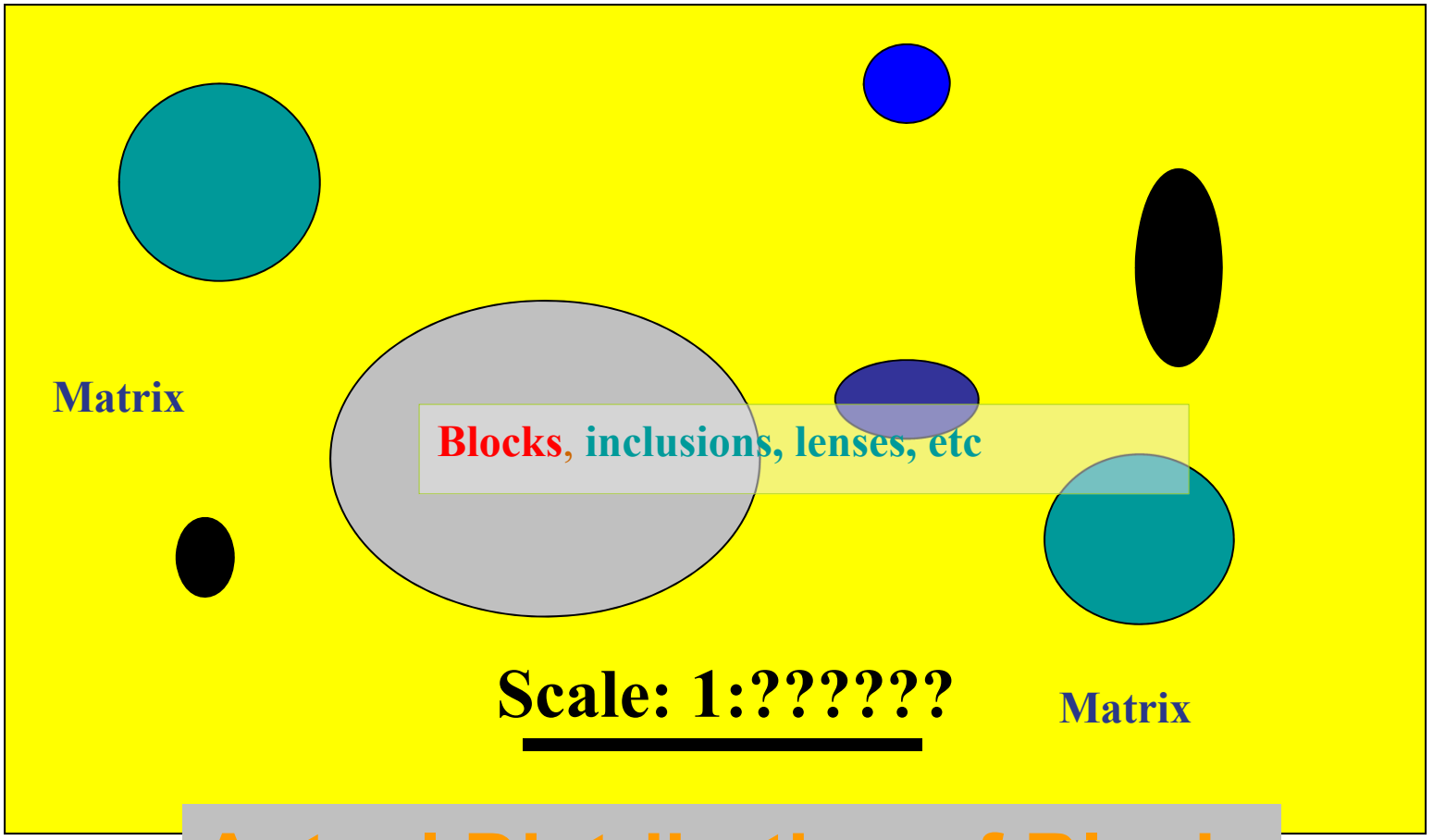
BIG CONCLUSION 1: Remember this picture!!!



Actual Distribution of Blocks

Medley, 2000

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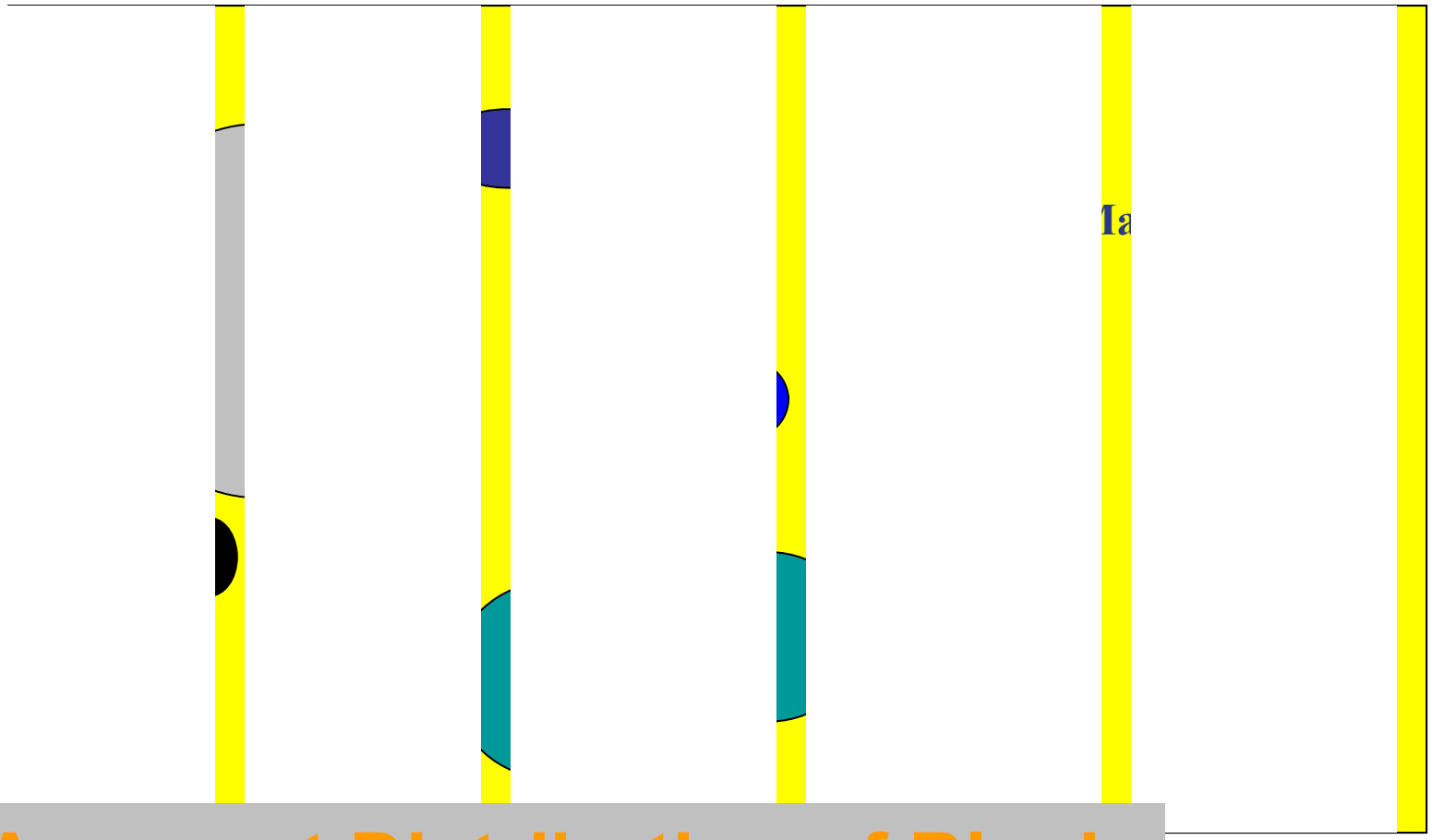
BIG CONCLUSION 2: Remember this picture as well!!!



Apparent Distribution of Blocks

Willis, 2000

engineering

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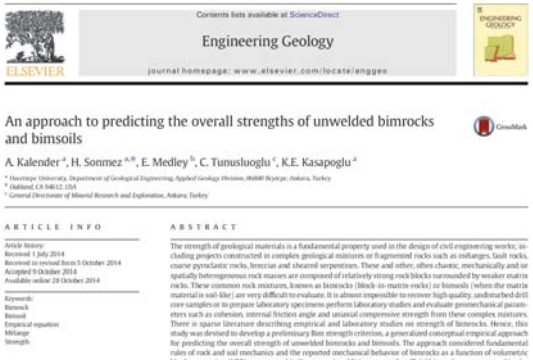
Prof. Harun Sönmez' empirical method for bimrocks

- see Kalendar (2014) for full description
- method based on large database of geotech data for bimrocks
- simple input parameters such as compressive strength of matrix, volumetric block proportion, shape and angularity of blocks, and angle of repose of blocks
- Method requires estimate of Parameter "A": a measure of block/matrix contact strength (see chart following)
- Method uses several empirically-derived equations. Looks a bit frightening, but can use spreadsheet formulae to do calcualtions!



Contents lists available at ScienceDirect

Engineering Geology

journal homepage: www.elsevier.com/locate/enggeo

An approach to predicting the overall strengths of unwelded bimrocks and bimsoils

A. Kalender [a], H. Sonmez [a,*], E. Medley [b], C. Tunusluoglu [c], K.E. Kasapoglu [a]

ARTICLE INFO

ABSTRACT

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Method requires estimate of Parameter “A”: a measure of block/matrix contact strength. Can use useful guide below

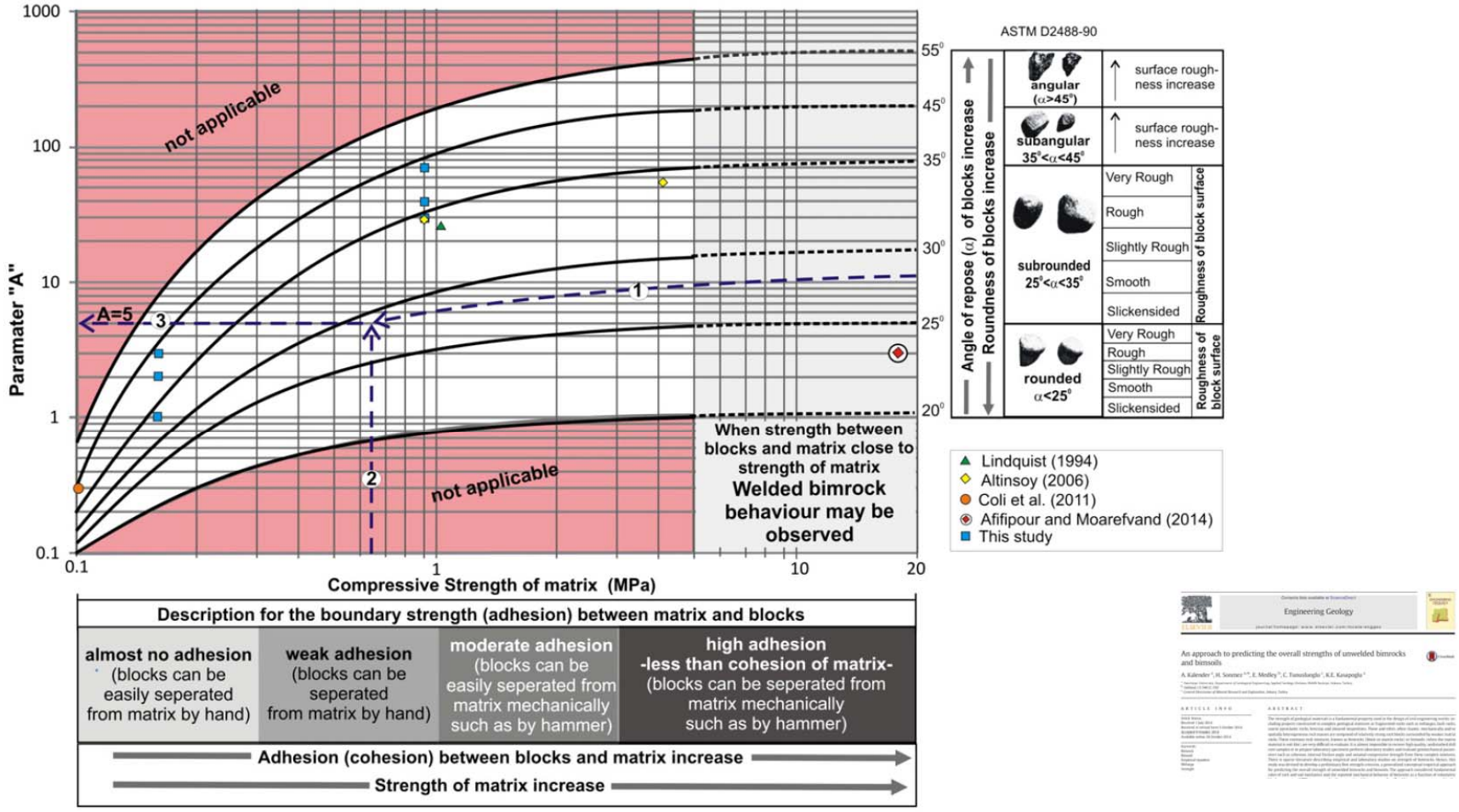

Fig. 14. A practical guide for the selection of “A” depending on the contact properties between blocks and matrix.

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step-by-step procedure provides $\phi_{bimrock}$, $c_{bimrock}$ and $UCS_{bimrock}$

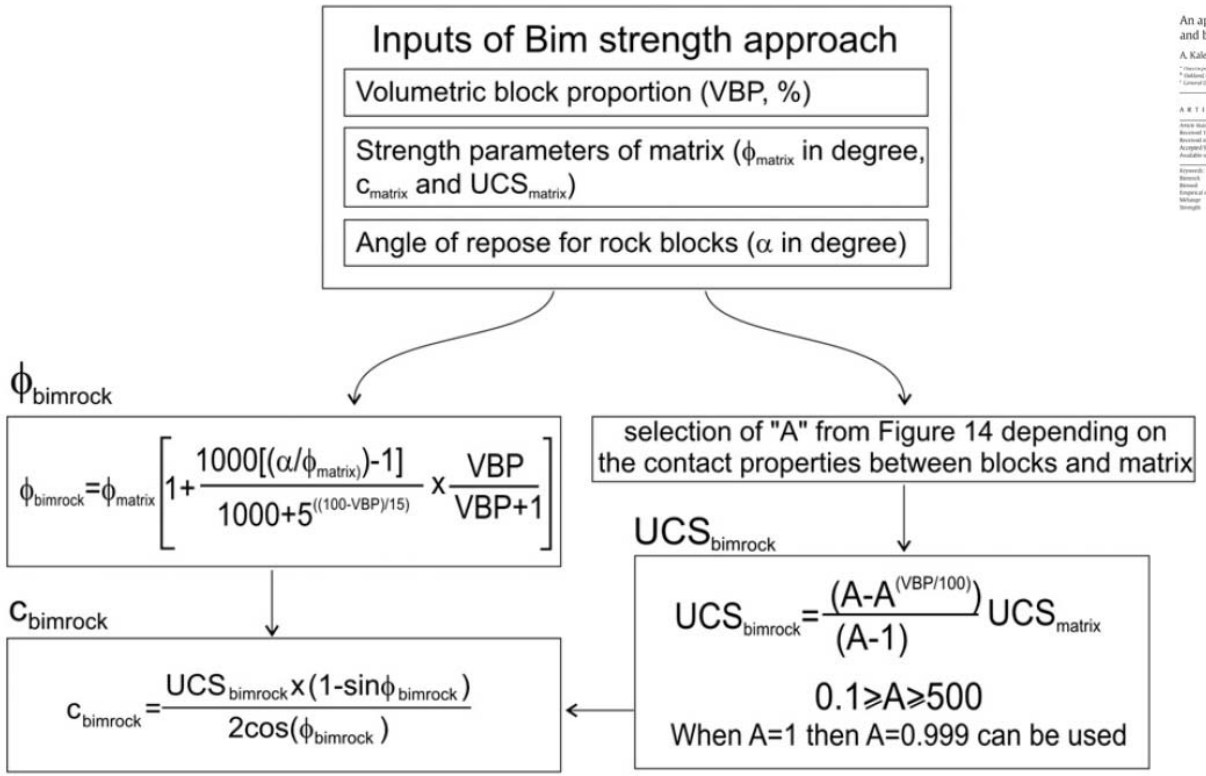

Fig. 17. Flow diagram for the use of Bim strength approach to predict overall strength parameters of bimrocks (or bimsoils).

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Method used to back-calculate all measured input data aginst predicted $\phi_{bimrock}$ and $c_{bimrock}$ values – for validity

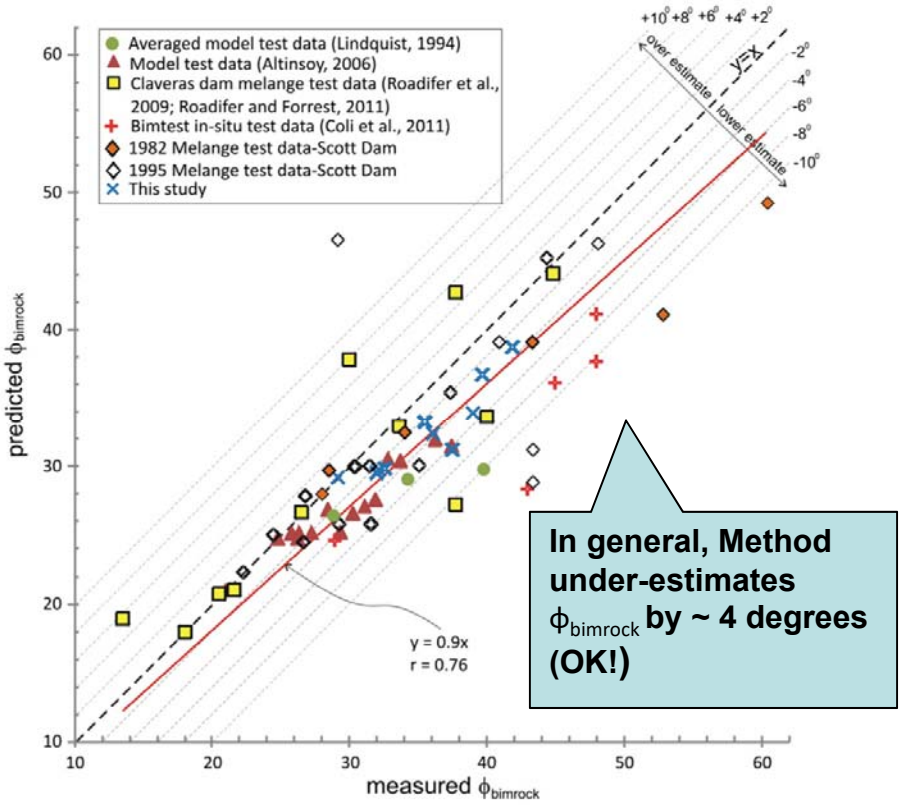

Fig. 15. Prediction performance of preliminary Bim strength criterion on the values of $\phi_{bimrock}$.

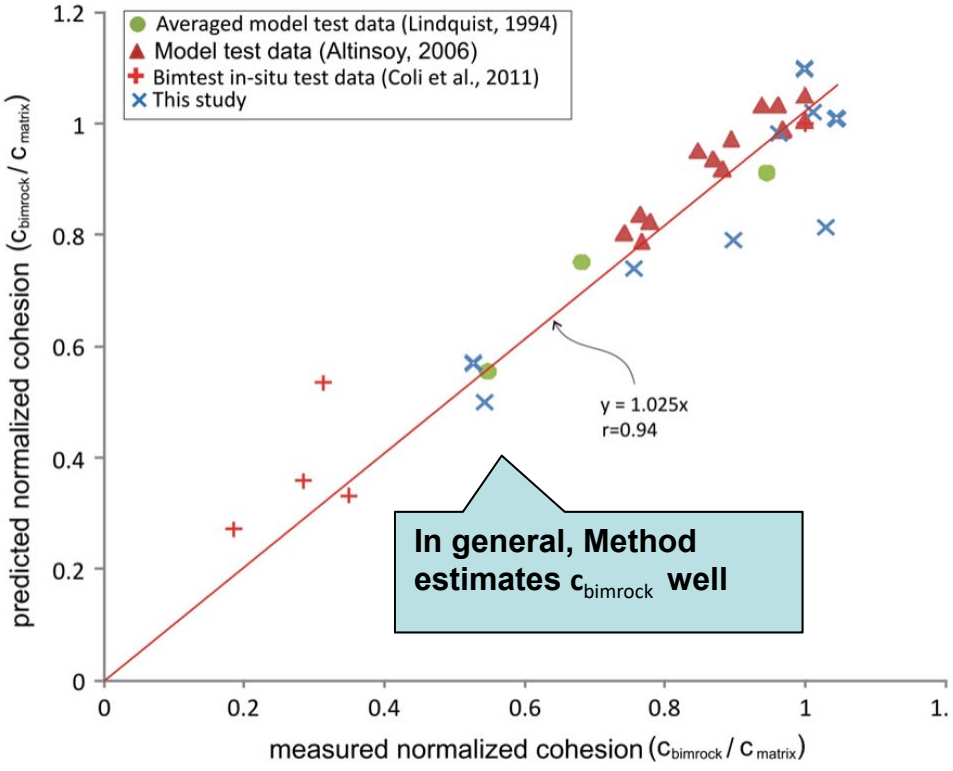

Fig. 16. Prediction performance of preliminary Bim strength criterion on the values of $c_{bimrock}$.

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Rockmass Strength Characterization Hoek-Brown Failure Criterion Approach

Hoek-Brown Criterion characterizes the **strength of the rock mass**

- Mathematical equations involving 4 parameters that are selected based on geologic characterization and laboratory testing.
- Estimation of c and ϕ produces linear Mohr-Coulomb failure envelopes. Can also produce non-linear plots.
- All this is made by **RocLab**, a free program by RocScience (www.rocscience.com)

Input parameters

- **GSI** Geologic Strength Index
- σ_{ci} Intact rock Uniaxial Compressive Strength
- m_i material parameter
- **D** disturbance factor

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Hoek-Brown Failure Criterion with GSI (Geological Strength Index) suitable for bimrocks

- Hoek-Brown Failure Criterion method since originally developed in 1936 (for concrete) (see Hoek, 2004). Adapted by Hoek and Brown for rock masses by incorporation of Bieniawski's Rock Mass Rating system in 1980
- Has undergone many changes, principally by using Paul Marinos' GSI (Geological Strength Index)
- GSI also adapted several times, including incorporation of chaotic rock masses such as flysch and melanges (see Marinos, Hoek and Marionos, 2005)
- Most recent GSI is 2010 arranged P. Marinos for several rock mass types including heterogeneous masses
- As in most empirical approaches, there are a set of scarey-looking equations, involving parameters that generally have to be estimated from charts, testing and/or experience.

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Current Hoek-Brown Criterion

Hoek, Carranza-Torres and Corkum, 2002

A new set of relationships between GSI, m_b, s and a is introduced to give a smoother transition between very poor quality rock masses (GSI < 25) and stronger rocks. A disturbance factor D to account for stress relaxation and blast damage is also introduced. Equations for the calculation of Mohr Coulomb parameters c and ϕ are introduced for specific ranges of the confining stress σ'_{3max} for tunnels and slopes.

All of these equations are incorporated into the Windows program RocLab that can be downloaded from the Internet site www.rocscience.com. A copy of the full paper is included with the download.

$$\sigma'_1 = \sigma'_3 + \sigma_{ci}\left(m_b \sigma'_3/\sigma_{ci} + s\right)^a$$

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

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

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

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

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

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

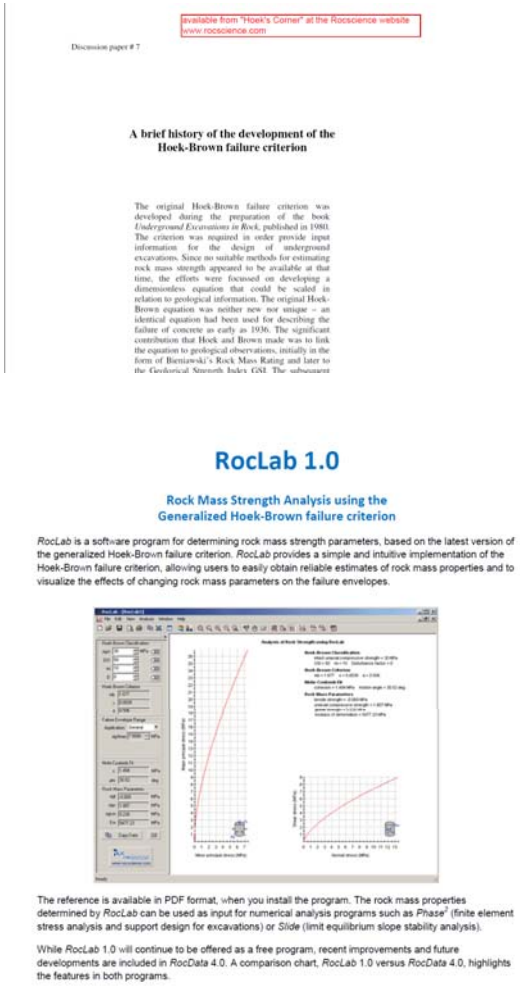
where, for tunnels

$$\frac{\sigma'_{3\max}}{\sigma'_{cm}} = 0.47\left(\frac{\sigma'_{cm}}{\gamma H}\right)^{-0.94}$$ - H is the depth below surface

for slopes

$$\frac{\sigma'_{3\max}}{\sigma'_{cm}} = 0.72\left(\frac{\sigma'_{cm}}{\gamma H}\right)^{-0.91}$$ - H is the slope height

γ is the unit weight of the rock mass



available from "Hoek's Corner" at the Rocscience website www.rocscience.com

Discussion paper # 7

A brief history of the development of the Hoek-Brown failure criterion

The original Hoek-Brown failure criterion was developed during the preparation of the book *Underground Excavations in Rock*, published in 1980. The criterion was required in order provide input information for the design of underground excavations. Since no suitable methods for estimating rock mass strength appeared to be available at that time, the efforts were focussed on developing a dimensionless equation that could be scaled in relation to geological information. The original Hoek-Brown equation was neither new nor unique – an identical equation had been used for describing the failure of concrete as early as 1936. The significant contribution that Hoek and Brown made was to link the equation to geological observations, initially in the form of Bieniawski's Rock Mass Rating and later to the Geological Strength Index GSI. The subsequent

RocLab 1.0

Rock Mass Strength Analysis using the Generalized Hoek-Brown failure criterion

RocLab is a software program for determining rock mass strength parameters, based on the latest version of the generalized Hoek-Brown failure criterion. *RocLab* provides a simple and intuitive implementation of the Hoek-Brown failure criterion, allowing users to easily obtain reliable estimates of rock mass properties and to visualize the effects of changing rock mass parameters on the failure envelopes.

The reference is available in PDF format, when you install the program. The rock mass properties determined by *RocLab* can be used as input for numerical analysis programs such as *Phase*^{2} (finite element stress analysis and support design for excavations) or *Slide* (limit equilibrium slope stability analysis).

While *RocLab* 1.0 will continue to be offered as a free program, recent improvements and future developments are included in *RocData* 4.0. A comparison chart, *RocLab* 1.0 versus *RocData* 4.0, highlights the features in both programs.

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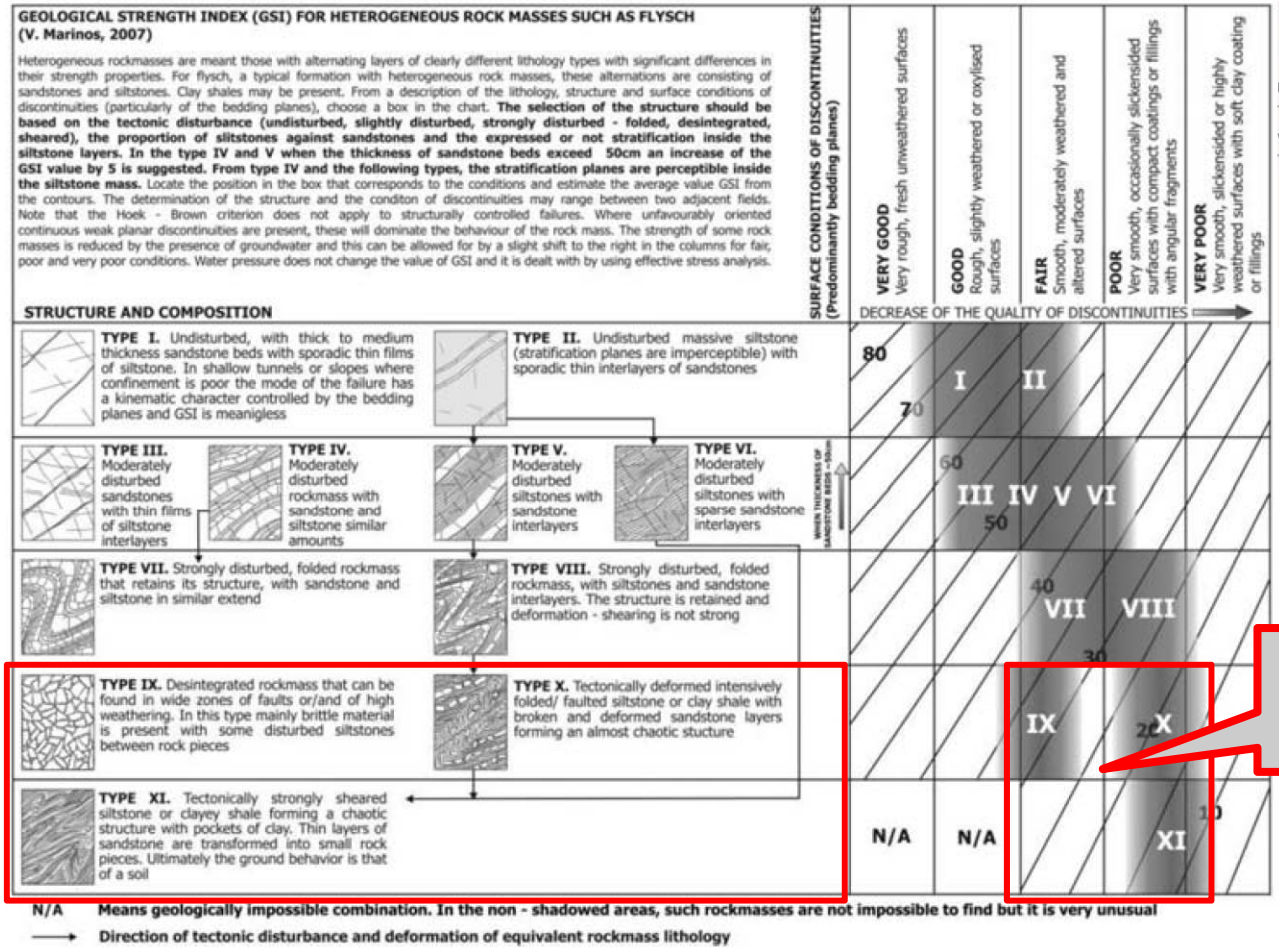
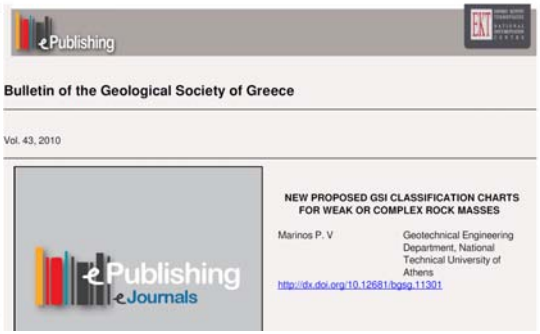
Current GSI chart for heterogeneous rock masses





Marinos P. V,, 2010;
New Proposed Gsi Classification Charts For Weak Or Complex Rock Masses;
Bulletin of the Geological Society of Greece, Vol. 43, 2010;
http://dx.doi.org/10.12681/bgsg.11301

GSI 10-35

Fig. 1: A new GSI classification chart for heterogeneous rock masses such as flysch.

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Example: using Hoek-Brown Failure Criterion for a bimrock

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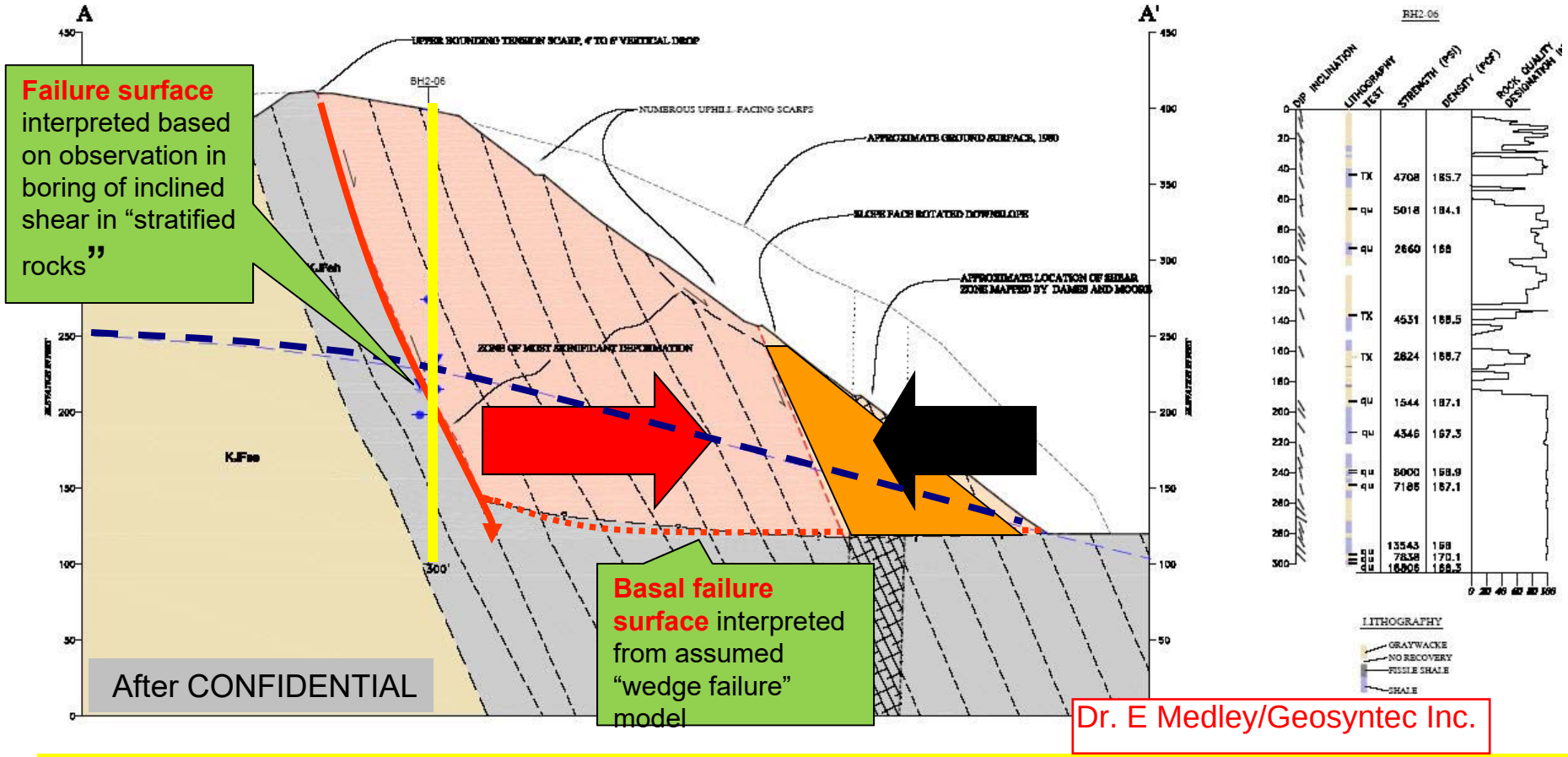
Cross-Section
Slope Stability Model – “Wedge Failaure”



Geotech Engineer conservatively assigned rock strengths to yield FS = 1.0 for a deep-seated “wedge” geologic model composed on steeply dipping sandstone-shale strata.

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Field Observations of a high cut slope

slope underlain by rock mass composed of steeply dipping discontinuities; mixture of blocks of shales, sandstones and claystones ranging from relatively coherent to minor melange (i.e.: “broken formation”)

EXPECT HETEROGENEITY

Dr. E Medley/Geosyntec Inc.

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Field Observations- Varied Rock Mass

Relatively chaotic: sandstone block in sheared shale

Dr. E Medley/Geosyntec Inc.

Relatively coherent sandstone-shale interbeds

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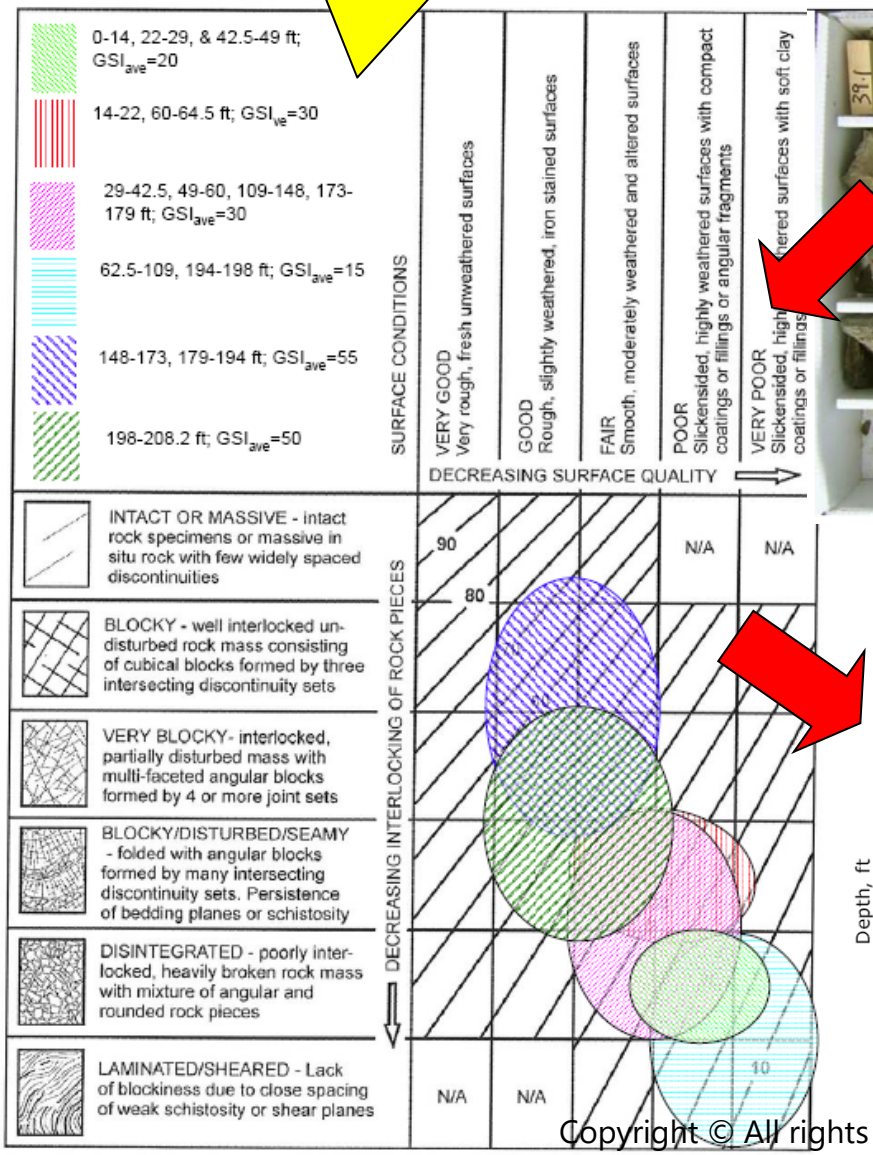
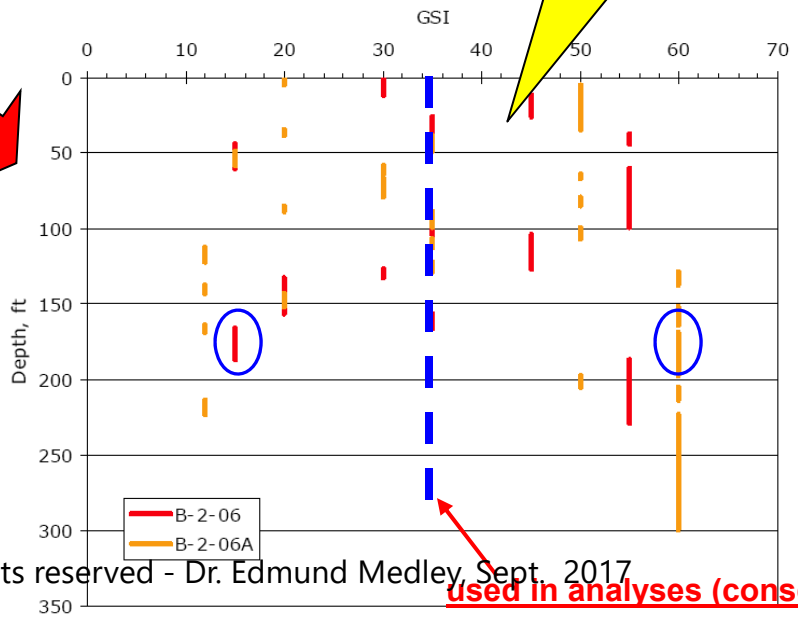
GSI (Geologic Strength Index)

Variable GSIs from observations at depths in two boreholes

Dr. E Medley/Geosyntec Inc.



Variable GSIs from observations at depths in two boreholes



used in analyses (conservatively)

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σ_{ci} intact Uniaxial Compressive Strength

Grade*	Term	Uniaxial Comp. Strength *MPa/(ksf)*	Point Load Index (MPa)	Field estimate of strength	Examples
R6	Extremely Strong	> 250 *(>5000)*	>10	Specimen can only be chipped with a geological hammer	Fresh basalt, chert, diabase, gneiss, granite, quartzite
R5	Very strong	100 - 250 *(2000-5000)*	4 - 10	Specimen requires many blows of a geological hammer to fracture it	Amphibolite, sandstone, basalt, gabbro, gneiss, granodiorite, limestone, marble, rhyolite, tuff
R4	Strong	50 - 100 *(1000-2000)*	2 - 4	Specimen requires more than one blow of a geological hammer to fracture it	Limestone, marble, phyllite, sandstone, schist, shale
R3	Medium strong	25 - 50 *(500-1000)*	1 - 2	Cannot be scraped or peeled with a pocket knife, specimen can be fractured with a single blow from a geological hammer	Claystone, coal, concrete, schist, shale, siltstone
R2	Weak	5 - 25 *(100-500)*	**	Can be peeled with a pocket knife with difficulty, shallow indentation made by firm blow with point of a geological hammer	Chalk, rocksalt, potash
R1	Very weak	1 - 5 *(20-100)*	**	Crumbles under firm blows with point of a geological hammer, can be peeled by a pocket knife	Highly weathered or altered rock
R0	Extremely weak	0.25 - 1 *(5-20)*	**	Indented by thumbnail	Stiff fault gouge

* Grade according to Brown (1981).
** Point load tests on rocks with a uniaxial compressive strength below 25 MPa are likely to yield highly ambiguous results.

selected 750 ksf

Hoek (2007) guidance:

- Shale: 500-2000 ksf
- Sandstone: 1000-5000 ksf
- NOTE: Laboratory specimens failed along discontinuities. Do not use to evaluate σ_{ci}
- **Selected**: σ_{ci}=750 ksf

Conservative estimate

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m_i material parameter

Rock type	Class	Group	Texture			
			Coarse	Medium	Fine	Very fine
SEDIMENTARY	Clastic		Conglomerates* (21 ± 3) Breccias (19 ± 5)	Sandstones 17 ± 4	Siltstones 7 ± 2 Greywackes (18 ± 3)	Claystones 4 ± 2 Shales (6 ± 2) Marls (7 ± 2)
	Non-Clastic	Carbonates	Crystalline Limestone (12 ± 3)	Sparitic Limestones (10 ± 2)	Micritic Limestones (9 ± 2)	Dolomites (9 ± 3)
		Evaporites		Gypsum 8 ± 2	Anhydrite 12 ± 2	
		Organic				Chalk 7 ± 2
METAMORPHIC	Non Foliated		Marble 9 ± 3	Hornfels (19 ± 4) Metasandstone (19 ± 3)	Quartzites 20 ± 3	
	Slightly foliated		Migmatite (29 ± 3)	Amphibolites 26 ± 6		
	Foliated**		Gneiss 28 ± 5	Schists 12 ± 3	Phyllites (7 ± 3)	Slates 7 ± 4
IGNEOUS	Plutonic	Light	Granite 32 ± 3 Granodiorite (29 ± 3)	Diorite 25 ± 5		
		Dark	Gabbro 27 ± 3 Norite 20 ± 5	Dolerite (16 ± 5)		
	Hypabyssal		Porphyries (20 ± 5)		Diabase (15 ± 5)	Peridotite (25 ± 5)
	Volcanic	Lava		Rhyolite (25 ± 5) Andesite 25 ± 5	Dacite (25 ± 3) Basalt (25 ± 5)	Obsidian (19 ± 3)
		Pyroclastic	Agglomerate (19 ± 3)	Breccia (19 ± 5)	Tuff (13 ± 5)	

* Conglomerates and breccias may present a wide range of m_i values depending on the nature of the cementing material and the degree of cementation, so they may range from values similar to sandstone to values used for fine grained sediments.

* *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.

- **Hoek (2007) guidance:**
- Sandstone: 17±4
- Shale: 6±2

Used in analyses: 5

Conservative assumption

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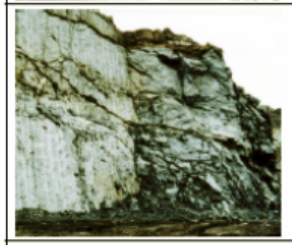
D disturbance factor

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

Used in analyses: 0.7

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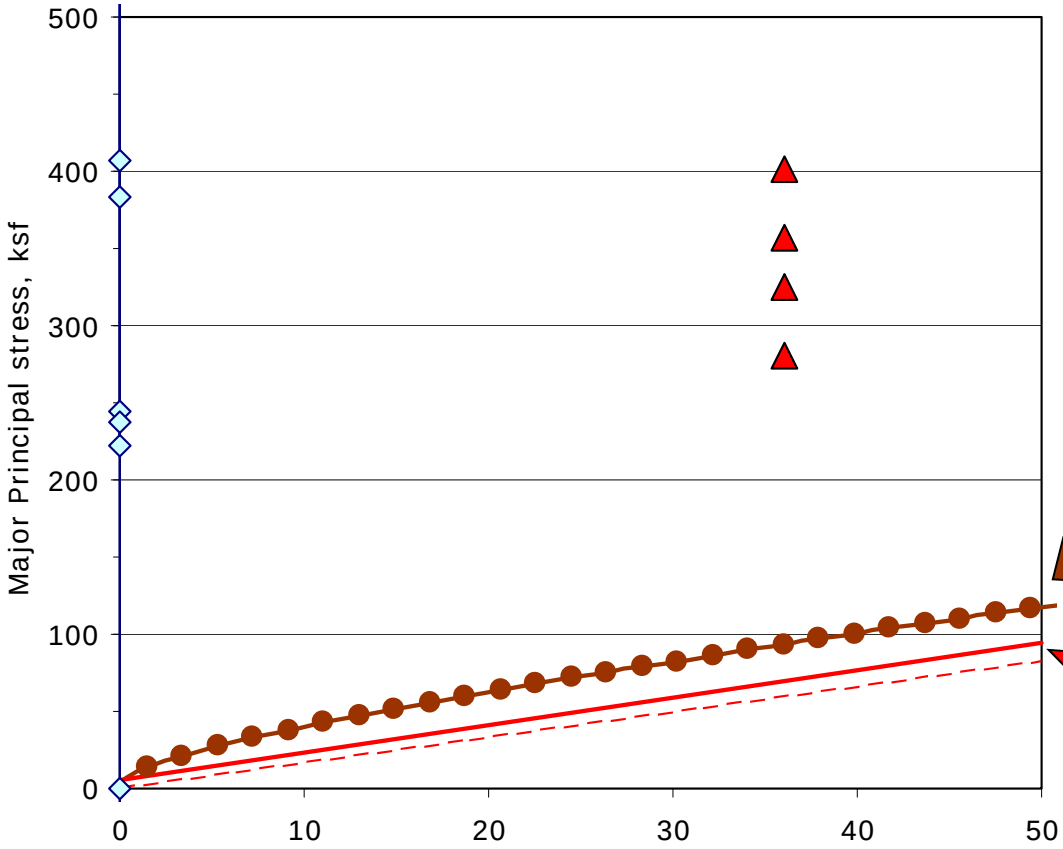
Rock Mass Strength Envelope from Hoek-Brown Criterion

- **Strength used in analyses significantly lower than laboratory data and slightly above Geotech Enginner's preliminary estimate**



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▲ Only lower range
◇ laboratory data shown

Strength used in final analyses based on Hoek-Brown

Preliminary estimate of strength based on data applied to "wedge Model"

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Rock Mass Strength Envelope from Hoek-Brown Criterion

Strength used in analyses significantly lower than laboratory data and slightly above Geotech Enginner's preliminary estimate

Slope Stability Analyses based on Hoek Brown Criterion yield FS of 1. 5
So: the high slope is stable and not failing as a wedge stable.

But the Slope LOOKS like it is Failing, with apparent upper and lower "failure scarps"

What is Occurring?

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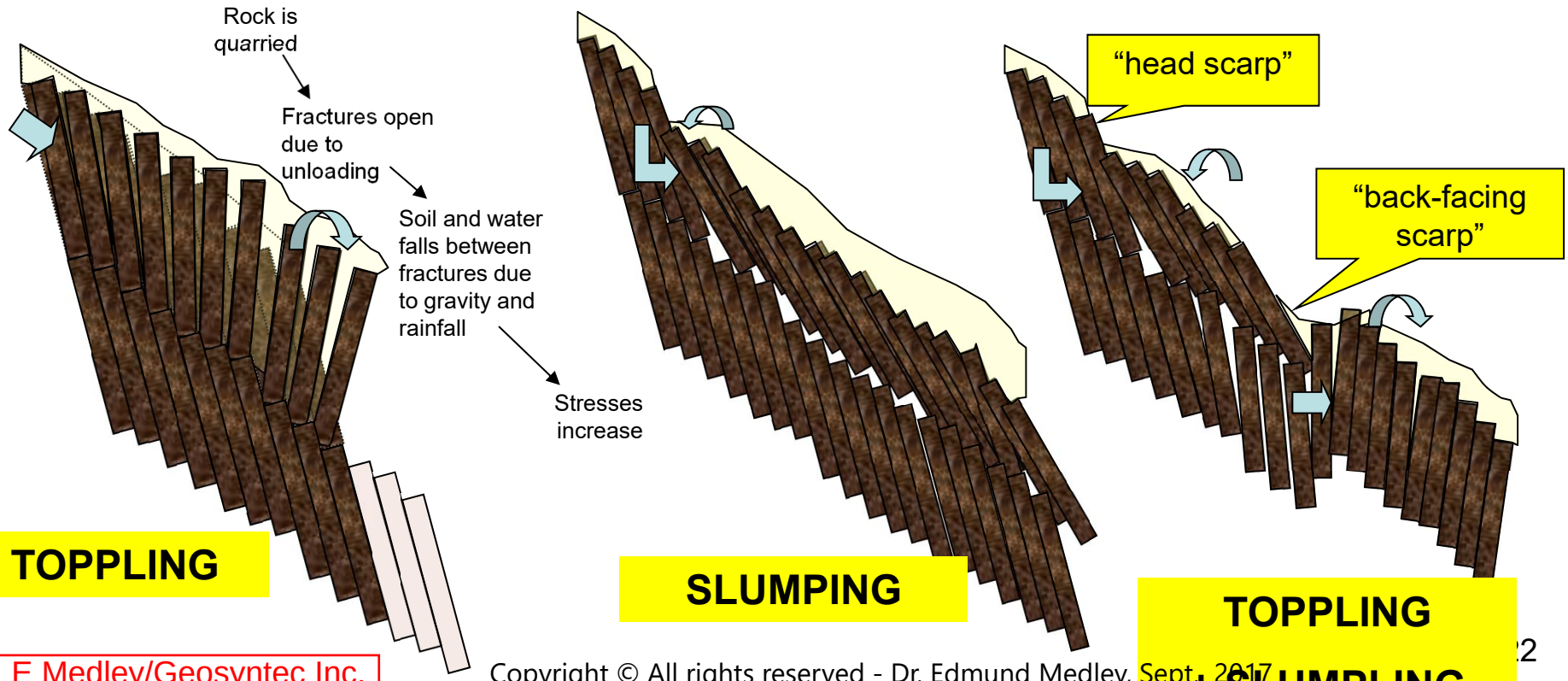
THINK Rock Mechanics instead of Soil Mechanics!

- Major rock mass discontinuities dip close to vertical and strike sub-parallel to the slope contours
- Significant relaxation occurred due to former quarrying and reclamation activities; discontinuities opened close to slope surface
- Conditions ideal for expected rock **mass topples, slumps or both**



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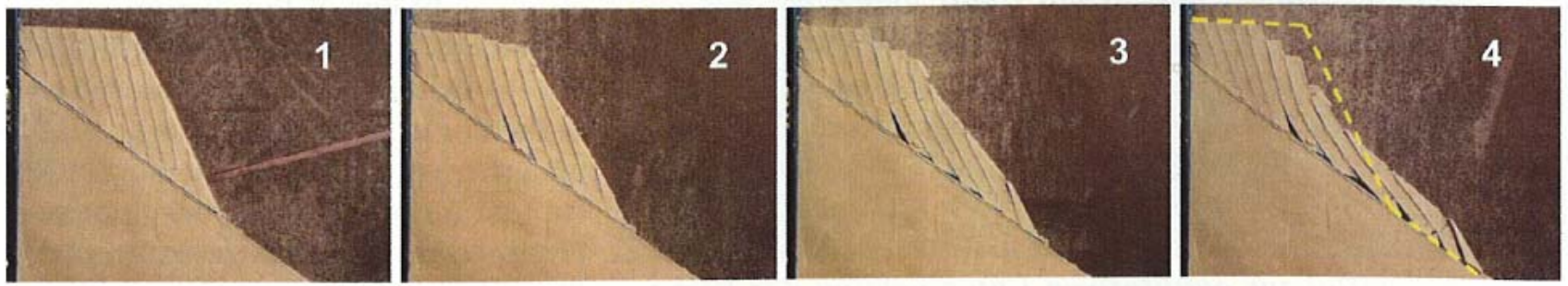
Rock Mass Slumping

Goricki and Goodman, 2003



Physical base friction model tests (confirmed by DDA analyses)

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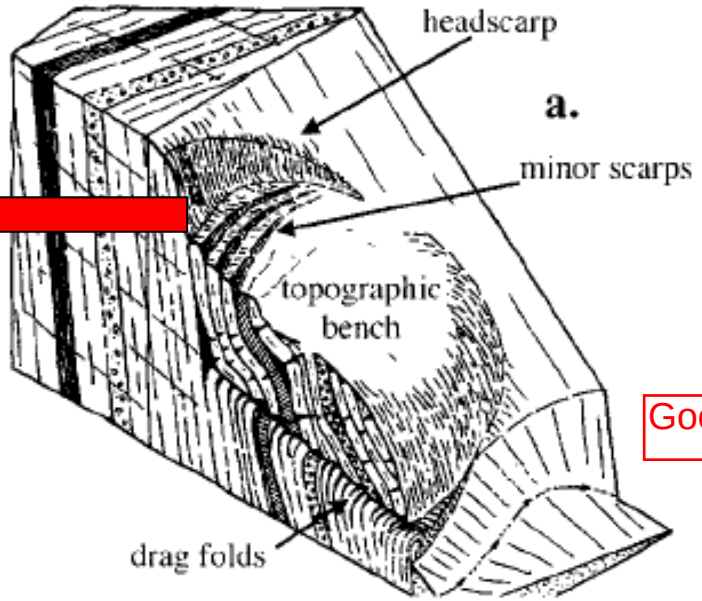

Goodman and Kieffer, 2000

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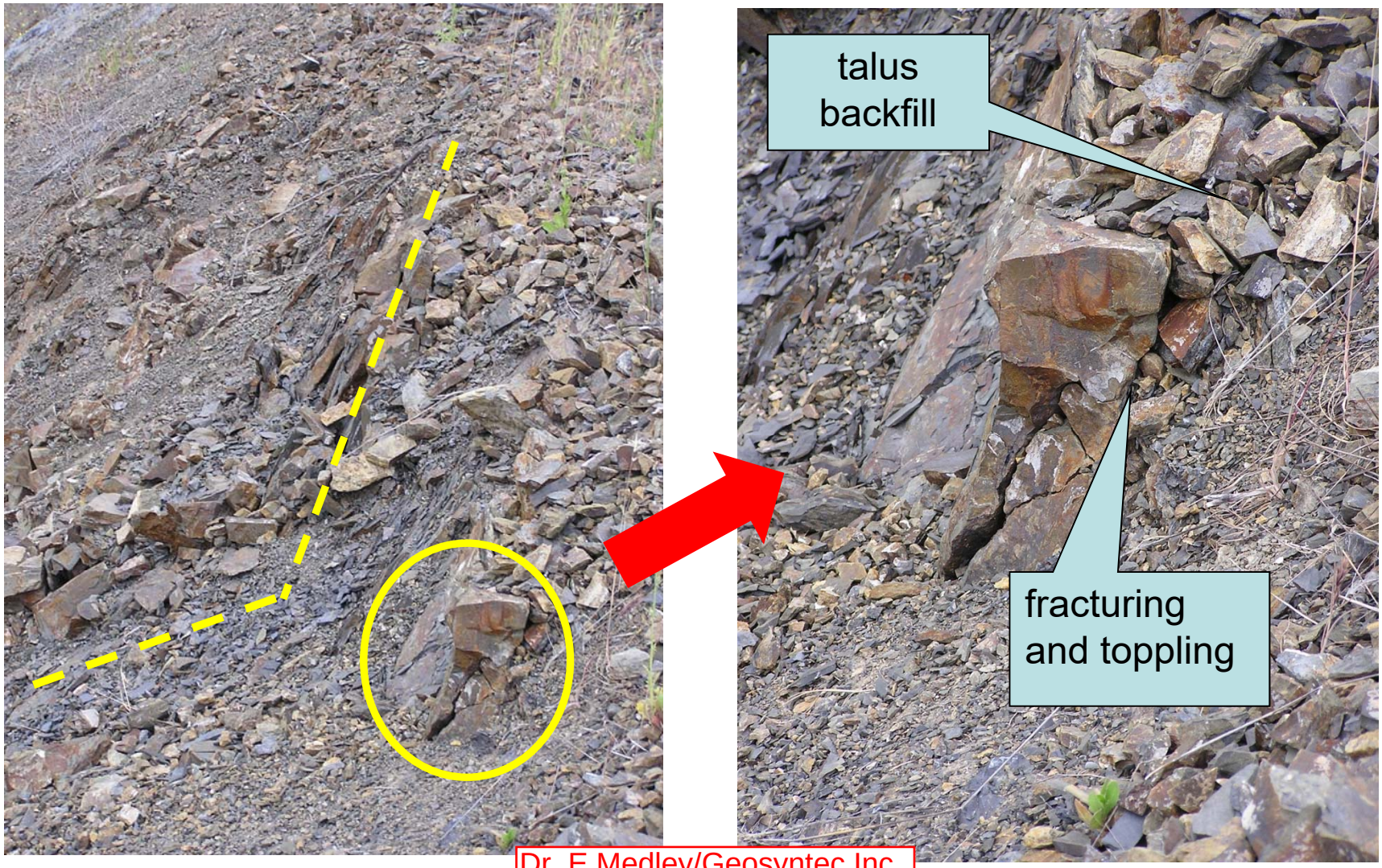
Goodman and Kieffer, 2000

Shallow-seated slope failures



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Conclusions:

- **Empirical Methods are useful for quickly checking a number of "what-If?" scenarios.**
- **Useful if you have an approximate idea of the geology**
- **Dangerous if you have an approximate idea of the geology**

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EXTRAS

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