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Engineering Geology for Underground Works

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Preface

The construction of tunnels involves the resolution of more or less complex technical problems depending on the geological and geological—environmental context in which the work fits.

Only a careful analysis of all the geological and geological—environmental issues and a correct reconstruction of their conceptual model, can lead to optimal design solutions from all points of view (including financial) and to ensure safety to the workers during construction, and to users, in the operation phase.

Therefore, the need to collect the synthesis of current knowledge about underground excavations in a volume is felt, especially with respect to: the geological and environmental issues related to the construction of underground works (Chaps. 1 and 2); the different methodologies used for the reconstruction of the conceptual model (Chap. 3); the underground excavation analysis (Chap. 4); the different risk typologies that it is possible to encounter or that can arise from the underground construction and the most important risk assessment, management and mitigation methodologies that are used in the underground work planning (Chaps. 5 and 6); the ground structure interaction (Chap. 7) and the characteristics and the equipment of the monitoring activity, which should be performed during an underground excavation (Chap. 8).

The authors are aware that the aim of this book is only to introduce the problems related to the construction of underground works rather than finding the solutions from them all and to provide readers useful concepts for a correct scientific approach to the subject.

Acknowledgments

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Contents

Chapter 1
Geological Problems in Underground Works Design and Construction

1.1 Introduction

Underground excavations consist of progressive removal—by different methods, timings and techniques—of natural ground (rock mass or soil) in order to obtain a cavity of chosen shape and size. Before the excavation, the ground is generally in an equilibrium condition in its original state of stress. Therefore, no deformations or displacements occur. The excavation progressively modifies the state of stress in the ground by generating a stress deviation around the cavity, with particular stress concentration close to its boundary surfaces. As a consequence, the ground is forced to reach a new equilibrium state through deformations and, in case of fractured rocks, relative displacements of rock blocks. The magnitude of such deformation phenomena and the related kinematics depends on:

- The shape and the dimension of the cavity
- The method, timing and technique of excavation
- The nature and the original stress state of the ground

In particular, a stable condition can be expected at the cavity opening only for those materials which are defined as self-supporting. This type of condition is possible only due to their good geomechanical features. Materials having self-supporting characteristics are generally massive or slightly fractured rock masses or fractured rock masses in which the release of blocks is prevented (i.e. characterised by high shear joints strength or by favourable joints orientation).

The behaviour of the mass being excavated essentially depends on three main aspects: first of all, on the lithological nature, which determines the mechanical characteristics of the matrix; then, on the structural features (stratification, schistosity, fracturing etc.) which determine the mechanical properties of the mass itself; and lastly, on the state of stress existing before the excavation. In particular, the variation of the above-described factors can induce a broad spectrum of instability and deformation phenomena, from the already mentioned kinematics of rock blocks (Fig. 1.1) to major cavity wall movements both in brittle (rock burst, Fig. 1.2) or ductile (squeezing, Fig. 1.3) conditions.

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Fig. 1.1 Collapse due to block instability. (By Pizzarotti)

Fig. 1.2 Collapse under severe rock-burst conditions. (Hoek and Brown 1980)

Furthermore, soils and rocks are multiphase media; consequently, another factor affecting their behaviour during the excavation is related to the groundwater presence and flowing, which depend on the hydrogeological characteristics of the medium.

Last but not the least, other aspects also can be very relevant for good underground construction performance. These can be the location of the excavation in relation to the topographic surface, risk of natural gas finding, presence of aggressive water, weathering and swelling minerals, increase in temperature with depth (geothermal gradient), seismicity, radioactivity and the presence of hazardous minerals.

1.2 Lithological and Structural Features

From an engineering point of view, the geomechanical quality of a rock mass is the set of properties that affectsits behaviour, for example, when an underground excavation is opened. In Chaps. 3 and 4, the main and the most used methods to

Fig. 1.3 Heavy deformation due to intense squeezing. (Agostinelli et al. 1995)

assess the geomechanical quality of a rock mass will be described, as well as some methods that allow a rapid and preliminary evaluation of the excavation behaviour. In general, the lower the geomechanical quality of the rock mass, the more the problems during the excavation within. It is obvious that the most favourable conditions, from the static point of view for the excavation of an underground cavity, exist in the presence of massive rocks (i.e. not significantly disjoined, fractured or laminated) that have high mechanical strength. On the contrary, if the cavity has to be excavated in soft or highly fractured rocks or, in an extreme condition, in soils, precarious stability conditions always occur.

As stated before, the rock quality, and thus the rock mass behaviour, is influenced both by lithological nature that affects the strength of the rock matrix and by structural features.

1.2.1 Lithological Features

The geomechanical behaviour of the rock mass depends primarily on its lithological features, e.g. its mineralogical-petrographic composition and on the type of process which generated the lithology itself.

The magmatic rocks (with the exception of pumice and obsidian) and the metamorphic non-schistose rocks are generally of lithological types with the best strength characteristics; considering the same fracturing and weathering conditions, massive sedimentary rocks rank second, followed by metamorphic schistose ones, highly stratified sedimentary rocks and, at last, soils.

Table 1.1 Range of uniaxial compressive strength (UCS) for some common rock materials

Term for uniaxial compressive strength	Symbol	UCS Strength (MPa)	Range for some common rock materials				
			Granite, basalt, quartzite, marble	Schist, sandstone	Limestone, marl	Claystone slate	Soil
Extremely weak	EW	0.25–1				X	X
Very weak	VW	1–5		X	X	X	X
Weak	W	5–25		X	X	X	
Medium strong	MS	25–50	X	X	X	X	
Strong	S	50–100	X				
Very strong	VS	100–250	X				
Extremely strong	ES	> 250	X				

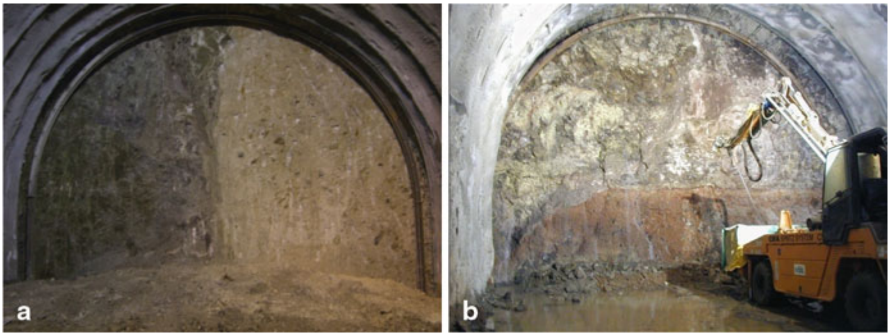

Fig. 1.4 Examples of mixed lithology sections (by Pizzarotti): **a** on the face of the tunnel excavation, a tectonic contact is clearly visible between alternation of basalts and vulcanoclastiti (left) and calcarenites with a high degree of cementation (right), **b** on the face of the tunnel excavation, contact between Plio-Pleistocene basic vulcanites (low) and an alteration layer (paleo soil, high) can be observed

According to the Basic Geotechnical Description given by ISRM (1980), the parameters used to define the limits between soils, weak rocks and hard rocks are uniaxial compressive strength and cohesion (Table 1.1).

The materials having cohesion lower than 0.3 MPa and uniaxial compressive strength less than 2 MPa are classified as soils; the materials with compressive strength between 2 and 20 MPa are defined as "weak rocks", while the materials with uniaxial compressive strength higher than 20 MPa are considered "hard rocks".

From a purely lithological point of view, a rock is "weak" because of the weak links among its components (for example shales, siltstones, marls, chalks, phyllites etc.)

The technical behaviour of a rock mass can be also be affected by the simultaneous presence of different lithology in the same cavity stretch (Fig. 1.4). This can be a factor causing instability or major difficulties during the advancement.

1.2.2 Structural Features

A further very important factor that affects the behaviour of the rock mass is undoubtedly its structural setting. It depends on:

- The processes that led to the formation of the different types of rock; they generate primary structural weaknesses, such as layering, schistosity or cooling joints.
- The tectonic phenomena to which rocks were subjected during their geological history; in this case, secondary structural weaknesses develop in different ways depending on the brittle or ductile response and on the stress acting on the rock mass.

It is evident that the type of response depends on the lithology, on the conditions of temperature and pressure and on the duration of deformation events. It is therefore essential to collect all data related to the following structural characteristics: geometry (inventory of all brittle or ductile structures), kinematics (examination of the displacements and movements that led to the change of position, orientation, size and/or shape of the rock bodies) and dynamics (reconstruction of the nature and orientation of the stresses that produced the deformation).

In presence of bedded and/or fractured rock masses, the following parameters should be carefully evaluated:

- The layer thickness and/or the fracturing degree, i.e. number of fractures per linear meter, or rather the inverse of the distance between the discontinuities (strata or fractures)
- The joint characteristics (persistence, roughness, aperture, filling, alteration etc.)
- The joint orientation relative to the walls of the underground cavity

Taking as a reference, by way of example, a family of discontinuities (i.e. the bedding) the following cases can be schematically analyzed:

- Horizontal layers (Fig. 1.5): The issues are becoming more pronounced with the thinning of the layer thickness. In particular, if the layers are constituted by banks of high thickness, a behaviour similar to that of massive rock masses can be expected (especially if the more resistant banks are located at the ceiling and along the sides); if the layers are thin, or even worse if they have reduced strength, instability at ceiling will be frequent, caused by flexural break of the layers.
- Sub-vertical layers (Fig. 1.6): If a generic cross-section of a cavity of undefined length (tunnel) is considered, conditions are much more favourable in case of interception of layers whose direction is perpendicular to the axis: in each crossed layer, the stresses can be laterally deviated with respect to the ceiling (arch effect), as in an intact rock; as the angle between the tunnel axis and the layer direction decreases, conditions gradually become more unfavourable with the development of failure phenomena of the layers (especially in presence of thin layers with low shear strength of the joints) caused by load concentration on the sides. Obviously, similar conditions are present at the face in case of a tunnel developing perpendicularly to the direction of the layers.

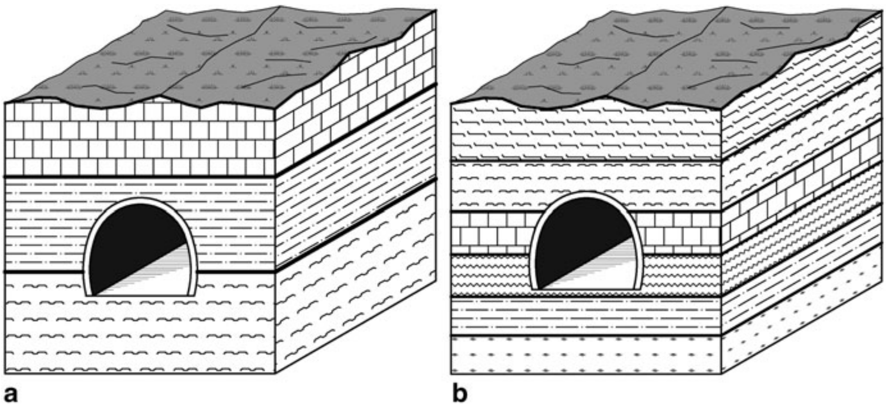

Fig. 1.5 Tunnels excavated in horizontally stratified rock masses: **a** high thickness of the layers, **b** thin layers

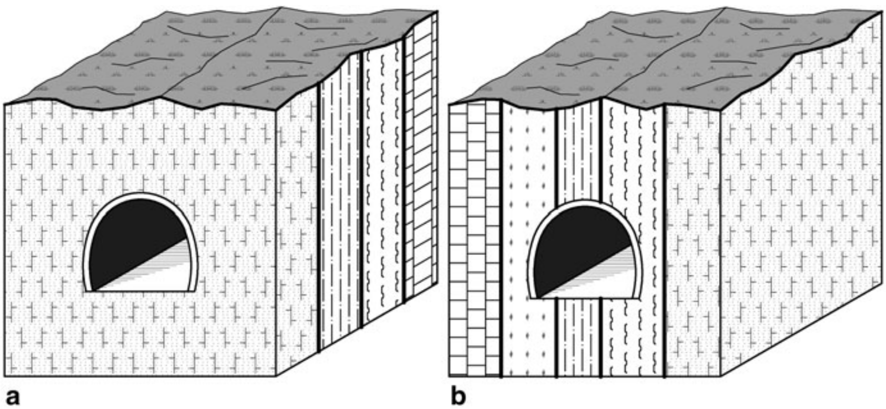

Fig. 1.6 Tunnels excavated in vertically stratified rock masses: **a** tunnel axis perpendicular to the layers' direction, **b** tunnel axis parallel to the layers' direction

- Inclined layers (Fig. 1.7): Equilibrium conditions vary considerably depending on the direction of the tunnel axis with respect to the layers orientation. If the cavity is parallel to the direction of the layers ("tunnel in direction"), lateral dissymmetrical and almost continuous deformations or instability phenomena can develop longitudinally. If the tunnel axis is perpendicular to the direction of the layers, these phenomena are distributed symmetrically, whereas it is possible to have a strength change in the longitudinal direction depending on the nature and thickness of the crossed layers. In case of "obliquely" inclined layers, an intermediate situation between the two above-described cases occurs, even in case of prevailing dissymmetrical kinematics and deformations. Moreover, it is evident that in the presence of a low or high dip angle of the layers,

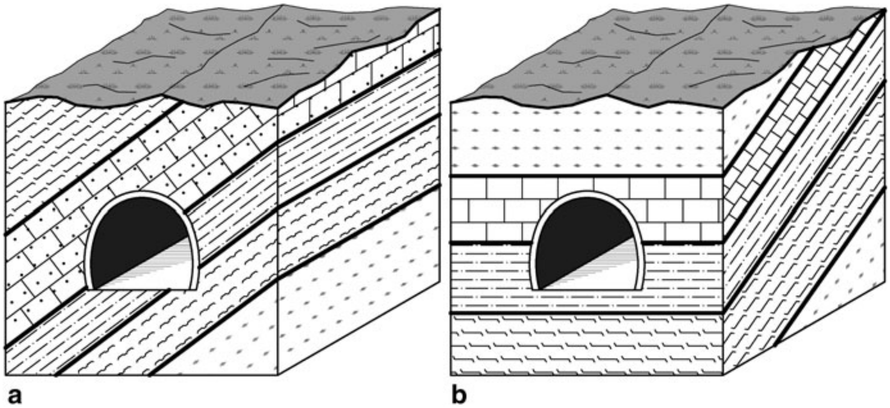

Fig. 1.7 Underground works in rocks with inclined bedding planes: **a** the underground work (in direction) always develops in the same strata: possible kinematics due to bending on the left side and sliding blocks along the layers on the right side; **b** the underground work crosses obliquely the layers for length greater than the layers' thicknesses: possible kinematics due to bending of the layers at the ceiling and sliding along the face

the situation will not be exactly the same as the ones previously described, as the rock mass tends to show a behaviour similar to the already described cases of horizontal or vertical layers.

Finally, it should be noted that all the features described above for bedded rock mass are totally transferable to other situations in which the presence of a systematic disjunctive element confers a layered attitude (cleavage, schistosity, lava plans, cooling layers, etc.) to the rock mass.

The above-outlined concepts also apply in presence of two or more discontinuity systems. In this case, potential mechanisms of sliding and/or falling wedges and, less frequently, toppling must be considered.

1.3 Tectonic Setting

It is well known that the lithosphere is continuously modified by internal forces that tend to deform it. Therefore, the lithosphere is divided into plates that may converge, diverge or scroll side by side. As a consequence, much of the geological hazards (volcanism, earthquakes, continental drift, expansion of the oceans, orogenesis etc.) are results of this interaction between plates.

It is therefore clear that an underground work carried out in a tectonically active area (recurrently the margin of the plates) will meet a stress state that depends, in terms of orientation and intensity, on the prevailing movement between the plates.

In case of divergent or transform tectonic movements, brittle tectonic structures as faults will be generated. If, on the contrary, the movements are convergent, folds and thrusts will frequently develop.

1.3.1 Faults

It is very well known that the presence of faults along the layout of an underground opening can cause significant problems.

If the shear stress along the discontinuity was particularly high, the rock mass became so fractured that can behave like a soil. Such deformations can interest more or less wide bands of rock mass. Particular attention is given to these fracture zones within underground works, since they are usually affected by the toughest structural-geological and hydrogeological problems. Such materials at the opening of the cavity often have limited, if any, self-supporting features.

Moreover, fracture zones frequently form preferential paths for groundwater: Therefore, water inflows, also of significant extent, are quite common in those situations. Similarly, the presence of major discontinuities may allow harmful gases to channel inside them and reach the excavation. Materials originated in correspondence of friction zones are defined as “fault rocks” and distinguished according to the classification in Table 1.2 (from Sibson 1977, modified).

Due to the above-mentioned problems, during the preliminary geological survey, it is important to accurately define the presence of tectonised zones in the area involved by future underground works. If a cataclastic band is intercepted, this should be crossed as orthogonally as possible in order to minimize its interference with the cavity.

The presence of overthrusts may cause similar problems. In this case, the low dip angle of the tectonic element implies the retrieval of poor material during the excavation of particularly long stretches.

1.3.2 Folds

The interception of a fold structure by underground works causes some particular consequences from the structural point of view, such as dissymmetry of the defromation and lithological inhomogeneity.

Folds can also contain residual stresses; there are, in particular, compressive stresses in correspondence of the core and tensile at its hinge.

If the folds are located at great depth, the residual stresses can be particularly high due to the difficulty of geological units to stress release because of the presence of heavy lithostatic confinement.

Therefore, it is extremely important to know not only where underground works intercept a fold, but also the fold type (Fig. 1.8): for example, the crossing of a syncline along its axial plane involves strong lateral stresses and important water inflows, while crossing an anticline in its hinge can facilitate releases and collapses at the ceiling and sides deformations.

Table 1.2 Texture classification and deformation type of fault rocks

"Random fabric" rocks				Foliated rocks		
Brittle deformation				Ductile deformation		
Not cohesive	Fault breccia (if the rock fragments are more than 30 %)		Cataclasis	Foliated gouge	Cataclasis	
	Fault gouge (if the rock fragments are less than 30 %)		Cataclasis			
Cohesive	Pseudotachilite (vitreous rock)		Frictional melting	Tectonites	Dissolution reprecipitation	
	Breccia	0–10 % matrix	Cataclasis	Mylonites		
	Protocataclasites	10–50 % matrix	Cataclasis	Protomylonites	10–0 % matrix	Intracristallin plasticity
	Cataclasites	50–90 % matrix	Cataclasis	Mylonites	50–0 % matrix	Intracristallin plasticity
	Ultracataclasites	90–100 % matrix	Cataclasis	Ultramylonites	90–100 % matrix	Intracristallin plasticity

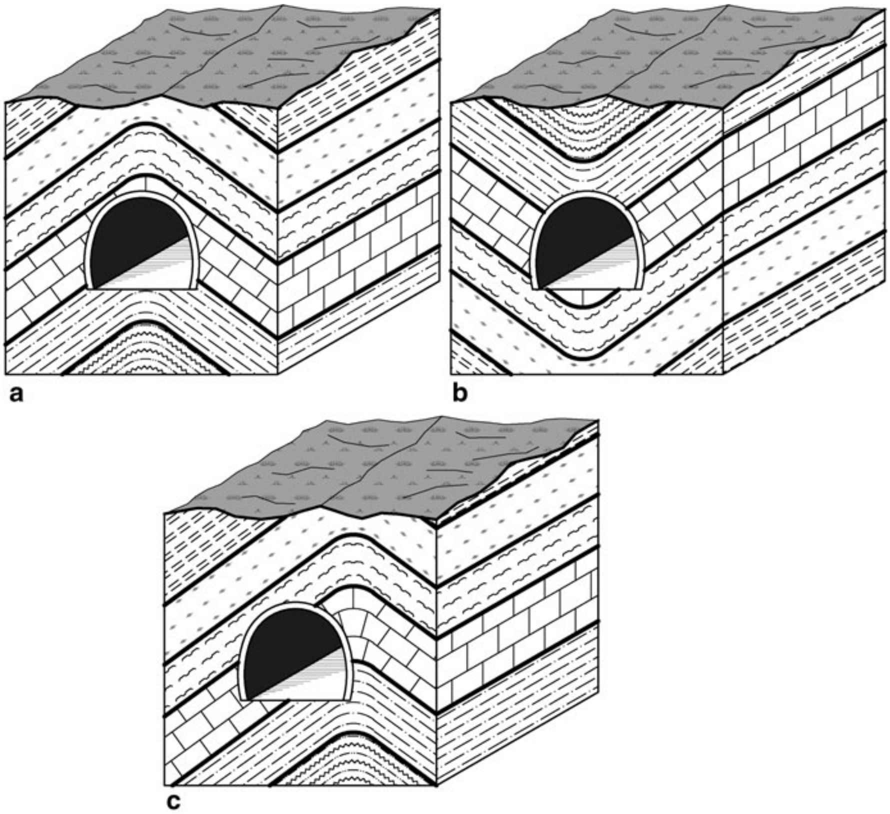

Fig. 1.8 Relation between underground works and folds: **a** tunnel at the anticline core; **b** tunnel at the syncline core; and **c** tunnel at the syncline hinge

1.4 Scale Effect

Strength features of rock masses are highly dependent on the scale of analysis. If the underground cavity size is small with respect to the joint spacing, the number of intercepted discontinuities is reduced. Then, the intact rock behaviour assumes great importance. On the contrary, if the tunnel diameter increases with respect to the joint spacing, the role of the discontinuities becomes more and more important in defining the rock mass behaviour. In this case, the strength of a joint rock mass depends on the properties of the intact rock blocks and also on the freedom of these blocks to slide and rotate under different stress conditions.

Of course, when defining the scale effect, the degree of fracturing of the rock and the size of the cavity have to be considered.

In general, it is reasonable to suggest that, when dealing with large-scale rock masses, the strength will reach a constant value when the size of individual rock

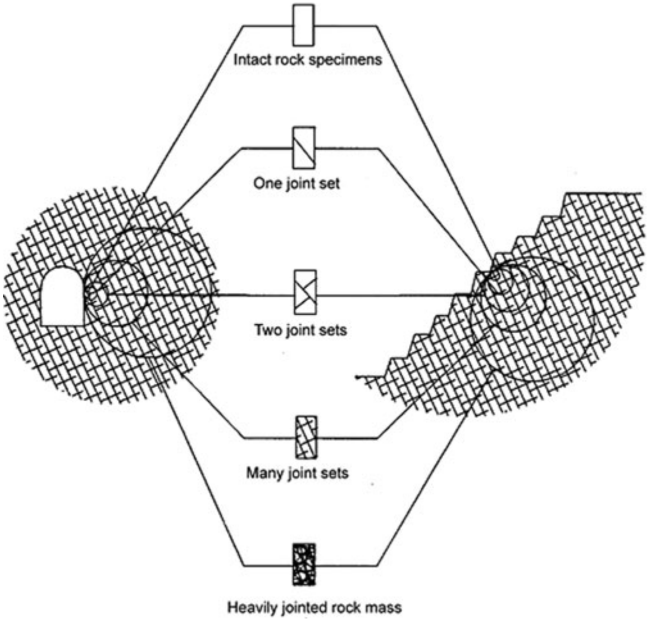

Fig. 1.9 Idealised diagram showing the transition from intact to a heavily jointed rock mass with increasing sample size. (From Hoek 2013, modified)

blocks is sufficiently small in relation to the overall size of the cavity being considered. This suggestion is embodied in Figure 1.9, which shows the transition from an isotropic intact rock specimen, through a highly anisotropic rock mass in which failure is controlled by one or two discontinuities, to an isotropic heavily jointed rock mass.

1.5 In Situ Stress State

Rock at depth is subject to stresses resulting from the weight of the overlying strata and from locked-in stresses of tectonic origin.

The weight of the vertical column of rockresting on a rock element is the product of the depth and the unit weight of the overlying rock mass (Fig. 1.10).

The horizontal stresses acting on an element of rock at a depth z below the surface are much more difficult to estimate than the vertical stresses. Measurements of horizontal stresses at civil and mining sites around the world show that the ratio of the average horizontal stress to the vertical stress tends to be high at shallow depth and that it decreases at depth (Hoek and Brown 1980; Herget 1988). Sheorey (1994) provided simplified equation which can be used for estimating the horizontal to

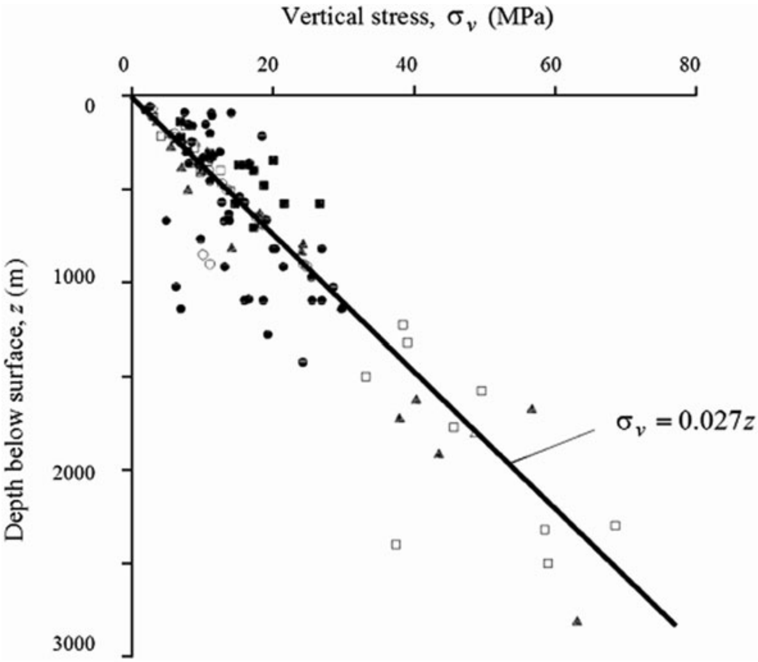

Fig. 1.10 Vertical stress measurements from mining and civil engineering projects around the world. (Modified from Hoek and Brown 1980)

vertical stress ratio k:

$$k = 0.25 + 7E_h(0.001 + 1/z)$$

where z (m) is the depth below surface and E_h (GPa) is the average deformation modulus of the upper part of the earth crust measured in a horizontal direction.

The Sheorey's theory does not explain the occurrence of measured vertical stresses that are higher than the calculated overburden pressure, the presence of very high horizontal stresses at some locations or why the two horizontal stresses are seldom equal. These differences are probably due to local topographic and geological features, strictly related to the tectonic setting (see Sect. 1.3). In this regard, the World Stress Map will give a good first indication of the possible complexity of the regional stress field and possible directions for the maximum horizontal compressive stress. A map showing the orientation of the maximum horizontal compressive stress for the Mediterranean is reproduced in Fig. 1.11. Afterwards, the results of in situ stress measurements can be used to refine the analysis. Where regional tectonic features such as major faults are likely to be encountered, the in situ stresses in the vicinity of the feature may be rotated with respect to the regional stress field and the stresses may be significantly different in magnitude from the values estimated from the general trends.

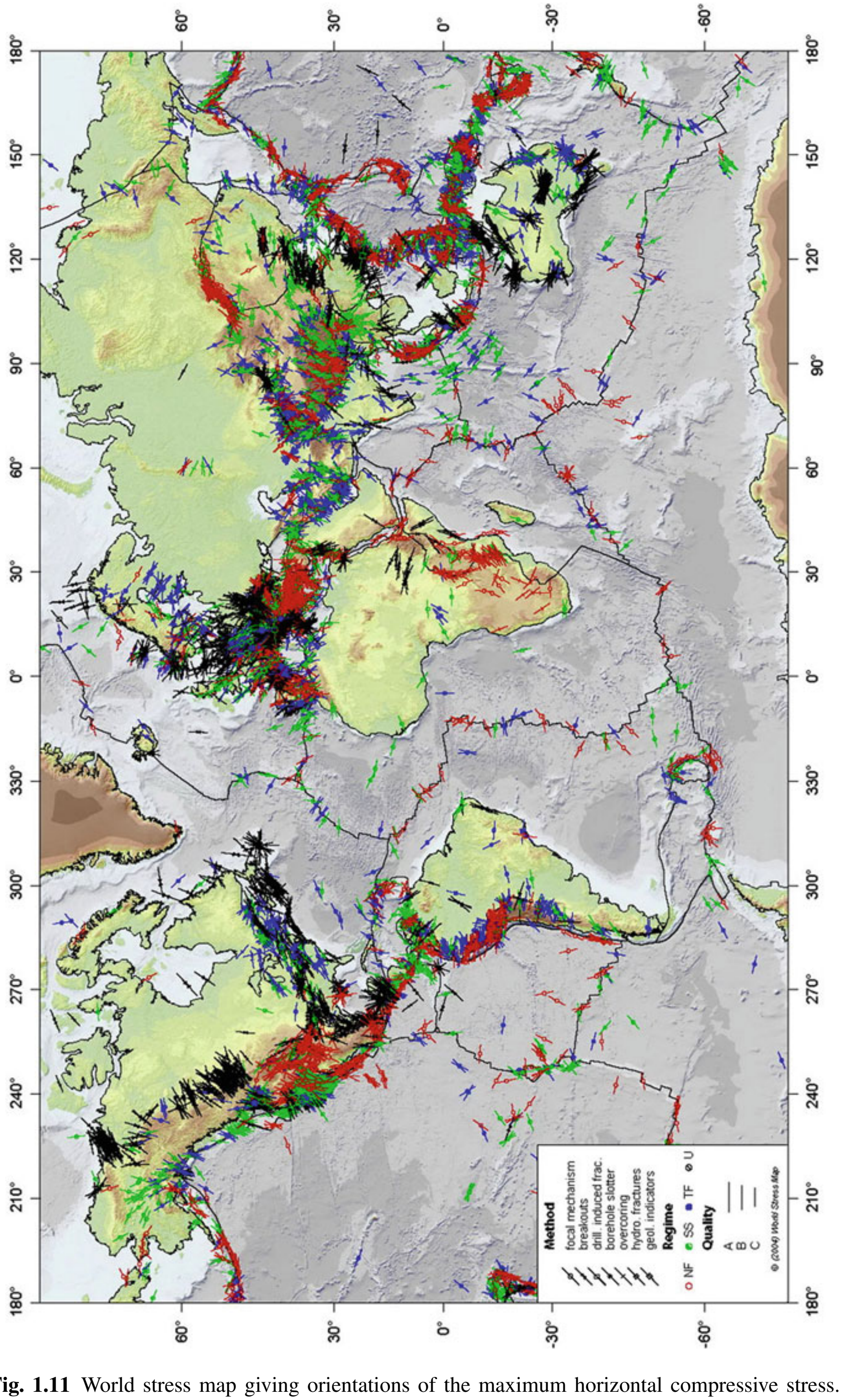

Fig. 1.11 World stress map giving orientations of the maximum horizontal compressive stress. (From www.world-stress-map.org)

Other relevant modifications of the lithostatic stress state also at great depth can be linked to the surface morphology, that is to the position of the underground work with respect to the side or to the valley ridge and to the morphodynamic evolution of the site, e.g. the presence of glaciers in the past.

When an opening is excavated in this rock, the stress field is locally disrupted and a new set of stresses are induced in the rock surrounding the opening. Knowledge of the magnitudes and directions of these in situ and induced stresses is an essential component of underground excavation design since, in many cases, the strength of the rock is exceeded and the resulting instability can have serious consequences on the behaviour of the excavations.

1.6 Morphological Conditions

Morphological conditions also play an important role during the execution of underground works. For this reason, it is important to distinguish among shallow, deep underground works and tunnels close to the side of the slope, and to analyze the different geomorphological problems characterizing each type. In addition to these aspects, specific problems present in portal areas must be taken into consideration.

1.6.1 Underground Works at Shallow Depth

Underground works can be referred to as "shallow" when the disturbed area around the tunnel interferes with the ground surface. This situation may lead to instability also involving surface materials, with serious effects on general environmental equilibrium.

As an indication, these situations can take place when the overburden thickness is less than four times the excavation diameter.

Shallow underground works are also strongly affected by meteoric events; therefore, they are often subject to significant water inflows, also depending on material permeability. Water inflows may also result in alterations that are responsible for a weathering of the mechanical properties of rocks and soils (Figs. 1.12 and 1.13).

Due to these reasons, the construction of shallow underground works is often preceded by the implementation of systematic consolidation measures which, in the more critical cases, allow the improvement of soil mechanical properties before the excavation.

Shallow underground works are also strongly affected by topography and surface loads. An example is that of tunnels which extend within a valley side with a pattern transversal to the valley itself and maintain particularly low overburden conditions in correspondence to the downstream side.

These tunnels are affected by the same problems described for shallow underground works, but in addition, they are also affected by dissymmetrical stress

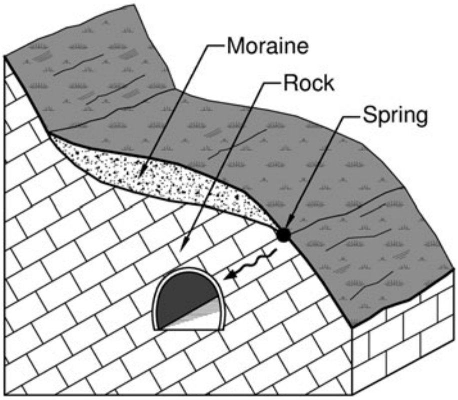

Fig. 1.12 Debris and glacial deposits allow the groundwater flow through the fractures towards the tunnel

distributions and by consequent deformation phenomena, which lead to design and construction difficulties depending on layers' arrangement and fracturing degree (Figs. 1.14–1.16).

For deep underground works (overburden approximately four times greater than the tunnel diameter), geomorphological conditions progressively lose their importance, unless the work is located in very steep slopes or on the boundary of glacial valleys, where the influence of surface morphology and morphodynamics can have effects even at a great depth. Another exception is constituted by areas characterized by deep-seated landslides or important karst phenomena.

1.6.2 Portals

Among geomorphological issues, tunnel portal areas also must be examined in detail, since they are characterized by specific problems independent from the excavation.

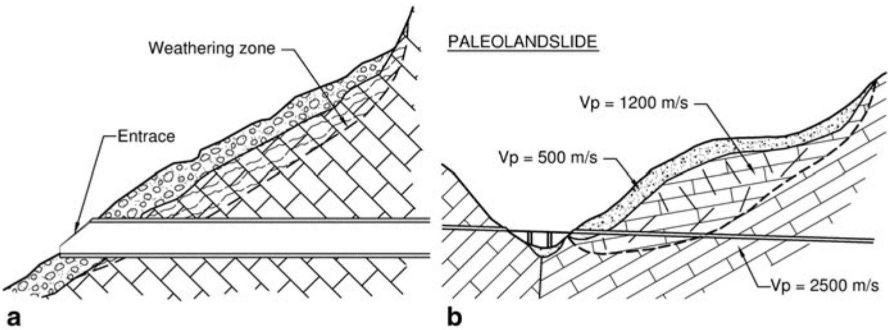

Fig. 1.13 Debris instability condition (**a**) and a paleo landslide (**b**) at the tunnel portal

Fig. 1.14 An example of a shallow tunnel along the side of a valley. (By Pizzarotti)

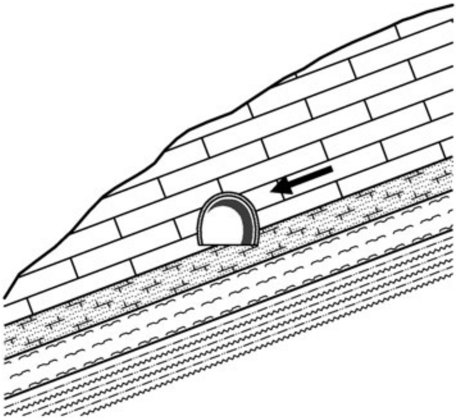

Fig. 1.15 Dissymmetric stresses affecting a shallow tunnel along slope

The underground excavation disturbs the pre-existing equilibrium condition of a natural slope as a notch is realized to host the portal (Fig. 1.17).

In presence of rock masses, problems at tunnel portals can be ascribed to decompression, alteration or fracturing phenomena undergone by the rocks. On the contrary, if the portal is excavated in loose materials (slope debris, glacial deposits, etc.), issues are to be found in the poor geotechnical properties of these soils (e.g. their low cohesion) and in slope steepness. These factors strongly influence slope stability and groundwater flow, which may require peculiar works to stabilize excavation in portal areas. These works can range from punctual excavation support (for example the nailing of unstable rock blocks) to actual support of the side (Fig. 1.18), stretches of artificial tunnels, etc. (Fig. 1.19).

In any case, portal excavation should be performed frontally to the slope, or at least keeping the highest possible angle of incidence, since this condition greatly facilitates the achievement of a new equilibrium.

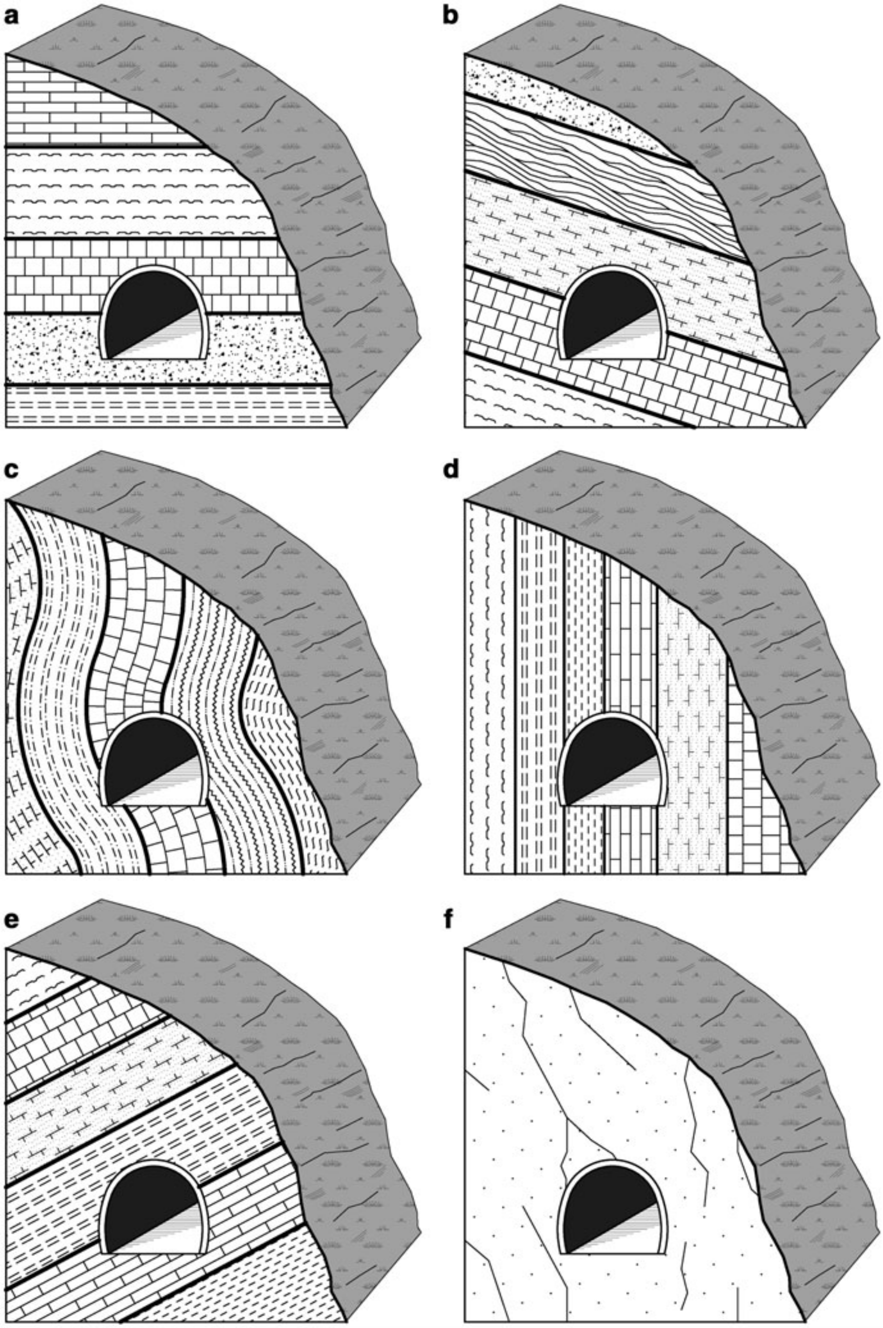

Fig. 1.16 Stability conditions for shallow tunnel along slope in relation to joint orientation: **a**, **d** and **e** very stable; **c** quite stable; **b** and **f** instable

Fig. 1.17 An example of a tunnel portal with nailing of the slope. (By Pizzarotti)

1.7 Hydrogeological Setting

As far as hydrogeological conditions are concerned, groundwater inflow during underground excavations is a very common occurrence: Therefore, it is important to envisage the hydrogeological situations which could lead to significant water inflow.

Factors favouring water inflow within the excavation are related to (Fig. 1.20):

- High permeability materials (granular soils, rocks permeable for porosity or fracturing etc.)
- Sudden changes in permeability
- Tectonic structures (faults, overthrust etc.) having a great water supply
- Karst phenomena
- Syncline folds
- Buried river beds

Fig. 1.18 Stabilization of a tunnel portal by retaining walls with anchors **a** during construction, **b** final configuration. (By Pizzarotti)

Fig. 1.19 An example of a portal stabilized by means of retaining walls with anchors **a** during construction, **b** final configuration. (By Pizzarotti)

The depth of the underground work with respect to the groundwater table has to be considered, as well as the characteristics of the aquifer itself. If the tunnel is located above the water table, problems due to water inflow are small and basically connected with water reaching the excavationby infiltration or percolation. Only in karstified rock masses a large, although temporary, inflow rateis possible even above the piezometric surface. On the contrary, if the excavation develops below the water table, water inflow can become very important and make excavation difficult.

Hence, during the design phase, the identification of tunnel stretches that can be subject to severe hydraulic problems leads to the adoption, both in design and execution phases, of peculiar techniquesaimed at draining, conveying and pumping out the water from the tunnel (Fig. 1.21).

1.7.1 Aggressive Waters

During underground excavation, it is possible to intercept water that can chemically attack the concrete. Its identification during the design phase is of primary importance, because this water could lead to a complete breakdown of the final lining, with very significant economic losses.

This risk is directly related to the lithological features of the rock formations intercepted by the underground work, since aggressive substances are released into groundwater by the geological materials in which the water flows. Aggressive water may originate from grounds other than those directly intercepted by the cavity: