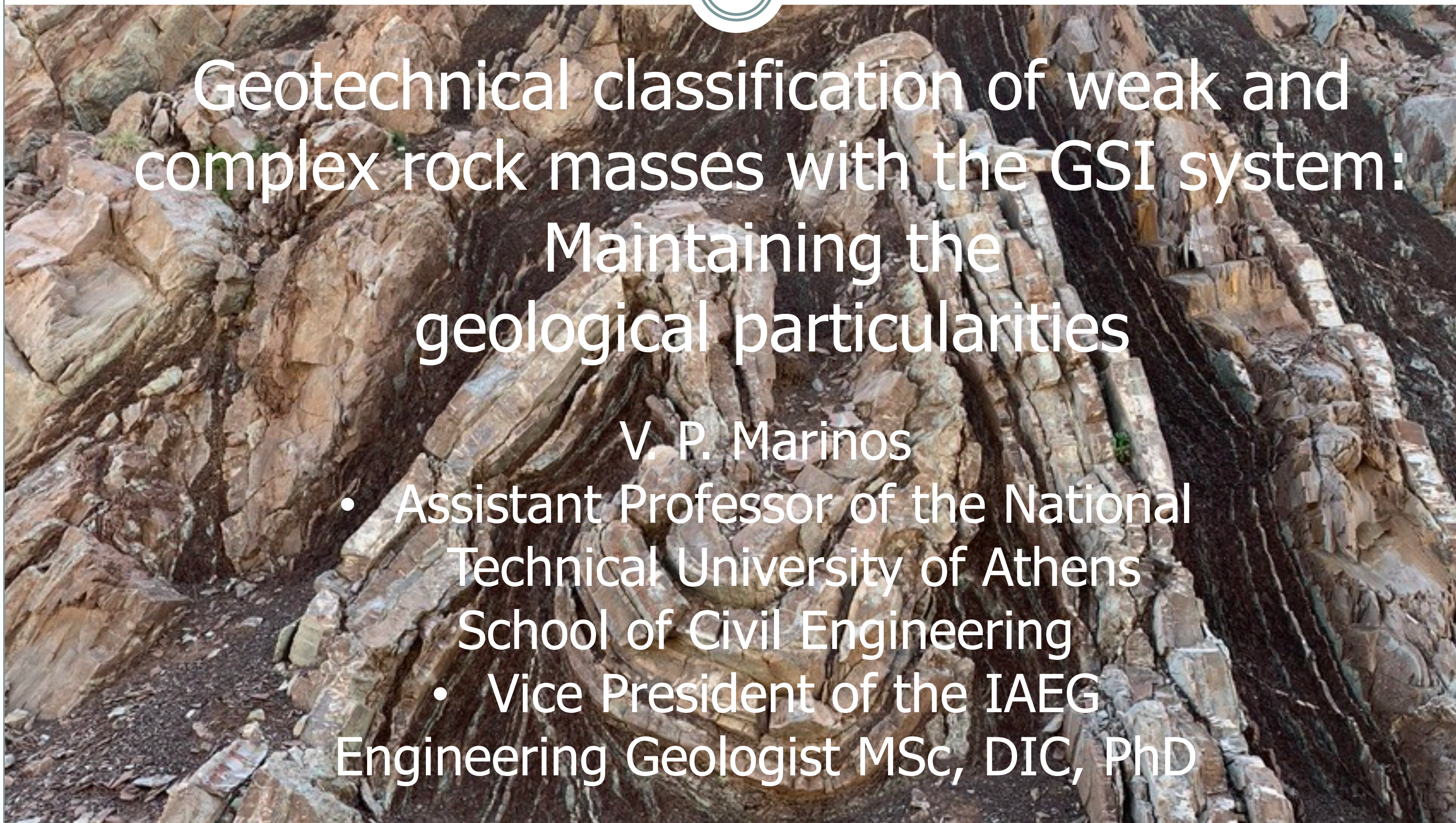
National Technical University of Athens

CFMS CFGI CFMR



Geotechnical classification of weak and complex rock masses with the GSI system: Maintaining the geological particularities

V. P. Marinos

- Assistant Professor of the National Technical University of Athens School of Civil Engineering
- Vice President of the IAEG

Engineering Geologist MSc, DIC, PhD

Outline

I. Introduction – Putting numbers to Geology
II. Rock mass characterization; a vehicle to translate Geology into Rock Engineering Design
III. Interaction between GSI and tectonism
IV. Interaction between GSI and weathering
V. Interaction between GSI and alteration
VI. Conclusions

I. Introduction – Putting numbers to Geology

- Despite the fact that significant advances have occurred within almost every area of geotechnical design, with arguably the greatest developments in rock engineering being in numerical modelling capability, to date similar levels of advance have not been achieved in improving characterization of the geological variability that exists in natural rock masses.
- Geological representativeness is key to achieving effective rock engineering design. This requires that reliable estimates be available of strength and deformation characteristics of the rock masses on which or within which engineering structures are to be created, be it a tunnel, a foundation or a slope cut.

I. ASSESSMENT OF GROUND
IN THE DESIGN FOR ENGINEERING CONSTRUCTION

1. Geological data and conditions

2. Translation into an engineering geological description

Geological Model

3. Ground type ⟶ properties

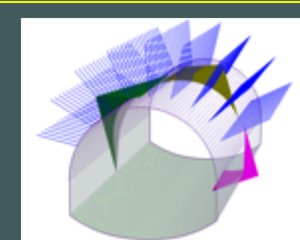
Rock mass Model

Environment (stress, groundwater, …)

Selection of suitable geotechnical parameters and appropriate criteria

DESIGN

The use of empirical, analytical, numerical methods



CONSTRUCTION

implementation of the design

Estimation of rock mass properties

- Laboratory testing
- In situ testing
- Back analysis
- Appropriate use of rock mas classifications

Rock mass characterization and classification; a vehicle to translate Geology into the design of Engineering Structures

THE ROCK MASS TYPE CHARACTERISATION IS A RESULT OF THE TOTAL GEOLOGICAL HISTORY

(GEOLOGICAL MODEL)

Genesis is reflected on the quality of intact rock and inherent structures

Tectonic evolution reflects on mass structure (fabric) and quality of joints

Palaeogeographical evolution reflects on weathering and final fabric

With the development of extremely powerful microcomputers and of user-friendly software there was a higher demand for reliable input data related to rock mass properties required as input into numerical analysis or close form solutions for designing tunnels.

This necessity led to the development of a different set of rock mass classification.

The GSI (Geological Strength Index) is such a classification

II. Calculation of rock mass parameters using geotechnical classifications: Tight to direct engineering geology observation on the nature of the rock mass

1. Hoek-Brown failure criteria (Hoek *et al*, 2002)

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

σ_1\` , $\sigma_3$\` = principal effective stresses at failure

σ_{ci} = Uniaxial compressive strength of the intact rock

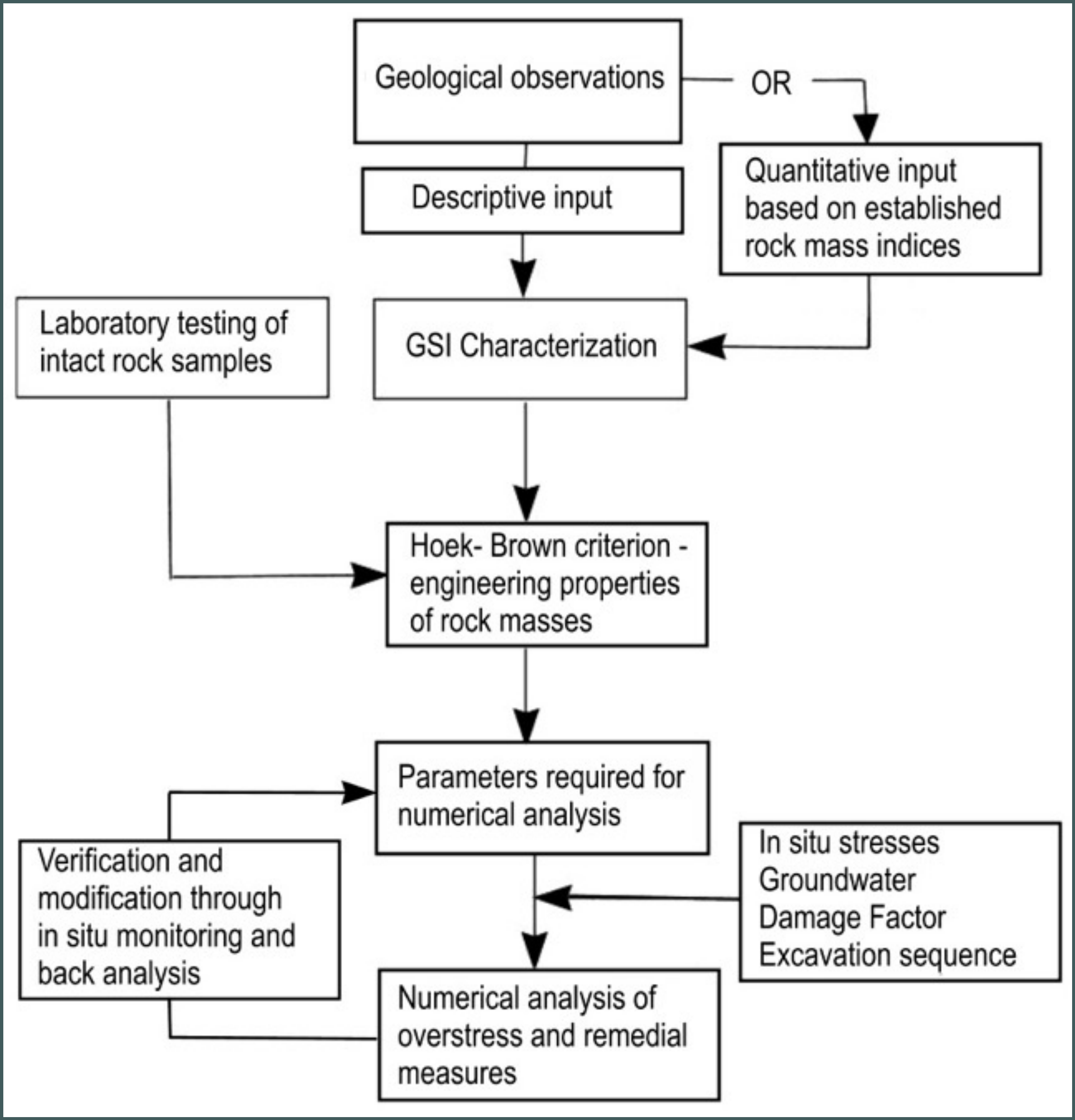
$$m_b = m_i \exp\left(\frac{GSI - 100}{28 - 14D}\right)$$

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

D: Disturbance Factor due to the excavation method or relaxation (0-1)

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

Data entry stream for using the Hoek-Brown system for estimating rock mass parameters for numerical analysis



Hoek et al., 2013

GSI for jointed rock masses,

Hoek & Marinos 2000

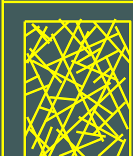
GSI for jointed rock masses,

Hoek & Marinos 2000

STRUCTURE | **SI**

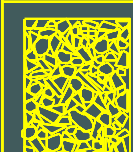
INTACT OR MASSIVE
intact rock specimens or massive in situ rock with few widely spaced discontinuities

BLOCKY - well interlocked un-disturbed rock mass consisting of cubical blocks formed by three intersecting discontinuity sets

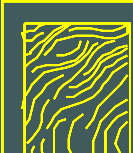


VERY BLOCKY- interlocked, partially disturbed mass with multi-faceted angular blocks formed by 4 or more joint sets

BLOCKY/DISTURBED/ SEAMY folded with angular blocks formed by many intersecting discontinuity sets. Persistence of bedding planes or schistosity



DISINTEGRATED
poorly interlocked, heavily broken rock mass with mixture of angular and rounded rock pieces



LAMINATED/SHEARED
Lackof blockiness due to close spacing of weak schistosity or shear planes

DECREASING INTERLOCKING OF ROCK PIECES

GSI for jointed rock masses,

Hoek & Marinos 2000

SURFACE CONDITIONS X:

DECREASING SURFACE QUALITY

VERY GOOD
Very rough, fresh unweathered surfaces

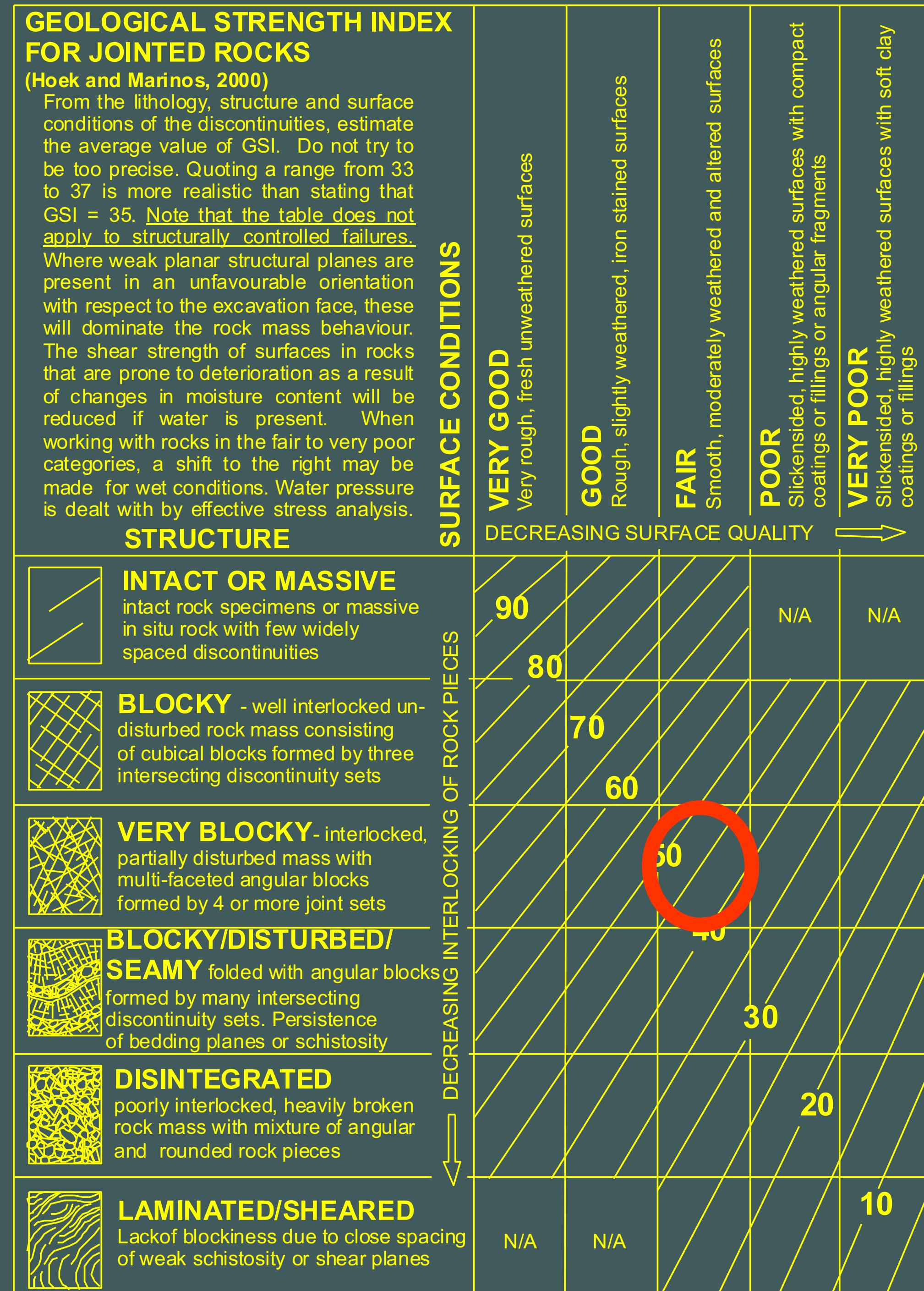
GOOD
Rough, slightly weathered, iron stained surfaces

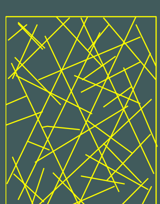
FAIR
Smooth, moderately weathered and altered surfaces

POOR
Slickensided, highly weathered surfaces with compact coatings or fillings or angular fragments

VERY POOR
Slickensided, highly weathered surfaces with soft clay coatings or fillings

GSI for jointed rock masses

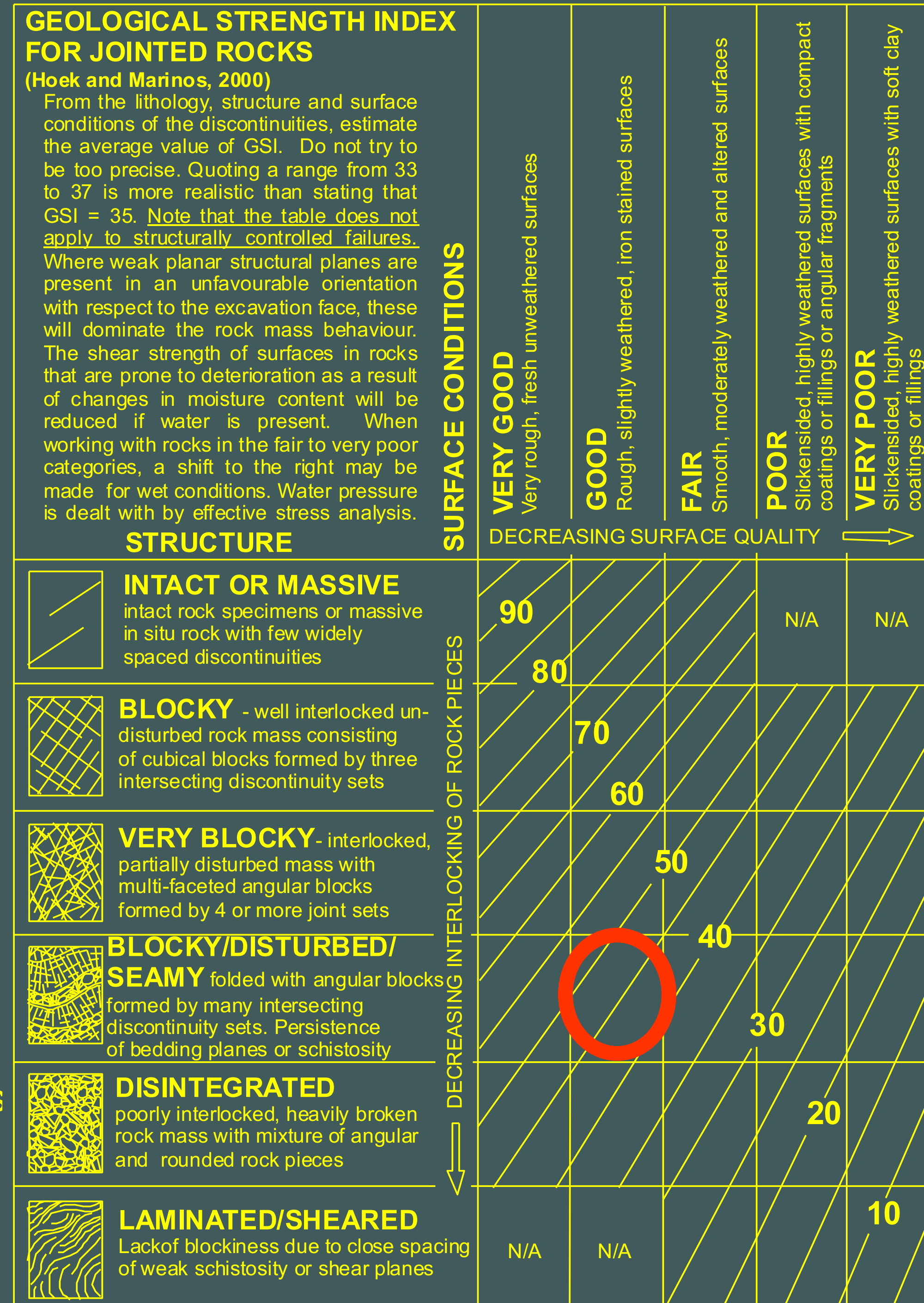




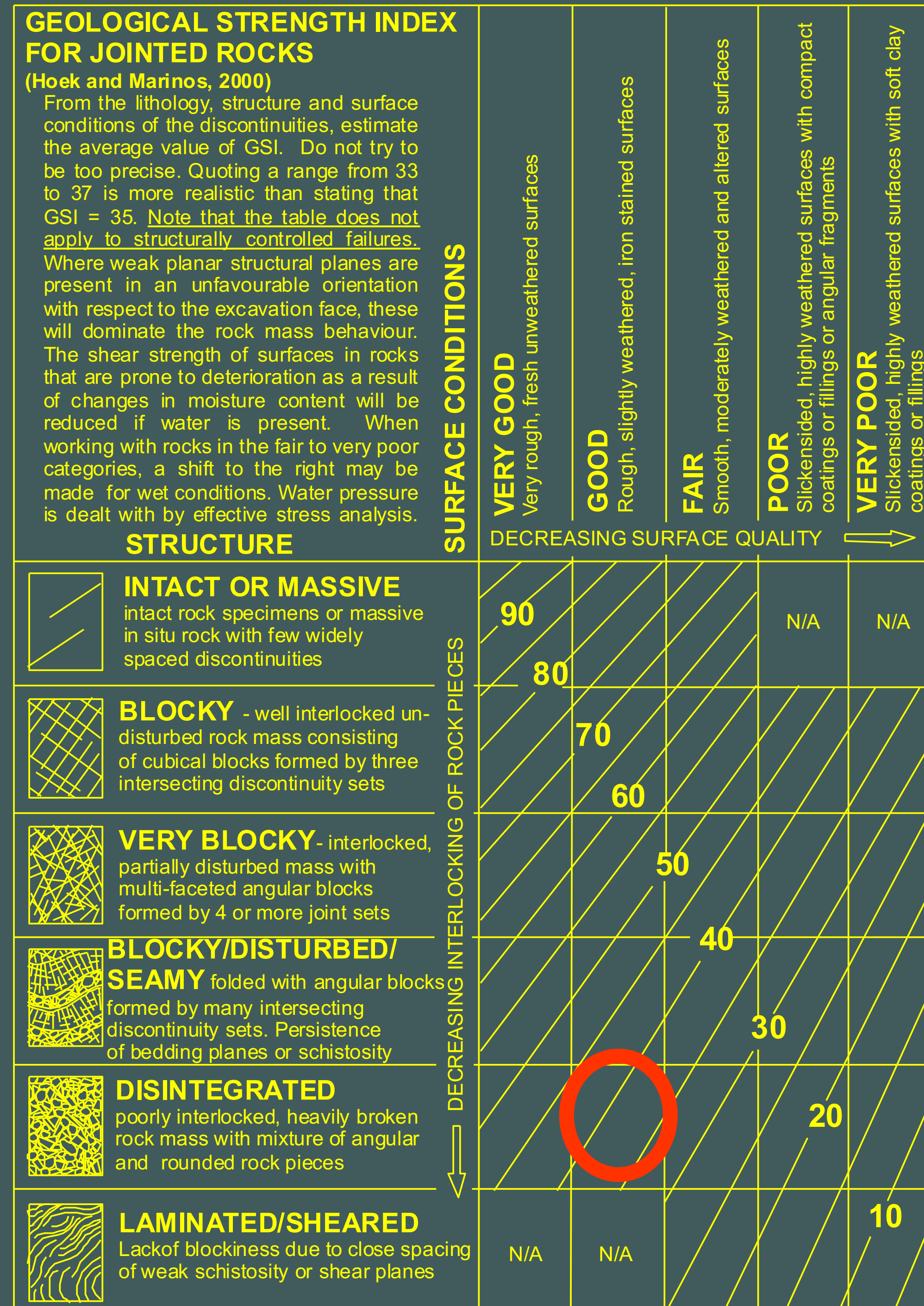
VERY BLOCKY- interlocked, partially disturbed mass with multi-faceted angular blocks formed by 4 or more joint sets

GSI for jointed rock masses

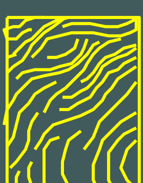
BLOCKY/DISTURBED/ SEAMY folded with angular blocks formed by many intersecting discontinuity sets. Persistence of bedding planes or schistosity



GSI for jointed rock masses



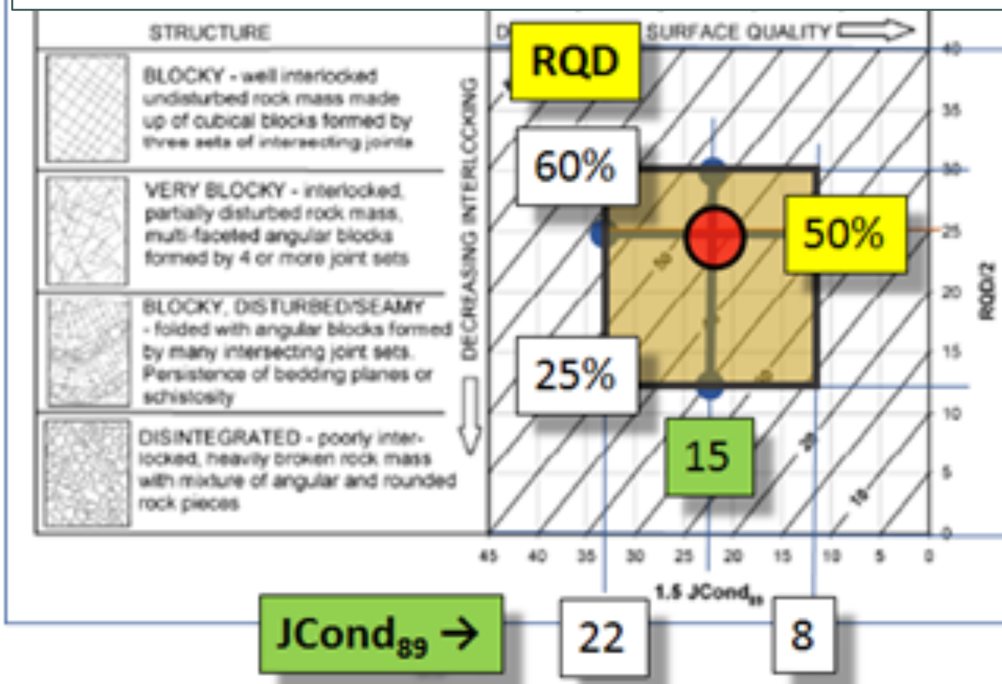
GSI for jointed rock masses

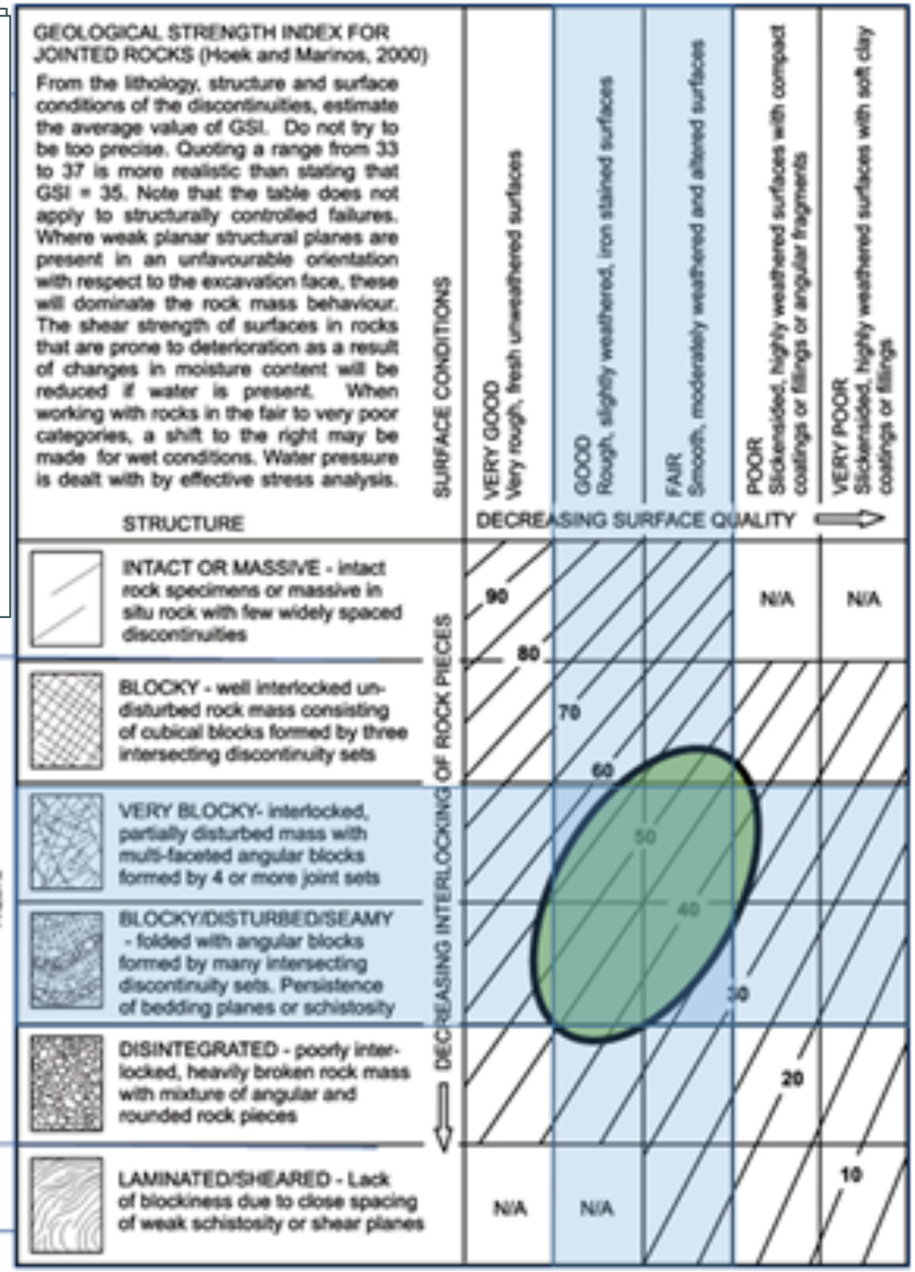


LAMINATED/SHEARED

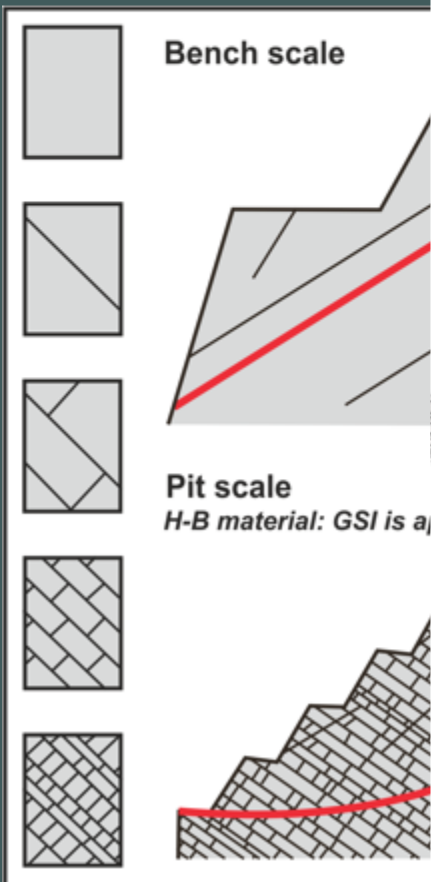
Lackof blockiness due to close spacing of weak schistosity or shear planes

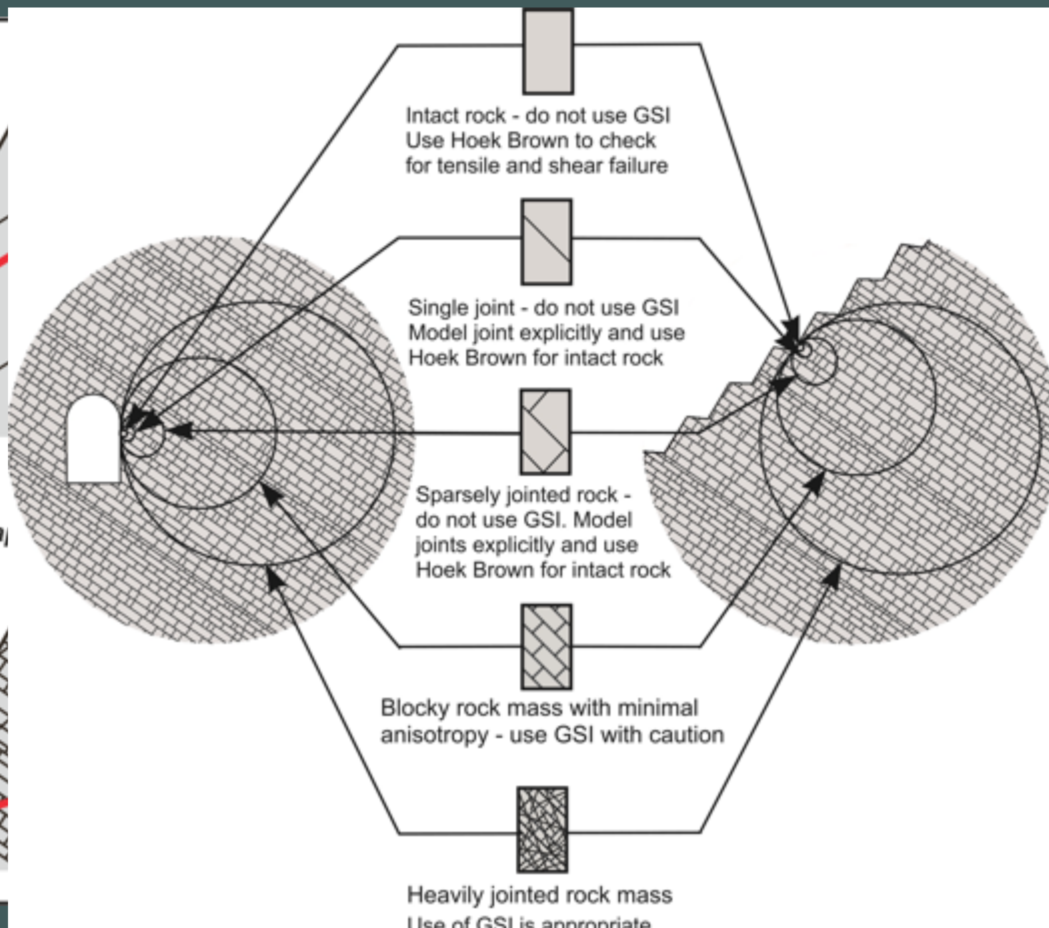
One of the key advantages of the Geological Strength Index is that the geological reasoning it embodies allows characterization to be made of a very wide range of rock masses and conditions, including both weak and complex situations, but always maintaining care to keep within valid applicability limits.





Definition of Rock Mass Type according to the scale of the project





Bench scale slopes at Chuquicamata are obviously structurally controlled

It can be argued that, on the scale of a 500 m high slope, the rock mass can be treated as "homogeneous" and that rock mass classification can be used to estimate the properties

Photos E.Hoek

The overall failure will not be guided by rock mass anisotropy.
Thus GSI is applicable

Pindos mountain, Greece

Once a GSI has been selected, the system becomes highly quantitative.

and GSI can be used as input into numerical analysis or closed form solutions.

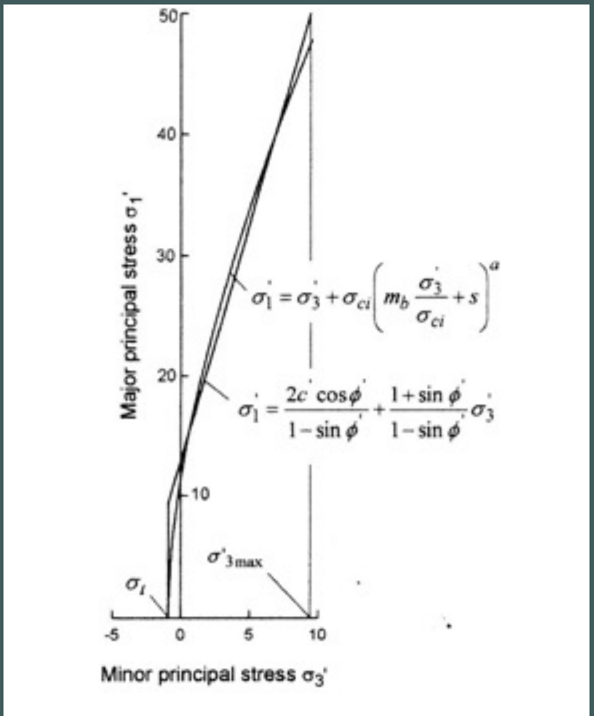
Note that the GSI system is not intended as a replacement of the RMR or Q since it has no rock mass reinforcement capability

<u>its only function is the estimation of rock mass properties</u>

Hoek-Brown criterion - Geotechnical parameters of rock mass through GSI, σ_{ci}, m_i

Equivalent c′, φ’ for MOHR COULOMB criterion:

2002 edition



Relationships between major and minor principal stresses for Hoek-Brown and equivalent Mohr-Coulomb criteria.

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

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

$$\text{where} \quad \sigma_{3n} = \sigma'_{3\max}/\sigma_{ci}$$

s'_{3max} : the upper limit of confining stress over which the relationship between Hoek-Brown and Mohr-Coulomb criteria is considered

The geotechnical parameters can be calculated with the Windows program "RSdata" , that can be downloaded from www.rocscience.com.

Hoek, Carranza-Torres, Corkum, 2002

Empirical relations for the calculation of the Deformation Modulus of the rock mass E_m, through GSI, σ_{ci}, E_i

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

Hoek et al, 2002

$$E_m = E_i\left[0.02 + \frac{1-D/2}{1+e^{((60+15D-GSI)/11)}}\right]$$

Hoek & Diederichs , 2006

E_m = Deformation modulus of the rock mass

σ_{cm} = Uniaxial compressive strength of the rock mass

σ_{ci} = Uniaxial compressive strength of the intact rock

Thus,

σ_{ci}

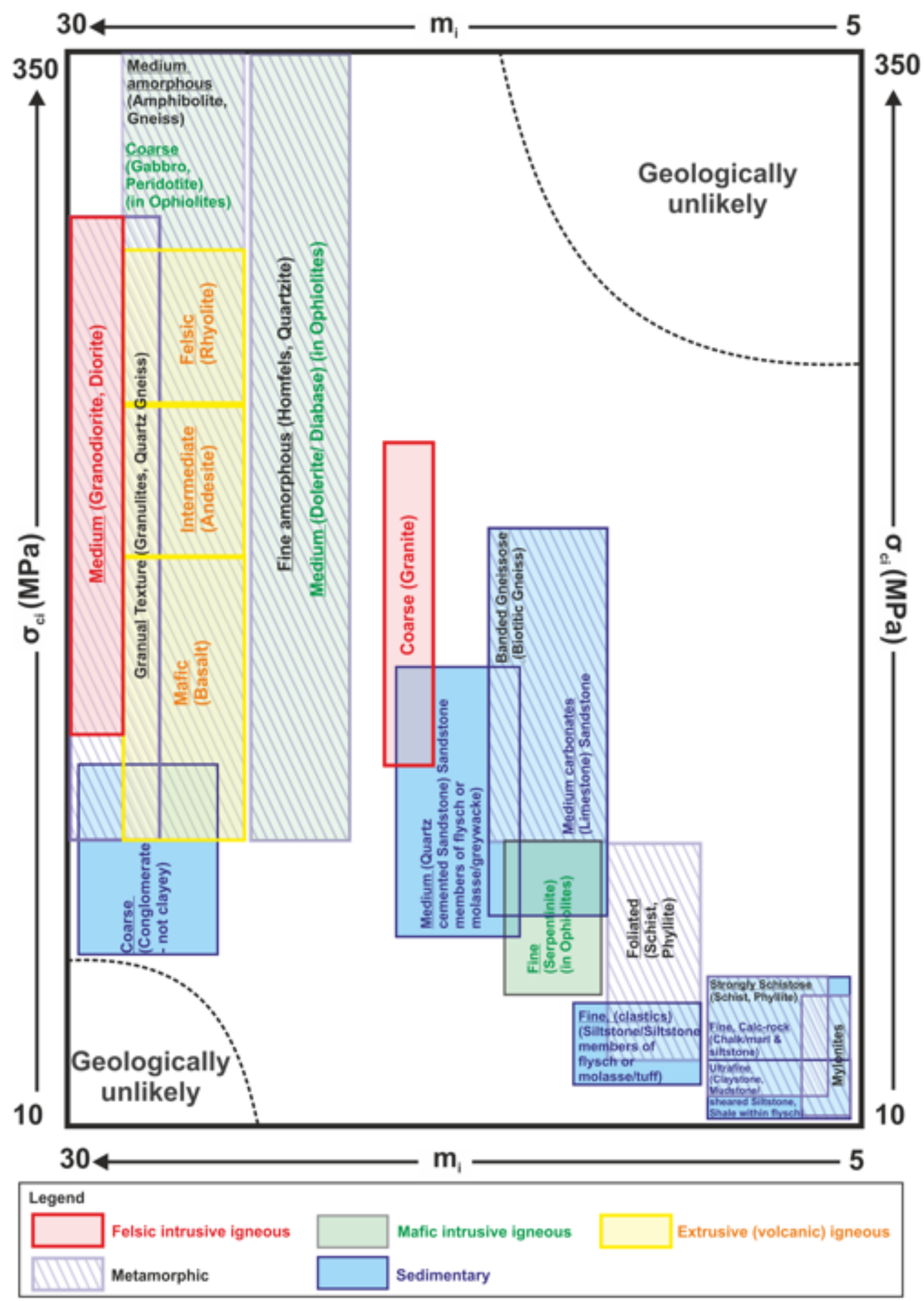
E_i

m_i

GSI

the numerical “ID” of the “isotropic” rock mass for analysis

Typical values for Hoek and Brown parameters, constant m_i and strength σ_{ci}, for typical rocks - formations

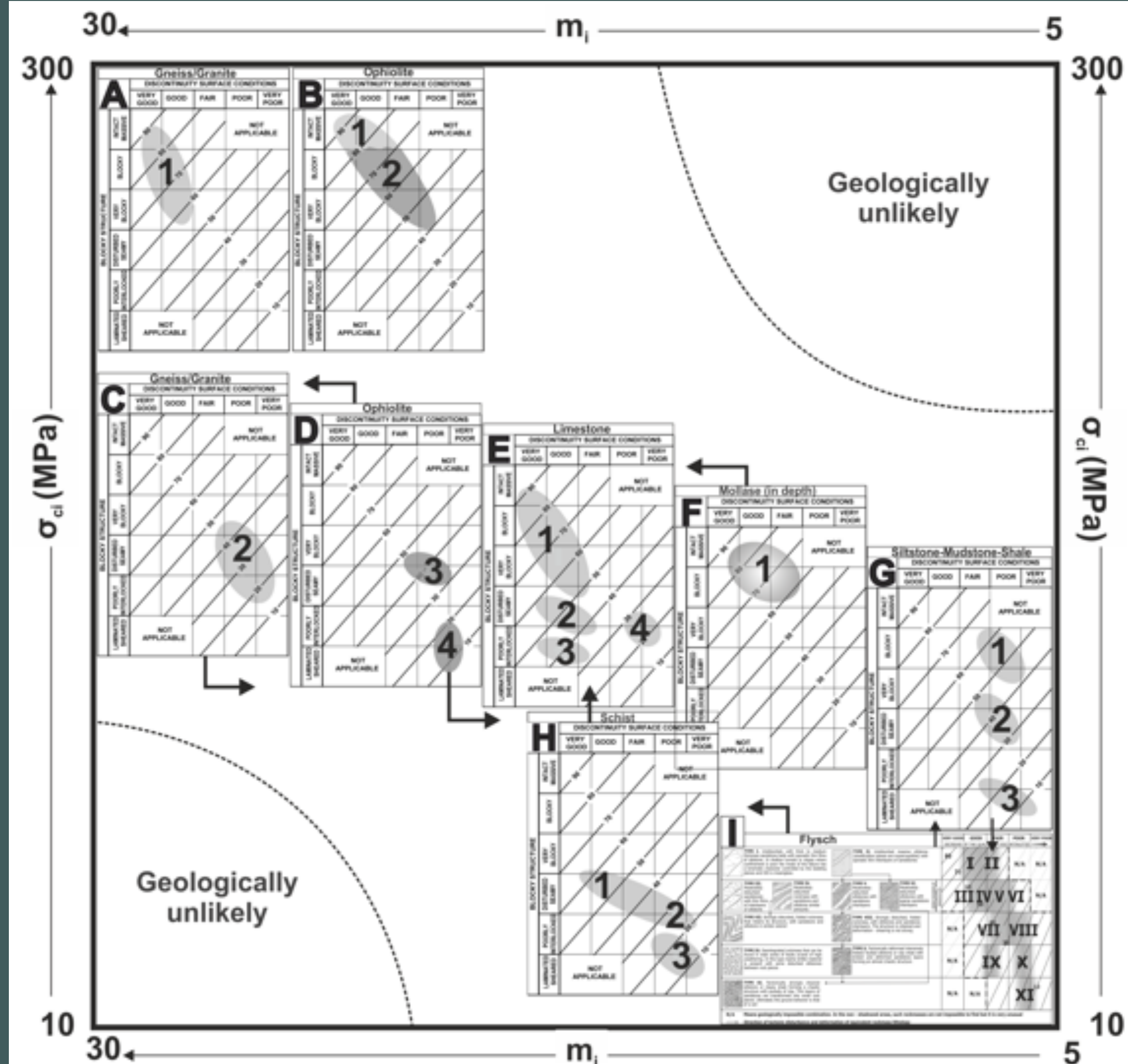


Carter and Marinos, 2020

Hoek - Brown parameters for different rock mass types

The usual projections - GSI values according to geological rules and characters of genesis and evolution for typical rocks - formations in combination with the Hoek and Brown parameters, constant m_i and strength σ_{ci}.

Marinos and Carter, 2018



Legend

A. & C. Gneiss/Granite
1. Fresh rock masses
2. Weathered rock masses (most common range is illustrated here)

B. & D. Ophiolite
(Details are presented in the paper Marinos, Hoek and Marinos, 2005)
1. Massive strong peridotite with widely spaced discontinuities.
2. Good to fair quality peridotite or compact serpentinite with discontinuities
3. Schistose serpentinite.
4. Poor to very poor quality sheared serpentinite.

E. Limestone
1. Massive
2. Thin bedded
3. Brecciated
4. With clay presence along the joints

F. Mollase (Details are presented in the paper Hoek, Marinos and Marinos, 2005)
1. Confined molasse at depth

G. Siltstone-Mudstone -Shale
1. Massive siltstones or mudstones
2. Bedded, foliated, fractured
3. Sheared, brecciated

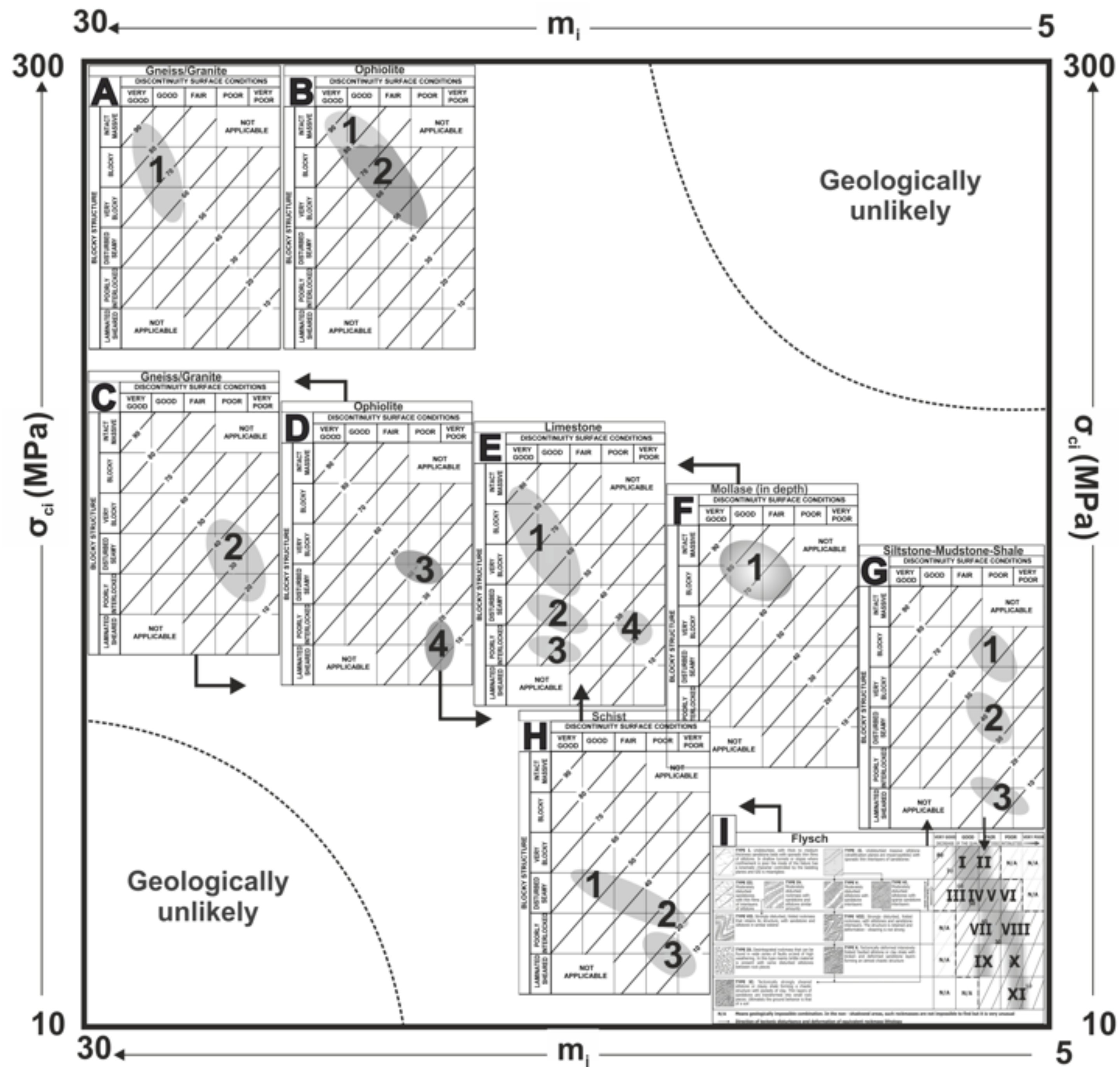
H. Schist
1. Strong (e.g. micaschists)
2. Weak (e.g.chloritc schists, phyllites)
3. Sheared schist

I. Flysch (Details are presented in the paper Marinos, 2017)
Types I to XI according to sandstone-siltstone prevalence and tectonic disturbance

Warning:
* The shaded areas are indicative only and may not be appropriate for site specific design purposes. Mean values are not suggested for indicative characterisation; the use of ranges is recommended
* The positions of the formations within the σ_{ci} - m_i chart are indicative. Exact values of σ_{ci} - m_i must be analytically defined by laboratory testing

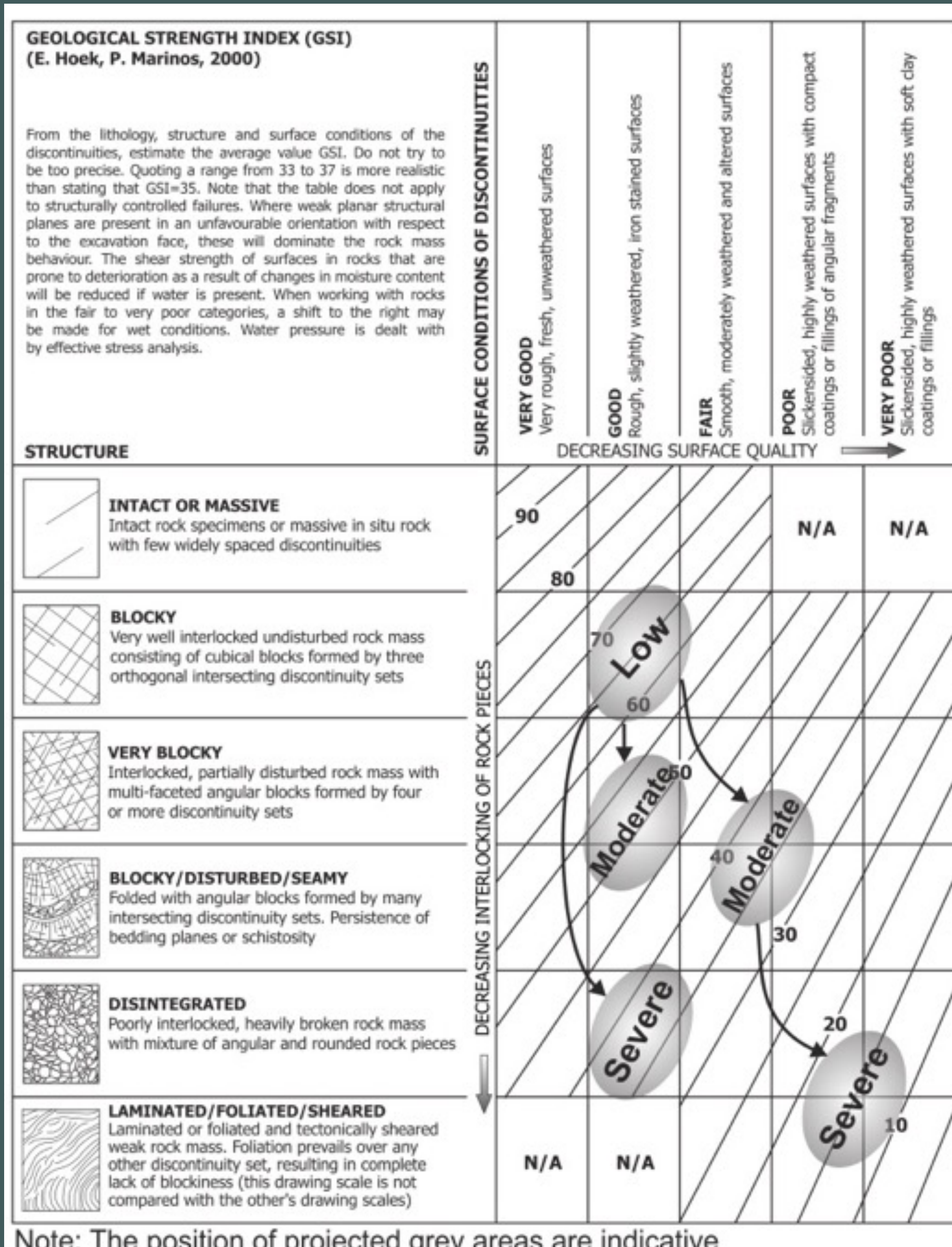
→ The arrows show possible extension of the small scale chart

Hoek - Brown parameters for different rock mass types

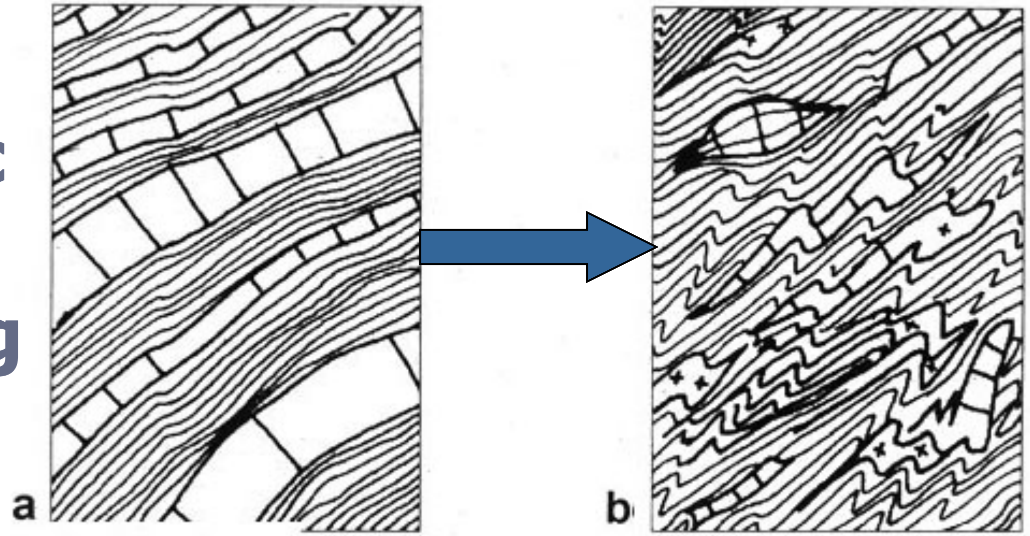


Marinos and Carter, 2018

III. Interaction between GSI and Tectonism



Tectonic Shearing



a. The seamy rock mass type consisting of intercalated rock members of strikingly different competence which are differentially deformed (sheared, folded and faulted)

b. A chaotic rock mass comprising lensified hard rock bodies and boudinaged quartz or calcite lenses floating in a sheared soil-like environment.

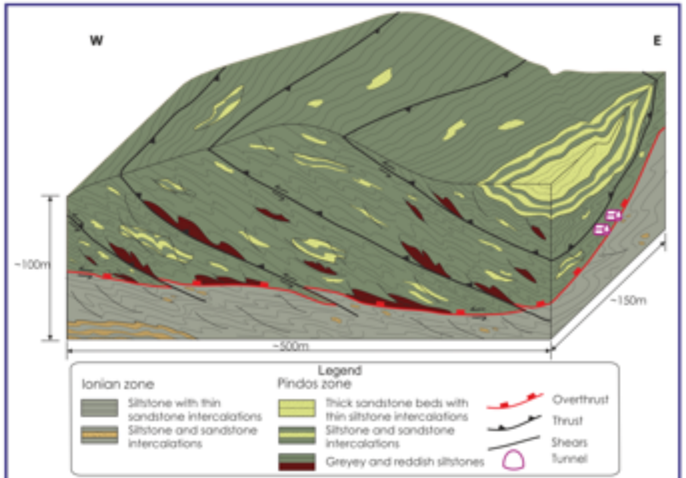
Scale of boxes: order of meter or few meters

Degradation due to shearing and fissuring the original rock

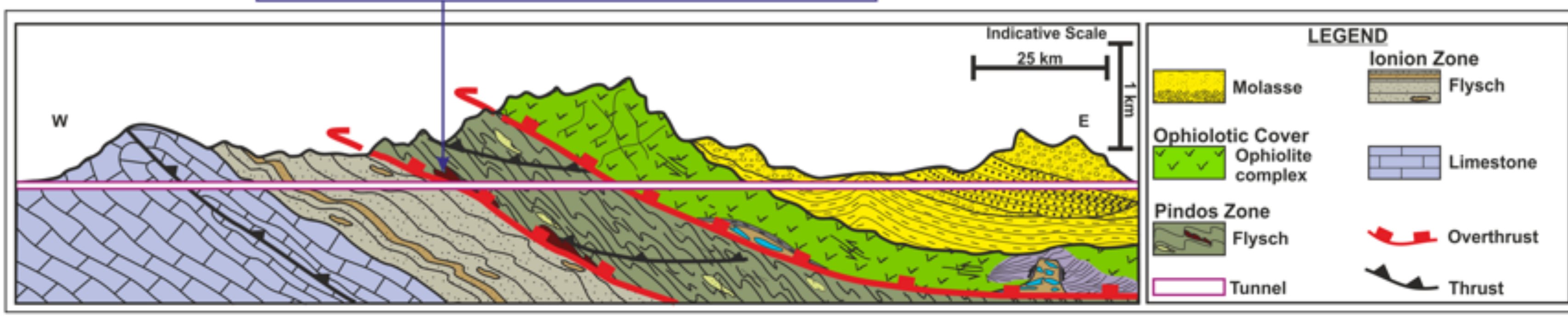
Moderately disturbed rock mass with sandstone and siltstone alternations in similar amounts

Tectonically disturbed sheared siltstone with broken deformed sandstone layers. These layers have almost lost their initial structure. Almost a chaotic structure

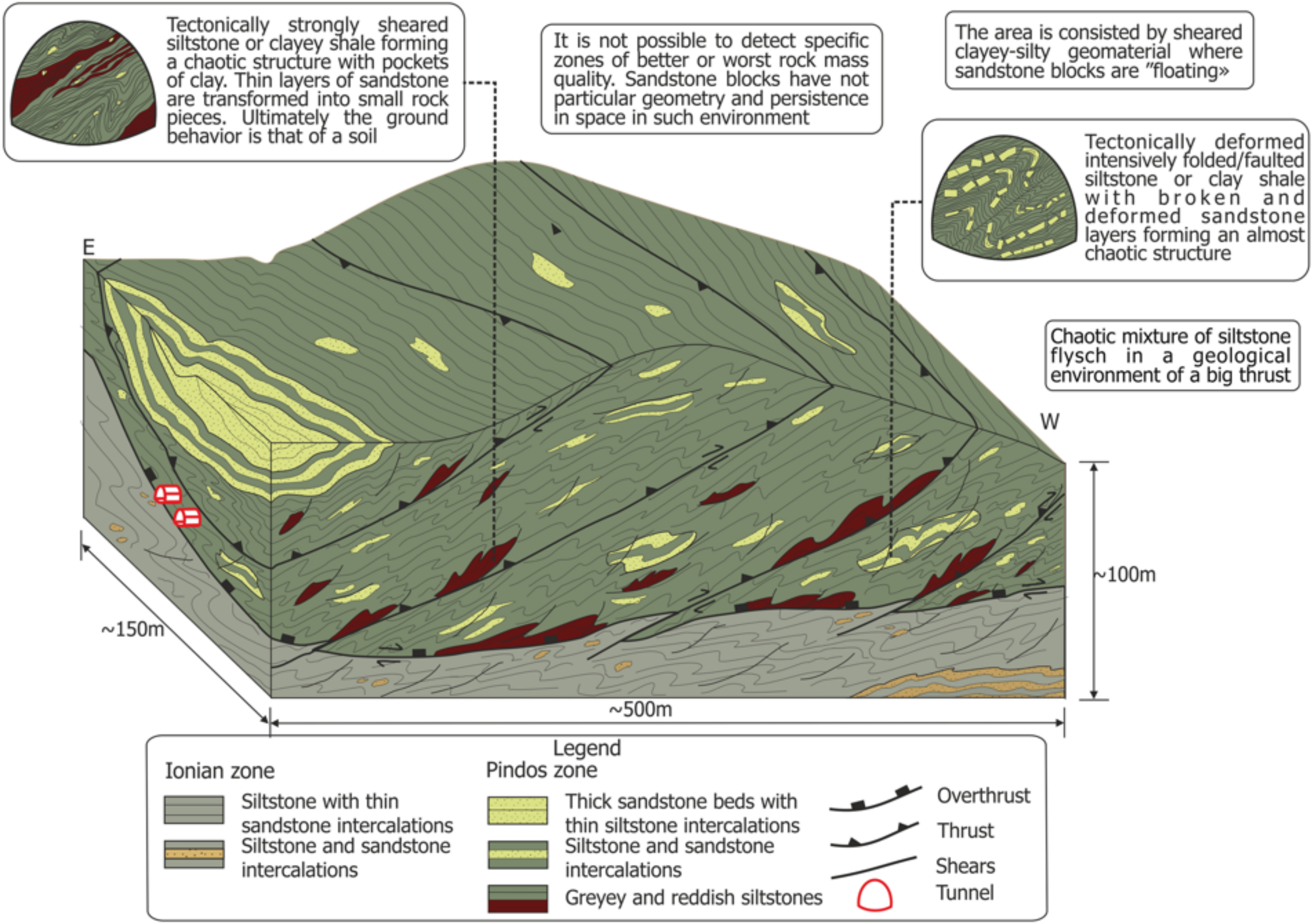
Engineering geological evaluation in tunnelling – *An example in flysch environment*



Engineering Geological model in flysch

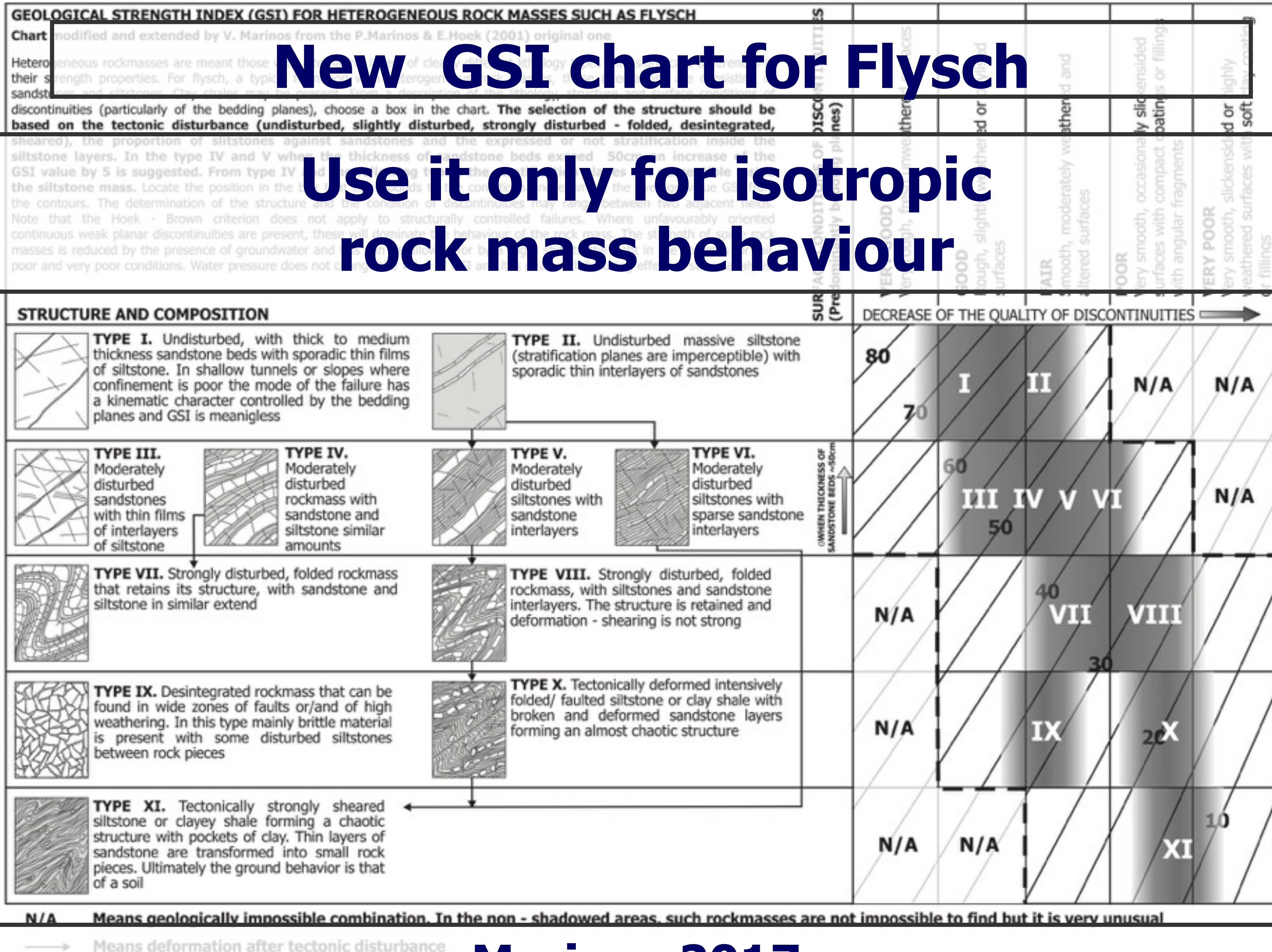


Geological conditions	
Rock mass type	
Rock mass behaviour	


Tectonically strongly sheared siltstone or clayey shale forming a chaotic structure with pockets of clay. Thin layers of sandstone are transformed into small rock pieces. Ultimately the ground behavior is that of a soil
It is not possible to detect specific zones of better or worst rock mass quality. Sandstone blocks have not particular geometry and persistence in space in such environment
The area is consisted by sheared clayey-silty geomaterial where sandstone blocks are "floating»
Tectonically deformed intensively folded/faulted siltstone or clay shale with broken and deformed sandstone layers forming an almost chaotic structure
Chaotic mixture of siltstone flysch in a geological environment of a big thrust
E
W
~150m
~500m
~100m
Legend
Ionian zone
Siltstone with thin sandstone intercalations
Siltstone and sandstone intercalations
Pindos zone
Thick sandstone beds with thin siltstone intercalations
Siltstone and sandstone intercalations
Greyey and reddish siltstones
Overthrust
Thrust
Shears
Tunnel

New GSI chart for Flysch

Use it only for isotropic rock mass behaviour



Marinos 2017

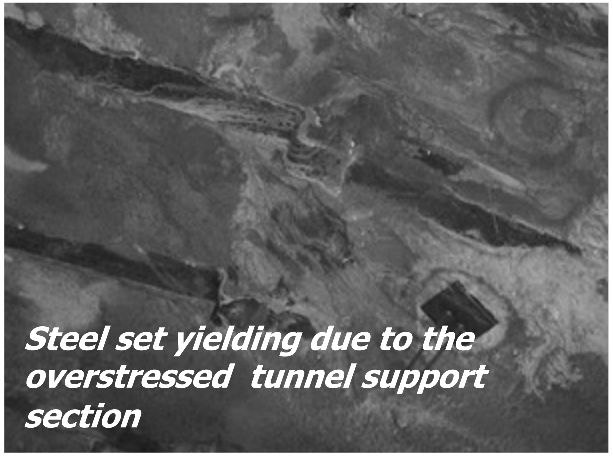
Engineering Geological Types of Flysch

Intact rock and rock mass parameters

ΤΥΠΟΣ ΦΛΥΣΧΗ	GSI	σ_{ci} MPa	m_i	E_i GPa	σ_{cm} MPa	$E_{m\ (2006)}$ GPa
I	65	40	17	10	12	7
II	60	15	7	3	3	1,5
III	55	40	17	9	10	3,5
IV	50	23	10	5,5	4	1,5
V	45	18	8	4	2,5	0,9
VI	40	15	7	3	1,7	0,5
VII	35	23	10	5,5	2,5	0,6
VIII	25	18	8	4	1,5	0,25
IX	30	22	9,5	5,2	2	0,4
X	20	15	7	3,3	1	0,15
XI	15	<10	6	2	0,5	0,08

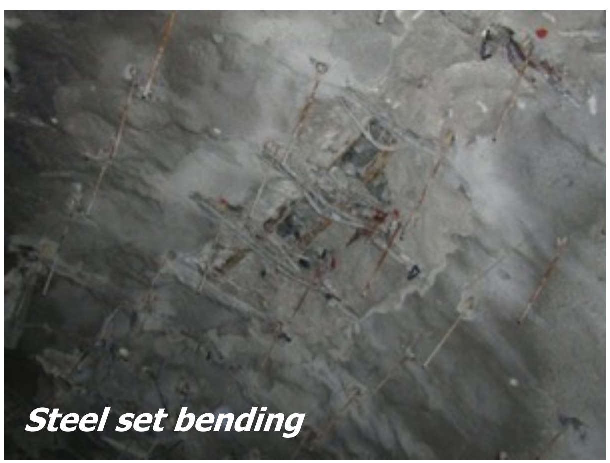
** Calculated from software Rocdata (Rocscience Inc.)*

It is extremely difficult to take a sample of an ”intact" core and a representative specimen of rock as well as to prepare laboratory specimens.



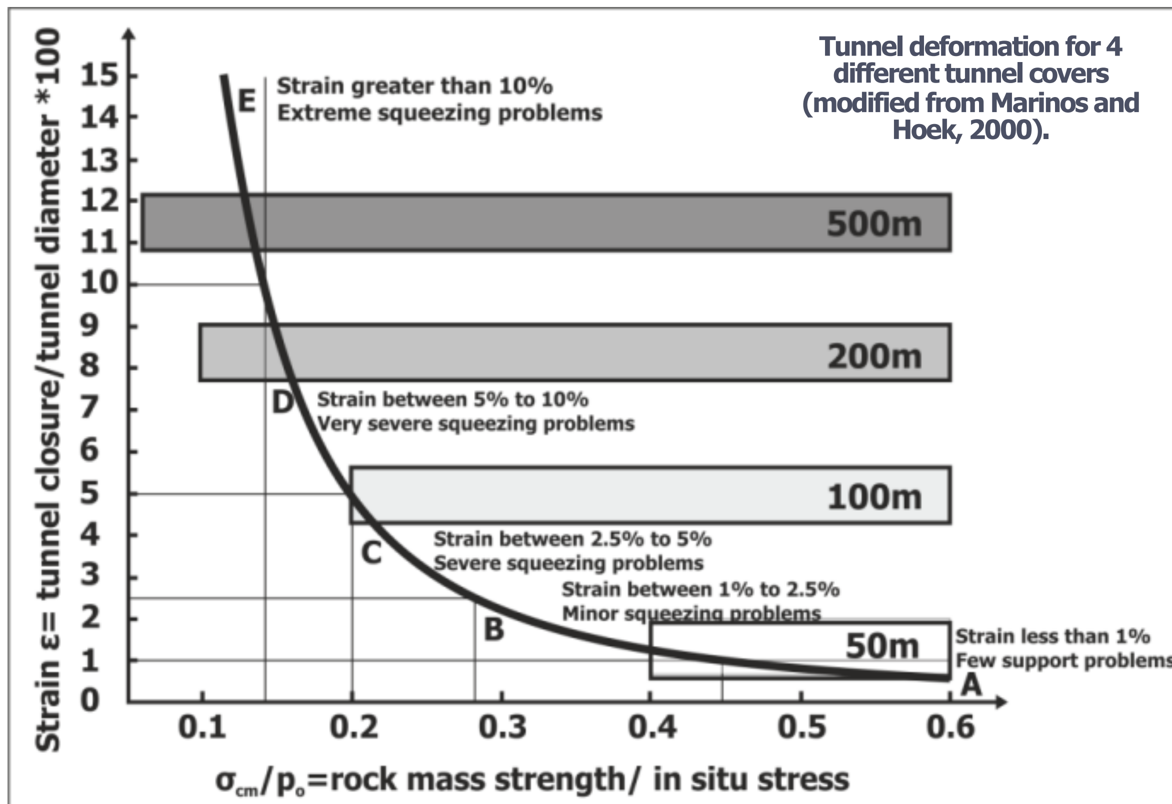
Steel set yielding due to the overstressed tunnel support section

Shotcrete failure



Steel set bending

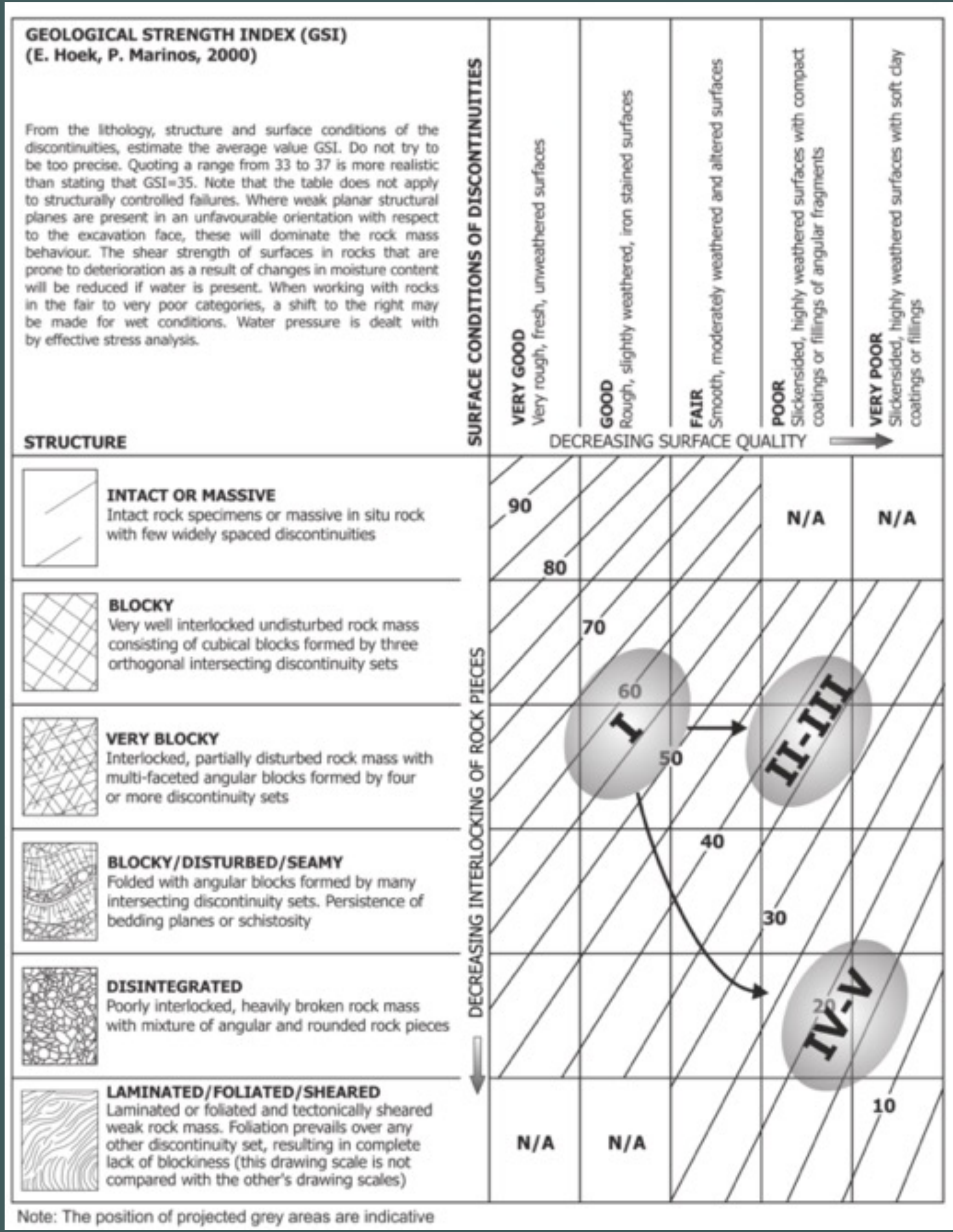
Shotcrete failure at the invert area



Tunnel deformation for 4 different tunnel covers (modified from Marinos and Hoek, 2000).

IV. Interaction between GSI and Weathering

Indicative example of how weathering degree (W-I to W-V) affects GSI

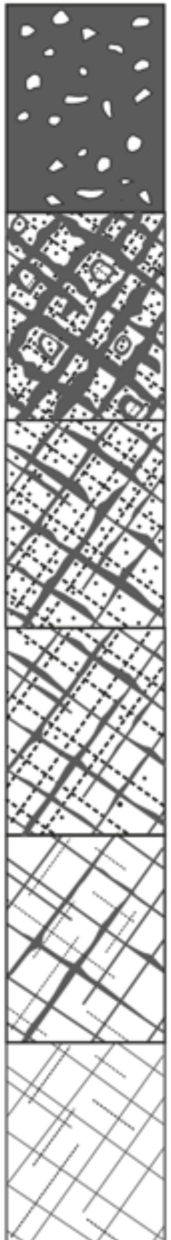


Basic engineering geological consideration

Focuses on the:

- **foliated structure**
- **tectonic disturbance**
- **weathering degree**
- **presence of shear zones**

Gneissic rock masses categorized in rock mass types according to key engineering geological characteristics that define the rock mass behaviour.



GRADE SCALE (ISRM)	TERM	Description	σ_{ci} reduction factor (After Stacey and Page, 1986)	GSI notes
VI	Residual soil	Soil derived from in situ weathering (100% soil) (from grades IV,V)	N/A (advise soil mechanics testing)	N/A (advise soil mechanics testing)
V	Completely weathered	All rock material is decomposed and/or disintegrated to soil (less than 30% rock of grades I,II,III). The original mass structure is still visable Shearing can be affected through matrix.	0.001-0.004	Area where GSI is marginally applicable. The structure has been severely disturbed and the interlocking between the fragments has been lost. Clayey-sandy zones follow the original structure and rock fragments are not interlocked. Joint condition is Very Poor.
IV	Highly weathered	More than a half of the rock material is decomposed and/or disintegrated to a soil (30% to 50% rock of grades I,II,III). Severe weathering along the surfaces. Fresh or discoloured rock is present either as a discontinuous framework or as corestones. The rock material is friable. Corestones still affect shear behaviour of the rock mass.	0.04	The structure has been highly disturbed and the interlocking between the fragments has been highly loosened. Clayey and sandy products are filling all the discontinuities. Joint condition is Very Poor. The GSI shifts down and right in the chart.
III	Moderately weathered	Less than half of the rock material is decomposed and/or disintegrated to a soil (50% to 90% rock of grades I,II,III). High to severe weathering along the surfaces. Fresh or discoloured rock is present either as a discontinuous framework or as corestones. The rock material is not friable. The structure is locked.	0.1	The interlocking between the fragments has been considerably loosened. Weathering coatings and fragments are filling principle discontinuities (e.g. gneissic bands) and other joints.Joint condition is Poor. The GSI shifts to the poorer structure(e.g. from Very Blocky to Blocky/Disturbed and to the right in the chart.
II	Slightly weathered	Discolouration indicates weathering of rock material and discontinuity surfaces (>90% rock of grades I,II,II). All the rock material may be discoloured by weathering and may be somewhat weaker than its fresh condition.	0.4	The structure is not changed but the quality of the discontinuity surfaces is (shift to the right). The GSI is reduced to Fair conditions.
I	Fresh	No visible sign of rock material weathering (100% rock); perhaps slight discolouration on major discontinuity surfaces	1.00	Fresh rocks are generally massive (Intact to Very blocky). Joint condition is Very Good(very rouch) to Good(rouch). Blocks and surfaces are strongly interlocking. Rock mass may be even more fractured but only in depth (along a fault zone) where wethering has not been favored. In surface, a fractured rock mass is rarely fresh.

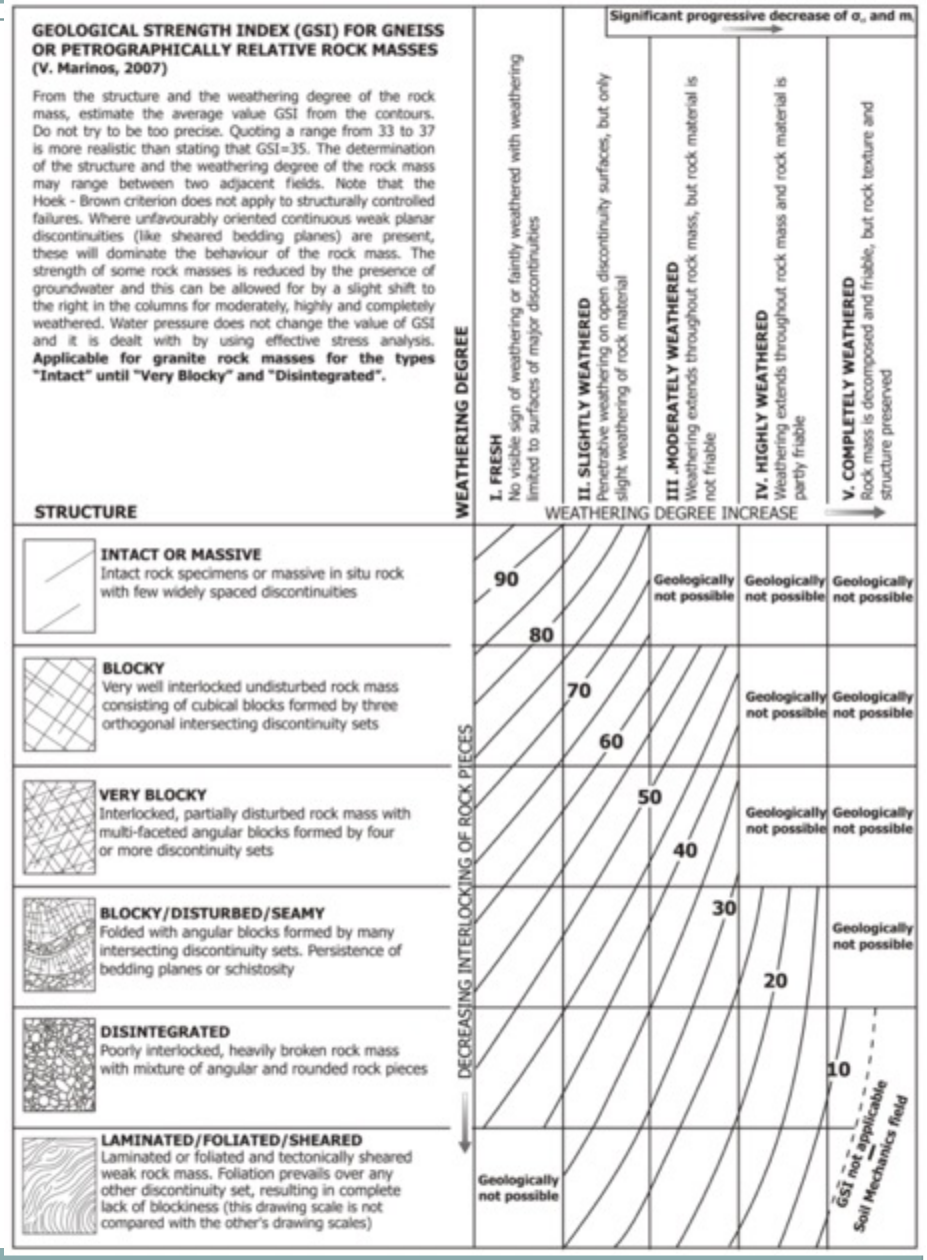
Geotechnical characterization: A GSI chart for gneissic rock masses

The chart maintains the basic structures

the surface conditions of joints are replaced by the weathering grades (ISRM, 1981).

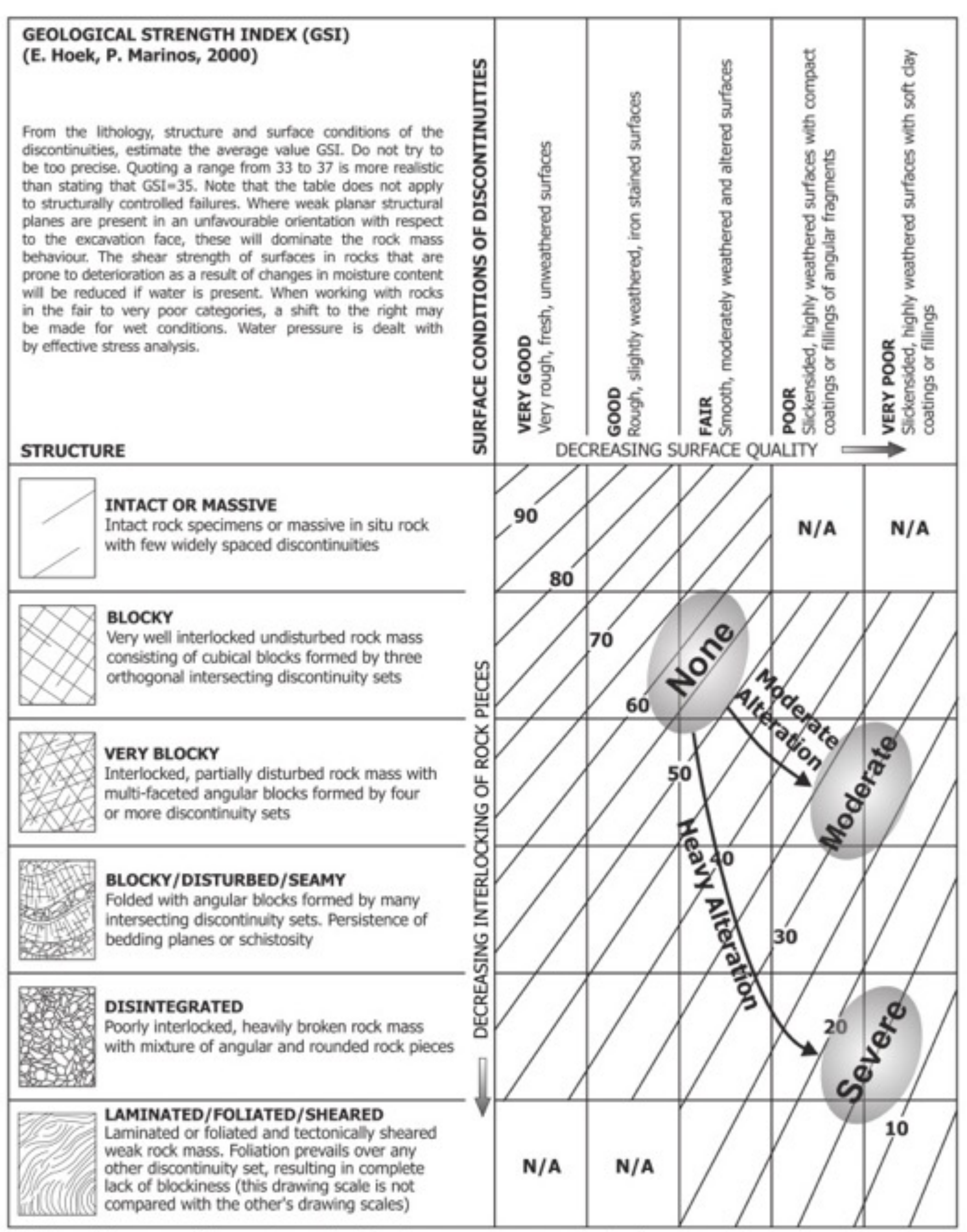
Calibration and substitution of the straight lines of the fundamental chart with curved lines, bended to the left side of the chart.

As weathering degree increases bending is increased as well



V. Interaction between GSI and alteration

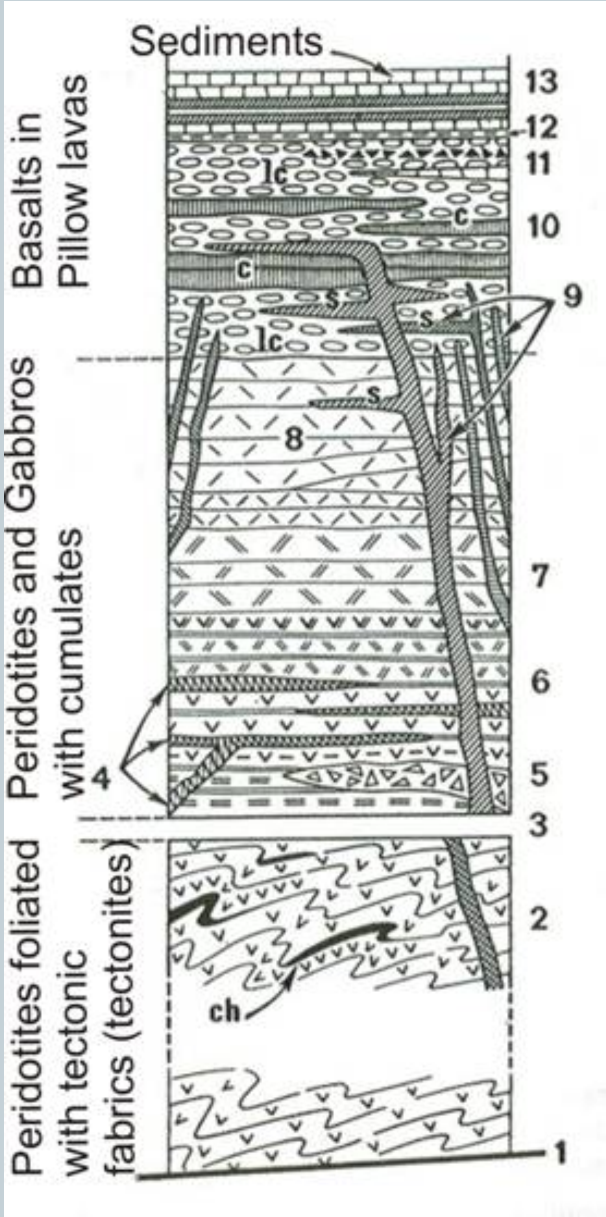
V. Interaction between GSI and alteration



Note: The position of projected grey areas are indicative

Geological Model in Ophiolitic complex

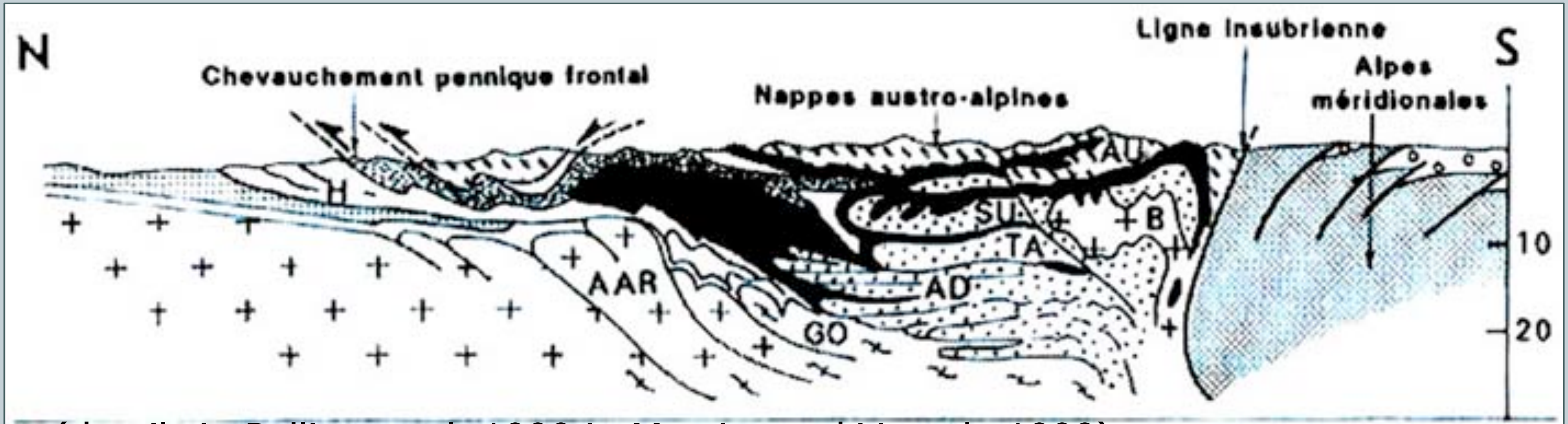
- A sequence of mafic (basic) and ultramafic (ultrabasic) rocks
- More or less serpentinised and metamorphosed, occurring in the Alpine chains.
- Ophiolites are at present considered as pieces of the oceanic crust generated at an oceanic ridge and the upper mantle of an ancient ocean, thrust up on the continental crust during mountain building



Geological Model in Ophiolitic complex

This geometry is highly disturbed:

- *occur mainly in tectonic zones with superposition of numerous overthrusts.*
- *metamorphism changes the initial nature of the rock*
- *the high serpentinisation and the tectonic shearing degree make it difficult to recognize the original nature and texture*



(details in Pollino et al. 1990 in Mercier and Vergely 1999)

Engineering Geological Types in Ophiolitic complex

Main Characteristics : Tectonism + Serpentinization

Transformation of ferromagnesian minerals, olivine in particular, to serpentine – a lattice mineral of either fibrous or laminar form.

originally compact, relatively soft and more easily

Complex rockmass

- Serpentinisation: Irregular and in any depth
- Complexity in the identification of certain zones of different quality
- Tectonic alternations with other formations like clayey shales with certs

Weak rockmass

- Serpentinization – folliation – clay presence
- Tectonical disturbance: Brecciated– schistosed– sheared



Engineering Geological Types in Ophiolitic complex

Detect the Rock Mass Types

Rock Mass Type I (Peridotites, gabbros)

massive, with only a few widely spaced discontinuities, even close to the surface in tectonically quiet areas or in zones of "tectonic shadow".

- Condition of the joints has good to very good quality
- GSI >65.
- σ_{ci} =100-250 MPa

Engineering Geological Types in Ophiolitic complex

Detect the Rock Mass Types

Rock Mass Type II
(Serpentinised Peridotites)

- Serpentinisation is limited along the surface of discontinuities.
- The initial rough conditions of the joints are dramatically reduced to poor or very poor with coatings of smooth and slippery minerals such as serpentine or even talc.
- GSI: 40 - 65.
- σ_{ci} =100-250 MPa

Engineering Geological Types in Ophiolitic complex

Detect the Rock Mass Types

Rock Mass Type III

Highly serpentinised ophiolite or serpentinite

- serpentinisation process often affects and disintegrates parts of the rock, not only contributing to lower GSI values but also reducing the intact strength values
- Fair quality peridotite with discontinuities of low frictional properties due to the presence of films of seprentinised material
- GSI: 30 - 45.
- σ_{ci} =45-60 Mpa (The influence of “schistosity” results in a significant reduction in the strength ~ 30%)

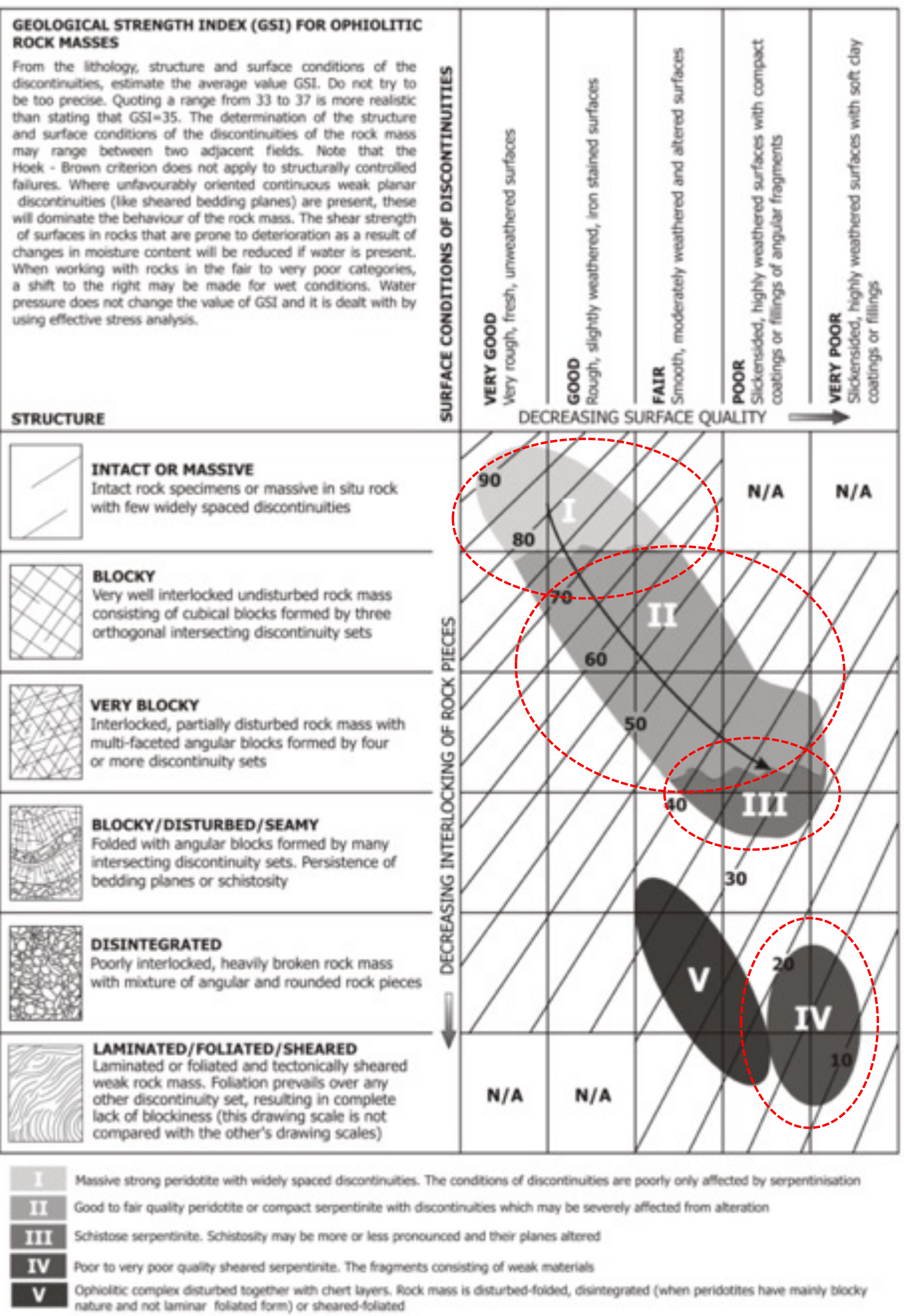
Engineering Geological Types in Ophiolitic complex

Detect the Rock Mass Types

Rock Mass Type IV (Sheared foliated serpentinites)

- Lack of blockiness: allows the rock to disintegrate into slippery laminar pieces and small flakes of centimetres or millimetres in size.
- Completely disintegrated peridotite with loss of blockiness and presence of clayey sections
- GSI: 15-25
- σ_{ci} =5-20 MPa

Engineering Geological Types in Ophiolitic complex



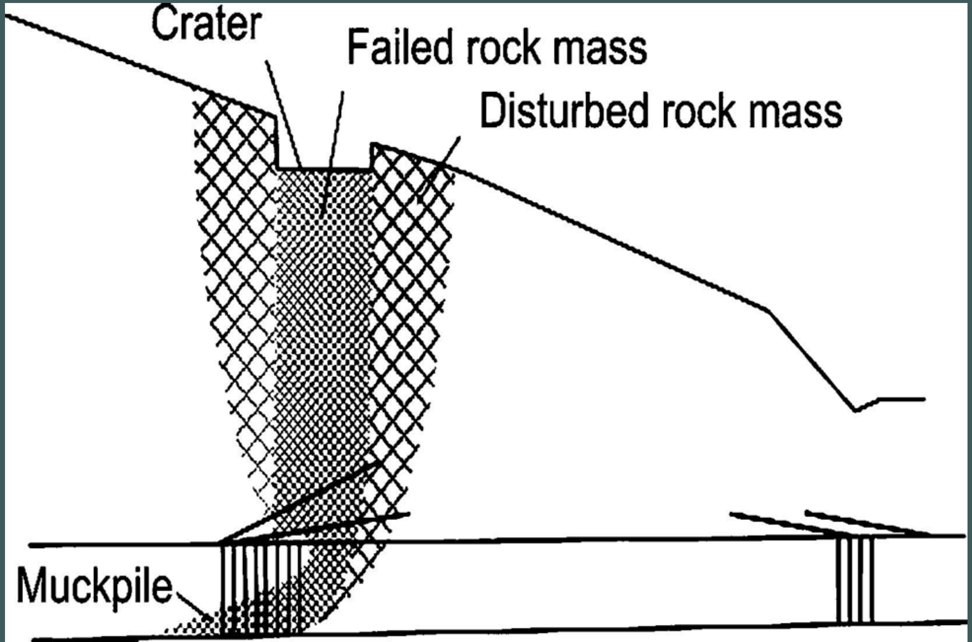
Projection of GSI values in a ophiolitic complex.

Main characteristics of the rock masses:

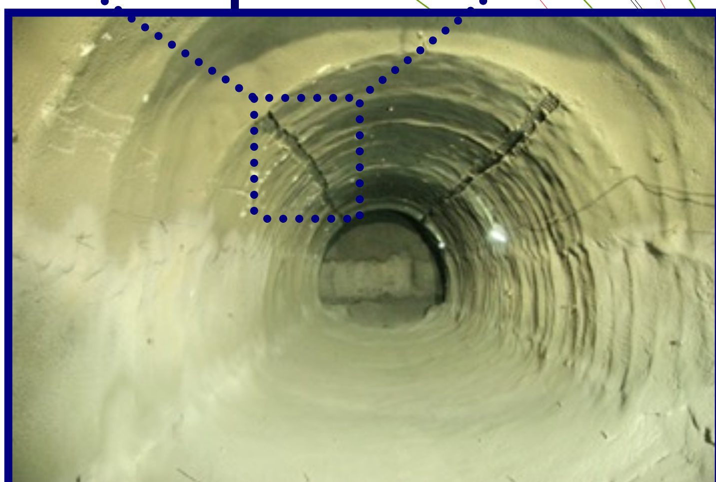
- **Serpentinisation** as a change in both in the characteristic of the discontinuities but in some cases also in the structure
- **Shearing of the rock masses** leading to the change of structure

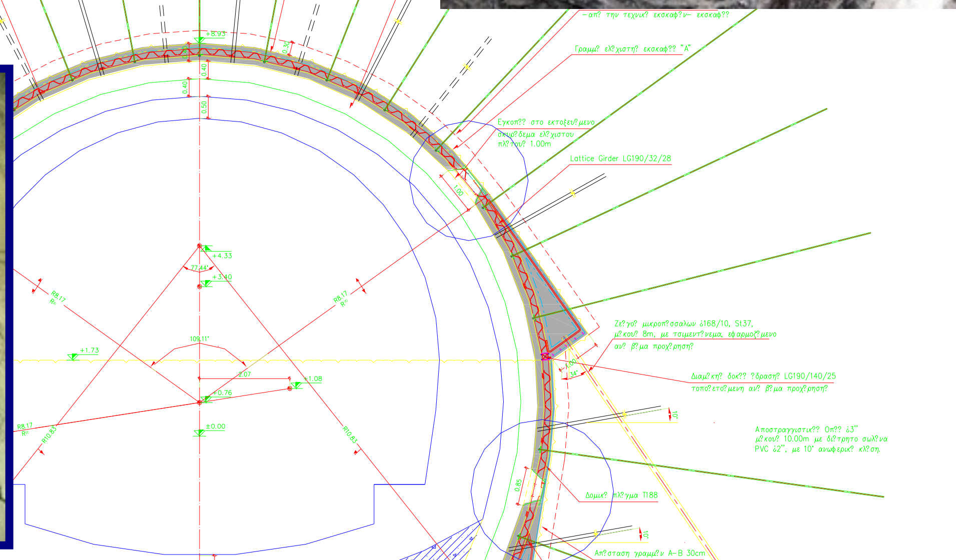
Serpentinised peridotite: A case of raveling - Support

- Light forepole umbrella (75 or 100 mm diameter pipes).
- Pre-grouting an umbrella in the rock mass over the forepoles: increase the cohesive strength of the rock mass.
- Stabilisation: installation of a double forepole umbrella and by extensive grouting through the forepoles and also through horizontal holes drilled through the muckpile.



Tunnel Support in ophiolite (type IV)





Yielding primary support (sliding joints in steel sets and gaps in shotcrete) in very weak serpentinite (type IV) in areas of thick cover, 220m, GSI 15-20, σ_{ci} 8MPa and m_i 10

V. DISCUSSION

But let say that the approaches we apply,
associated with an appropriate factor of safety,
based on the degree of uncertainties,
are satisfactory, provided they are not erroneous

It is then obvious why THE GEOLOGICAL JUDGMENT
must be always present and why is so important

VI. Conclusions 1

Rock engineers have to work within the limitations of available technology and some of the most severe limitations are associated with the estimation of rock mass properties.

Efforts to overcome have resulted in tools such as the GSI classification which, at this moment, can be regarded as interim solutions. These efforts has been in most cases useful since there are very few practical alternatives available

VI. Conclusions 2

-The GSI classification and the associated Hoek-Brown failure criterion being empirical tools should be used interactively during design and the input parametres should be adjusted and refined as back analysis information from actual field behaviour becomes available.

- In some cases it may be necessary to develop project specific GSI charts in order to permit classification of rock masses that have not been adequately covered in published papers.

-Indeed such a form of rock mass characterization as the GSI, has considerable potential for use in rock engineering because it permits the manifold aspects of rock to be quantified enhancing geological logic even in extremely heterogeneous and complex geological formations

VI. Conclusions 3

We look forward to the time when these numerical tools will allow us to at least calibrate better if not replace some of the empirical methods, such as the GSI classification and the Hoek-Brown criterion that we use today

E.Hoek & P. Marinos, EUROCK 2009, Dubrovnik

"…My long term hope is that numerical tools such as the Synthetic Rock Mass and its off-shoots will eventually enable us to replace classification type approaches or at least to calibrate these classifications. It may be a while before these hopes can be realized…"

Hoek, personal communication

Thank you

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