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ORIGINAL PAPER

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Variability of the engineering properties of rock masses quantified by the geological strength index: the case of ophiolites with special emphasis on tunnelling

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Abstract The paper presents a quantitative description, using the Geological Strength Index (GSI), of the rock masses within an ophiolitic complex including types with large variability due to their range of petrography, tectonic deformation and alteration. This description allows the estimation of the range of rock mass properties and the understanding of the dramatic changes in behaviour which can occur during tunnelling, from stable conditions to severe squeezing within the same formation at the same depth. The paper presents the geological model in which the ophiolitic complexes develop, their various petrographic types and their tectonic deformation, mainly due to overthrusts. The structure of the various rock masses includes all types from massive strong to sheared weak, while the conditions of discontinuities are in most cases fair to poor or very poor due to the fact that they are affected by serpentinisation and shearing. Serpentinisation also affects the initial intact rock itself, reducing its strength. Associated pillow lavas and tectonic mélanges are also characterised. Based on the GSI, a classification of the behaviour in terms of tunnelling is presented, including stable conditions, structural instability, mild overstressing, stress dependant instability, squeezing and ravelling.

Keywords Ophiolites · Rock mass classification · Geological strength index · Tunnels

Résumé Une description quantitative des massifs rocheux des complexes ophiolitiques est présentée par le moyen de l'index GSI. Les ophiolites forment un cas particulier à cause de leur variété pétrographique, leur déformation tectonique et leur altération. Cette description permet l'estimation des propriétés géotechniques et la compréhension des différents types de comportements souvent très variables rencontrés lors du creusement de tunnels. L'article discute brièvement le modèle géologique de ces formations, leurs variétés pétrographiques et leur déformation à cause surtout des charriages. La structure des massifs rocheux ophiolitiques inclut tous les types, (du milieu continu au cisaillé), tandis que l'état des joints est toujours faible à cause de la serpentinisation de leurs épontes. La serpentinisation peut aussi affecter la masse entière de la roche saine. Une classification du comportement en tunnel est présentée basée sur l'index GSI: conditions stables, instabilité structurale, instabilité due à des convergences.

Mots clés ophiolites · massif rocheux · index GSI · tunnels

Introduction

Over the past decades, rock mass classification methods have been developed in order to meet the needs for designing specific projects. The rock mass classification systems of Bieniawski (1973) and Barton et al. (1974) were originally developed to provide guidance on the selection of support for tunnels in blocky rock masses and they played an important role in the expansion of the tunnelling industry.

During the last decade, the development of "user-friendly" software has provided alternative design tools that are more appropriate in many cases. However, this has brought with it the need for reliable input data, particularly that related to rock mass properties. In order to meet this requirement a different set of classification schemes for the characterisation of rock masses has been developed. A system that is now widely used is the Geological Strength Index (GSI) developed by Hoek (1994) and extended by Hoek et al. (1998), Marinos and Hoek (2001) and Hoek et al. (2005) to incorporate weak, heterogeneous rock masses and rock masses with lithological variability. This classification system is used in conjunction with the Hoek and Brown failure criterion to estimate the geotechnical parameters of rock masses which fall within the range specified by the authors. A presentation and a discussion on the use of GSI can be found in Marinos and Hoek (2000) and more recently in Marinos et al. (2005) hence there is no need to repeat the details here.

The GSI has considerable potential for use in rock engineering because it permits the manifold aspects of rock to be quantified, enhancing geological logic and reducing engineering uncertainty. Its use allows the influence of the variables which make up a rock mass to be assessed and hence the behaviour of rock masses has to be explained more clearly. One of the advantages of the Index is that the geological reasoning that it embodies allows adjustments of its ratings to cover not only a wide range of rock masses and conditions but also variations that may develop within the same rock type. It also allows the limits of its application to be understood.

This paper presents a quantitative description, through the GSI, of the rock masses of a particular type of geological formation with both petrographic variety and structural complexity due to tectonic deformation and alteration. This description allows an estimation of the variation in rock mass strength and how much this rock mass strength can be reduced by shearing or alteration as well as an understanding of the dramatic changes in behaviour where, in tunnelling, stable conditions and severe squeezing can occur within the same formation at the same depth.

Ophiolites: geological model

Setting

The term ophiolite was initially given to a sequence of mafic (basic) and ultramafic (ultrabasic) rocks, more or less serpentinised and metamorphosed, occurring in the Alpine chains. These complexes were considered, not long ago, as enormous submarine volcanic effusions inside which magmatic differentiations took place sheltered by a cuirass of pillow lavas. Although this can be the case in some regions, 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 (e.g. collision between two continents or between a continent and an insular arc; see Fig. 1). They can exhibit sections of more than 10 km in thickness which leads to the conclusion that not only the oceanic crust (6–7 km) but also part of the mantle are included in the process (Debelmas and Mascle 1997).

The ophiolitic complex

The ophiolitic sequence (or complex in order to emphasise the diversity of materials) is fundamentally characterised by underlying peridotitic rocks which are covered by gabbroic/peridotitic rocks which, in turn, are covered by basalts or spilites. The basal peridotites are foliated ("tectonites"). The subsequent alternations of peridotites and gabbros often have a layered structure of cumulates and are followed by massive gabbros, norites or other basic rocks richer in SiO_2. The overlying basalts are either massive or in the form of pillow lavas. In between these lavas sedimentary rocks may be deposited. In Fig. 2 a synthetic and theoretical column of an ophiolitic complex is presented. The succession is idealised and in many cases some members may be absent, as for instance the volcanic lava at the top.

This geometry is highly disturbed as the ophiolitic complexes occur mainly in tectonic zones with superposition of numerous overthrusts. Metamorphism, which is also present, changes the original nature of the materials. The high degree of serpentinisation and the intensity of shearing can make it difficult to identify any initial cumulate texture or fabric (Skemp and McCraig 1984).

Serpentinisation

Serpentinisation is the transformation of ferromagnesian minerals, olivine in particular, to serpentine—a

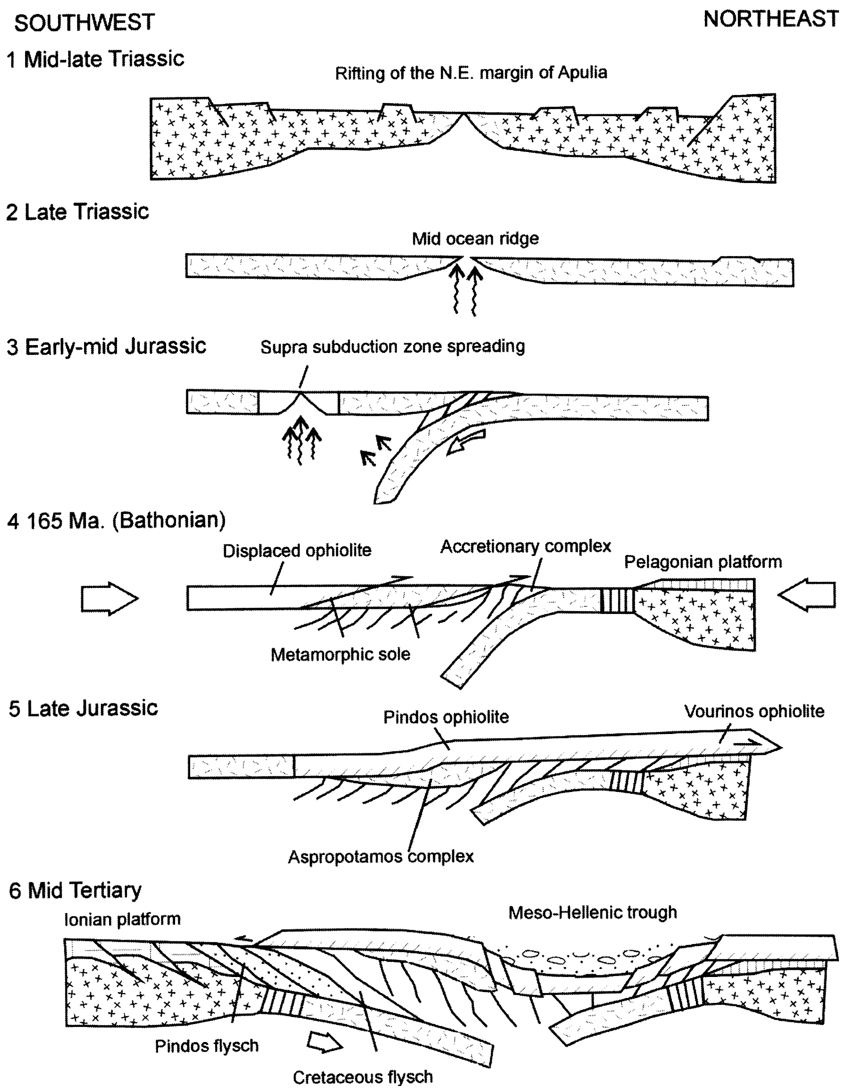

Fig. 1 Tectonic model for the evolution of the Pindos and Vourinos mountain ophiolites in Northern Greece (modified from Jones et al. 1991, in Pe-Piper and Piper 2002)

lattice mineral of either fibrous or laminar form. This unusual alteration is a phenomenon of autohydratation which takes place during the last phases of the crystallisation of magma where there is an excess of water. Thus it can be considered as a type of autometamorphism. In other cases the serpentinisation corresponds to a low grade metamorphism of peridotites (Foucault and Rault 1995). In all these cases the peridotites can be transformed into serpentinite. This new rock is originally compact, relatively soft and more easily sheared by tectonic processes.

Serpentinisation can also be developed under exogenic conditions with meteoric water under usual weathering processes. In this case the alteration disintegrates the parent peridotite to a clayey soil-like mass. The development at depth of weathered peridotites is less generalised and obviously limited compared with the endogenic serpentinisation described previously.

Pillow lavas

Pillow lavas, usually of basaltic or andesitic composition, have been extruded under water and consist of a mass of more or less ellipsoidal bodies each with a billowy surface. The pillows range from 10 cm to a few metres in diameter and lie merged with one another, not unlike an irregular collection of “sofa pillows” (in Visser 1980). Radial joints are conspicuous in cross sections, forming radial columnar fragments (Pantazis 1973).

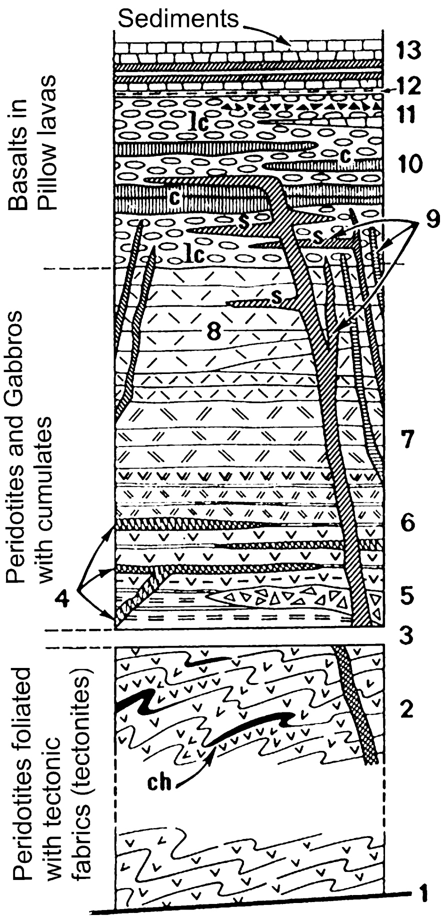

Fig. 2 Ophiolites: synthetic and theoretical column (from Foucault and Raoult 1995 with simplified descriptions). *1* basal contact, overthrust; *2* basal body of peridotites with foliation (tectonites), generally harzburgites with chromites (*ch*) layered with dunites; *3* tectonic cut or confused zone, *4* dykes, sills and layers of basic and ultrabasic rocks; *5* layered peridotites (cumulates of dunites, lherzolites) and magmatic breccia; *6* alternations of peridotites with gabbros, *7* non layered gabbros over layered gabbros, *8* variety of basic rocks, dolerites, diorites and granophyres (increase of SiO_2); *9* dykes, veins, sills (*s*) of basic rocks; *10* and *11* basalts (spilites) with compact flows (*c*) or pillow-lavas (*lc*), a tectonic contact is often present at the base of *10*, *12* Argilites rich in Fe and Mn, *13* sedimentary rocks with siliceous beds (radiolarites) over or interlayered with the lavas (volcano–sedimentary complex). Total thickness: usually 4–5 km, can achieve 10–15 km (as an example: 11 and 10 = 0, 5–1 km, 8 = 0, 5 km, 7 and 6 = 0, 5 km, 5 = 0, 2 km, 2 = 2–3 km). These numbers can change dramatically due to overthrusts

Mélanges

As ophiolites are associated with large-scale overthrusts, tectonic mélanges can be formed in the base and at the front of such megastructures. These ophiolitic mélanges contain ophiolitic rocks and other rocks of various paleogeographic origins; the whole entity being in considerable tectonic disorder with chaotic masses where blocks and packages of various sizes of any kind of rock (sedimentary or volcanic) ‘‘float’’ inside a sheared soil-like mass.

Sketches of models around the world

Most of the ophiolites belong to the Alpine cycle (their age ranges from 180 to 60 MA) but older deposits are also known (e.g. in the Apalaches—Paleozoic, or in Maroc—Precambrian) (Debelmas and Mascle 1997).

Figures 3, 4 and 5 show schematically the general geological model of the ophiolitic formations in a number of mountain chains of the world, where petrographic and tectonic complexities exist (Fig. 6).

Geological engineering characterisation of various rock masses in the ophiolitic bodies

The geotechnical parameters

From the discussion on the geological model of ophiolites it is clear that this formation contains a variety of rock types with geotechnical qualities varying from excellent to fair, becoming poor to very poor when serpentinisation is extensive and/or shearing present. These last processes are both very frequent in the ophiolitic complexes.

The main fundamental types are peridotites, gabbros, peridotites more or less serpentinised, serpentinites, schisto-serpentinites, sheared serpentinites, pillow lavas and chaotic masses in ophiolitic mélanges.

In this section the engineering geological characterisation of these various rock type areas are discussed. The discussion concludes with the assignment of the range of values of the (GSI) which are most likely to occur for the fundamental types of rock masses occurring in the ophiolites. The field data are from outcrops, cuts in slopes, borehole cores and tunnel excavations from various significant ophiolitic complexes and mélanges in northern and central Greece. It is hoped that this assignment is not simply site specific but of general value and can be applied in a more universal way, given the similarities between the geological setting of numerous ophiolitic complexes of the Alpine cycle around the world.

The GSI values characterising the various masses, together with the strength of the intact rock, σ_{ci}, and the petrographic parameter, m_i, allow the geotechnical parameters of strength and deformability of the various rock masses to be estimated with a level of accuracy which is generally adequate for engineering design. For this estimation the program RocLab can be used. The program can be downloaded free from http://www.rocscience.com.

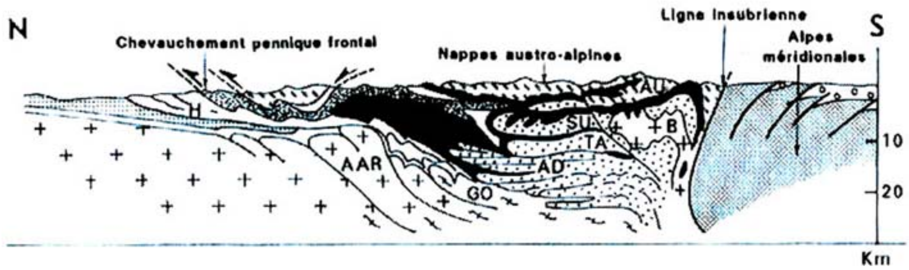

Fig. 3 Schematic section of nappes (overthrusts) in central Alps. Nappes of Mesozoic ophiolites in *black* (details in Pollino et al. 1990 in Mercier and Vergely 1999)

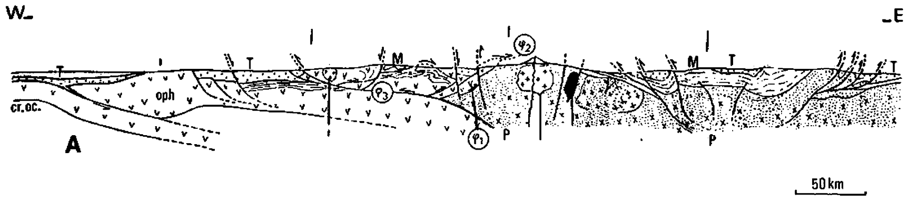

Fig. 4 The ophiolites (*oph*) in the context of Andes. Model in the Colombian Andes. (details in Megard 1987)

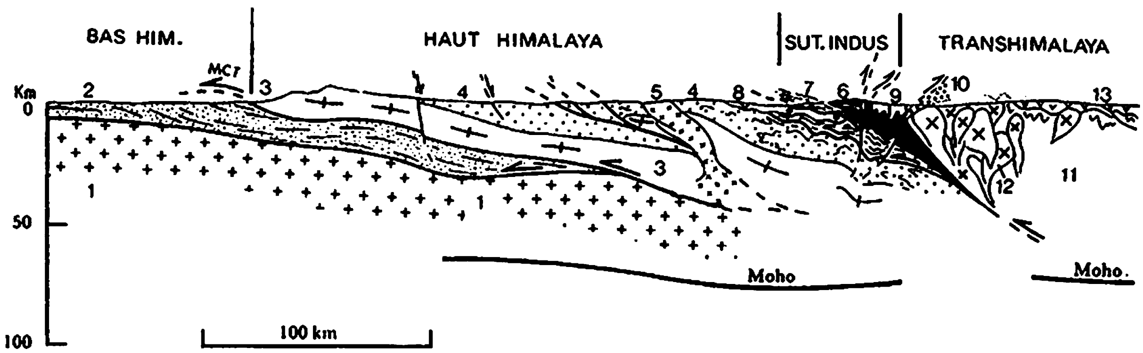

Fig. 5 Simplified section in the Himalayas with ophiolites in *black* (details in Bassoulet et al. 1984)

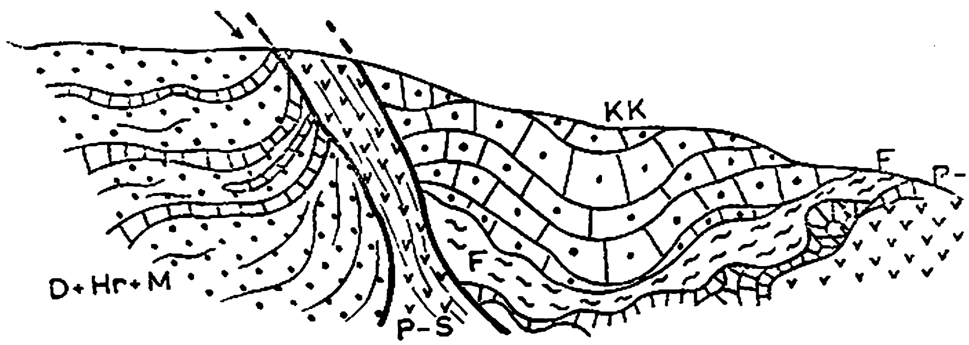

Fig. 6 Geological sketch in Orthrys mountain, central Greece with ophiolites (P–S) in tectonic relation with sedimentary series of rocks (limestones and siliciferous schists) (from Marinos 1974). Scale of tens of meters

Peridotites

Peridotites (hartsbourgites, dunites etc.) are strong with a range of unconfined strength for the intact mass from many tens of MPa to more than 100 MPa at which stage they behave as typical brittle materials. Koumantakis (1982) gives mean values of about 90 MPa from tests on 130 samples of peridotites, more or less serpentinised, from various locations in Greece. The values of σ_{ci} used in tunnelling design approaches in Greece are at least 50 MPa. Their tectonic disturbance is expressed in terms of intersecting joint sets distributed in accordance with the state of stress under which they were developed.

Serpentinisation, as a result of a typical weathering process or a process of alteration from endogenic causes, can be present on the surface of discontinuities. In such

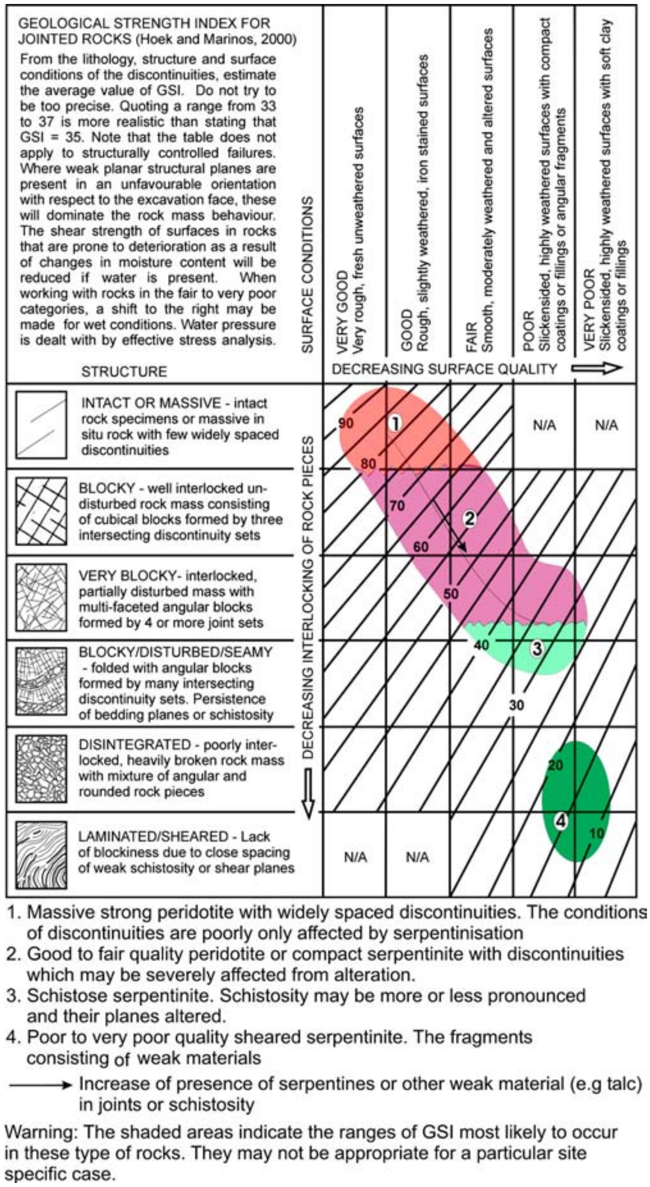

Fig. 7 Ranges of GSI for various qualities of peridotite–serpentinite rock masses in ophiolitic complexes

cases 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.

The range of GSI for peridotitic types of rock masses of the ophiolitic complex is shown in Fig. 7 (areas 1 and 2). The rock mass can be almost massive, with only a few widely spaced discontinuities, even close to the surface in tectonically quiet areas or in zones of "tectonic shadow". High values of GSI are to be attributed to this type of peridotitic mass (GSI greater than 65—area 1 in Fig. 7). Figure 8 shows representative cores of this good quality peroditite. Figures 9 and 10 show outcrops of sound and weathered peridotite.

Fig. 8 Good quality peridotite from the mountain of Orthrys in central Greece. The conditions of the widely spaced discontinuities are only mildly affected by serpentinisation. Tunnel stability is controlled by occasional structural failures. Depth of the cores in the photograph about 380 m. GSI 80 ± 5

Fig. 9 Good quality surface outcrop of blocky structure in peroditite with fair (smooth, moderately weathered and altered) surface conditions of discontinuities. Width of photograph about 1.5 m. GSI~55

When the rock mass is jointed or fractured the GSI values drop as low as 35, not only due to a disturbed structure but also because of the conditions of the discontinuities which become smooth and slippery due to serpentinisation. In a disturbed peridotitic mass, the serpentinisation process often affects and disintegrates parts of the rock, not only contributing to lower GSI values but also reducing the intact strength values. Such

Fig. 10 Weak weathered ophiolitic outcrop of serpentinised peridotite

Fig. 11 Fair quality peridotite, from the mountain of Orthrys in central Greece, with discontinuities of low frictional properties due to the presence of films of seprentinised material. Blocky-jointed with short lengths of disintegrated or serpentinised sections. Tunnel stability will be controlled by structural stability of small blocks or by mild overstressing. Depth of the cores in photograph about 200 m. GSI 35 ± 5

disturbed peridotites fall in the lower bound of area 2 of the GSI diagram of Fig. 7 and are shown in Fig. 11.

Gabbros

The gabbros follow the same principles in their engineering geological characterisation as all strong rocks. If they are sound their behaviour depends on their degree of fracturing. Their discontinuities can have better conditions than those of the peridotites as they suffer less from alteration. When weathered, the disintegrated materials contain clay which may be highly expansive.

Serpentinites

When the serpentinisation is due to weathering which has affected all of the mass, in addition to the reduction of the intact strength there is a dramatic disintegration of the structure of the rock mass. If this process of serpentinisation is due to autometamorphism and/or associated with tectonic thrust, the rock mass is poor, with a schistose disturbed structure which may reduce the GSI to values to 30 or less (area 3 in the GSI diagram of Fig. 7).

Measuring the strength of the intact rock, σ_{ci}, from such rock masses is always a problem. When testing schisto-serpentinites, the influence of "schistosity" results in a significant reduction in the strength of a large proportion of the specimens. Consequently, it is very difficult to obtain reliable values for σ_{ci} from laboratory tests and it is suggested that the uniaxial compressive strength of the schisto-serpentinite should be estimated from that of the normal serpentinite and reduced by about 30% to account for the schistosity. From cases in northern Greece it is considered that 40 MPa may be a realistic value for the uniaxial compressive strength (σ_{ci}) of the serpentinite (Fig. 12) and 30 MPa for the schisto-serpentinite. Koumantakis (1982) gives values of 45 MPa from 12 samples of serpentine.

It is essential to differentiate between intact rock strength and rock mass strength as this has a significant impact on the assessment of potential tunnelling conditions. Assigning the rock mass a low value of GSI and a low value of intact strength penalises the rock mass twice and results in too low a value of the estimated rock mass strength.

Fig. 12 Compact serpentinite

Fig. 13 Poor quality sheared serpentinite from the mountain of Orthrys in central Greece. Completely disintegrated peridotite with loss of blockiness and presence of clayey sections. Tunnel stability will be controlled by stress dependent rock mass failure with significant squeezing at depth. Depth of samples in photograph about 175 m, GSI 15–20

Fig. 14 Piece of sheared ophiolite, which has been disintegrated into flakes of weak serpentinite

Sheared serpentinites

In the sheared zones of serpentinites there is a lack of blockiness, which allows the rock to disintegrate into slippery laminar pieces and small flakes of centimetres or millimetres in size. GSI values can drop to less than 20 (Fig. 7, area 4). Such sheared serpentinite is shown in Figs. 13 and 14. The intact strength may vary from 20 to 5 MPa or less.

In a recent paper, Glawe and Upreti (2004) illustrate and discuss the differences that occur in two serpentinites, one in Turkey and one in Indonesia. Varying strength values may result from differences in local lithological factors, micro- and macro- structures, mineralogical compositions, variations in interlocking of smaller grains, sheared and angular rock fragments and re-cementation of matrix in serpentinite with bimrock fabric (Glawe and Upreti 2004).

Fig. 15 Basic volcanics in pillow lava structure. Blocky disturbed with poor condition of discontinuities (highly weathered with coatings or fillings). GSI approximately 30 in this particular site. A thin shear plane is also present (indicated by the notebook)

Pillow lavas

Pillow lavas of basaltic nature exhibit exfoliated spherical zones. Friable or sheared material surrounds a stronger main mass thus reducing the overall quality (Fig. 15). The condition is particularly likely to occur in areas of low overburden and in the tectonic zones of the ophiolitic complex. Thus, the quality can be poor only when weathering and tectonic shearing is generalised. The range of the geotechnical quality of the pillow lava given in terms of GSI may vary from 50 to 25. The GSI chart for these pillow lava structures is given in Fig. 16. Occasional shear planes occur (Fig. 15) and in tunnelling these could result in local structural failures unless adequately supported. Under such conditions tunnelling in this mass may be fair to good and only poor when the rock mass is at its lower bound (sheared and weathered). However, it will be essential to maintain confinement during the excavation procedures in order to optimise the temporary support.

Mélanges

Low to very low GSI values can be attributed to masses in ophiolitic mélanges where, as discussed earlier, rocks of the ophiolitic sequences are mixed in complete

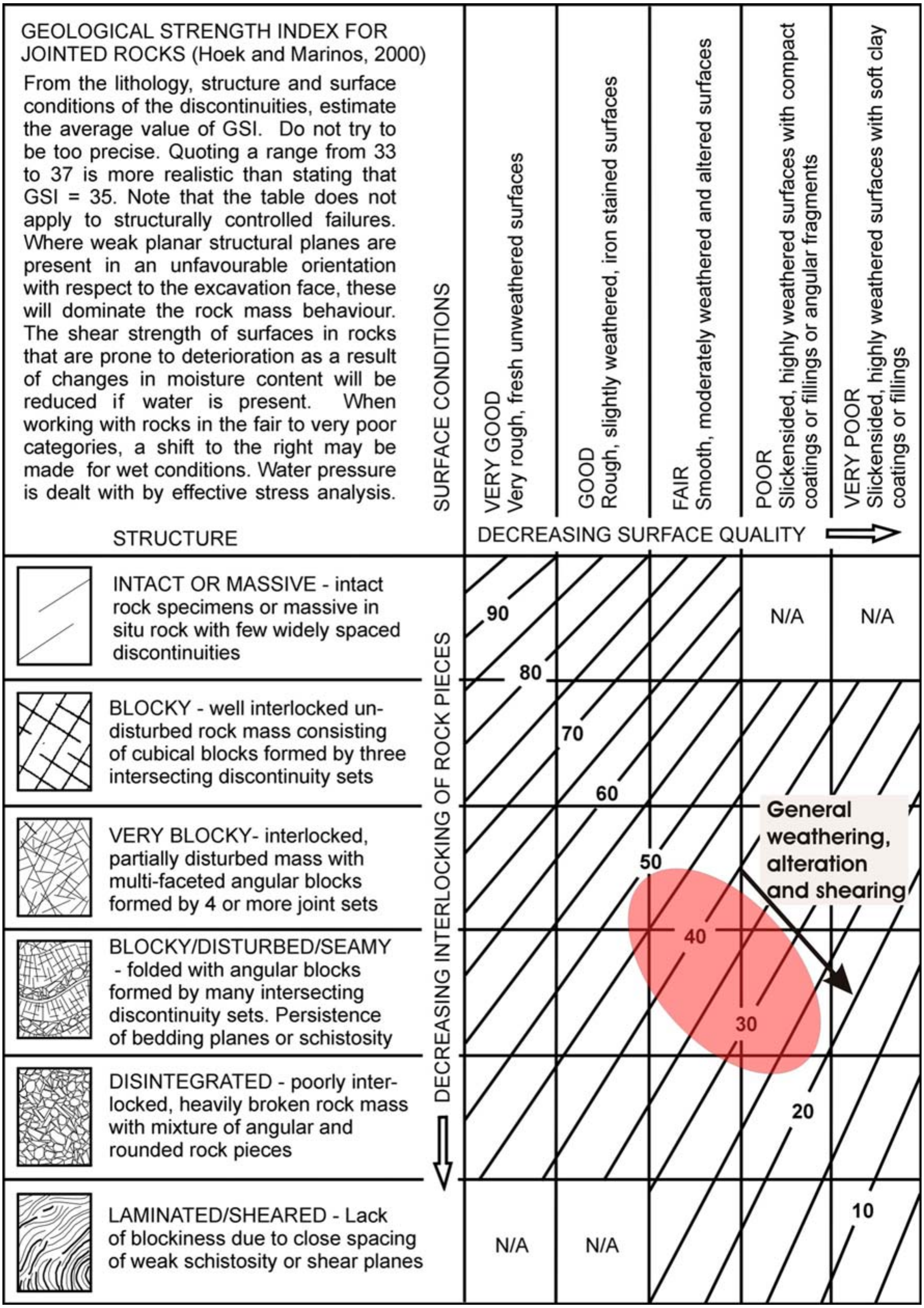

Fig. 16 Range of GSI ratings for basaltic pillow lavas. (Warning: the *shaded area* indicates the ranges of GSI values most likely to occur in this type of rock. It may not be appropriate for a particular site specific case)

disorder with other rocks of various origins and are situated at the base or in the front of great ophiolitic overthrust nappes. In soil-like material a GSI assignment is meaningless. However, it is possible that during tunnelling inside these masses, extensive blocks of sedimentary rocks of good engineering quality (e.g. limestones or sandstones) can be encountered. Nevertheless, the transition to the surrounding sheared rock mass of either ophiolitic or other clayey sedimentary rocks (flysch, siltstones, argillites) is sharp and unpredictable. Probe drilling ahead of the face is always prudent when tunnelling in such conditions.

The m_i values

In the Hoek and Brown failure criterion the m_i value reflects the frictional characteristics of the component minerals and grains of the intact rock. In the ophiolitic rocks in the Greek Alpine context the m_i values can be: peridotites more than 20; schistose serpentine: 12 ± 2; altered material due to shearing: 8 ± 2.

Behaviour in tunnelling

The great variety of the rock mass types, the irregular changes and the alteration make the ophiolites a formation where extreme care is needed in the design of any engineering structure founded on or crossing them. This is particularly true for tunnels as their linearity and their depth increase the possibility of encountering the adverse conditions and weak zones associated with the ophiolites while the uncertainty as to their occurrence and extent exacerbate the difficulty. In Fig. 17 the tunnelling behaviour of peridotites—serpentinites is classified following the characterization of their rock masses discussed in the previous section and shown in Fig. 7.

Peridotites

In good quality masses of peridotite, simple straight forward tunnelling conditions can be expected. Attention has to be concentrated on avoiding structural instabilities from wedges. For these structurally controlled failures involving only a few discontinuities, the problem is essentially one of three-dimensional geometry and stereographic techniques or numerical analyses such as Unwedge (see http://www.rocscience.com) should be used for an analysis of failure processes and the design of reinforcement. However, compared with other rock masses of similar structure, the peridotites generally have smoother discontinuities with low frictional properties. As explained earlier this is due to the presence of serpentinised material which is very often present even if the serpentinisation has not affected the fundamental rock material. This makes the structurally dependant instability more critical and generally demands heavier rock bolting patterns and/or thicker shotcrete (zone II in Fig. 17). In very hard massive rock masses at great depths, spalling, slabbing and rockbursting are the modes of failure that may develop, controlled by brittle fracture propagation in the intact rock with the discontinuities having only a minor influence (zone I of Fig. 17). In these cases the use of brittle rock failure criterion should be considered, such as that proposed by Kaiser et al. (2000).

Fractured peridotites or schistose serpentinites

In the case of a more fractured peridotite, schistose or weaker serpentinite (GSI values of 25–40), the behaviour is controlled by sliding and rotation on discontinuity surfaces with relatively little failure of the intact rock pieces (zone II/III of Fig. 17). In this range of GSI values the RQD values can be very low. This is normal, given the structure of the rock masses, but some of the frictional behaviour of the unaltered pieces of the mass is retained. Thus, the control of stability can be effectively improved during excavation of the tunnel by keeping the rock mass confined.

Sheared serpentinite—squeezing behaviour

In the poor quality serpentinite, due either to weathering or shearing, blockiness may be almost completely lost and clayey sections with swelling materials may be present. Tunnel stability will then be controlled by stress dependant rock mass failure with significant squeezing at depths (Fig. 17, zone III). In these cases detailed design has to be carried out using a numerical analysis which permits progressive failure and support interaction analysis to be modelled. However, it is very instructive to carry out a closed form analysis of the behaviour of the tunnel in order to get some idea of the significance and magnitude of convergence and squeezing. The plot presented in Fig. 18 is taken from a paper by Hoek and Marinos (2000) in which it was shown that, for tunnels in weak rocks, the "strain" can be estimated from the ratio of rock mass strength to in situ stress by means of the equation shown in the figure. This plot is for single circular shaped tunnels. The strain for twin tunnels which are reasonably close together is expected to be higher than that indicated by the plot, which is for unsupported tunnels in a hydrostatic stress field.

Two cases from a tunnel in Greece in ophiolites in the form of more or less sheared serpentinites are plotted in points 7 and 8 in Fig. 18. Point 7 corresponds to a rock mass of a strength, σ_{cm}, of about 1.4 MPa and a deformation modulus, $E = 800$ MPa, under a cover of

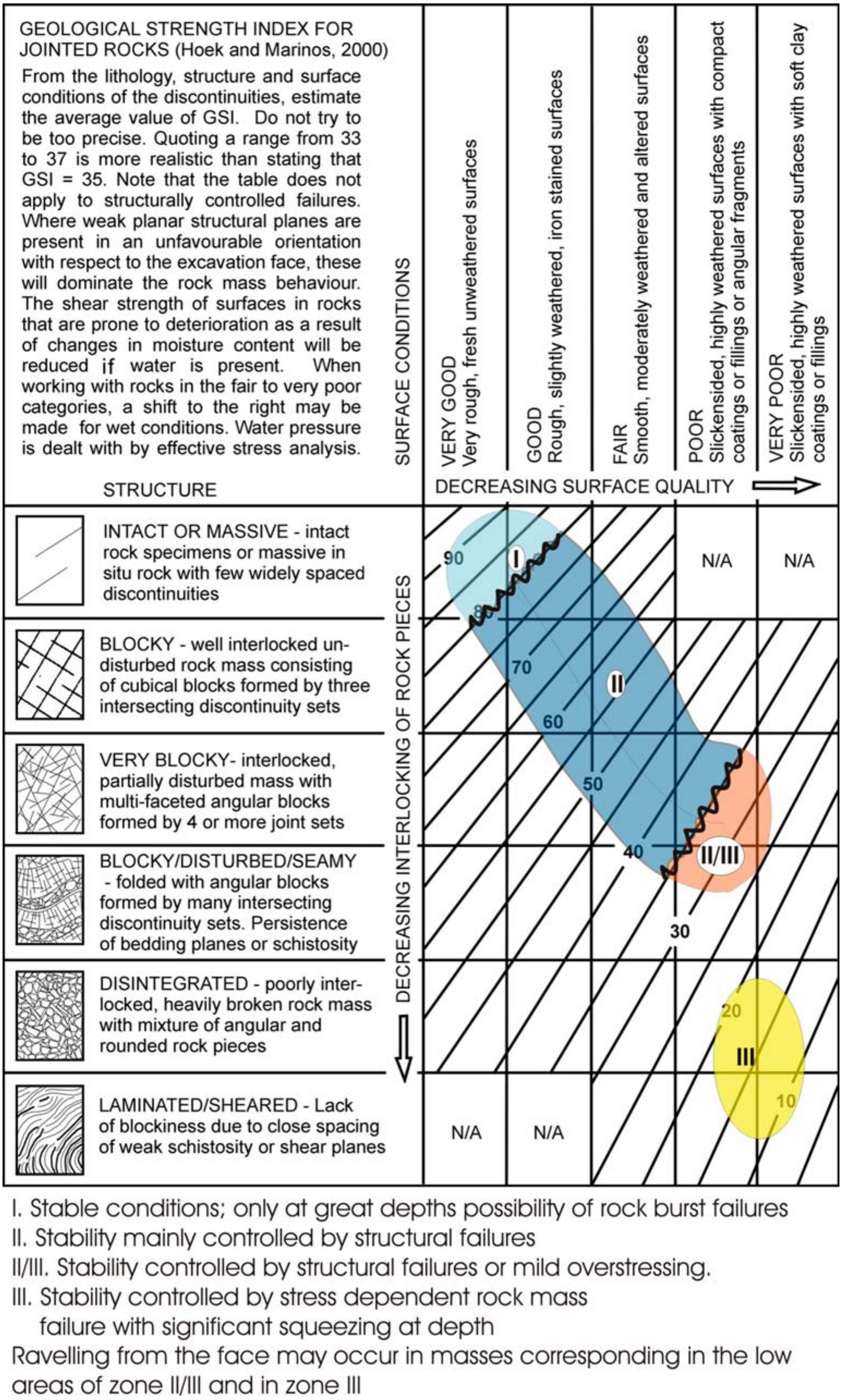

Fig. 17 Classification of the behaviour in tunnelling for peridotite–serpentinite rock masses in ophiolitic complexes (to be read in conjunction with Fig. 7)

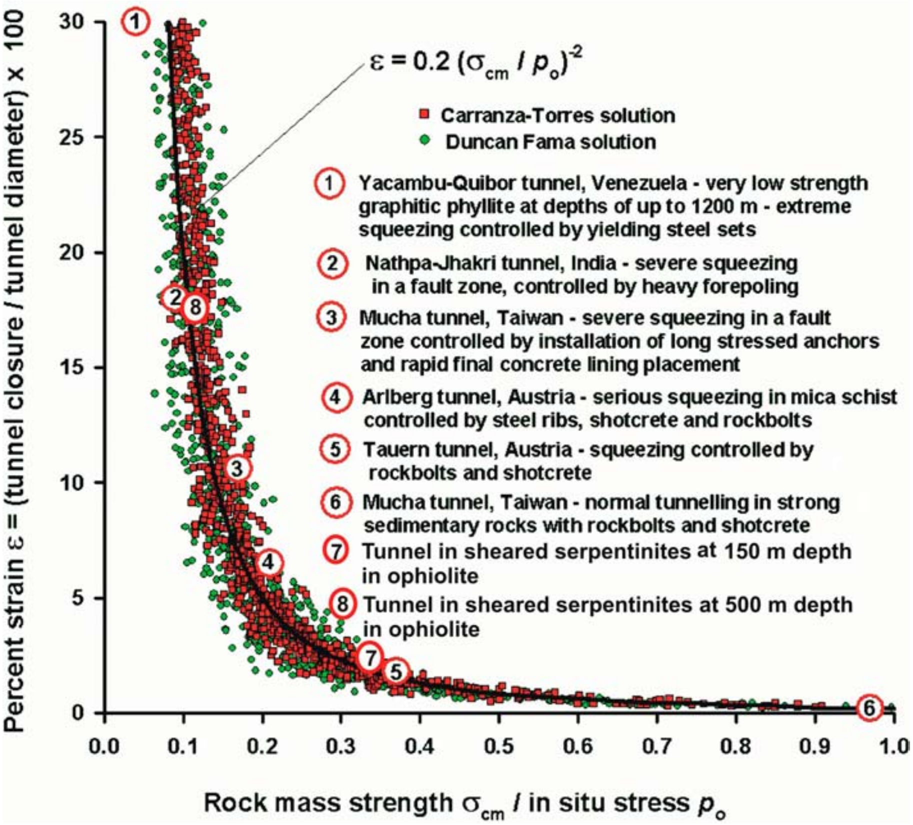

Fig. 18 Plot of percentage strain versus the ratio of rock mass strength to in situ stress (after Hoek and Marinos 2000). Calculated and predicted strains for a tunnel in ophiolite are plotted as *points 7* and *8* at ratios of rock mass strength to in situ stress of 0.35 and 0.11, respectively

about 150 m. These values were derived from a back analysis of the behaviour of a tunnel section where the measured and computed displacements of about 1.5% were in close agreement. These properties correspond to a weak ophiolitic rock mass (sheared serpentinite) with a $GSI = 20$, $\sigma_{ci} = 16$ MPa and $m_i = 10$.

For a depth of 500 m, the ratio of rock mass strength to in situ stress is 0.11 and this gives a strain of 17% for a single tunnel. This means that there may be a closure of as much as 2 m in a 12 m span tunnel unless appropriate steps are taken to control this deformation.

Squeezing and face stability can be controlled by forepoling, commonly used in many weak rock tunnels in southern Europe. However, when severe squeezing is anticipated in very weak serpentinite in areas of thick cover, the use of yielding primary support (sliding joints in steel sets or gaps in shotcrete) in conventional tunnelling may be required. In these cases the ideal tunnel section is circular. Where such difficult tunnelling conditions are encountered it is recommended that a robust design be provided with the possibility of varying the amount of yielding depending on the overburden and the rock mass quality. In general, it is recommended that the chosen support types should be able to accommodate changes without the need to change the principal elements of the support system.

It is unlikely that rockbolts will be effective in severe squeezing conditions as they are too stiff in relation to the surrounding rock mass and the resulting strain differential causes shearing of the grout bond. Ravelling of completely disintegrated serpentinite may also be a problem and keeping confinement of the face is the key action to be undertaken.

Special provisions may be required to eliminate the possibility of trapping the machine in the case of excavation by TBM. It is critically important that a TBM should never be stopped in zones of severe squeezing. Experience has shown that this squeezing occurs relatively slowly and that a moving machine is seldom trapped. Overboring devices are necessary and in some cases TBMs have been specially designed to permit reduction of the shield diameter. However, several machines have been lost when they have been parked for one reason or another. An appropriately designed precast segmental lining is generally installed directly behind the machine.

As the occurrence of weak or sheared rock masses is randomly distributed along the tunnel alignment due to the particular geological model of the ophiolites, it is prudent to probe ahead of the tunnel face continuously, keeping a length of probe hole of at least 20 m ahead of the face at all times. In the case of TBM excavation,

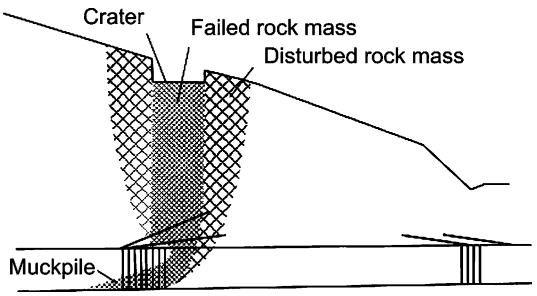

Fig. 19 Failure and interpretation of possible extent of rock mass disturbance resulting from the collapse due to ravelling of weathered peridotite during tunnelling in a heavily disturbed ophiolitic complex in Greece. The overburden is about 35 m. Forepoling and a grout umbrella for remediation are shown

Fig. 20 Appearance of stabilised muckpile at the face. No material has been removed since the collapse and stabilisation has been carried out by the installation of a double forepole umbrella and by grouting

provision should be made for probe drilling through the cutter head or by means of inclined holes drilled over the shield.

Weathered peridotite. A case of ravelling

Tunnelling through weathered peridotite (serpentinite) close to the surface will require great care in order to avoid subsidence and slope movement and a light forepole umbrella (75 or 100 mm diameter pipes) can be used. Pre-grouting an umbrella in the rock mass over the forepoles may be advisable in order to increase the cohesive strength of the rock mass. Figures 19 and 20 illustrate a failure in weathered peridotite.

The tunnel face has been stabilised by the installation of a double forepole umbrella and by extensive grouting through the forepoles and also through horizontal holes drilled through the muckpile. Figure 20 shows a situation in which no material has been removed from the muckpile which has been covered with shotcrete.

Groundwater conditions

Groundwater can be present in fractured but otherwise sound peridotites. However, weak masses are usually of low permeability; thus, water pressure has to be considered in the design and systematic relief holes may be required during construction.

Conclusions

Rock masses in an ophiolitic complex exhibit a wide range of engineering behaviour, particularly in tunnelling. This is due to their petrographic variety and structural complexity. The GSI, enhanced by geological logic permits the characterisation of this wide range. Its use allows adjustments of the rating to cover not only the wide range of the ophiolitic rock masses and conditions but also the variations that may occur within the same rock type. As a consequence a classification of tunnelling behaviour can be formulated for this wide range of ophiolitic rock masses from stable to severe squeezing conditions.

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