Applicability of the geological strength index (GSI) classification for very weak and sheared rock masses. The case of the Athens Schist Formation

E. Hoek · P. Marinos · M. Benissi

Abstract The Athens Schist Formation includes a wide variety of metasedimentary rocks, varying from strong or medium strong rocks such as sericite metasandstone, limestone, greywacke, sericite schist through to weak rocks such as metasiltstone, clayey and silty shale and phyllite. The overall rock mass is highly heterogeneous and anisotropic owing to the combined effect of advanced weathering and severe tectonic stressing that gave rise to intense folding and shearing followed by extensional faulting, which resulted in highly weathered rock masses and numerous shear and/or mylonite zones with distinct downgraded engineering properties. This paper is focused on the applicability of the GSI classification system to these highly heterogeneous rock masses and proposes an extension of the GSI system to account for the foliated or laminated weak rocks in the lower range of its applicability.

Résumé La formation des Schistes d' Athènes correspond à une large variété de roches légèrement métamorphiques, comprenant de roches à résistance élevée, comme les grès à séricite, des calcaires crystallins, des schistes à séricite, mais aussi des roches tendres comme les schistes argilleux et les phyllades. La masse rocheuse constitue un ensemble très hétérogène et anisotrope, surtout si l'on y ajoute une altération souvent avancée et une tectonique intense. Une phase compressive sévère a en effet provoqué des cisaillements importants, le massif ayant été par la suite affectée de failles normales; les zones mylonitiques sont donc très fréquentes. Cet article engage la discussion sur l'application de la classification GSI proposée par Hoek à ces masses rocheuses tres hétérogènes et propose une extension de son champ d'application aux roches feuilletées et cisaillées à faible résistance.

Key words Rock mass classification · Weak rocks · Strength parameters · Deformability modulus · Rock mass structure · Sheared shales

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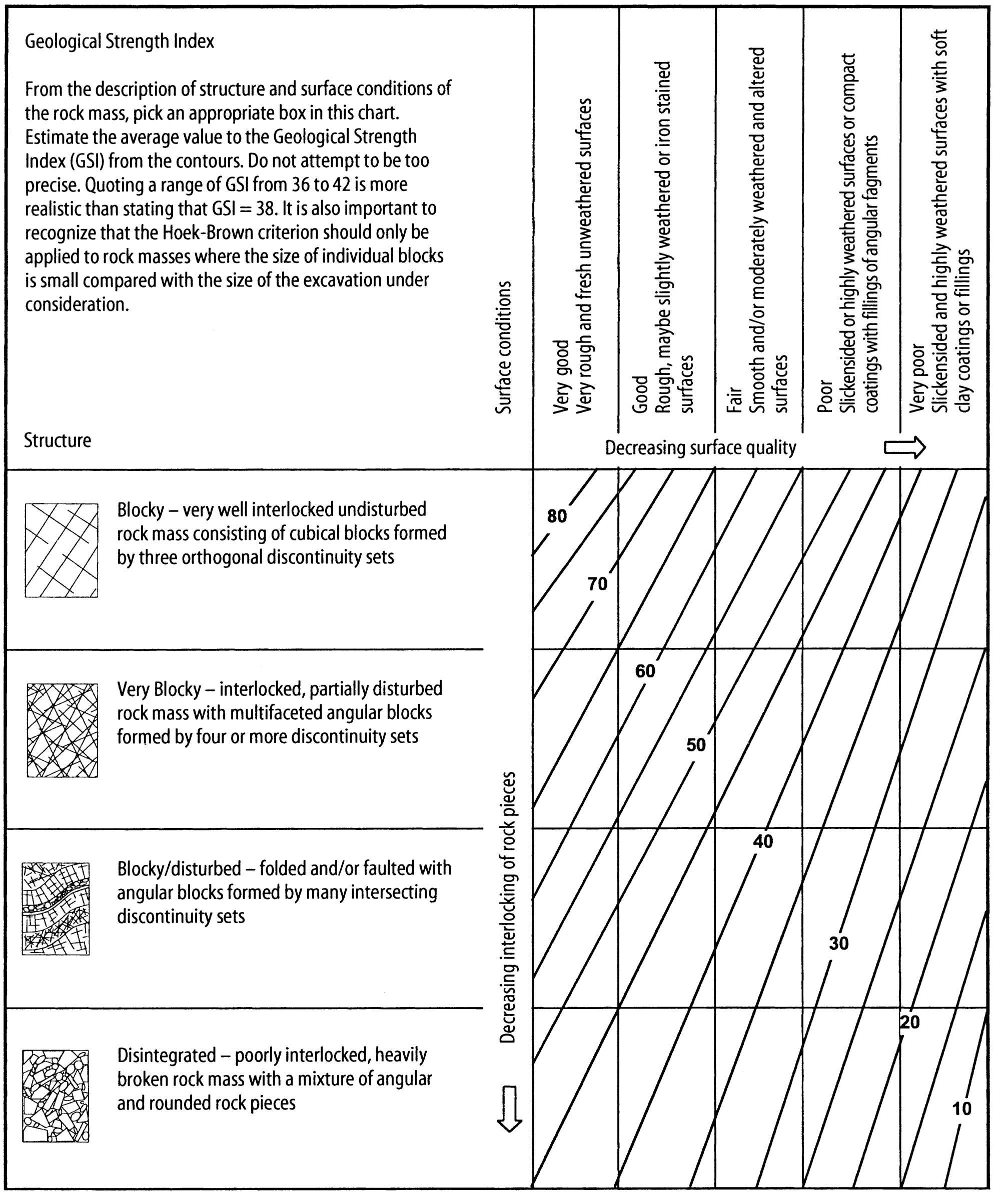
Introduction

The Geological Strength Index (GSI), introduced by Hoek (1994), Hoek et al. (1995) and Hoek and Brown (1998) provides a system for estimating the reduction in rock mass strength for different geological conditions as identified by field observations. The rock mass characterisation is straightforward and it is based upon the visual impression of the the rock structure, in terms of blockiness, and the surface condition of the discontinuities indicated by joint

Table 1
Characterisation of rock masses on the basis of interlocking and joint alteration (Hoek and Brown 1998 adjusted from Hoek 1994)



roughness and alteration (Table 1; from Hoek and Brown 1998). The combination of these two parameters provides a practical basis for describing a wide range of rock mass types, with diversified rock structure ranging from very tightly interlocked strong rock fragments to heavily crushed rock masses. Based on the rock mass description the value of GSI is estimated from the contours given in Table 1.

The uniaxial compressive strength σ_{ci} and the material constant m_i are determined by laboratory testing or estimated from published tables, reproduced here as Tables 2 and 3 respectively. Wherever possible the values of these constants should be determined by statistical analysis of the results of a set of triaxial tests on carefully prepared core samples. The shear strength of the rock mass, defined by the angle of internal friction ϕ and cohesion c, are estimated from the curves plotted in Figs. 1 and 2.

Using the GSI system, provided the UCS value is known, the rock mass deformation modulus E_m for $\sigma_{ci} < 100$ MPa is estimated in GPa from the following equation (Hoek and Brown 1998):

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

The relationships between the parameters incorporated in this equation are illustrated in Fig. 3.

The Athens Schist rock masses

The Athens Schist Formation is a term used to describe a highly heterogeneous, flysch-like formation of Cretaceous

Table 2
Field estimates of the uniaxial compressive strength of intact rock pieces

Grade[a]	Term	Uniaxial compressive strength (MPa)	Point load index (MPa)	Field estimate of strength	Examples
R6	Extremely strong	>250	>10	Specimen can only be chipped with a geological hammer	Fresh basalt, chert, diabase, gneiss, granite, quartzite
R5	Very strong	100–250	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	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	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	[b]	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	[b]	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	[b]	Indented by thumbnail	Stiff fault gouge

[a] Grade according to Brown (1981)
[b] Point load tests on rocks with a unaxial compressive strength below 25 MPa are likely to yield ambiguous results

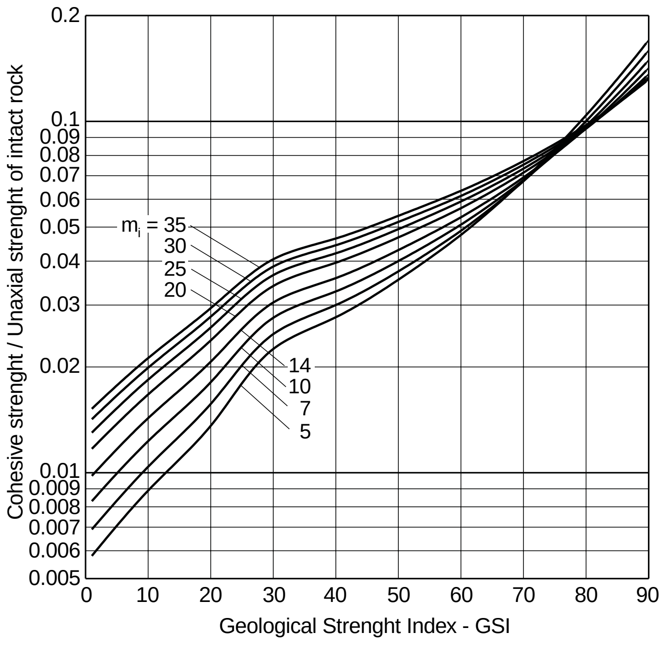


Fig. 1
Relationship between cohesive strength and Geological Strength Index (*GSI*); example: GSI = 20, $m_i = 10$, $c/\sigma_{ci} = 0.018$

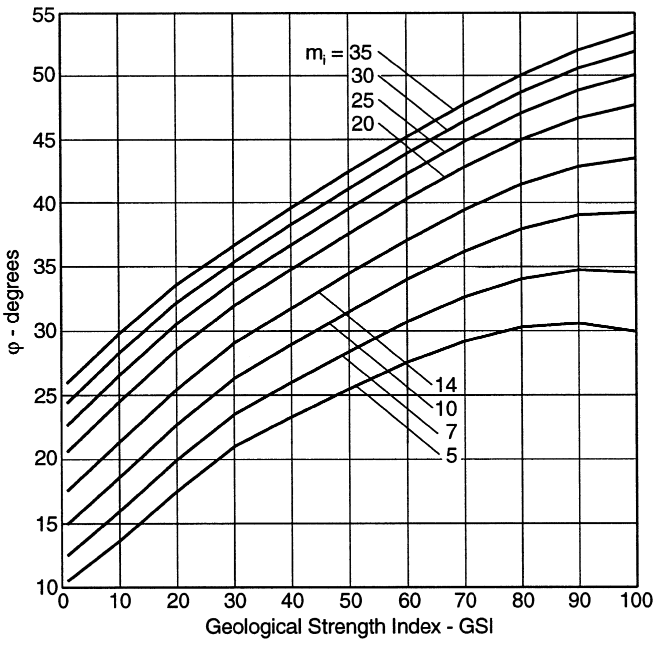


Fig. 2
Relationship between friction angle and GSI; example: GSI = 20, $m_i = 10$, $\phi = 23°$

Table 3
Values of the constant m_i for intact rock, by rock group. Note that values in parenthesis are estimates

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

[a] 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

age (Marinos G. et al. 1971). It comprises schists, phyllites and metasedimentary shales, siltstones and sandstones. Limestones and marls may also occur while igneous activity has introduced peridotitic and diabasic intrusions at certain localities. The Athens Schist bedrock is primarily marked by an advanced degree of weathering and intense folding, shearing and extensional faulting, which completed the structural "downgrading" of the rock mass.
The Athens Schist rock mass is characterised by:

1. Frequent changes of lithological facies at short distances accentuated by an irregular alteration and weathering pattern.
2. Variability of materials ranging from hard rocks to soils in terms of strength (frequently mixed at the scale of the engineering structures).
3. A highly complex structural pattern of numerous structural shears and faults.

The tectonic activity whenever associated with weak rocks often produces engineering soil materials. The tectonic fabric of the Athens Schist Formation includes mylonite materials that are not only limited to the major fault zones but also occur as thick gouge infilling of systematic or non-systematic shears. The response of rock mass volumes composed of hard rock and weak rock intercalations to the severe tectonic activity gave rise to disharmonic folding and faulting that often entailed a clearly visible chaotic structure of isolated lensed blocks of hard rock 'floating' within a soft clayey matrix (Marinos P. et al. 1997a and b).
Most of the Athens Schist Formation members are aptly described by the term *blocky/disturbed* as the rock masses are often folded and faulted. The Athens Schist Formation rock mass exhibits well-defined shears, frequently oriented parallel to the foliation planes that constitute the prevailing structural feature of the rock mass. These shear surfaces are commonly polished and slickensided with clayey coatings or in some cases thick (>10 cm) mylonitic clay gouge. The discontinuity condition falls between the *fair*

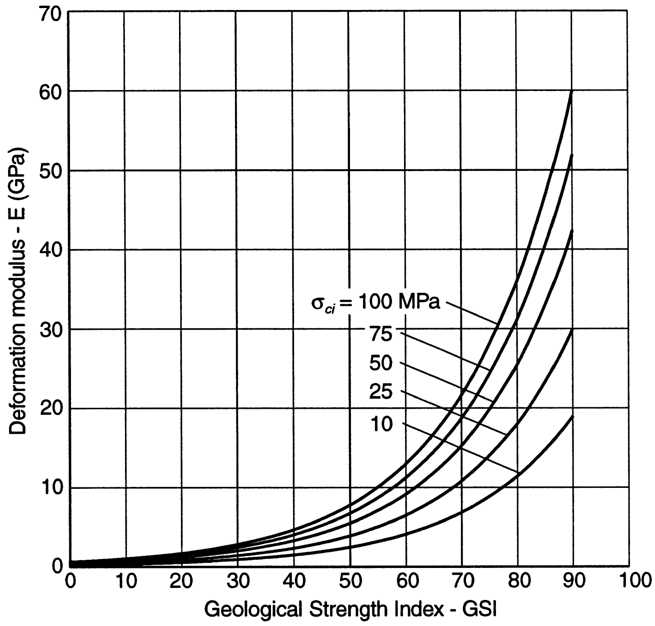


Fig. 3
Relationship between GSI, intact rock strength (σ_{ci}) and in situ modulus of deformation E_m for $\sigma_{ci} < 100$

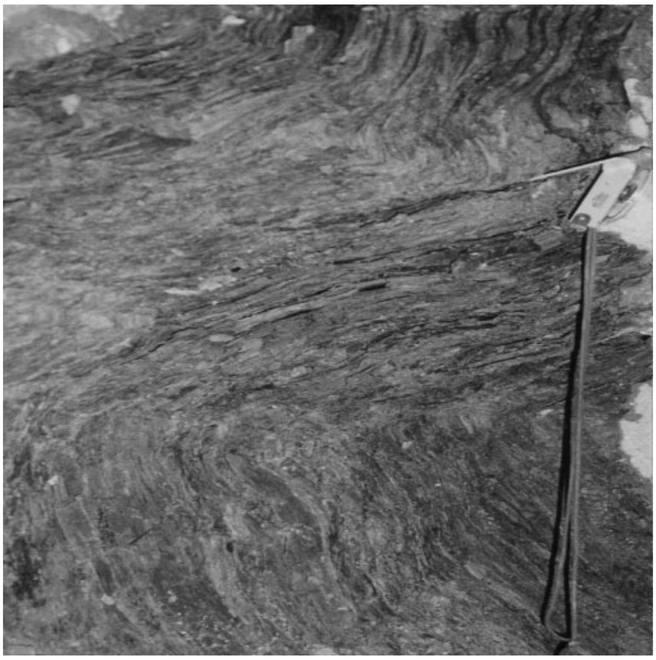


Fig. 4
The foliated sequences of sericite sandstone and schist of slight difference in competence are classified as blocky/disturbed, with a fair to very poor discontinuity condition

Fig. 5
Well interlocked very blocky strong sandstone rock mass

and the *very poor* range of categories. The categories *blocky/disturbed – fair to blocky/disturbed – very poor* (Table 1) are typically assigned to rock masses composed of sericite metasandstone, greywacke, metasiltstone, marly limestone, schist (Fig. 4) or to alternations of these rocks where however they exhibit a slight difference in competence.

Competent rocks and well interlocked rock masses with three or more joint set systems that better fit to the model of a *blocky* rock structure are less common in the Athens Schist Formation and have been classified as *very blocky* (see Fig. 5). They include slightly weathered, medium strong to strong, rock types such as arkosic metasandstone, limestone and fresh diabase-peridotite, which are encountered as isolated occurrences within the Athens Schist Formation.

However, several rock mass types, which are quite abundant in the Athens Schist Formation, cannot be adequately described by the above classification. This category involves primarily originally weak laminated non-competent rocks of low strength and high deformability, such as the dark grey clayey and silty shales or phyllites of the Athens Schist Formation. Also the same category involves rock masses of downgraded strength and enhanced deformability, as a combined result of intense *shearing* and mylonitization along the lamination or foliation planes assisted by significant weathering of the intact rock pieces. As for regards the rock structure a well-defined persistent and closely spaced lamination or foliation system is dominant and is clearly recognisable by the slickensided surfaces and the gouge-infilled shears (Fig. 7). These types of rock masses, an example of which is shown in Fig. 6, are of a non-blocky/non-anglular structure, and cannot be adequately described by any of the available GSI rock structure categories. The closest fit, considering a *very poor* surface condition, is that of the *disintegrated* rock structure.

The ranges of GSI values corresponding to the rock mass descriptions given above indicated by the ellipses plotted in Table 4.

Fig. 6
The intensely sheared and mylonitized argillaceous shales could only fit to the disintegrated category of Table 1 with a very poor surface condition

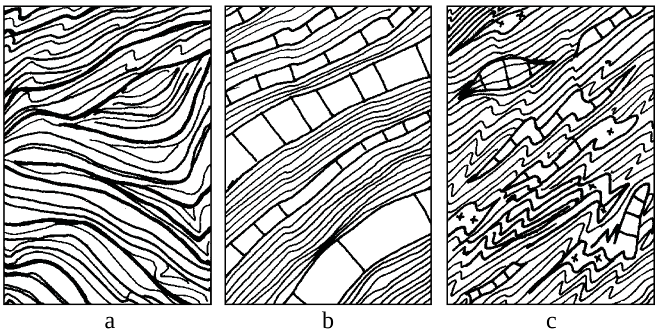


Fig. 7
a Foliated/laminated/sheared rock structure. **b** The seamy rock mass type consisting of intercalated rock members of strikingly different competence which are differentially deformed (sheared, folded and faulted). **c** A chaotic rock mass comprising lensified hard rock bodies and boudinaged quartz or calcite lenses floating in a sheared soil-like environment. The rock mass structure is scale-independent and its influence depends upon the scale of the engineering structure

Extension of GSI to accommodate the weakest Athens Schist rock masses

The uniaxial strength of some of the rock types comprising the Athens Schist Formation was established by testing approximately 60 samples.
In the case of weak dark grey shale, weak laminated metasiltstone or highly weathered sericite sandstone for which it was generally not possible to form testable samples, a strength range was empirically estimated in the field on the basis of the descriptions given in Table 2.
Based on the measured/estimated UCS strengths and ranges of material constants (m_i) values and the GSI values attributed to the different rock mass types, the cohesive strength and friction angle for each rock mass type were estimated from Figs. 1 and 2 (see upper section of Table 5).
The range of the rock mass deformability modulus E_m was calculated for each rock mass by means of equation (1); the values are shown in Table 6.
In the case of the 'dark grey clayey shales', the weakest among the Athens Schist Formation, *Menard* pressuremeters show a typical range of E_m values between 50–150 MPa. Back analysis of settlements from underground excavations in the city of Athens yield values of between 150–250 MPa. These low E_m values derived from both *Menard* pressuremeters and from back analysis of settlements are not always consistent with the calculated E_m values by use of equation (1) when the input GSI value is the minimum that falls in the lower right portion of the *disintegrated* category of Table 4 (see rock mass types C^+ and partly B^- of table 6). This fact alone necessitated the addition of a new rock mass category where the calculated E_m values are in better accordance with the measured ones.
Moreover the mechanism of deformation in the above described foliated and sheared rocks is not governed by rock-to-rock contacts of *angular or subrounded rock fragments* as in the *disintegrated* category, but it is rather controlled by the displacements along the numerous very thinly spaced presheared foliation planes of the rock mass.
A new *foliated/laminated/sheared* rock mass category has thus been considered to better represent thinly laminated or foliated and structurally sheared weak rocks. In these rock masses the lamination or foliation is the predominant structural feature which prevails over any other discontinuity set, resulting in complete lack of blockiness. The new *foliated/laminated/sheared* rock mass structure, shown in Table 7, is not associated with *good* or *very good* discontinuity surface quality, since it entails a degree of preshearing along the lamination/foliation surfaces. For the remaining *fair* to *very poor* surface qualities the equivalent GSI contours range from the new value of 5 up to 30 and the derived E_m values are shown in the graph of Table 6 as type C^- rock mass.
More specifically, in terms of shear strength and deformability, by moving the Athenian black shales down to the

Table 4
Field of GSI classification of distinct rock mass types encountered in the Athenian substratum: the prevailing foliated sandstone-schist rock mass (*diagonal hatch*), the occasional strong blocky metasandstone or limestone (*vertical hatch*) and the sheared mylonitic black shales (*horizontal hatch*)

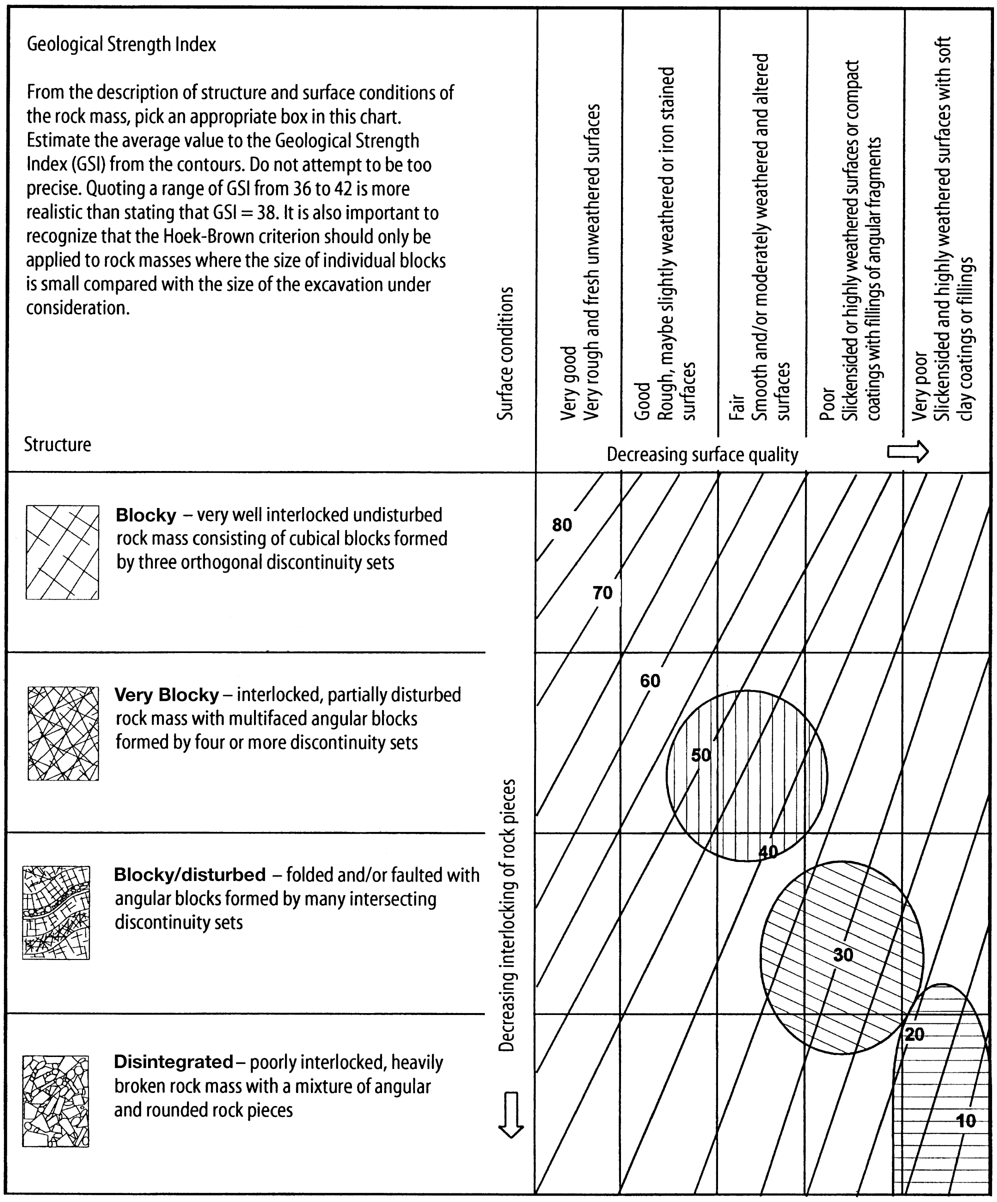
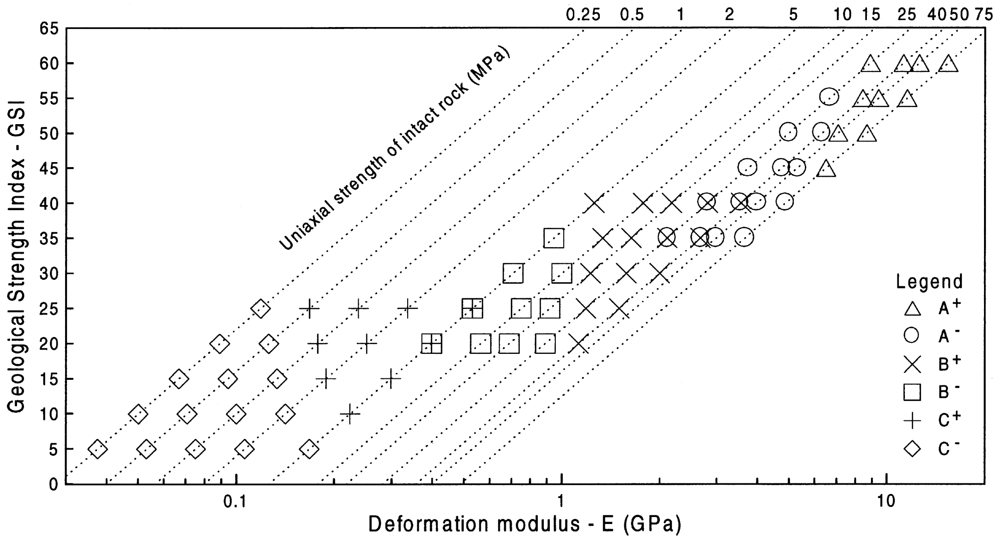


Table 5
Rock mass characteristics and estimated shear strengths for different rock mass units

Rock mass type	UCS σ_{ci} MPa	Constant m_i	Estimated GSI	Cohesion c-MPa	Friction angle $\phi°$
Limestone	54	10	50 ± 10	2.3 ± 0.4	35 ± 2
Sericite sandstone	37	19	50 ± 10	1.7 ± 0.2	37 ± 2
Greywacke	25	18	30 ± 8	0.7 ± 0.1	31 ± 2
Dark grey siltstone	18	9	30 ± 8	0.55 ± 0.2	25 ± 2
Black shales (classified as Disintegrated)	1–5	8	15 ± 8	0.05 ± 0.04	19 ± 3
Black shales (classified in the new Folliated laminated/ sheared, rock structure)	1–5	8	10 ± 6	0.04 ± 0.03	17 ± 2

Table 6
Estimated deformation modulus values (in GPa) for various rock mass types of the Athens Schist' Formation (A^+ to C^-)



A^+	Medium strong to strong metasandstone or limestone rock mass, interlocked, with angular blocks formed by four or more discontinuity sets with rough and MW to SW surface condition.
A^-	The lower E_m values of this field derive either from lower σ_{ci} values due to weathering-tectonic weakening of the intact rock material, or from lower GSI values reflecting the decreased surface quality due to shearing / mylonitization and weathering.
B^+	Medium strong to weak, thinly foliated sericite sandstone / schist or greywacke, with occasional boudins of quartz.
B^-	The lower E_m values may derive either from lower σ_{ci} values due to weathering-tectonic weakening of the intact rock material, or from lower GSI values reflecting the decreased surface quality due to shearing / mylonitization and weathering.
C^+	Weak to very weak, laminated argillaceous shale or phyllite, with boudins of quartz or lenticular blocks of intact rock in a soft rock environment.
C^-	The lower E_m values bottom left derive either from lower σ_{ci} values due to weathering-weakening of the intact rock material, or to lower GSI values reflecting the absence of blockiness and the decreased surface quality due to shearing / mylonitization and weathering.

foliated/laminated/sheared category, the estimated GSI is reduced to 10 ± 6 and this gives a cohesive strength of 0.04 ± 0.03 MPa, a friction angle of 17 ± 2 deg and an E_m value of 70–300 MPa (see Table 5 and Table 6 where 1 MPa $< \sigma_{ci} <$ 5 MPa lower row).

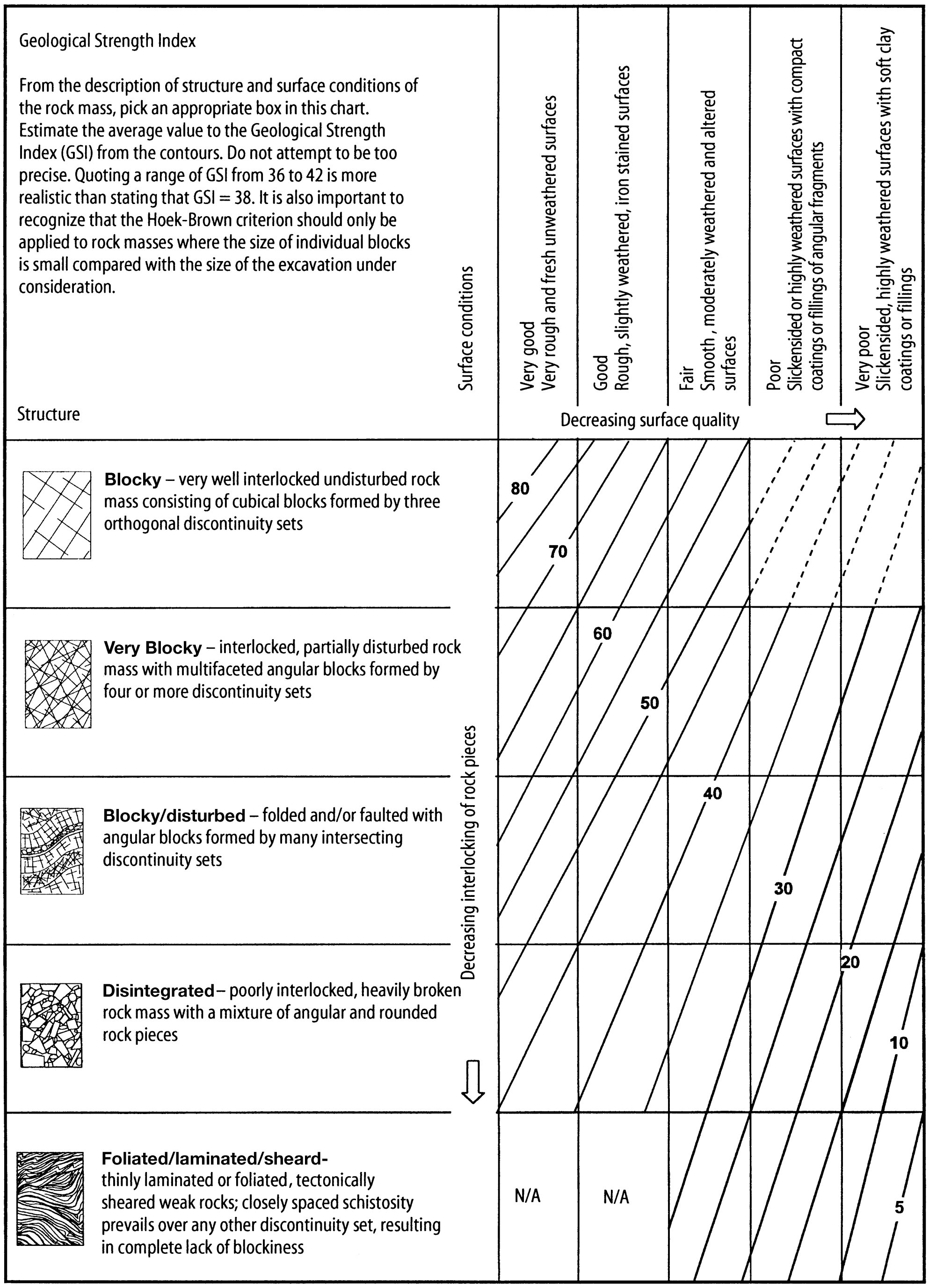
Rock mass types not described by the GSI classification

In addition to the weak sheared rock masses which have been integrated in the GSI classification system as described above, there are two more distinct rock mass types frequently encountered in the Athens Schist complex that cannot be accomodated within the existing GSI classification.

The first category involves seamy structures consisting of intercalated rock members of strikingly different competence, which are differentially deformed (sheared, folded and faulted), e.g. sandstones vs. mudstones as a common feature for flysch (Fig. 7b). In this case the geotechnical behaviour of the rock mass is beyond the philosophy of the GSI concept of rock mass structure, since it is always controlled by the persistent interfaces between the two media of strikingly different strength and deformability.

The second rock mass type is where extended tectonic fatigue has produced chaotic structures comprising lensified intact rock bodies and boudinaged quartz/calcite lenses that healed former structural discontinuities, and which now 'float' in a sheared soil-like environment (Fig. 7c). The geotechnical behaviour of this type of rock mass can be identified in between the *disintegrated* and *foliated/laminated* categories of Table 7.

Table 7
A new laminated/foliated/sheared rock structure accounts for presheared thinly foliated very weak rocks, in which the prevailing rock mass feature controlling strength and deformability are not the rock-to-rock contacts of the broken rock pieces (as in breccias) but rather the shear strength of the fines along the numerous clayey coated foliation or shear surfaces



Conclusions

The Geological Strength Index (GSI) classification scheme, through which the rock mass strength and deformability parameters are estimated based on the rock mass structure and discontinuity surface condition does not adequately describe some of the rock mass types commonly encountered in the Athens' bedrock. The materials not included are the thinly foliated or laminated, folded and predominantly sheared weak rocks of non-blocky structure. In these rock masses the strength and deformability characteristics are not governed by rock-to-rock contacts of angular or rounded rock pieces but rather by the displacements along the numerous very thinly spaced presheared and slickensided foliation planes of the rock mass.
A new *foliated/laminated* rock mass structure category is proposed to accommodate these rock types in the lowest range of applicability of the GSI system. Given the presheared nature of the rock's discontinuities their surface

condition could not be classified either as *very good* or as *good* and therefore the classification is non-applicable. For the remaining *fair* to *very poor* surface qualities the equivalent GSI contours now range from the new value of 5 up to 30.

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