ASSESSING ROCK MASS BEHAVIOUR FOR TUNNELLING*

RICHARD WOLTERS PRIZE CONTEST

12TH CONGRESS OF THE IAEG, TORINO 2014

V. Marinos
Assistant Professor of the Aristotle University of Thessaloniki, Greece
Laboratory of Engineering Geology and Hydrogeology

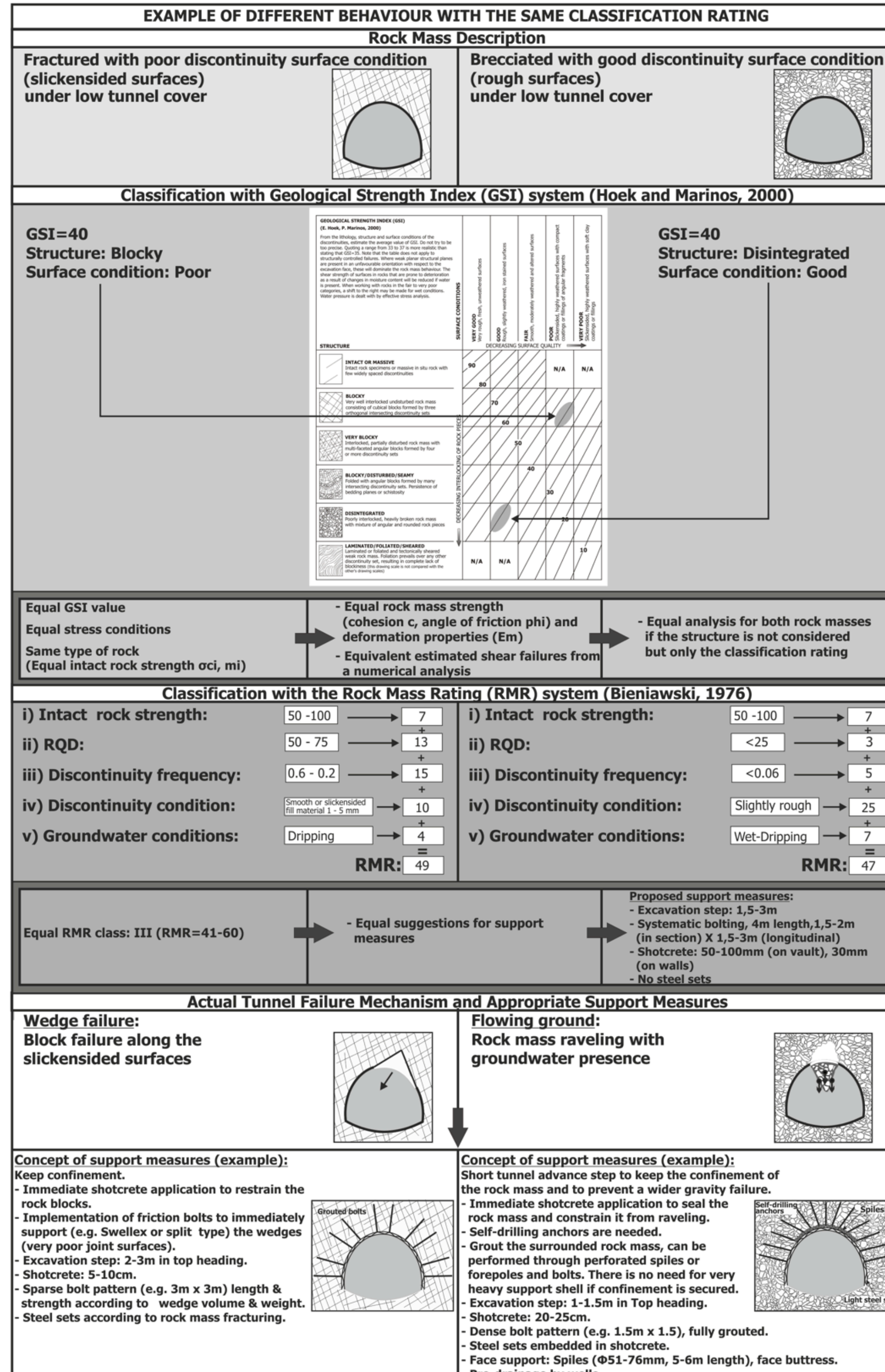
* *Published in the Journal of Environmental and Engineering Geoscience, Vol. XVIII, No. 4, pp. 327–341*

Introduction – scope of research

- Great progress has been made in analytical and computational methods in tunnel engineering. Nevertheless, the results may still involve errors and uncertainties when they are used without considering the actual failure mechanism of an excavated rock mass.
- So the first step is <u>no</u> to start performing numerous calculations (probably misleading) but to define what is the potential failure mechanisms, ensure the selection of the appropriate design parameters used in the suitable analysis and qualitatively guide the tunnel support philosophy to account for them.
- The Engineering Geology practice can considerably assist towards a realistic tunnel design.

Understanding the behaviour in tunnelling

Why it is important in the design process

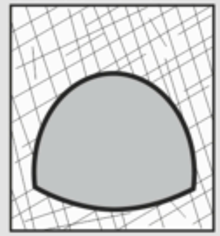


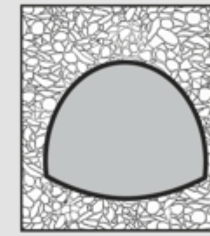
Example of two equally rated rock masses with the GSI or RMR system but with completely different behaviour in tunnelling.

EXAMPLE OF DIFFERENT BEHAVIOUR WITH THE SAME CLASSIFICATION RATING

Rock Mass Description

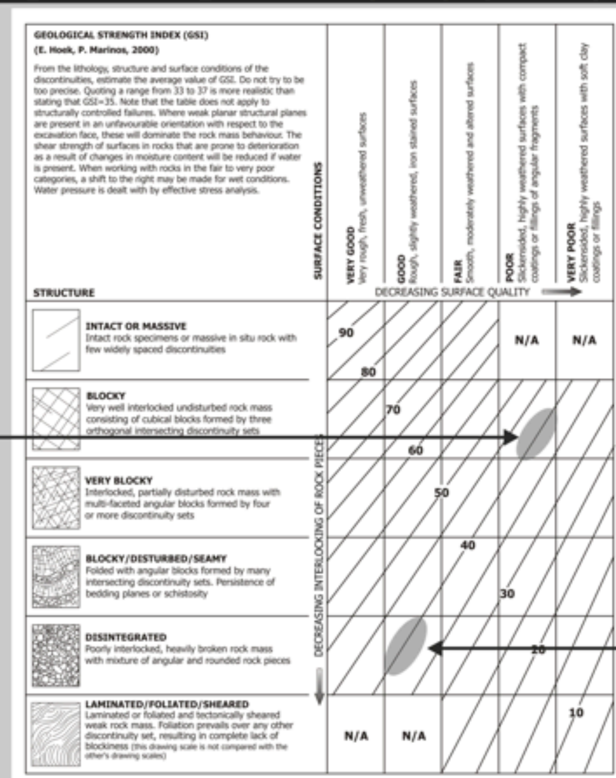
Fractured with poor discontinuity surface condition (slickensided surfaces) under low tunnel cover	Brecciated with good discontinuity surface condition (rough surfaces) under low tunnel cover





Classification with Geological Strength Index (GSI) system (Hoek and Marinos, 2000)

GSI=40
Structure: Blocky
Surface condition: Poor



GSI=40
Structure: Disintegrated
Surface condition: Good

Equal GSI value Equal stress conditions Same type of rock (Equal intact rock strength σci, mi)	➡	- Equal rock mass strength (cohesion c, angle of friction phi) and deformation properties (Em) - Equivalent estimated shear failures from a numerical analysis	➡	- Equal analysis for both rock masses if the structure is not considered but only the classification rating

Classification with the Rock Mass Rating (RMR) system (Bieniawski, 1976)

i) Intact rock strength:	50 -100	7
ii) RQD:	50 - 75	13
iii) Discontinuity frequency:	0.6 - 0.2	15
iv) Discontinuity condition:	Smooth or slickensided fill material 1 - 5 mm	10
v) Groundwater conditions:	Dripping	4
	RMR:	49

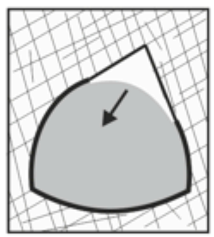
i) Intact rock strength:	50 -100	7
ii) RQD:	<25	3
iii) Discontinuity frequency:	<0.06	5
iv) Discontinuity condition:	Slightly rough	25
v) Groundwater conditions:	Wet-Dripping	7
	RMR:	47

Equal RMR class: III (RMR=41-60) → - Equal suggestions for support measures →

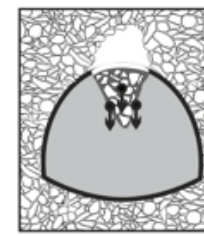
Proposed support measures:
- Excavation step: 1,5-3m
- Systematic bolting, 4m length,1,5-2m (in section) X 1,5-3m (longitudinal)
- Shotcrete: 50-100mm (on vault), 30mm (on walls)
- No steel sets

Actual Tunnel Failure Mechanism and Appropriate Support Measures

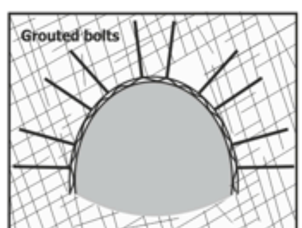
Wedge failure:
Block failure along the slickensided surfaces



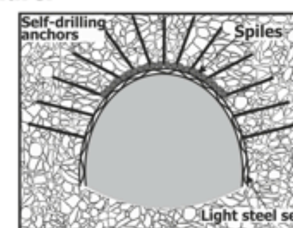
Flowing ground:
Rock mass raveling with groundwater presence



Concept of support measures (example):
Keep confinement.
- Immediate shotcrete application to restrain the rock blocks.
- Implementation of friction bolts to immediately support (e.g. Swellex or split type) the wedges (very poor joint surfaces).
- Excavation step: 2-3m in top heading.
- Shotcrete: 5-10cm.
- Sparse bolt pattern (e.g. 3m x 3m) length & strength according to wedge volume & weight.
- Steel sets according to rock mass fracturing.



Concept of support measures (example):
Short tunnel advance step to keep the confinement of the rock mass and to prevent a wider gravity failure.
- Immediate shotcrete application to seal the rock mass and constrain it from raveling.
- Self-drilling anchors are needed.
- Grout the surrounded rock mass, can be performed through perforated spiles or forepoles and bolts. There is no need for very heavy support shell if confinement is secured.
- Excavation step: 1-1.5m in Top heading.
- Shotcrete: 20-25cm.
- Dense bolt pattern (e.g. 1.5m x 1.5), fully grouted.
- Steel sets embedded in shotcrete.
- Face support: Spiles (Φ51-76mm, 5-6m length), face buttress.
- Pre-drainage by wells.



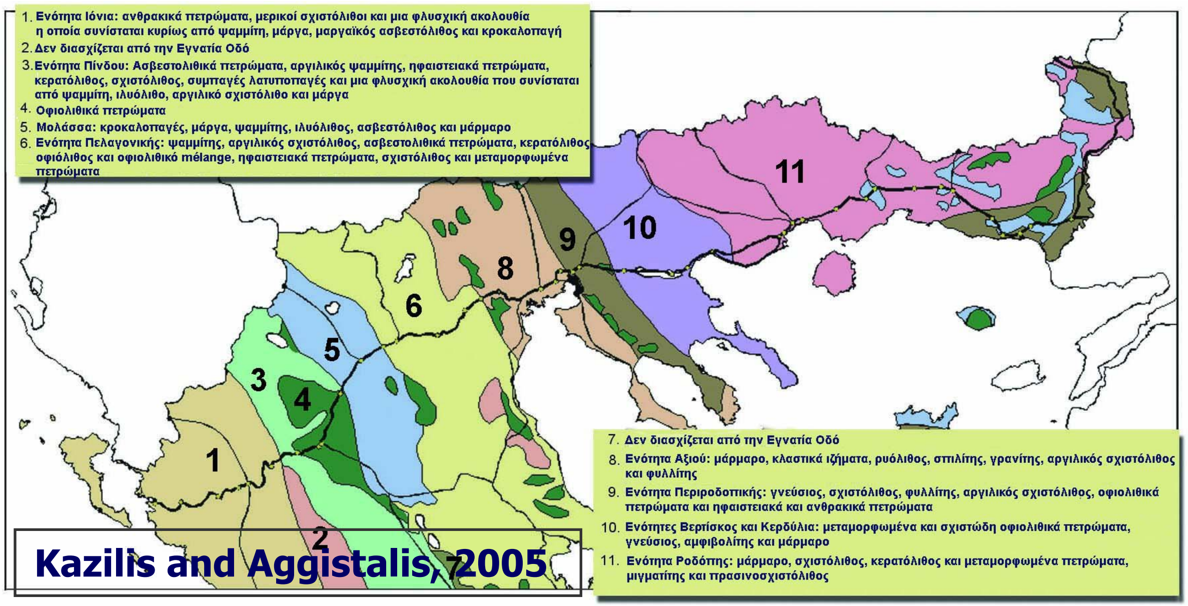
Outline

I. The data – A geotechnical database from 62 tunnels
II. Tunnel design steps - Where Engineering Geology must be involved
III. Identification of tunnel behaviour modes
IV. Proposed classification scheme for assessing the rock mass behaviour in tunnelling
V. Suggestions on the temporary support measures
VI. Conclusions – Contribution of Engineering Geology

Outline

I. The data – A geotechnical database from 62 tunnels
II. Tunnel design steps - Where Engineering Geology must be involved
III. Identification of tunnel behaviour modes
IV. Proposed classification scheme for assessing the rock mass behaviour in tunnelling
V. Suggestions on the temporary support measures
VI. Conclusions – Contribution of Engineering Geology

I. The data: Design and construction of 62 Tunnels of Egnatia Highway

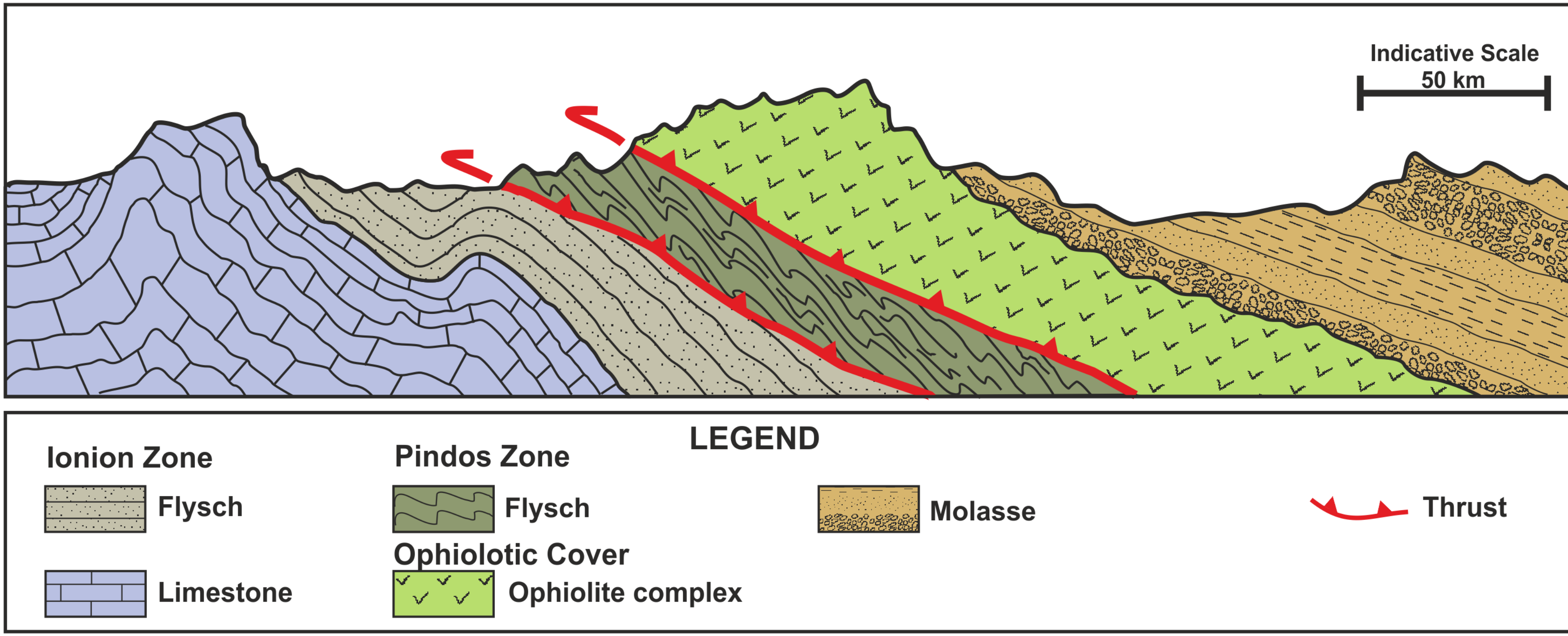


Kazilis and Aggistalis, 2005

- 680 km Highway (East-West). 100% constructed.
- 76 road tunnels (length of 99km in total)
- 62 bored tunnels
- Tunnel span: 12m
- Opened by the method of top heading and bench
- The cross-section of these tunnels is 80-120m^2
- Tunnelling conditions range from relatively straightforward to extremely difficult

From the Geological Model to the Rock Mass model:

Identification of rock mass types

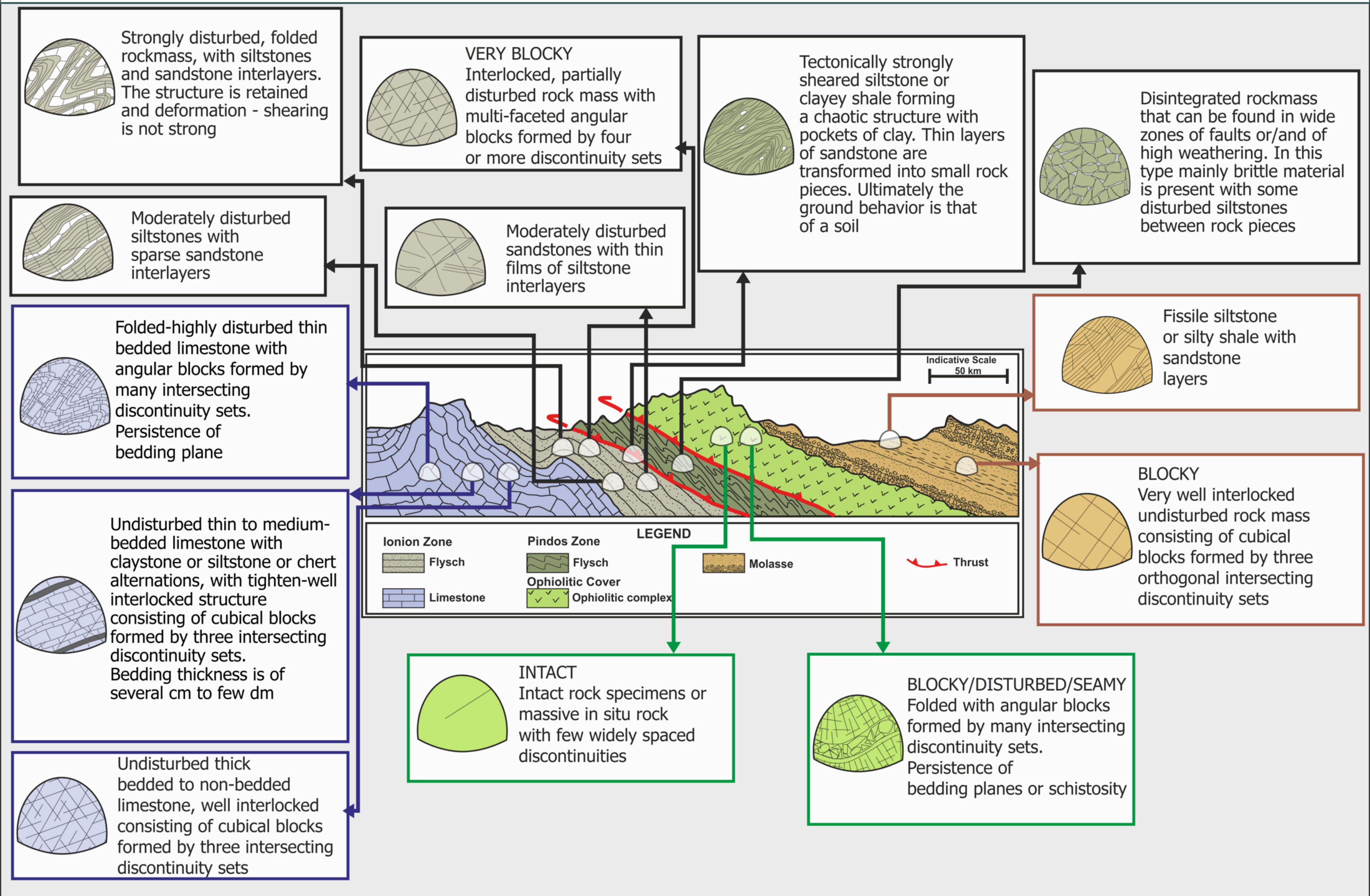


Tunnelling in a great variety of geological situations, under different in situ stress conditions, in both mildly and heavily tectonised rock masses.

Experience in tunnelling from: 12 tunnels in flysch rocks , 13 in molassic rocks, 7 in ophiolites, 5 in limestones, other in gneiss, marbles, schists and granites.

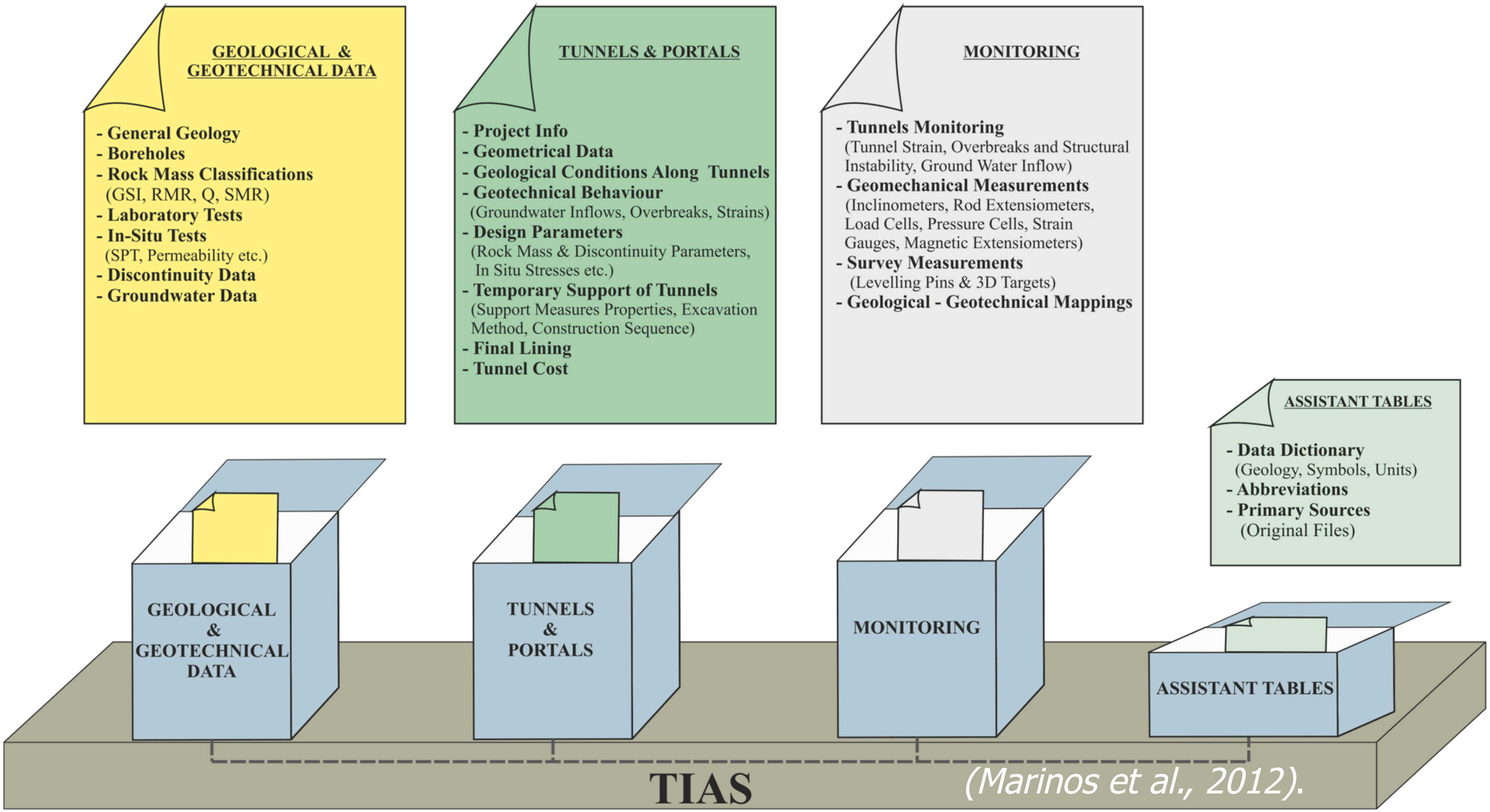
From the Geological Model to the Rock Mass model:

Identification of rock mass types



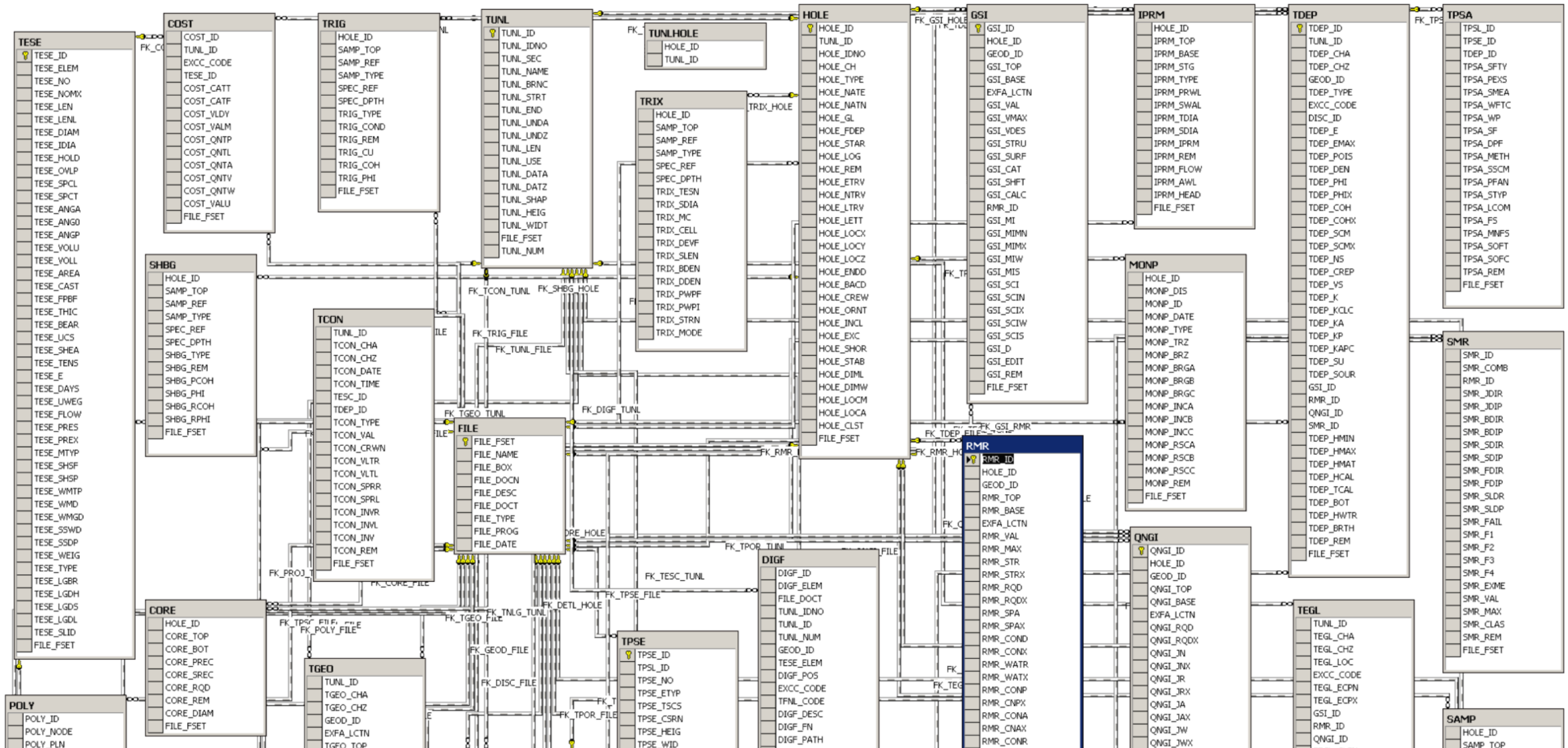
The tool: a creation of a geotechnical tunnel database

Tunnel Information Analysis System (TIAS)



(Marinos et al., 2012).

Architecture of TIAS Database



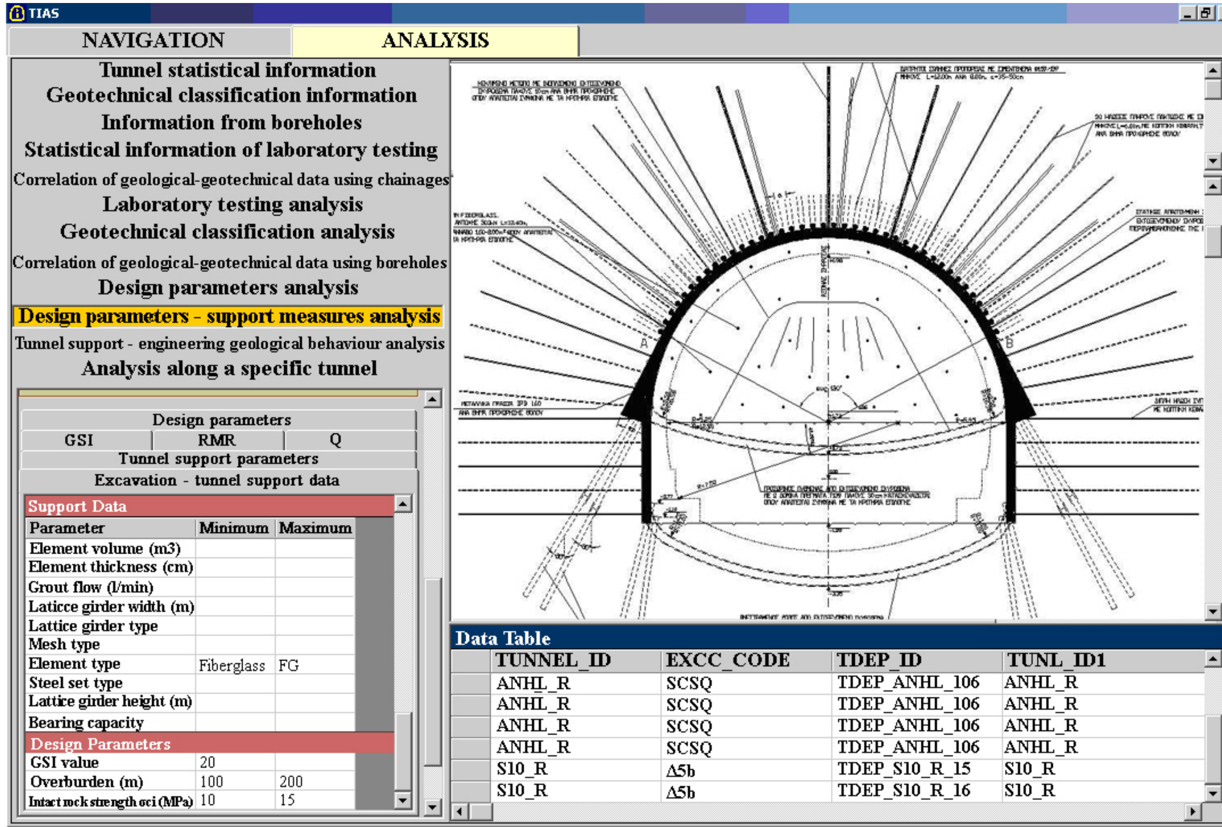
Tunnel Information and Analysis System (TIAS) : A geotechnical database for tunnels and analysis system with a purpose to manage and correlate all the data generated from site investigation, design and construction *(Marinos et al., 2012)*.

Thousands of data from 62 tunnels are incorporated.

Example of Analysis in TIAS database:

Correlation of design parameters – tunnel behaviour – support measures

Export results: Relevant support measures categories with these criteria



- <u>Criteria:</u>

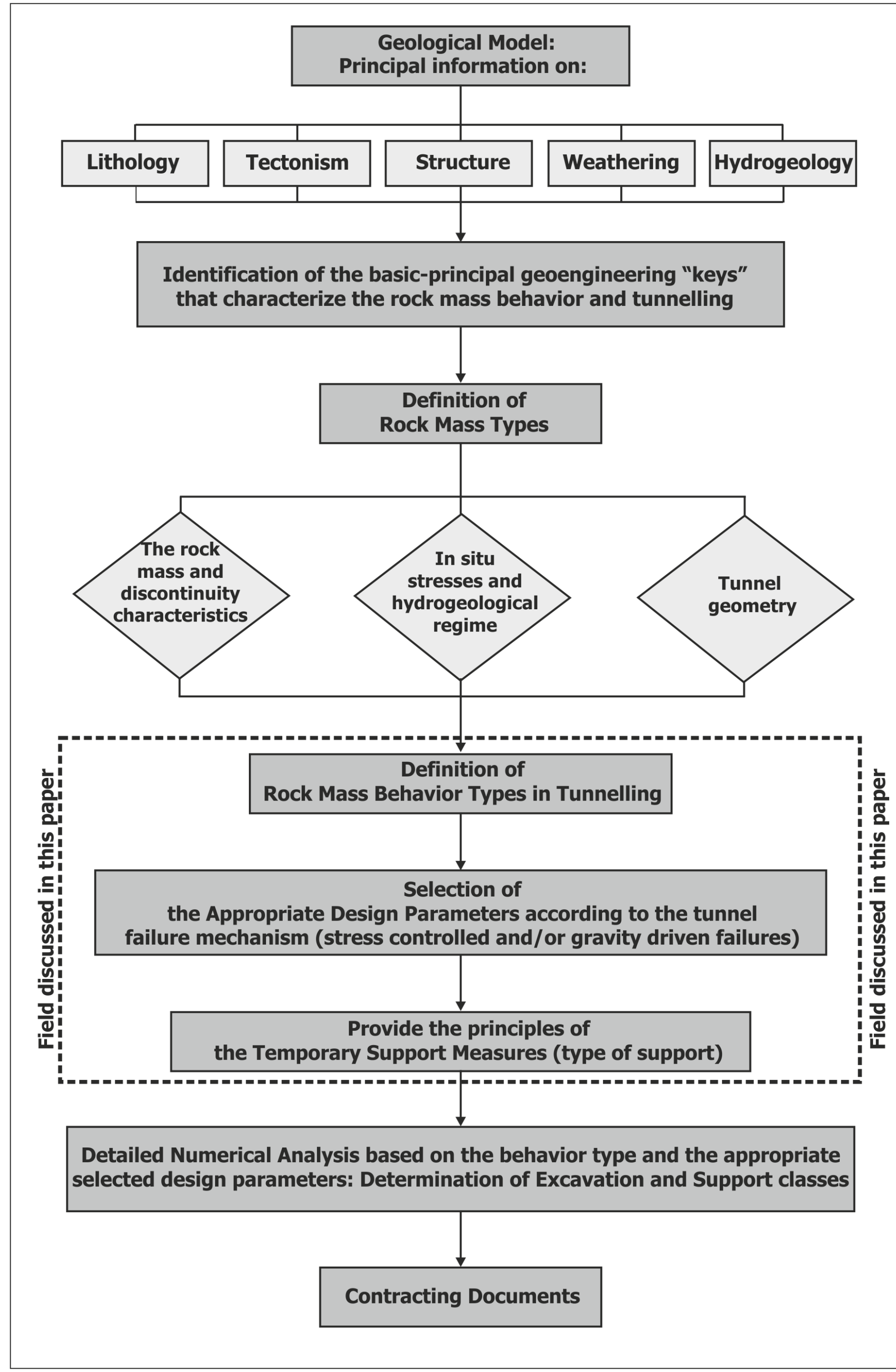
Tunnel cover: 100-200m, Parameters: GSI=20, σ_{ci}=10-15MPa, Behaviour: Squeezing (Sq) Support: Fibreglass nails at tunnel face

Outline

I. The data – A geotechnical database from 62 tunnels
II. Tunnel design steps - Where Engineering Geology must be involved
III. Identification of tunnel behaviour modes
IV. Classification scheme for assessing the rock mass behaviour in tunnelling
V. Suggestions on the temporary support measures
VI. Conclusions – Contribution of Engineering Geology

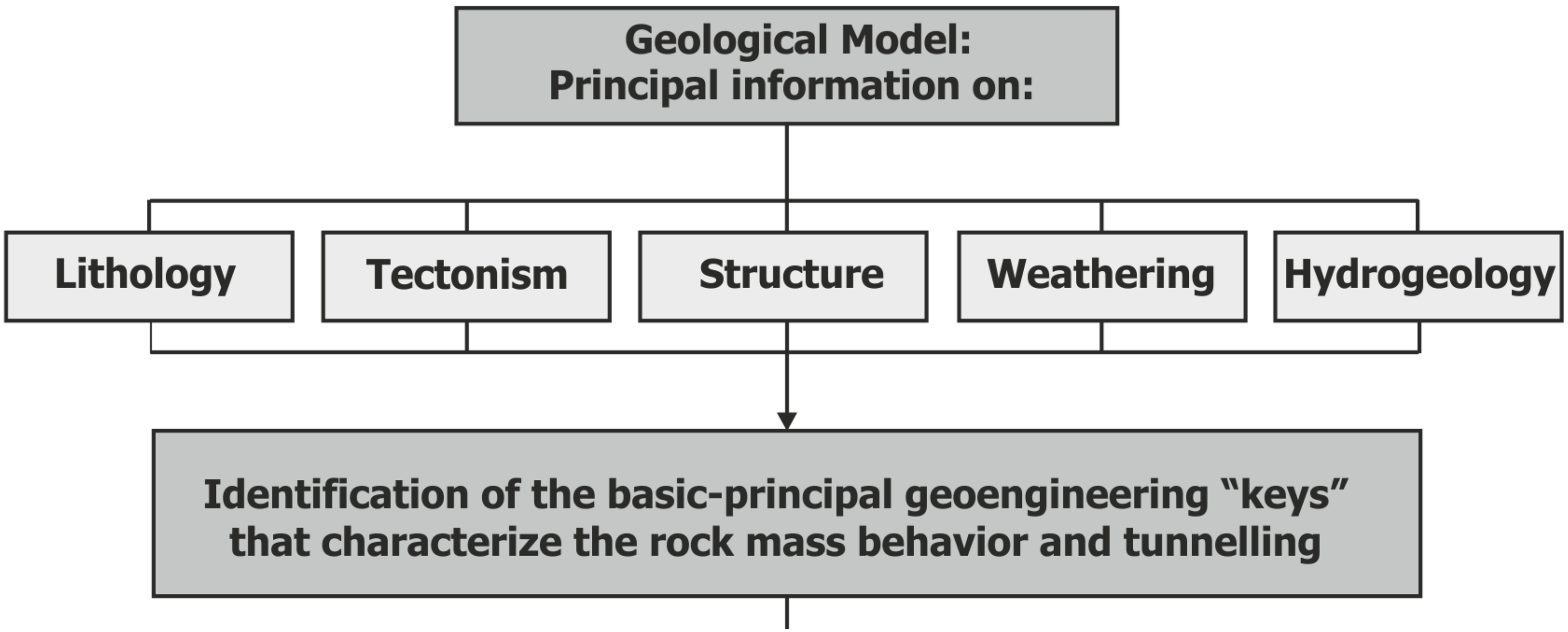
II. Tunnel Design Flowchart

How should tunnel behaviour be incorporated in the design.

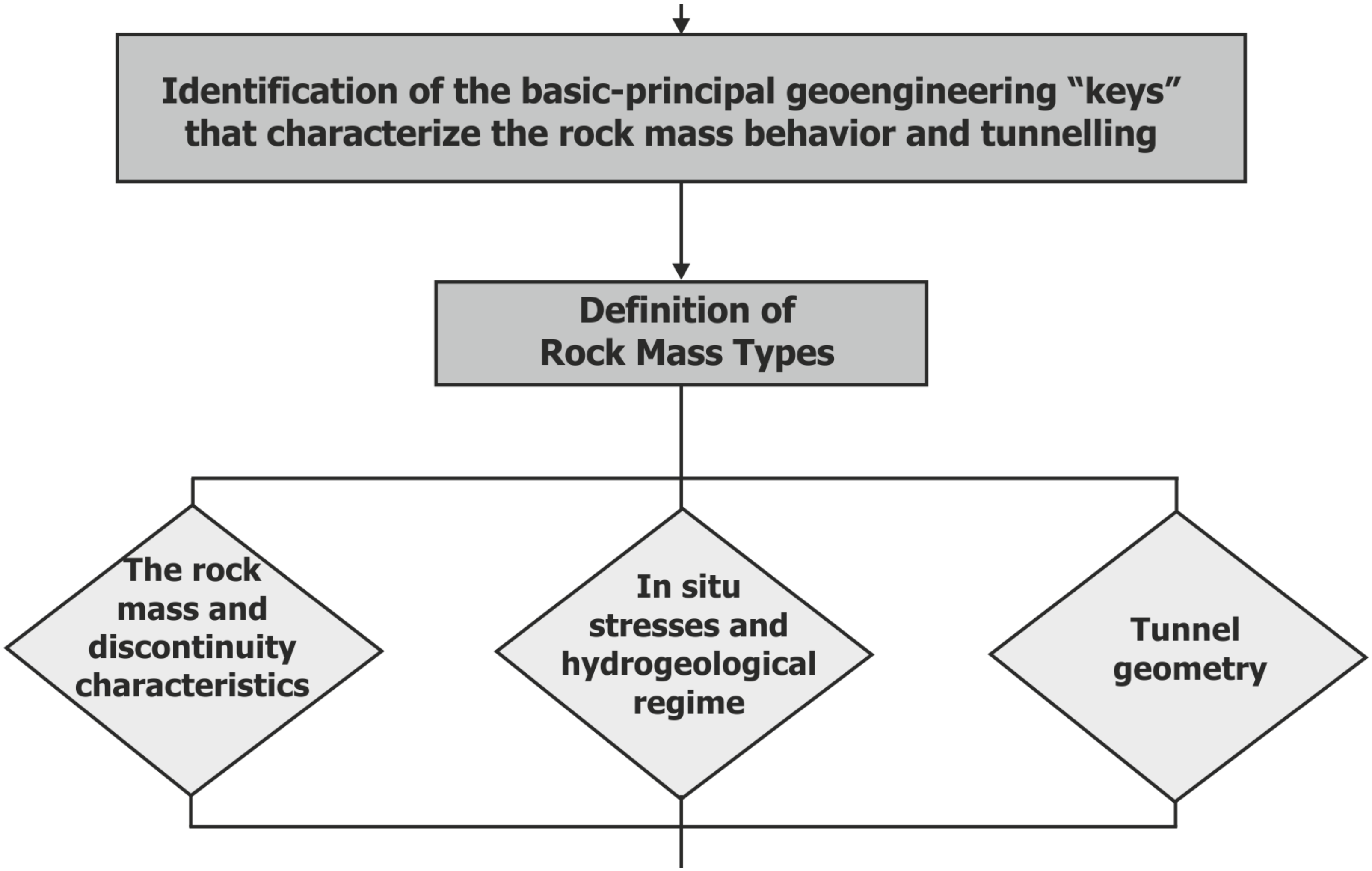


Based on Schubert et. al., 2003, and modified by the author

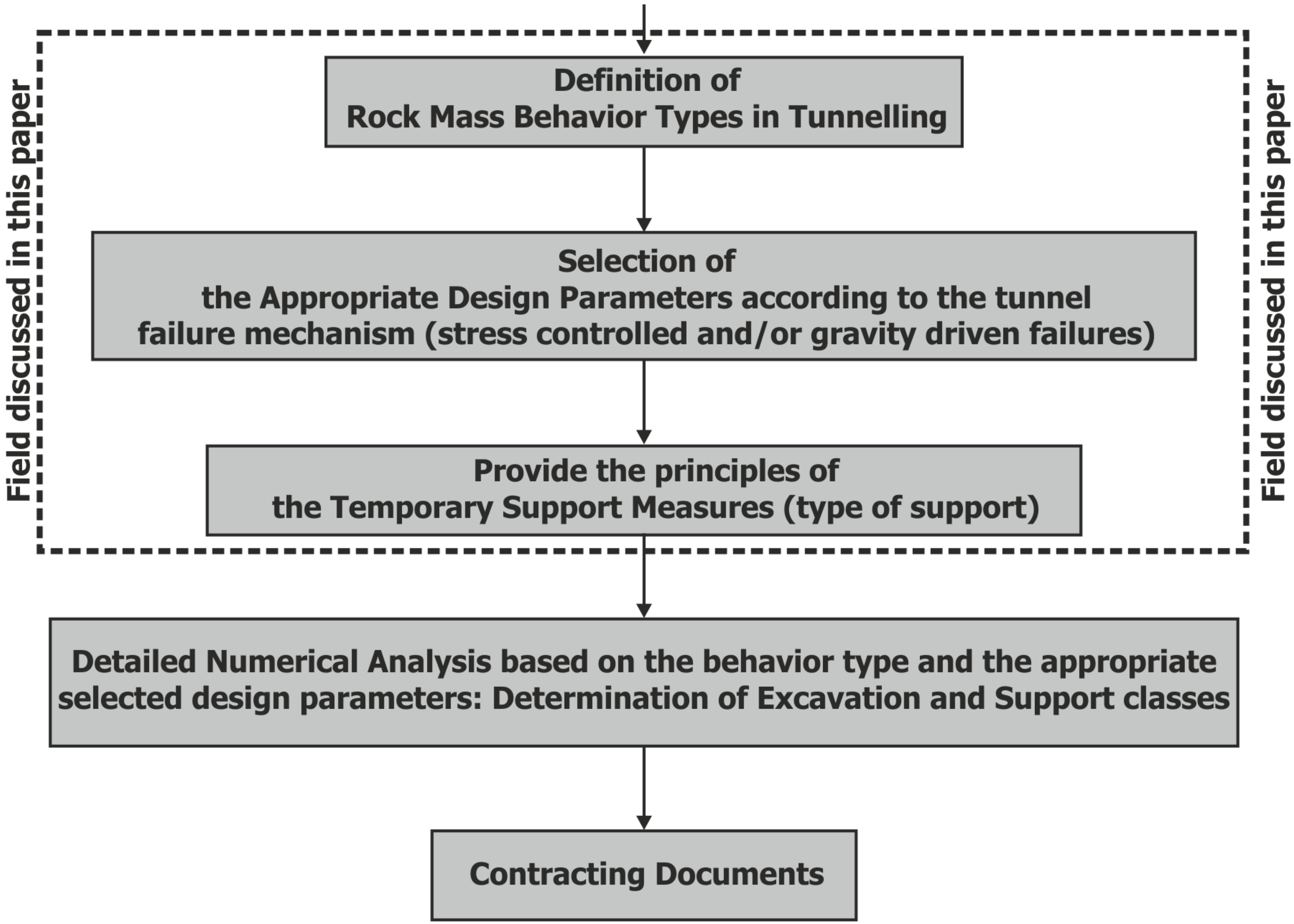
Tunnel Design Flowchart



Tunnel Design Flowchart



Tunnel Design Flowchart



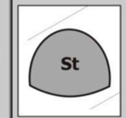
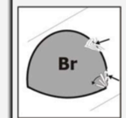
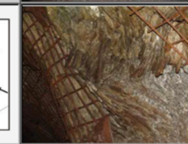
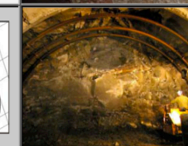
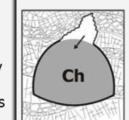
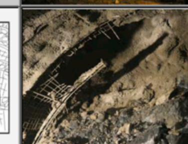
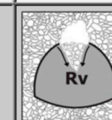
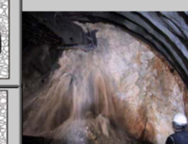
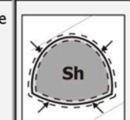
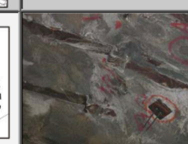
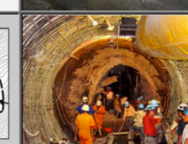
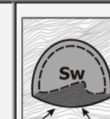
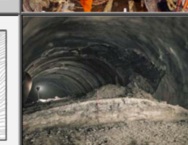
Outline

I. The data – A geotechnical database from 62 tunnels
II. Tunnel design steps - Where Engineering Geology must be involved
III. Identification of tunnel behaviour modes
IV. Classification scheme for assessing the rock mass behaviour in tunnelling
V. Suggestions on the temporary support measures
VI. Conclusions – Contribution of Engineering Geology

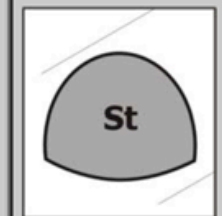
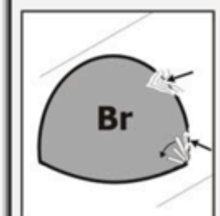
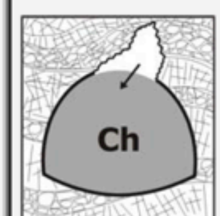
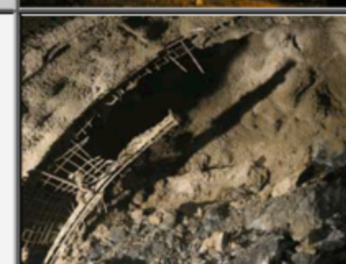
III. Identification of predominant behaviour types around tunnels.

The term “failure mechanism-behaviour type”, here, involves all the mechanisms that endanger the tunnel section when the rock mass has not yet been supported after excavation.

Based on Schubert et. al., 2003, Terzaghi, 1946 and from the presenter

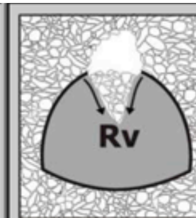
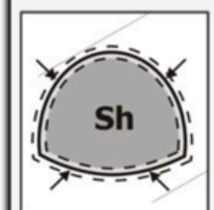
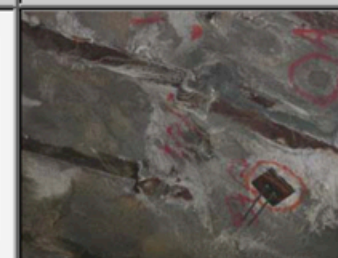
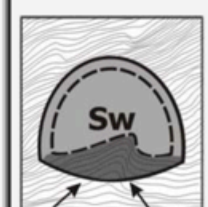
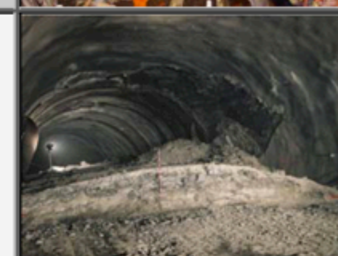
TUNNEL BEHAVIOUR TYPES			
St	**Stable ground:** Stable tunnel section with local gravity failures. Rock mass is compact with limited and isolated discontinuities		
Br	**Brittle failure:** Brittle failure or rock bursting at great depths		
Wg	**Wedge failure:** Wedge sliding or gravity driven failures. Insignificant strains. The rock mass is blocky to very blocky, blocks can fall or slide. The stability is controlled by the geometrical and mechanical characteristics of the discontinuities. The ratio of rock mass strength to the in situ stress (σ_{cm}/p_o) is high (>0.6-0.7) and there are very small strains (ε<1%)		
Ch	**Chimney type failure:** Rock mass is highly fractured, maintaining most of the time its structure (or at least that of the surrounded rock mass). Rock mass does not have good interlocking (open structure) and in combination with low confinement (lateral stress) can tend to block falls which develop to larger overbreaks of chimney type. The overbreaks may be stopped and “bridged” by better quality rock masses, depending on the in situ conditions. This type may be applied also in cases of brecciated and disintegrated rock mass in ground with high confinement (high lateral stress)		
Rv	**Ravelling ground:** The rock mass is brecciated and disintegrated or foliated with practically zero cohesion and depending on the intact rock interlocking (Rv1 case: without infilling) and possible secondary hosted geomaterial, (Rv2 case: with infilling, e.g. clay), rock mass can generate immediate rock mass ravelling in face and tunnel perimeter. The difference with Ch type lies in the block size, which is very small here, the self support timing, which is very limited here and the failure extension, where it is unrestricted due to the lack of better rock mass quality in the surrounding zone		
Fl	**Flowing ground:** The rock mass is disintegrated with practically zero cohesion and intense groundwater presence along the discontinuities. Rock fragments flow with water inside the tunnel		
Sh	**Shear failure:** Minor to medium strains, with the development of shear failures close to the perimeter around the tunnel. Rock mass is characterized by low strength intact rocks (σ_{ci}<15MPa) while the rock mass structure reduces the overall the rock mass strength. Strains develop either at a small to medium tunnel cover (around 50-70m) in case of poor sheared rock masses, or in larger cover in case of better quality rock masses. The ratio of rock mass strength to the in situ stress (σ_{cm}/p_o) is low ($0.3<\sigma_{cm}/p_o<0.45$) and strains are measured or expected to be medium (1-2.5 %)		
Sq	**Squeezing ground:** Large strains, due to overstressing with the development of shear failures in an extended zone around the tunnel. Rock mass consists of low strength intact rocks while the rock mass structure reduces the overall rock mass strength. The ratio of rock mass strength to the in situ stress (σ_{cm}/p_o) is very low (σ_{cm}/p_o <0.3) and strains are measured or expected to be >2.5%, and they can be also take place at the face		
Sw	**Swelling ground:** Rock mass contains a significant amount of swelling minerals (montmorillonite, smectite, anhydrite) which swell and deform in the presence of groundwater. Swelling often occurs in the tunnel floor when the support ring is not fully closed		
San	**Anisotropic strains:** The rock mass is stratified or schistose or consists of specific weak zones and develops increased strain characteristics along a direction defined by the schistosity.		

Predominant behaviour types around tunnels.

TUNNEL BEHAVIOUR TYPES			
St	**Stable ground:** Stable tunnel section with local gravity failures. Rock mass is compact with limited and isolated discontinuities		
Br	**Brittle failure:** Brittle failure or rock bursting at great depths		
Wg	**Wedge failure:** Wedge sliding or gravity driven failures. Insignificant strains. The rock mass is blocky to very blocky, blocks can fall or slide. The stability is controlled by the geometrical and mechanical characteristics of the discontinuities. The ratio of rock mass strength to the in situ stress (σ_{cm}/p_o) is high (>0.6-0.7) and there are very small strains (ε<1%)		
Ch	**Chimney type failure:** Rock mass is highly fractured, maintaining most of the time its structure (or at least that of the surrounded rock mass). Rock mass does not have good interlocking (open structure) and in combination with low confinement (lateral stress) can tend to block falls which develop to larger overbreaks of chimney type. The overbreaks may be stopped and "bridged" by better quality rock masses, depending on the in situ conditions. This type may be applied also in cases of brecciated and disintegrated rock mass in ground with high confinement (high lateral stress)		

Predominant behaviour types around tunnels.

TUNNEL BEHAVIOUR TYPES

Rv	**Ravelling ground:** The rock mass is brecciated and disintegrated or foliated with practically zero cohesion and depending on the intact rock interlocking (Rv1 case: without infilling) and possible secondary hosted geomaterial, (Rv2 case: with infilling, e.g. clay), rock mass can generate immediate rock mass ravelling in face and tunnel perimeter. The difference with Ch type lies in the block size, which is very small here, the self support timing, which is very limited here and the failure extension, where it is unrestricted due to the lack of better rock mass quality in the surrounding zone		
Fl	**Flowing ground:** The rock mass is disintegrated with practically zero cohesion and intense groundwater presence along the discontinuities. Rock fragments flow with water inside the tunnel		
Sh	**Shear failure:** Minor to medium strains, with the development of shear failures close to the perimeter around the tunnel. Rock mass is characterized by low strength intact rocks (σ_{ci}<15MPa) while the rock mass structure reduces the overall the rock mass strength. Strains develop either at a small to medium tunnel cover (around 50-70m) in case of poor sheared rock masses, or in larger cover in case of better quality rock masses. The ratio of rock mass strength to the in situ stress (σ_{cm}/p_o) is low ($0.3<\sigma_{cm}/p_o<0.45$) and strains are measured or expected to be medium (1-2.5 %)		
Sq	**Squeezing ground:** Large strains, due to overstressing with the development of shear failures in an extended zone around the tunnel. Rock mass consists of low strength intact rocks while the rock mass structure reduces the overall rock mass strength. The ratio of rock mass strength to the in situ stress (σ_{cm}/p_o) is very low ($\sigma_{cm}/p_o<0.3$) and strains are measured or expected to be >2.5%, and they can be also take place at the face		
Sw	**Swelling ground:** Rock mass contains a significant amount of swelling minerals (montmorillonite, smectite, anhydrite) which swell and deform in the presence of groundwater. Swelling often occurs in the tunnel floor when the support ring is not fully closed		

Tunnel behaviour types
Chimney type failure (Ch)

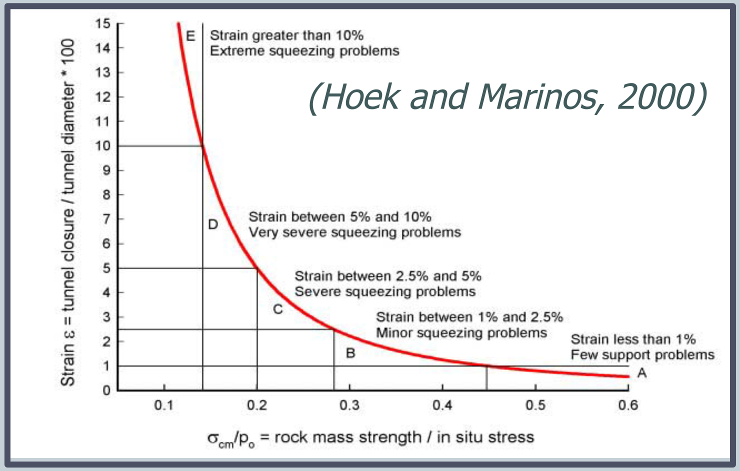
- Rock mass is highly fractured and/or weathered
- Maintains most of the time its structure.
- Not good interlocking. In combination with low confinement block falls which develop to larger overbreaks.
- Overbreaks may be stopped and "bridged" by better quality rock masses, depending on the in situ conditions.
- This type may be applied also in cases of disintegrated rock mass with high confinement

Chimney failure in highly weathered gneiss (Σ10 Tunnel, Egnatia Highway)

Tunnel behaviour types

Squeezing behaviour (Sq)

- Predicting Squeezing Magnitude (Sq) with the ratio (σ_{cm}/p_o) (rock mass strength to the in situ stress)
- Shear failures in an extended zone.
- Low strength intact rocks, rock mass structure reduces the overall rock mass strength.
- σ_{cm}/p_o is very low (<0.3) and strains are measured or expected to be >2.5%
- They can be also take place at the face



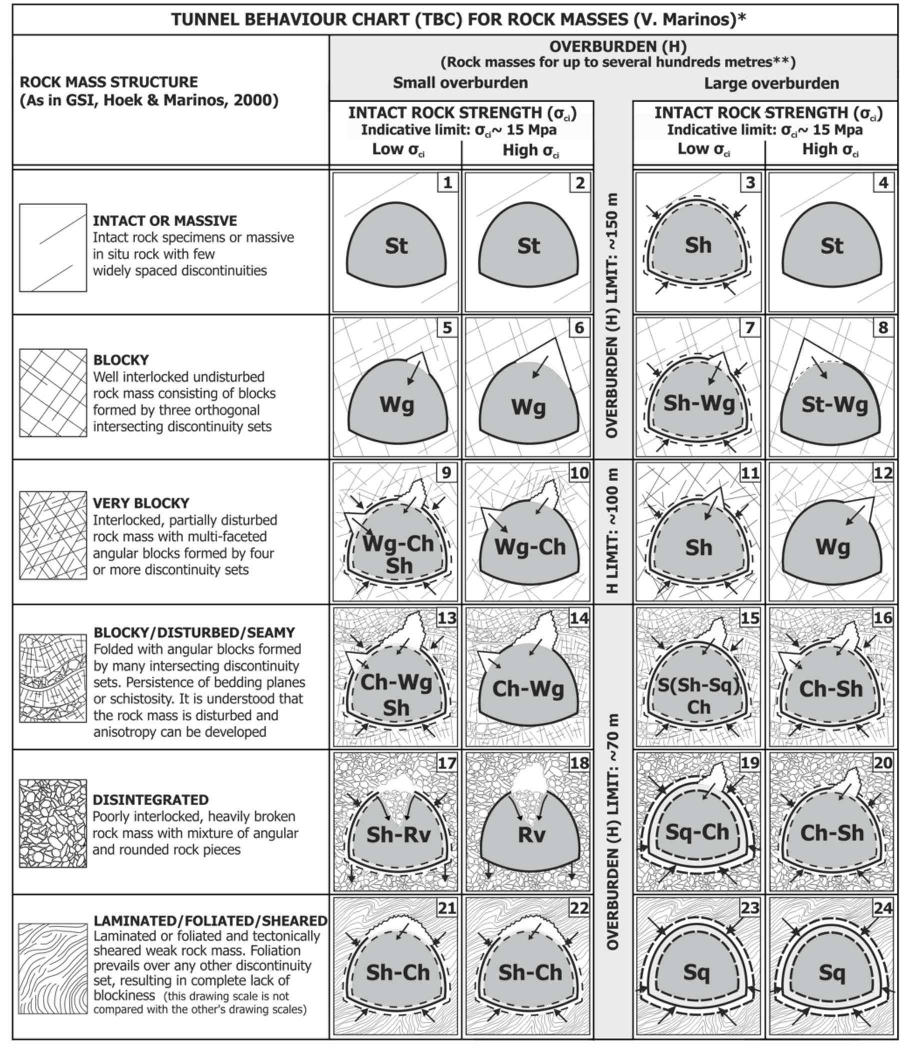

"Overstressed" steel sets
(Driskos tunnel, Egnatia Highway)

Outline

I. The data – A geotechnical database from 62 tunnels
II. Tunnel design steps - Where Engineering Geology must be involved
III. Identification of tunnel behaviour modes
IV. Classification scheme for assessing the rock mass behaviour in tunnelling
V. Suggestions on the temporary support measures
VI. Conclusions – Contribution of Engineering Geology

IV. Assessing rock mass behaviour for tunnelling:

A proposed Tunnel Behaviour Chart (TBC)



- Top heading and bench method
- Non-urban environment
- Overburden cover up to several hundred metres (not very high overburden (e.g. >700m)
- Tunnel diameter=9-12m

The user to read the "small letters" before using the chart

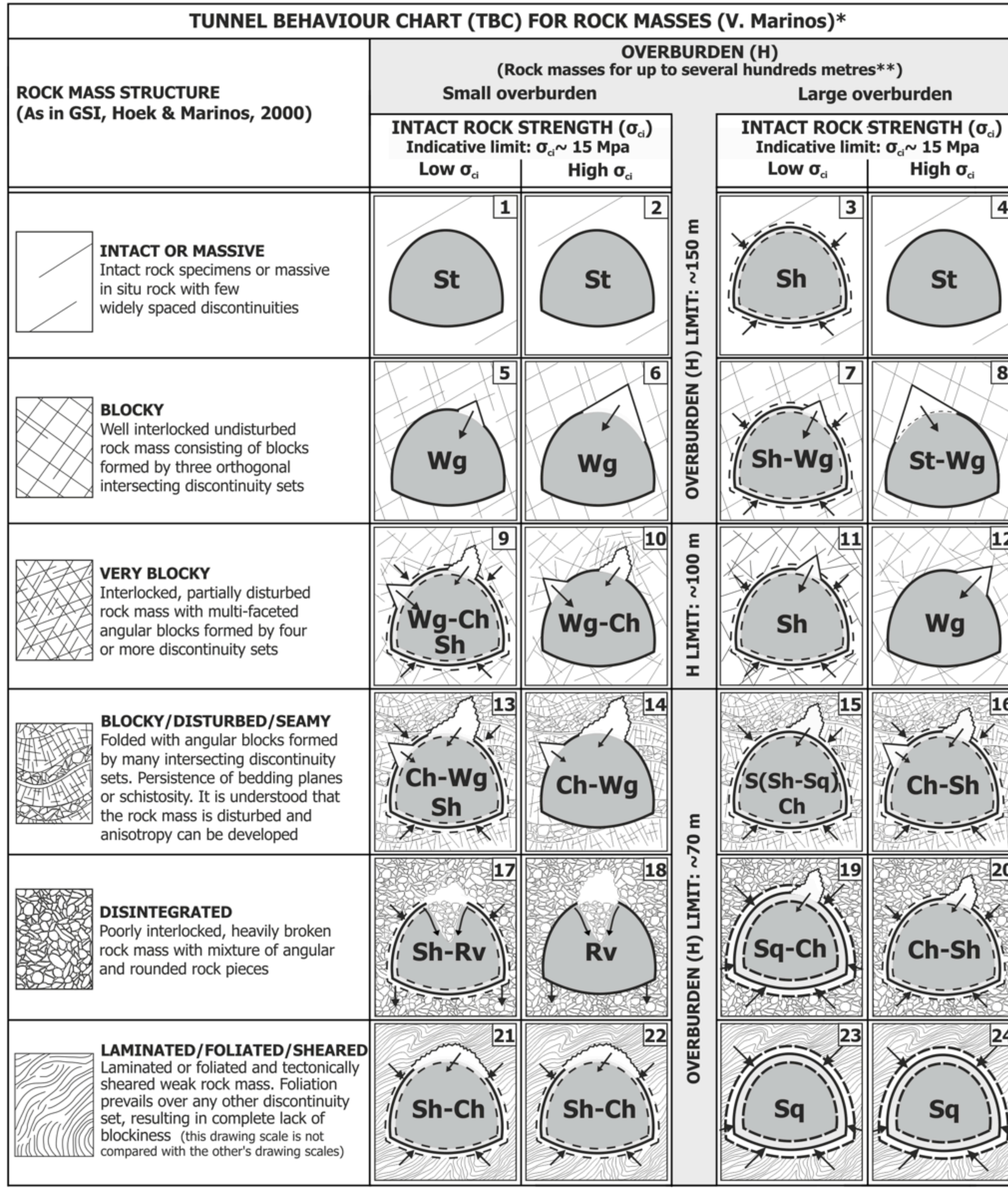
Marinos, 2012

Tunnel Behaviour Chart (TBC)

The behaviour depends on three major parameters:

- The Structure
- The Intact Rock Strength (σ_{ci})
- The Tunnel Overburden (H)

Marinos, 2012

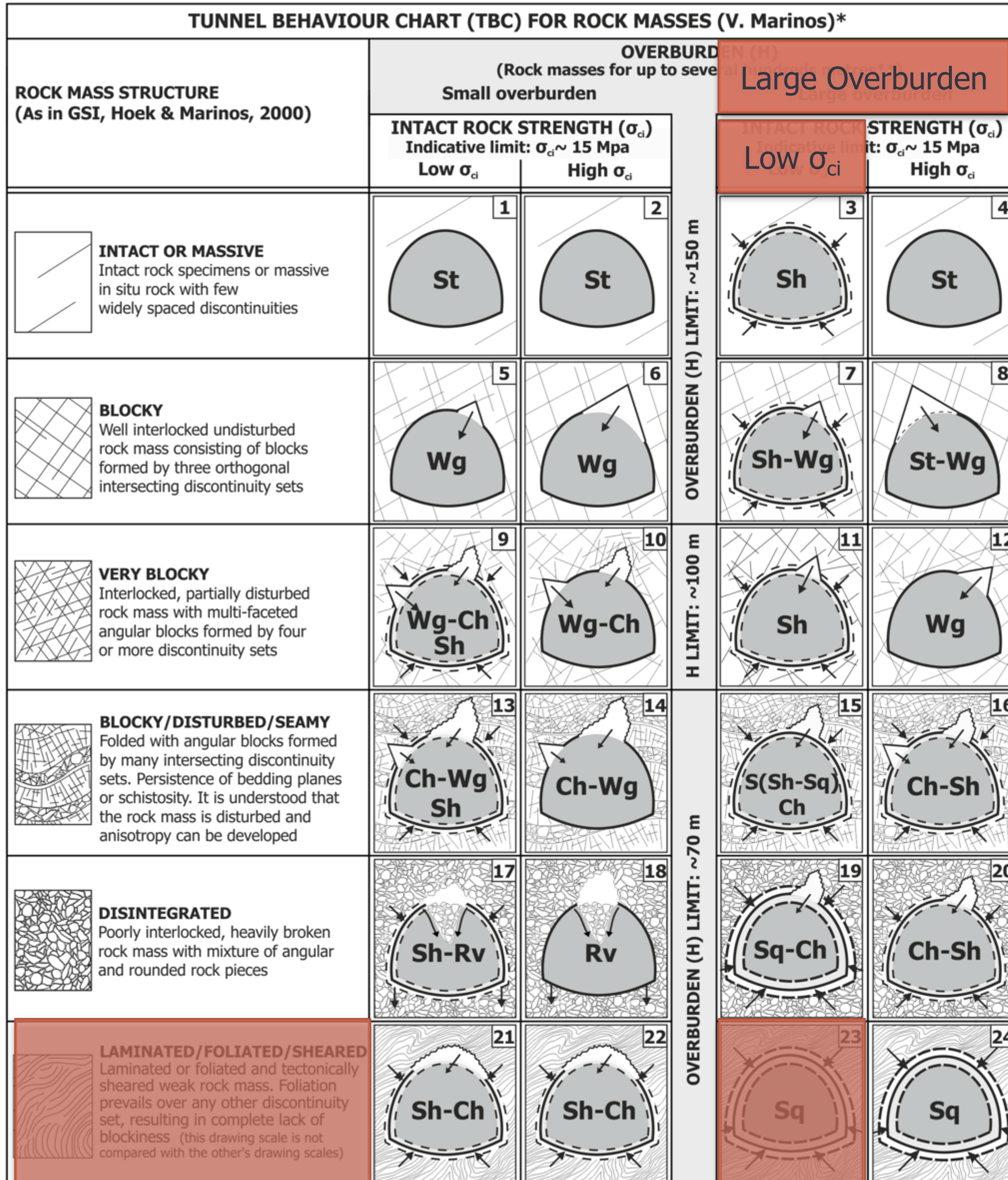


Tunnel Behaviour Chart (TBC)

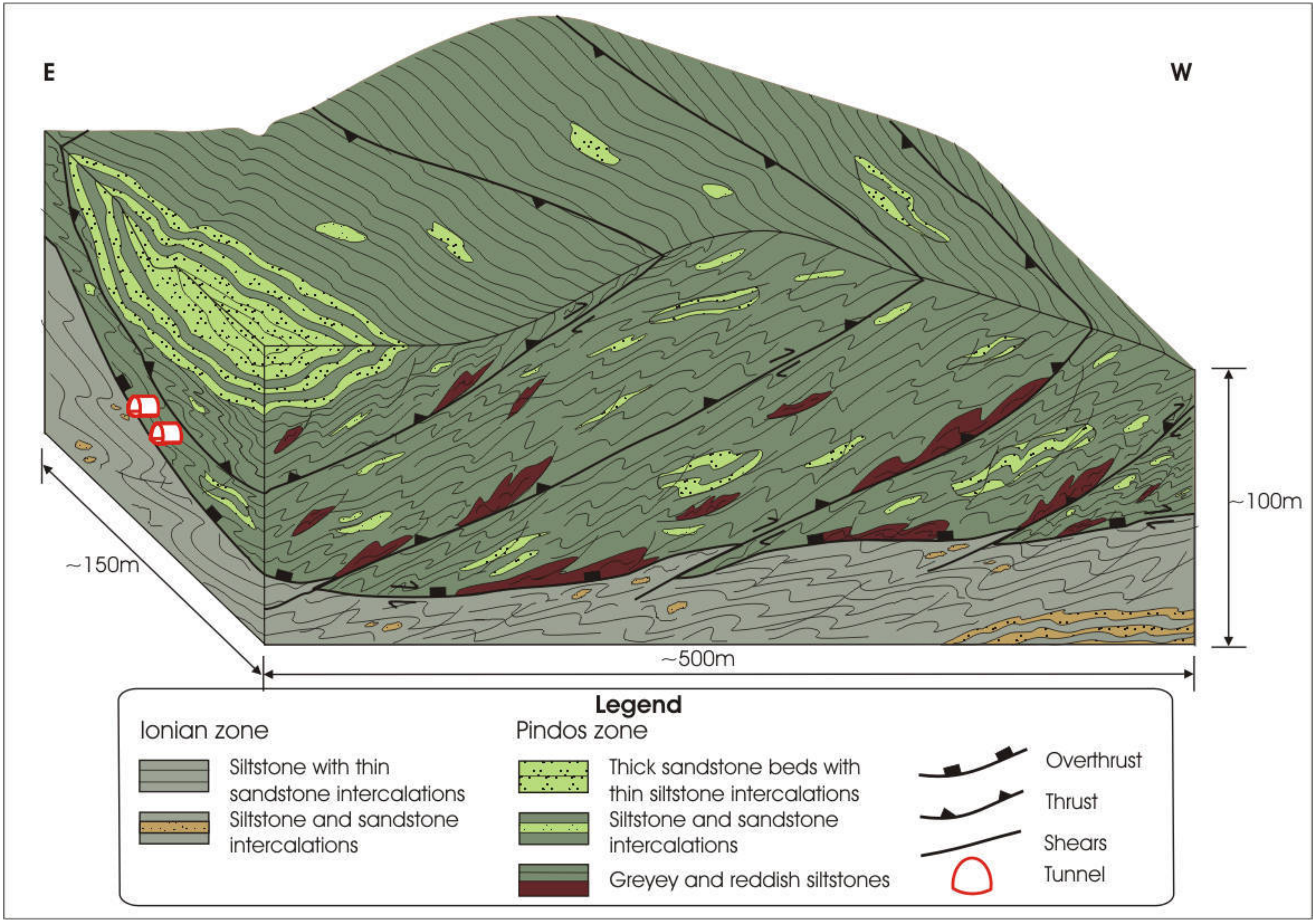
Example:

- Tectonically sheared siltstone
- σ_{ci}: 10 Mpa
- Overburden:90m

Marinos, 2012



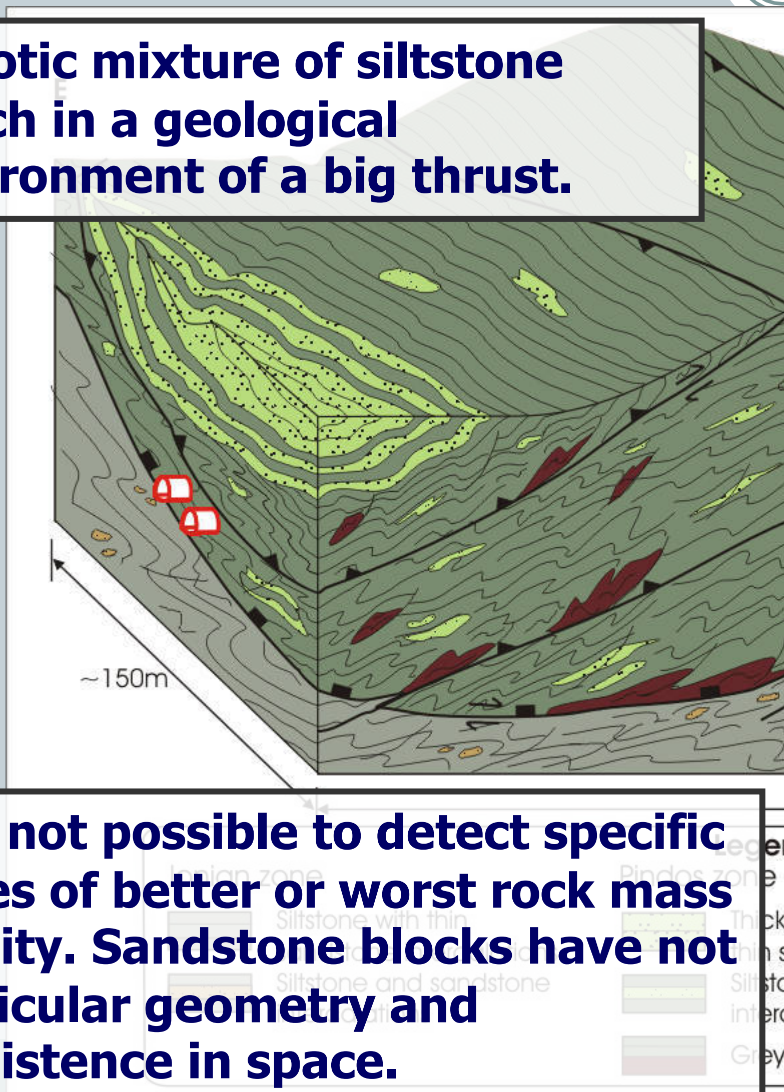
Conceptual model in a tectonic flysch environment



Conceptual model in a tectonic flysch environment

Chaotic mixture of siltstone flysch in a geological environment of a big thrust.

The area is consisted by sheared clayey-silty geomaterial where sandstone blocks , of different size, are floating.

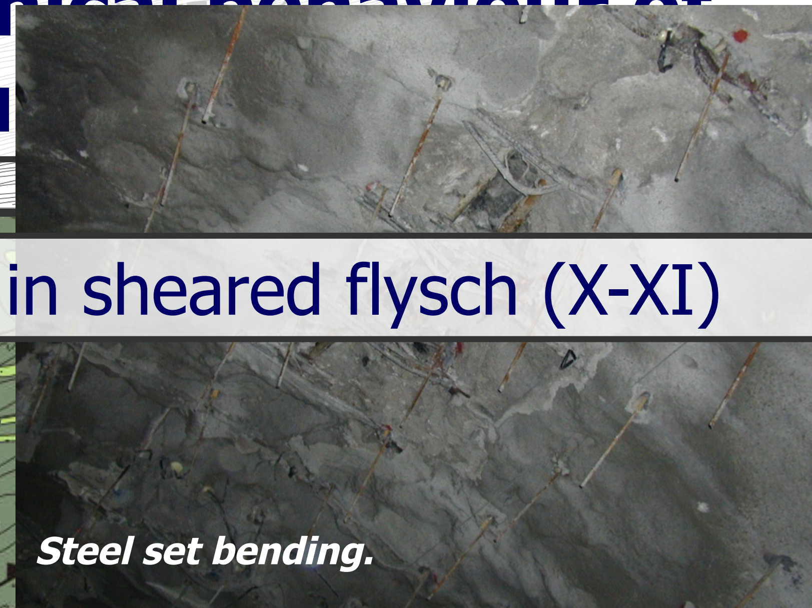


It is not possible to detect specific zones of better or worst rock mass quality. Sandstone blocks have not particular geometry and persistence in space.

geotechnical behaviour of ... sch in tu...

Squeezing conditions (Sq) in sheared flysch (X-XI)


Shotcrete failure at the invert area.


Steel set bending.

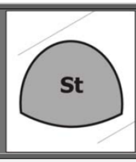
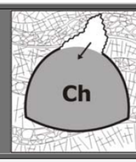
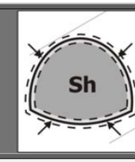

Shotcrete failure


Steel set yielding due to the overstressed tunnel support section

Outline

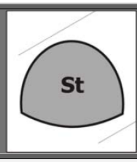
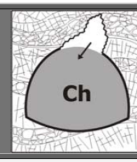
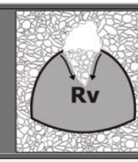
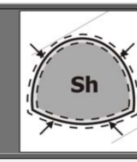
I. The data – A geotechnical database from 62 tunnels
II. Tunnel design steps - Where Engineering Geology must be involved
III. Identification of tunnel behaviour modes
IV. Classification scheme for assessing the rock mass behaviour in tunnelling
V. Suggestions on the temporary support measures
VI. Conclusions – Contribution of Engineering Geology

INDICATIVE TUNNEL SUPPORT MEASURES FOR EACH TUNNEL BEHAVIOUR TYPE*

						
Excavation step	>3m in Top heading	2-3m in Top heading	1.5-2.0m in Top heading	1-1.5m in Top heading	1.5-2m	1m
Shotcrete	5 - 7cm	5-10cm	10-15cm	20-25cm	20-25cm	35-70cm**
Bolts	Locally when necessary	Sparse pattern (e.g. 3m x 3m) length and strength according to block volume and weight, fully grouted or friction bolts if there is need for immediate action	Dense pattern (e.g. 1.5m x 1.5m), friction bolts	Dense pattern (e.g. 1.5m x 1.5m), fully grouted.	1.5-2m x 1.5-2m, fully grouted 5-6m length, friction bolts for immediate action	1-1.5m x 1-1.5m, fully grouted 6-9m length in tunnel vault, friction bolts for immediate action. Self drilling bolts may be necessary.
Steel sets		HEB120 or equivalent Lattice Girders Implementation according to rock mass fracturing	HEB120-140 or equivalent Lattice Girders with elephant foot or steel sets embedded in shotcrete	HEB120-140 or equivalent Lattice Girders with elephant foot sets are embedded in shotcrete	HEB120-140 or equivalent Lattice Girders with elephant foot sets are embedded in shotcrete	HEB160-180 or equivalent Lattice Girders with elephant foot sets are embedded in shotcrete
Shell foundation area				Reinforcement may be needed in the foundation area		Micropiles to be considered in case deformations due to subsidence are expected.
Face anchors					The application of fiberglass anchors may be required	Fiberglass anchors are required
Spiles - Forepolling			Φ25-32mm, 5-6m length. Spacing is important to contain the small rock fragments from falling	Spiles or forepoles, 5-6m length. Spacing is important to contain the small rock fragments from falling. If rock fragments are very small, they fall between the spiles and forepolling is necessary.		Φ114, 12m length for face stability problems can be considered
Face buttress			Probable. 5cm shotcrete	Yes with 5cm shotcrete	Probably yes when the rock mass has poor structure	Yes when the rock mass has poor structure
Temporary invert for the top heading				To be considered	To be considered ($\sigma_{cm}/p_o<0.4$)	Yes
Permanent invert					To be considered ($\sigma_{cm}/p_o<0.4$)	Yes
Drainage		According to groundwater presence	Necessary if groundwater present	Pre-drainage with the presence of water	Drainage relief holes	Drainage relief holes
General remarks	Simple support measures are required	Tunnel step must be decided from the need to confine the wedge failures and from the stand-up time. Immediate application to restrain the rock blocks. Friction bolts have the advantage of immediate action (e.g. Swellex or split set type)	A smaller excavation step can help with the confinement of the rock mass and prevent chimney type failures. Drill and blast must be careful implemented. Immediate application of shotcrete to restrain the rock blocks and prevent subsequent gravity failures from the surrounded rock mass. The philosophy of bolting here is to create a dense pattern where grouting must be performed through bolts. Length is not as crucial as the pattern. Self-drilling anchors may be necessary. Steel sets must be well embedded in shotcrete (Lattice girders help here)	The short step of tunnel advance can help in the confinement of the rock mass and to prevent a wider gravity failure. Immediate shotcrete application to seal the rock mass and constrain it from raveling. The use of closely spaced wire mesh is recommended for immediate restraint of the loose rock "cubes". Self-drilling anchors are needed because the hole instantly collapses. Grouting the surrounded rock mass, to increase its cohesion, can be performed through perforated spiles or forepolles. There is no need for a very heavy support shell if confinement and interlocking is secured	The accurate shotcrete thickness, bolt lengths and strength characteristics are defined from the in situ conditions and the rockmass strength.	**The accurate shotcrete thickness, bolt lengths and strength characteristics are defined according to the squeezing magnitude. Alternatively, very dense bolt pattern around the tunnel vault and sides, a great number of fiberglass bolts at the face and fast closure of the top heading with a temporary invert. -In cases where temporary invert and face support measures cannot control the deformations, fast closure of the tunnel ring with a permanent invert can be implemented. A more circular tunnel shape improves-stability. When $\sigma_{cm}/p_o<0.2$ and squeezing problems are very severe, <u>flexible support system with yielding elements should be considered.</u>

Notes:

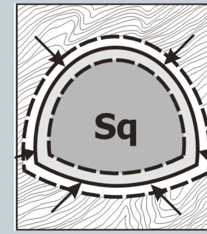
-The specific support measures and loads must be calculated numerically through detailed design analysis
-The principle of the proposed support measures is to contain and control the specific mechanism of failure
- These suggestions can be applied for tunnels of about 10-12m diameter, with conventional excavation by Top Heading and Bench, for depths up to several hundred meters
- Based on analysis of Egnatia Highway tunneling experience

INDICATIVE TUNNEL SUPPORT MEASURES FOR EACH TUNNEL BEHAVIOUR TYPE*						
						
Excavation step	>3m in Top heading	2-3m in Top heading	1.5-2.0m in Top heading	1-1.5m in Top heading	1.5-2m	1m
Shotcrete	5 - 7cm	5-10cm	10-15cm	20-25cm	20-25cm	35-70cm**
Bolts	Locally when necessary	Sparse pattern (e.g. 3m x 3m) length and strength according to block volume and weight, fully grouted or friction bolts if there is need for immediate action	Dense pattern (e.g. 1.5m x 1.5m), friction bolts	Dense pattern (e.g. 1.5m x 1.5m), fully grouted.	1.5-2m x 1.5-2m, fully grouted 5-6m length, friction bolts for immediate action	1-1.5m x 1-1.5m, fully grouted 6-9m length in tunnel vault, friction bolts for immediate action. Self drilling bolts may be necessary.
Steel sets		HEB120 or equivalent Lattice Girders Implementation according to rock mass fracturing	HEB120-140 or equivalent Lattice Girders with elephant foot or steel sets embedded in shotcrete	HEB120-140 or equivalent Lattice Girders with elephant foot sets are embedded in shotcrete	HEB120-140 or equivalent Lattice Girders with elephant foot sets are embedded in shotcrete	HEB160-180 or equivalent Lattice Girders with elephant foot sets are embedded in shotcrete
Shell foundation area				Reinforcement may be needed in the foundation area		Micropiles to be considered in case deformations due to subsidence are expected.
General remarks	Simple support measures are required	Tunnel step must be decided from the need to confine the wedge failures and from the stand-up time. Immediate application to restrain the rock blocks. Friction bolts have the advantage of immediate action (e.g. Swellex or split set type)	blast must be careful implemented. Immediate application of shotcrete to restrain the rock blocks and prevent subsequent gravity failures from the surrounded rock mass. The philosophy of bolting here is to create a dense pattern where grouting must be performed through bolts. Length is not as crucial as the pattern. Self-drilling anchors may be necessary. Steel sets must be well embedded in shotcrete (Lattice girders help here)	shotcrete application to seal the rock mass and constrain it from raveling. The use of closely spaced wire mesh is recommended for immediate restraint of the loose rock "cubes". Self-drilling anchors are needed because the hole instantly collapses. Grouting the surrounded rock mass, to increase its cohesion, can be performed through perforated spiles or forepolles. There is no need for a very heavy support shell if confinement and interlocking is secured	The accurate shotcrete thickness, bolt lengths and strength characteristics are defined from the in situ conditions and the rockmass strength.	Alternatively, very dense bolt pattern around the tunnel vault and sides, a great number of fiberglass bolts at the face and fast closure of the top heading with a temporary invert. -In cases where temporary invert and face support measures cannot control the deformations, fast closure of the tunnel ring with a permanent invert can be implemented. A more circular tunnel shape improves-stability. When $\sigma_{cm}/p_o<0.2$ and squeezing problems are very severe, flexible support system with yielding elements should be considered.

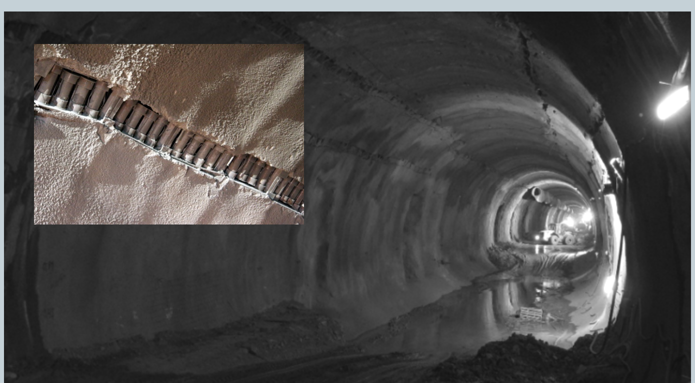
Note: It is emphasised that the support proposals do not replace the proper design methodology but allow an early assessment of the principles of the appropriate support measures and their basic dimensioning, as they are dictated by the ground behaviour and the associated failure mode.

***Notes:**
-The specific support measures and loads must be calculated numerically through detailed design analysis
-The principle of the proposed support measures is to contain and control the specific mechanism of failure
- These suggestions can be applied for tunnels of about 10-12m diameter, with conventional excavation by Top Heading and Bench, for depths up to several hundred meters
- Based on analysis of Egnatia Highway tunneling experience

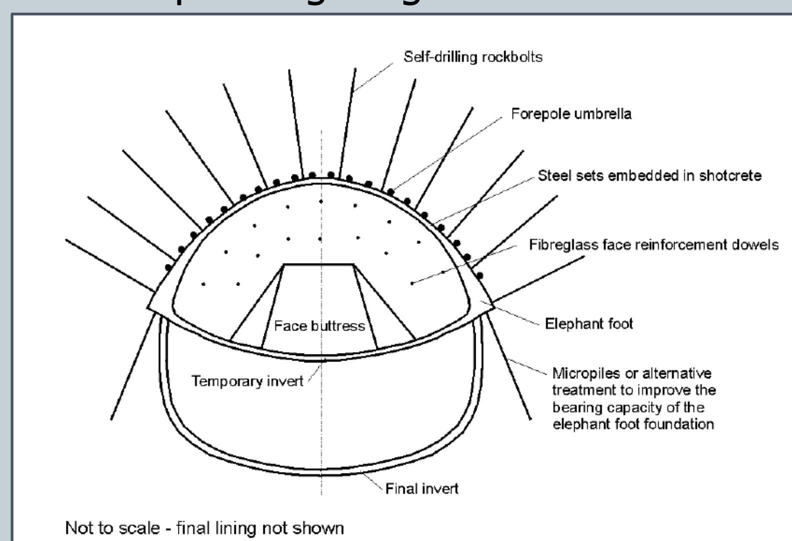
Recommendations of temporary support in Squeezing ground (Sq)



- Control the deformation
- Alternatively, very dense bolt pattern around the tunnel vault and sides, great number of fiberglass bolts at the face and fast closure of the top heading with a temporary invert.
- Other.....fast closure of the tunnel ring with a permanent invert
- When $\sigma_{cm}/p_o<0.2$ and squeezing problems are very severe, <u>flexible support system with yielding elements should be considered.</u>



- 1m in Top heading
- 35-70cm shotcrete
- 1-1.5m x 1-1.5m, fully grouted.
- HEB160-180 or equivalent Lattice Girders with elephant foot sets
- Fiberglass anchors , Forepoles, Face buttress
- Temporary and final invert
- The shotcrete thickness, bolt lengths, strength characteristics are defined according to the squeezing magnitude.



Outline

I. The data – A geotechnical database from 62 tunnels
II. Tunnel design steps - Where Engineering Geology must be involved
III. Identification of tunnel behaviour modes
IV. Classification scheme for assessing the rock mass behaviour in tunnelling
V. Suggestions on the temporary support measures
VI. Conclusions – Contribution of Engineering Geology

VI. Conclusions

- The classification proposed is focused on the evaluation of the tunnel behaviour in order to guide the selection of the appropriate design parameters and establish the temporary support philosophy.
- The proposed classification, called Tunnel Behaviour Chart, is a classification system for assessing the rock mass behaviour in tunnelling and covers a wide range of rock mass conditions.
- Following the evaluation of the mechanism of failure, one can be more confident either in using the rating of the applied classification system or to investigate which are the specific geological “keys” and the appropriate parameters that should be used for the design analysis.
- *This work intends to present how Engineering Geology, going beyond the establishment of a reliable geological model, contributes most effectively to the design, and in this case to the tunnel design.*