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Practical use of the concept of geotechnical categories in rock engineering

Håkan Stille[a],[*], Arild Palmström[b]

[a] KTH Sweden
[b] RockMass AS, Norway

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ABSTRACT

The aim of the paper is to show how Eurocode 7: Geotechnical Design Part 1: General Rules (EC7) could be developed in order to be in accordance with practise in rock engineering and construction. A main feature is the geological uncertianties, which imply that a risk based approch should be used. The use of Geotechnical Category (GC) has therefore to be improved by (1) combining the consequences of a failure to the geological uncertainties before excavation, and (2) combining the consequences to the ground quality found after excavation. Three GC classes are needed to properly use the GC in rock construction.

The paper further describes how GC influences the design, which design method to be applied. It also outlines the types of control, inspection and supervision to be applied in the various GC classes during various stages of a project. An example is presented showing how GC can be determined at various stages of a rock construction.

1. Introduction

In 1975, the Commission of the European Community promoted an action program in the field of civil works construction to harmonize the rules for design and construction. The European Committee for Standardization approved in 2002 the standard EN1990:2002 “Basis of Structural design” with the objective to establish the principles and requirements for the safety, serviceability and durability of structures.

The standard for geotechnical design EN 1997-1:2004, which is a part of EN1990, was given the name Eurocode 7: Geotechnical Design Part 1: General Rules (EC7). Approved in 2004, it has been given the status of national standard in all European countries from 2010. There is, however, a debate on whether the standard can be directly applied on rock engineering issues like foundations, slopes, cuttings and underground openings. This paper provides suggestions on how the Eurocode could be developed an interpreted in order to be in accordance with rock engineering practice. The objective is to show how investigation, design, control and monitoring can be related to geotechnical risks and their classification into geotechnical categories. The paper also shows the design tools suitable for various geotechnical categories.

2. Basis of geotechnical design and rock mechanics

A general base for design is that the prevailing uncertainties should be covered by the safety margin of the designed structure. The size of the safety margin (reliability index) is related to the consequences of failure. More severe consequences will require higher margins. This implies that the design ought to be carried out with a method based on reliability and probability. Modern codes like EN1990: 2002 *Basis of structural design* are based on such thoughts. In the code, three different consequence classes are defined, and to each class a minimum value for reliability index is recommended with the intention of keeping a constant risk level.

The design of underground openings in rock has been discussed in many papers and textbooks such as those by Hoek and Brown (1980), Bieniawski (1984, 1989) and Palmstrom and Stille (2015).

As for all other engineering structures, and as stated in modern building codes, such as the European codes (EN 1990: 2002 *Basis of structural design* and EN 1997-1:2004 *Geotechnical design*), the design goals in rock must include structural resistance, durability and serviceability. The environmental impacts from construction and usage of the structure are to be acceptable. The main differences between structural and geotechnical design is the building material. In structural design, materials are man-made with well-defined properties. In geotechnical design, the soil and rock material is as given by nature with larger variation and uncertainties in properties. As stated above, the actual geological conditions will be revealed only upon excavation. This implies that the final design cannot be carried out in advance. In rock mechanics, the terms preliminary and final design are used to describe the time-related procedures required to obtain adequate information of the ground and the adapted design.

Structural resistance and serviceability as well as environmentally acceptable impacts are defined by ultimate or serviceability limit states.

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[*] Corresponding author at: Östermalmsgatan 28, SE-114 26 Stockholm, Sweden.
E-mail addresses: Hakan.Stille@byv.kth.se (H. Stille), arild@rockmass.net (A. Palmström).

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Adequate reliability of the structure shall be achieved. Durability is a part of this issue, but is related also to working life and maintenance. These factors require consideration at all stages of the design, and the design process should be transparent and the design work is traceable. This is facilitated if the design is carried out in accordance with accepted rules or standards. Further, rock design is based on the use of structural elements like steel bolts and concrete linings in interaction with the rock mass to improve stability. Compatibility with standards for structural design will then be required.

The two main types of structures related to rock engineering are underground openings and rock slopes. The environmental impacts are often due to spoil disposal, the effect on the groundwater changes in the surroundings and of the vibrations from the construction works and from usage. The structures and impacts can be classified as both temporary and permanent. The measures used during constructions to satisfy given requirements are in many cases governing for the permanent design.

In rock engineering, all these different issues are described as different design situations. The design situation has to be used in broad sense for describing issues related both to temporary and to permanent structures, including impacts as well as local and total stability.

In Eurocode, the design situation is classified according to the type of loads: persistent (normal use), transient (temporary), accidental (exceptional) or from impact of seismic events.

The basic requirements set up in EN 1990, should in the opinion of the authors to be redefined and be met by:

- adequate investigation of prevailing materials (ground conditions);
- appropriate choice of design tool;
- appropriate design situation and stages;
- suitable construction methods; and
- specified control procedures for design, construction and usage relevant to the particular project.

3. Main features in geotechnical design

3.1. Geological uncertainties

Geological uncertainties are related to the assessment of the geological and geotechnical conditions. They include incomplete knowledge of the actual geological conditions as well as poor accuracy in terms of properties and geometries. The geological uncertainties are related to the limited extent of ground investigations and also that the basis for rock mechanics and rock engineering are largely empirical. This implies that the geological uncertainties will decrease during excavation as the actual geology is revealed. The nature of many rock excavation projects implies that the level of confidence in the estimated ground conditions can be low based on the pre-investigation, especially in complex geological formations.

Muir Wood (1994) argues that geology is the prime source of uncertainty in geotechnical engineering. Unidentified features of the ground may lead to unexpected behaviour (incompleteness), secondly: identified features may not be expressible in quantified terms or to some degree unknown (system uncertainty) and thirdly: there may be a failure in communication between parties (human factors).

3.2. Ground conditions and behaviour types

Rock mechanics and soil mechanics form the scientific basis for geotechnical engineering. The properties of soils can be determined in laboratory tests with reasonable accuracy and application of established theories and design methods give good predictions of prototype behaviour.

In rock mechanics, the interaction of the blocks that form a rock mass dominates its behaviour. The randomness of the joints (joint direction and strength) within each joint set makes it difficult to characterise the mechanical behaviour of the rock mass. Laboratory testing has limited application due to scale effects. The assessment of properties in rock mechanics is therefore empirically based (based on observation of rock behaviour). This implies generally larger uncertainties of mechanical properties of rock masses than for soil materials. Rock masses can behave in different ways depending on the rock mass properties and applied stresses. Different behaviours require the application of different methods of assessment and design. Therefore it is necessary to understand the actual type of behaviour, as a prerequisite for estimating of rock support and other evaluations.

Behaviour type is an important concept in rock mechanics (Terzaghi, 1946; Hoek et al., 1995; Martin et al., 1999; Schubert et al., 2004; Palmstrom and Stille, 2015). They can be put into three groups: gravity driven, stress induced and water influenced. These phenomena are in not mutually exclusive and can therefore occur at the same time at any location.

A list of behaviour types is shown in Table 2. Depending on the geology, some types can be regarded as local instability, while in other situations they may influence on the total stability. Some will only prevail during excavation, others may only influence on the permanent stability.

3.3. Risks and consequences

3.3.1. Risks in rock engineering

Risk is in engineering defined as the combination of consequences of failure and the probability of failure and emanate from the underlying uncertainties. Geological uncertainties are dominant in rock engineering. Hazard is defined as potential source of undesirable consequences.

Risk management can be defined (ISO 31000) as handling such uncertainties that might prevent the objectives of the project from being obtained. The objectives can be expressed as the quality of the result, which means that implied or stated needs are fulfilled (IS0 9000). Projects may fail in many ways. Some issues like assessments of strength of structure material are so well known that they are not normally defined as involving any risks although they have to be controlled. However, all issues controlled during the work can have associated risks. Thus, the standard quality control work is part of risk management.

Risk in rock engineering includes many different issues and types of hazards. General aspects have been given by many authors, e.g. Blockley (1994) and Stille (2017). Guidelines have been elaborated by Eskensen et al. (2004).

Geotechnical risks are risks associated with geology as it affects the behaviour of permanent structures and their construction. Mitigation of these risks is a significant factor in cost and schedule control on all major engineering projects, see Hoek and Palmieri (1998). The resistance, durability and serviceability of the permanent tunnel structure are issues, which are to be handled in the design comparable with other building projects. However, stability issues and environmental impact during construction have also to be covered of the design work and can give consequences comparable with failure of permanent structures.

Geotechnical uncertainties can be split into two categories related to the sources. The first category is related to uncertainties from assessment of actual geological conditions. Example of this type of uncertainties is the limitations of observations of the geology ahead of the tunnel front at the time of construction. The second type is related to the uncertainties from estimation of ground properties of observed geology. Even if detailed assessments of the geological conditions is possible from mapping of excavated rock surfaces there remains uncertainties of the mechanical properties to be used in the deign.

Geotechnical risks can managed in different ways. The epistemic nature of the uncertainties implies that further information about the geological conditions can reduce the uncertainties. This may be achieved by additional geological investigations in the preconstruction

Table 1
Excerpt of geotechnical categories described in EN 1997-1.

Geotechnical category		Reliability/risk
GC1	Only small and relatively simple structures	Negligible risk
GC2	Conventional types of structure and foundation with no exceptional risk or difficult soil or loading conditions	No exceptional risk or difficult soil or loading conditions
GC3	Structures or parts of structures, which fall outside the limits of Geotechnical Categories 1 and 2	Risk level is not described

stages or during excavation. In some cases, adoption of an observational approach will be required. The level of investigation, control and monitoring have to be adapted to the chosen design process and risk level.

3.3.2. Geotechnical categories

EN 1997-1 introduces three geotechnical categories (GC) based on associated risks or difficulties due to ground or loading conditions (Table 1). Section 2 of the Eurocode defines the three GC classes. According to this, most underground excavations in rock will fall within GC3, with a few in GC2, while very few (or none) will be in GC1. This is unsatisfactorily as the uncertainties and risks for underground constructions have a much wider span. Further, the descriptions in EN 1997-1 are not clear and do not cover the design issues related to rock excavation. The terms "*difficult soil or loading conditions"* are vague and unhelpful in this context.

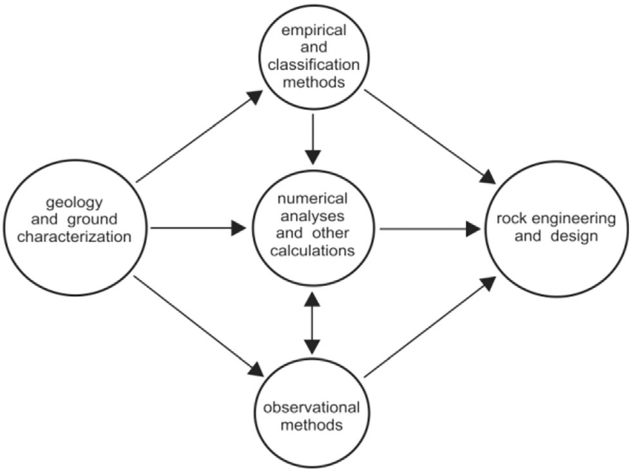

Fig. 1. Main tools in the process of rock design (Stille and Palmström, 2003).

This paper therefore proposes that GC classes for rock engineering purposes should be applied both for rock excavation and permanent rock structure. In both cases the GC classes should be related to the risk, i.e. the combination of consequences and uncertainties as described in Section 5, since risk is the central term describing the design condition.

Table 2
Behaviour types in underground excavations (Palmstrom and Stille, 2015, Data taken from Palmström and Stille (2007) based on Terzaghi (1946), Schubert et al. (2004).

Behaviour type		Definition	Comments
Group 1: Gravity driven			
a. Stable		The surrounding ground will stand unsupported for several days or longer	Massive, durable rocks at low and moderate depths
b. Block fall(s)	of single blocks	Stable, with potential fall of individual blocks	Discontinuity-controlled failure
	of several blocks	Stable, with potential fall of several blocks (slide volume $< 10\ m^3$).	
c. Cave-in		Inward, quick movement of larger volumes ($> 10\ m^3$) of rock fragments or small blocks	Encountered in highly jointed or crushed rock
d. Running ground		A particulate material quickly invades the tunnel until a stable slope is formed at the face. Stand-up time is zero or nearly zero	Examples are clean medium to coarse sands and gravels above groundwater level
Group 2: Stress induced			
e. Buckling		Breaking out of fragments in tunnel surface	Occurs in anisotropic, hard, brittle rock under sufficiently high load due to deflection of the rock structure
f. Rupturing from stresses		Gradually breaking up into pieces, flakes or fragments in the tunnel surface	The time-dependent effect of slabbing or rock burst from redistribution of stresses
g. Slabbing		Sudden, violent detachment of thin rock slabs from sides or roof	Moderate to high overstressing of massive hard, brittle rock. Includes popping or spalling[a]
h. Rock burst		Much more violent than slabbing, and involves considerably larger volumes	Very high overstressing of massive hard, brittle rock considerably larger volumes (heavy rock bursting often registers as a seismic event)
i. Plastic behaviour (initial)		Initial deformations caused by shear failures in combination with discontinuity and gravity-controlled failure of the rockmass	Takes place in plastic (deformable) rock from overstressing. Often the start of squeezing
j. Squeezing		Time-dependent deformation, essentially associated with creep caused by overstressing.Deformations may terminate during construction or continue over a long period	Overstressed plastic, massive rocks and materials with a high percentage of micaceous minerals or of clay minerals with a low swelling capacity
Group 3: Water influenced			
k. Ravelling from slaking		Ground breaks gradually up into pieces, flakes or fragments	Disintegration (slaking) of some moderately coherent and friable materials Examples: mudstones and stiff, fissured clays
l. Swelling	of certain rocks	Advance of surrounding ground into the tunnel due to expansion caused by water adsorption. The process may sometimes be mistaken for squeezing	Occurs in swelling of rocks, in which anhydrite, halite (rock salt) and swelling clay minerals, such as smectite (montmorillonite), constitute a significant portion
	of certain clay seams or fillings	Swelling of clay seams caused by adsorption of water. This leads to loosening of blocks and reduced shear strength of clay	The swelling takes place in seams having fillings of swelling clay minerals (smectite, montmorillonite)
m. Flowing ground		A mixture of water and solids quickly invades the tunnel from all sides, including the invert	May occur in tunnels below the groundwater table in particulate materials with little or no coherence
n. Water ingress		Pressurised water invades the excavation through channels or openings in rocks	May occur in porous and soluble rocks, or along significant openings or channels in fractures or joints

[a] This term was often used by Terzaghi (1946) as synonymous with the falling out of individual blocks, primarily as a result of damage during excavation.

4. Design works

4.1. General

For the purposes of rock engineering design, different types of design tools or design systems can be applied to the available information on the ground conditions. Such tools can be numerical modelling, analytical calculation, empirical (classification) systems or observational methods. This is illustrated in Fig. 1.

The classical approach is to base the design on subjective experience (engineering judgement), existing empirical design rule (classification system), or calculation. For many rock engineering applications, however, an observational approach is preferable.

Paragraph 2.1(4) in EN 1997-1 requires that the limits state should be verified by one or a combination of four methods:

- Use of calculations.
- Adoption of prescriptive measures.
- Experimental models and load tests.
- An observational method.

Rock engineering design is largely based on empirical rules and methods, which are based on experiences of rock excavation works and can as such be described as *prescriptive*. Since the design is adapted to the geology observed in the tunnel, it also contains an *observational approach*. This combination of two of the methods to verify the design is regarded as most common in rock design. In more complex design situations, the observational approach also includes measurements of the geotechnical behaviour based on a monitoring program. *Calculation* is frequently carried out for projects with larger risks.

4.2. Design tools

4.2.1. Calculations

Verification of the design by calculation can be carried out with partial factor or reliability methods. According to EN 1997-1, partial factor method involves calculations with design values, which are the characteristic values divided with a constant partial factor defined in advance. This requires that the limit state functions are relatively simple and that the rank of influences of the parameters will not be changed from case to case. For many types of rock engineering problems based on rock-structure interaction, this is not the case. The application of partial factor method will therefore be limited in rock mechanics. It may be used for shallow foundations, retaining structures and simplified tunnel wedge stabilities.

More advanced numerical methods are frequently used in design of tunnels and caverns. The problems connected to using numerical analysis in the context of Eurocode 7 has been discussed by many authors, see e.g. Lees (2017) and Schweiger et al. (2018). Numerical methods are suited to calculate the expected behaviour. Such calculations based on design values may give conservative results.

Reliability methods are approved in EN 1990 – "*Basis of structural design*" even if not directly mentioned in the EN 1997-1. This approach gives a better overview of the influences each uncertainty will have on the result. The FORM (First Order Reliability Method) and the Monte Carlo simulation are most commonly applied.

4.2.2. Prescriptive measures

Adoption of prescriptive measures is common in rock mechanics. Rock mass classification systems with recommended rock support are based on experience and belong to this category. The defined rock support is adopted without calculation and is purely empirically based. The design by prescriptive measures may be used where experience make calculation unnecessary or where design tools are not available. The method involves conventional and generally conservative rules. It can be used for structures and structural members, without difficult ground and loading conditions and where the consequences at failure will be minor. It can be used for shallow foundations, tunnel support in blocky ground of satisfactory quality and stability in assessments of slopes with height up to about 10 m.

4.2.3. Experimental models and load tests.

Experimental models and load tests are not common in rock mechanics design and will not be further discussed in this paper.

4.2.4. The observational method

Another very common method for design in rock engineering is the observational approach. The recommendation given in EN 1997:1 is general and can be applied. An essential part of the Observational Method is that the interactive design process is based on predefined contingency actions, which are linked to results from the observations. Observational methods may be linked to reliability analysis by adapting an Baysian approach, (Spross and Johansson, 2017). The type of observation can be based on both measurements (monitoring) and visual inspections (ground mapping).

Design by the observational method is used when prescriptive measure cannot be applied due to too high consequences of failure and difficult ground or loading conditions. It may also be applied when the results of calculations will be uncertain due to limited knowledge of the geotechnical conditions. The method is applied for tunnel support in poor rock, stability assessments of high slopes and environmental impact from loss of ground water to tunnels.

Monitoring is also used to check the validity of the design and ensure that the structure will continue to perform as required after completion. In principle, this is a part of the quality control work (see Section 6) of the constructed structure and not a part of an interactive design process. It is important to distinguish between these two objectives of monitoring.

4.3. Documentation

The design work must be well documented and traceable. The results from the ground investigations should be presented in a Ground Investigation Report consisting of two parts. One should present the factual information and one showing the evaluation of the information describing the assumption made in the interpretation of the factual. Issues in the report related to higher risks ought to be checked by independent reviewer (see Section 5).

The design shall be presented in a Geotechnical Design Report. The assumptions and data used in the design should be presented together with the verification of the design related to requirements of resistance, serviceability and durability. The report should also include a plan of supervision and monitoring of the items to be checked and verified during construction (see Section 5). This is an important part of the rock design work especially when the uncertainties are large. It is crucial that the uncertainties related to the design will be brought forward to the personnel responsible for the supervision and inspection of the construction work.

5. Design and geotechnical category

5.1. General

Three Geotechnical Categories (GC1, GC2 and GC3) for projects in soil and rock are defined in EN 1997-1. The selection of actual category is based mainly on the associated risk. As discussed in Section 3.3.2, the set-up definitions are not consistent and do not adequately cover situations encountered in rock engineering. However, the basic concept to relate categories to risk is sound, as the level of the risks of the permanent support, environment and excavation should be governing how the project is designed and executed.

The Geotechnical Categories should therefore be related to the

Table 3a
Suggested division of Geotechnical Categories before excavation (for rock engineering and excavation planning).

BEFORE EXCAVATION for planning		Geotechnical Category		
Consequences class (CC)	Examples. Typical rock constructions	Ground Uncertainty		
		low	medium	**High**
CC1 Low	- Simple foundations on rock - Low – moderately high rock cuttings - Tunnels of small size (< 4 m span)	GC1	GC1 GC 2	GC2
CC2 Medium	- Complicated foundations on rock - High to very high rock cuttings - Large tunnels (4 to 15 m span) - Environmental requirements	GC1 GC2	GC2	GC2 GC3
CC3 High	- Undersea tunnels, all sizes - Unlined pressure tunnels, all sizes - Strict environmental requirements - Large caverns or very large tunnels (span > 15m) - Tunnels with limited rock overburden	GC2	GC2 GC3	GC3

associated risk, both to the consequences and to the level of uncertainties. The latter is strongly correlated to the probability of failure. By introducing Geotechnical Categories to cover both rock constructions with temporary support and permanent structures, better applications of GC will be achieved in rock engineering. Some clarifications and adjustments of the EN 1997-1 would then be required as described in this section.

We propose selection of Geotechnical Category by combining "Consequence Class" with either "Uncertainty" before excavation or known "Ground Quality" after excavation. Uncertainties before excavation is related to the probability of tunnel collapse due to unexpected and adverse rock condition. Poor ground quality revealed after excavation will imply a greater probability of misjudging the bearing capacity of the rock mass as the behaviour of poor rock mass can be difficult to predict. The consequence classes according to EN 1990 are related to various levels of losses: loss of human life, economic losses, and social or environmental consequences. The proposed system of Geotechnical Categories is shown in Tables 3a and 3b for both temporary and permanent structures. Three GC classes are proposed.

Since special projects (like storage of nuclear waste, nuclear power plant or other types of extraordinaire projects) are not included in EN 1997-1, they are not included in Tables 3a and 3b.

5.2. How to select and use the GC

5.2.1. General

The assessment of Geotechnical Category is an iterative process. The preliminary GC assessed in the beginning of a project is checked and changed as required, at each stage of the design and construction process. If the ground conditions vary along a tunnel, the GC may also vary accordingly. Different parts can have different classifications as described in the following and shown in the Section 7.

This iterative process has been recognized in EN 1997-1. In paragraph (11) of Section 2.1 it is stated that *"A first Geotechnical Category (GC) given should normally be performed prior to the geotechnical investigations. The category should be checked and changed, if necessary, at each stage of the design and construction process."* and in (13) of Section 2.1: *"The various design aspects of a project can require treatment in different Geotechnical Categories. It is not required to treat the whole of the project according to the highest of these categories."*

The Geotechnical Category defines the project and sets recommendations and requirements for planning, control and construction. Thus, it influences the extent of:

- The documentation of the ground conditions;
- The engineering and design of the rock excavation;
- The control and the supervision of the investigations and the design;
- The inspection and the monitoring of the rock construction works.

5.2.2. Investigations and GC

Geotechnical investigations are performed to collect information on the rock mass conditions, i.e. the locations and properties of the material in which the construction is to be located. The aim is to reduce uncertainty. The degree of uncertainty will depend on the site conditions such as depth of excavation, ease of access to perform investigations, the nature and extent of the investigations, degree of weathering of rocks, and complexity of the geology. A simple method to evaluate uncertainty is described in Section 7.1.

The geological conditions of a site may vary within wide limits. Therefore, there is no 'standard investigation procedure' which covers all cases. The expression *'appropriate investigations'* means *right pre-investigations performed at right time*. In addition to information on the geology and ground condition, the selected investigations should provide information on the uncertainty of the ground conditions.

Already at the start of the planning, preliminary GC classes should be defined based on the ground information known at that time, see the example in Section 7.2. During execution of the investigations, the GC and the plan for further investigations may be adjusted according to the results found. The types and extent of investigations should also be appropriate for the actual type of rock excavation technique (drill and blast, TBM, roadheader, etc.)

For rock excavations with a high degree of uncertainty and consequences of failure, additional investigations should also be carried out during the construction phase to provide more information on the ground conditions ahead of the tunnel excavation face. Measures can then be taken in time to reduce potential excavation problems, thus preventing loss or damage.

Another group of investigations during excavation is the monitoring of displacements (deformations). This is important in poor, unstable rock masses and includes tests of rock samples in zones of poor and weak rocks containing materials with swelling or slaking properties, materials with poor durability etc. The outcome of the monitoring and tests is used to follow up the development of the ground behaviour, in order to decide if or when the rock support has to be strengthened, and also for input to the permanent rock support design.

Other conditions to be investigated are the environmental impacts of the underground opening and the excavation works may have on the natural and man-made environment nature and on the use of the areas above the excavation.

Table 3b
Suggested division of Geotechnical Categories after excavation (for design and installation of permanent support).

AFTER EXCAVATION for permanent works		**Geotechnical Category**		
		Ground Quality		
Consequences class (CC)	**Examples. Typical rock constructions**	good	fair	Poor
CC1 Low	- Simple foundations on rock - Simple to moderately high rock cuttings - Mine drifts. Test adits - Simple water tunnels	GC1	GC1 GC2	GC2
CC2 Medium	- Complicated foundations on rock - High to very high rock cuttings - Access tunnels. Complicated water tunnels - Low to medium traffic tunnels - Storage caverns in rock	GC1 GC2	GC2	GC2 GC3
CC3 High	- Caverns with very large span - Unlined pressure tunnels/shafts - Excavations with strict environmental requirements - Heavy traffic tunnels - Underground stations in rock	GC2	GC2 GC3	GC3

Consequences classes (in accordance with EN 1990):

CC1: **Low** consequences for loss of human life, or economic, social or environmental consequences **small or negligible**

CC2: **Medium** consequences for loss of human life; or economic, social or environmental consequences **considerable**

CC3: **High** consequences for loss of human life, or economic, social or environmental consequences **very high**

Classes of Geological and Ground Uncertainty (before excavation):

Low: Clear and simple geology and ground conditions. Ground parameters can be easily found. Experience from construction in similar ground conditions.

Medium: Clear geology and ground conditions. Methods exist both to assess ground conditions and for dimensioning. Experience from construction in similar ground conditions can be documented.

High: Unclear geology and/or ground conditions with potential for problematic tunnel excavation. There are limited possibilities to assess the ground conditions before excavation starts

Classes of ground quality (after the ground has been encountered in the tunnel, shaft or cavern):

Good: Good or very good ground conditions and stability as documented from tunnel mapping using e.g. classification systems (RMR, Q, RMi, etc.)

Fair: Fair ground conditions and stability as found from tunnel mapping and, if found necessary, supported by investigations

Poor: Poor or very poor ground conditions and stability as found from tunnel mapping and description supported by investigations and tests

5.2.3. Selection of design tools

Table 4 may act as guideline to determine suitable design tools for different geotechnical categories.

Every project is unique. Recommendations on the suitability of different design tools can only be indicative, especially as various combinations of the available tools may be appropriate. In a project with major consequences of delay or failure, all the tools are often used to achieve an acceptable safe design, whilst for simple projects with low ground uncertainty, an approach based on empirical design methods or engineering judgement may be appropriate.

5.2.4. GC assessed for construction

For rock construction works, risks are associated with degree of ground uncertainties assessed from the investigations and the complexity of the rock excavation work, see Table 3a. The consequences are related to potentially severe accidents, environmental problems and economic losses. As the ground conditions along the tunnel cannot be determined accurately before excavation, a main issue is to make an assessment of the geological uncertainties from field investigation results and the information collected from comparable rock excavations nearby, see Table 10.

The ground conditions will often vary along the excavation; this may cause that the GC will vary accordingly, see Fig. 3.

5.2.5. GC for the permanent structures

The main risk of the permanent structure is related to the consequences and the probability of failure of the encountered rock mass conditions. The consequences are related to the usage. The probability of failure is related to the quality of the ground encountered in the tunnel. The ground quality will form the main issue in the design of the

Table 4
Guideline for choice of design tools.

Geotechnical Category	Design tool		
	Use of calculations	Adoption of prescriptive measures	An observational method
1	No, generally not used	Yes	No
2	Yes, analytical methods or numerical calculations are used as required	Yes, often in combination with one of the other design tools	Yes, based on visual observations of geology[a] and measurements of behaviour as required[b]
3	Yes, numerical methods are often used in combination with the observational method	Yes, in combination with one of the other design tools	Yes, based on visual observations of geology[a] and measurements of behaviour[v]

[a] Geology here means mainly ground conditions.

[b] Behaviour here includes deformation, convergence, etc. from monitoring and observations.

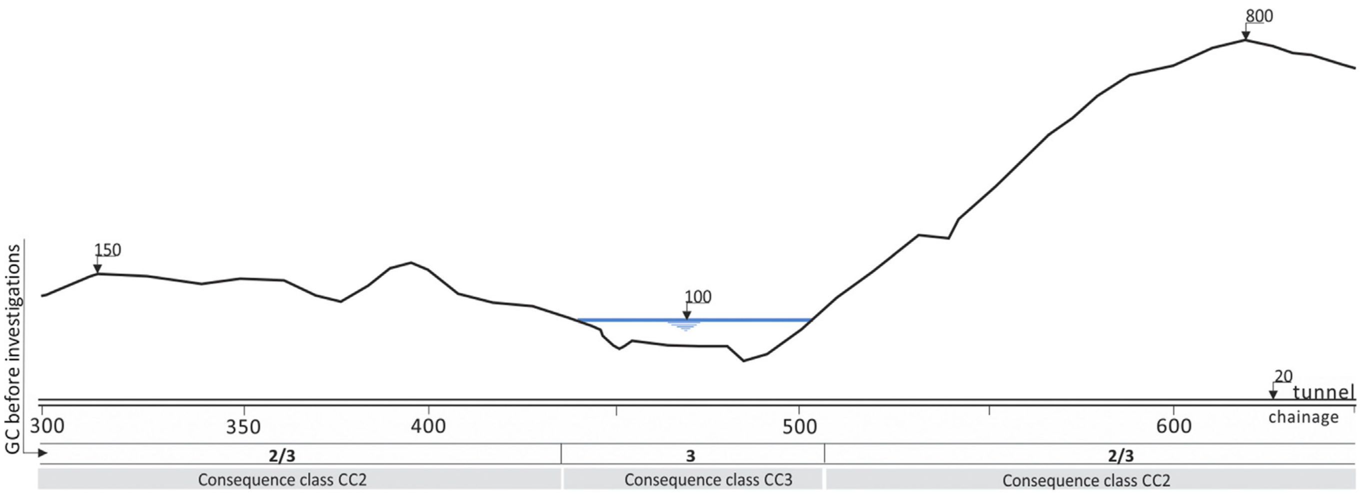

Fig. 2. Before investigations. The GC classes based on assumed high degree of uncertainty and the CC classes.

permanent support as well as in the maintenance and monitoring plans. Consequently, this is the main input in the selection of the GC, see Table 3b. The behaviour with good ground conditions is generally sufficiently well-known. In poor ground conditions, there may be more behaviour types present such as plastic behaviour, squeezing, swelling or ravelling, see Table 2. They all represent a higher risk of collapse. The risk for negative impact on the environment due to the usage of the excavation will also influence on the selection of Geotechnical Category.

Ground quality mapped and measured in the excavation may be characterized according to pre-set definitions, such as an appropriate rockmass classification system. In poor ground conditions, additional assessments are often required.

In locations where uncertain loads may occur (such as swelling, squeezing), special investigations of the ground conditions must be carried out to allow appropriate design of the permanent support. The selected GC will determine the method of control of the design and construction of the support. Additional requirements may be put on the design of the permanent support, especially when the economic losses may be significant.

6. Control and supervision

6.1. General

Control and supervision of the execution of the construction works is carried out in order to reduce the probability or the consequences of mistakes, and can be regarded as a part of the quality assurance. They are also part of the risk mitigation and should be based on the risk assessments. In this respect the quality control and supervision will be related to the actual geotechnical category. The risks connected to both operation and the execution of the work is also related to the design tools used since they have different risk profiles.

In many cases it is not feasible or optimal to collect adequate information of the ground conditions during the pre-investigation phase. Most underground projects must be regarded as development projects with unknown factors, which will be discovered during the execution of the project. For managing the project with acceptable risk, holding points have to be defined in advance, Stille et al. (1998). Such points are called tollgates and the contractor is not allowed to be passed before go-ahead from the responsible.

The following types of control and supervision are essential in rock constructions:

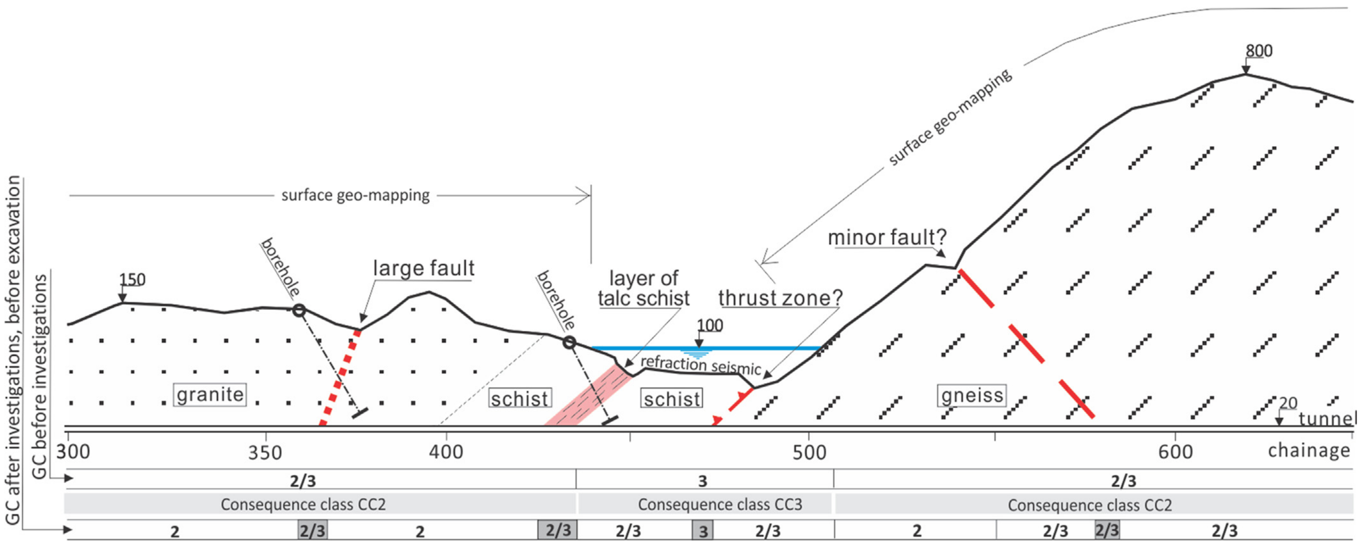

Fig. 3. GC classes before excavation. The investigations gave valuable information on the geology and the assumed ground qualities. Assumed weakness zones are shown in grey along the GC distribution line.

(1) Quality Control (QC) of the field investigations and tests, including:

- Means, methods and results.

(2) Design supervision, including:

- QC of the basic assumption, i.e. evaluations of the basic data used, of the Geotechnical Category defined, and of the planned control and inspection during excavation.
- QC of the principles involved in the proposed design and the calculation models.
- QC of the selected dimensions including safety and economy, and that drawings and descriptions are unambiguous and fit for purpose.

(3) Rock engineering supervision including:

- QC of selected excavation methods and plans, including workers' safety, economy and time.

(4) Inspection during excavation, including:

- Inspection and mapping of the ground conditions encountered:
- Supervision of the excavation and rock supporting works
- Monitoring and testing of the initial support
- QC of the construction materials used

(5) QC of the permanent structure including:

- QC of the mapped ground conditions
- QC of construction materials used
- Monitoring and testing of the final support

(6) Monitoring during permanent use of the project, including:

- Monitoring and testing of the long-term behaviour of the ground and the permanent support

All types of quality control should follow standardized procedures and plans and check lists. The extent of the control will depend and vary with the project stage as shown in Table 5.

6.2. *Quality control of field investigation*

The objective is to check that the findings and interpretations from the investigations are correct. This is required for both limited and normal control, see Table 6. Extended control also require checks that means and methods are adequate with respect to expected conditions and that the uncertainties are adequately described in the field investigation report.

6.3. *Design and rock engineering supervision*

The quality control of the design and the engineering should include assumptions, principles and results. The control should also verify that the empirical input data and the models are reliable and that the requirements regarding stability, environmental impact and safety level are achieved. This is mandatory for all control levels. Extended control will also include an independent review regarding the most critical issues and risks. The control level expressed as extent of control varies with the GC classes as shown in Table 6.

At the end of planning stage, plans for the construction control and the control of the permanent design are worked out, see Table 7. Program for inspection, monitoring, as well as principles for sampling during excavation and construction should be described in the planning report. The plans should be revised from the registration of information and experience gained as the works proceed.

The control plans must also contain means and methods to be used in the case the design is verified by the Observational Method. Design by adaption of prescriptive measures will require that the prerequisites of the prescriptive measures are checked.

In addition, the project planning report should define possible critical construction elements requiring regular control, inspections or monitoring during operation.

6.4. *Inspection during execution*

The normal daily follow-up of underground works including geological mapping, testing of shotcrete quality and thickness and control of rock support installation is one part of the inspection to ensure quality Methods and frequency should depend on associated risks. For example, traffic tunnels and openings with public access will require more inspection than a water tunnel since consequences of failure are larger and thus the required probability of failure lower for the same acceptable risk.

Table 5
Summary of controls in various stages of a project.

Project stage		Assessment of Geotechnical Category (GC)	Controls[a] and plans
Ground conditions are assumed	During investigation	A preliminary GC class (Table 3a). See also Fig. 2	1. Quality Control of the field investigation works and testing procedures
	After investigation, before design	Adjust GC class according to the investigations results (Table 3a). See also Fig. 3	Make a plan for control of the design
	During planning (engineering and design)	The GC class according to the expected conditions along the excavation (Table 3a). See also Fig. 3	2. Quality Control of design Work out plan for the control and inspection during excavation
Ground conditions are known	During excavation. Continuous information of ground conditions encountered	GC class for the ground conditions encountered supported by results from investigations performed (Fig. 3b). See also Fig. 4	3. Inspection during construction with: – QC of the ground conditions – QC of materials – QC of necessary investigations2) and tests – Monitoring of tunnel behaviour.
	After excavation	Adjust GC class (Table 3b) after all investigations and test results have been collected	4. QC of permanent structures (design) – upervision of the materials and works – Monitoring of tunnel behaviour
	Before permanent use		Make a plan for maintenance and monitoring.

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[a] Control level depends on the actual GC.

[b] Investigations during and after excavation.

Table 6
The design supervision levels.

Geotechnical category	Control level	Control class/control of the planning (engineering and design)
GC1	Limited control	Self-checking Checking performed by the person who has prepared the task.
GC2	Normal control	Checking by different persons than those originally responsible and in accordance with the procedures of the organisation.
GC3	Extended control	Third party checking: Checking performed by persons from an organisation different from that which has prepared the task.

Table 7
Example of quality control plans for construction.

Geotechnical category	Type of controls
GC1	Site inspections, quality controls of materials according to national standards, e.g. concrete control, shotcrete control, testing of rock bolts, etc. Control of the works
GC2	In addition to GC1, where relevant: observations or measurements of ground properties, e.g. field investigations (stress measurements, ground water pressure) or laboratory tests of representative samples (for strength measurements, swelling properties, quartz content, etc.)
GC3	In addition to GC2, where relevant: measurements, supervision, monitoring: e.g. convergence/displacement/deformation measurements, load cell measurements, rock stress measurements, etc.

Table 8
The site inspections depending on Geotechnical Category.

Geotechnical category	Types of control and reporting during construction
GC1	Self-inspection: Check that the site ground conditions and environmental disturbance are as assumed in the design. Simple, written reporting.
GC2	Check that the site ground conditions and environmental disturbance are as assumed in the design. Supervision by experienced persons during important phases of the work. Monitoring of very important construction parts and work operations. Regular, written reporting.
GC3	Control of work execution and materials Check that the site ground conditions and environmental disturbance are as assumed in the design. Continuous supervision by experienced persons. Important phases of the construction controlled by third party. Monitoring and sampling for testing may be required. Regular, written reporting with a final report.

The extent of inspection of the rock excavation works will increase with higher Geotechnical Category, as shown in Table 8. The focus of the inspection should include both stability issues of the excavation and environmental disturbances from the work, like noise, vibration, air pollution and changes of ground water regime.

The checking of the ground conditions should be regarded in a broad sense. It includes checks that the ground conditions are as expected, either from tunnel mapping or from investigation (such as presoundings, geophysical measurements, etc.) from the tunnel face.

Some comments on the various inspections:

- The inspection performed should be documented and signed by the person who has done it.
- Requirements for materials and quality control of the works are normally given in national standards other than EN 1997-1, and will be handled by the contractor in his quality system.
- Site inspection includes functions such as recording of the ground conditions encountered during excavation (see Table 8).
- Site inspection also includes monitoring of displacements (deformations) as well as tests of rock samples, for example from zones of poor and weak rocks, possibly with swelling or slaking properties, or with poor durability. The outcome of the monitoring and tests is used in the assessment of ground behaviour used in the design of permanent rock support.

6.5. *Control of permanent design*

The permanent construction shall be maintained so as to meet the stability requirements over time. For unlined water tunnels for example, downfall of fragments and single blocks are often accepted and limited maintenance work is necessary. At high consequences such as with underground space used by the public where no damage can be accepted, regular maintenance work and inspections are required over the lifetime of the structure.

The tunnel has to be inspected and maintained during operation. Both the rock, the rock support and the installations can deteriorate with time. Focus should be on issues related to the function of the project, damage to the environment and risks to the public.

These risks will vary with the conditions along the tunnel. Poor and altered rock may deteriorate faster and can give risk for tunnel collapse. Such conditions have to be monitored.

Ingress of water to tunnels and outflow from pressurized tunnels have to be checked by long-term monitoring. This will also be part of control of the permanent design.

7. Worked example

7.1. *A practical, simple method to evaluate geological uncertainty*

Simple geology requires less investigation effort than complicated geological conditions. Simple geology can be areas with fresh, exposed crystalline rocks in a surface created by ice erosion during the Quaternary, where the various geological features, such as faults and joints can be easily observed on the surface. From simple surface observation and aerial photographic studies, a fairly good interpretation of the geological and ground conditions can easily be provided at low cost Table 9.

Complex geology may occur where there is a mixture of rocks normally connected to intense faulting and folding. Large areas, along the tunnel or above the area of the open pit, covered by soil or loose materials increase uncertainties of the rocks below. Other features that complicate the interpretations of ground conditions can be deep surface weathering, areas below water or cover by urban development. The risk of encountering geological features, which have not been detected from the field investigations and therefore may appear unexpectedly during the excavation, is larger in complicated ground and where rock outcrops are not found.

The degree or class of ground condition uncertainty can be found by

Table 9
Inspections during operation of the project.

Geotechnical category	Types of inspections and reporting during operation
GC1	Inspection of the tunnel or the slope at periods of 5–10 years. Simple, written reporting
GC2	Inspection of the tunnel or the slope at periods of 3–5 years. Environmental control every year. Regular, written reporting.
GC3	Inspection of the tunnel or the slope at periods of 1–3 years. Environmental control every year. Monitoring may be required. Regular, written reporting.

giving ratings to certain parameters for geology, rock cover, and weathering of the rocks at the terrain surface (Table 10).

In rock excavations, there will always be some degree of uncertainty. However, more field investigations will generally lead to less uncertainty. As shown in the example below, uncertainty may vary along the tunnel.

7.2. *Examples. The GC found at various stages of a tunnel project*

The examples in Figs. 2–4 show a road tunnel with moderate rock cover (50–150 m) in the first part (chainage 300–550) and high overburden (up to 780 m) in its last part. Between these two parts, there is a section where the tunnel passes beneath a lake (with undersea conditions)

The planned access tunnel of medium size (span = 10 m) will be located in rocks of Precambrian age. Before the field investigations are carried out, the Consequence Classes (CC) (see Table 3a) of the project are evaluated along the tunnel, as shown in Fig. 2. Little geological information exists, but some experiences from other tunnel project in similar geology are known. The degree of geological uncertainty before the start of investigations is assumed as follows (see Table 10):

- Complicated geological conditions (rating = 4);
- Moderate degree of rock weathering at surface (rating = 1);
- Comprehensive cover of loose materials and vegetation (rating = 5);
- The rock cover of 50–200 m rock overburden along the first part and up to 700 m overburden along the last part (rating = 1 and 4).

The sum of the ratings, $\Sigma = 11–14$, places the geological uncertainty as ‘High’, which indicates that extensive field investigations should be performed to reduce uncertainty. The Geotechnical Categories are shown in Fig. 2

Extensive field investigations were carried out, consisting of geological, engineering geological survey, mapping, core drillings and refraction seismic measurements, as well as laboratory tests. From the results the Ground Uncertainties were characterized as (see Table 10):

- The geological setting can be characterized as ‘clear’ (rating = 2), except for the fault zones where the settings are assumed to be complicated (rating = 4).
- The overall degree of rock weathering at the terrain surface has been found as 'moderate' (rating = 1).
- The investigations have revealed that the rocks at terrain surface are partly covered by soil and vegetation. Because drillings and refraction seismic measurements (also along the bottom of the lake) have been carried out, the effect of loose material is assigned as ‘moderate’ (rating = 3).
- The rock overburden of 50–150 m along the first part (rating = 1) and up to 780 m overburden along the last part (rating = 4).

From this it is found that along the first part with low to moderate overburden, $\Sigma = 7$ (medium uncertainty), with $\Sigma = 9$ (high) for locations with weakness zones (faults, thrust zone, talc schist zone). Along the section with high overburden, $\Sigma = 10$ (high), with $\Sigma = 12$ (high) for weakness zones.

These Uncertainty and Consequence Classes are used in selecting the GC before excavation starts (using Table 3a). The Geotechnical Categories found are presented in Fig. 3. Under the lake, higher GC classes are used due to the Consequence Class for undersea conditions (CC3).

After the tunnel was excavated, the rockmass conditions were known from the tunnel geo-mapping. From this, the GC, according to the ground qualities found, can be given along the tunnel (Fig. 4).

Notes:

(1) Some of the weakness zones were encountered at other locations in the tunnel than assumed, others were not encountered.
(2) Where the Geotechnical Category is 1/2 or 2/3, the most appropriate value 1, 2 or 3 is selected from evaluation of the site conditions.

8. Conclusion

The General Rules of Eurocode 7: Geotechnical Design Part 1 is not directly applicable in rock engineering design work. The principle can be applied, but the special context emanating from geological uncertainties and related risks must be considered. Classification of risk level by Geotechnical Category (GC) is usable, but has to be improved

Table 10
Geological uncertainty found from various geological features influencing on geological and investigation conditions (revised from Palmstrom and Stille, 2015).

Site conditions influencing on geological and ground uncertainty	Division with ratings			Comments
1 Geological setting[a]	Simple 1	Clear 2	Complicated 4	The distribution and composition of rocks, tectonic structures, foldings, etc.
2 Degree of rock weathering at the terrain surface	Minor 0.5	Moderate 1	High 3	The degree of weathering at the rock surface, making observations and interpretations of the rocks at tunnel/cavern level more difficult
3 Area of the rock surface covered[b] (by soil, lake/sea, vegetation, buildings, etc.)	None or minor 1	Moderate 3	Comprehensive 5	The rock cover reduces the possibilities to forecast the rockmass conditions underground
4 Rock overburden. Distance from excavation to rock surface	< 10 m/ 10–50 m 2 / 0.5	50–300 m 1	> 300 m 4	Long distance from rock surface to the tunnel increases the uncertainties in forecasting the rockmass conditions. As limited (low) rock cover (< 10 m) is a risk, a rating = 2 is suggested. The same rating is set to surface excavation.
Degree of geological uncertainty		Sum (Σ) of the values from each topic Low: Σ < 5	Medium: Σ = 5–8	High: Σ > 8

[a] After information from investigations.

[b] Which has not been investigated.

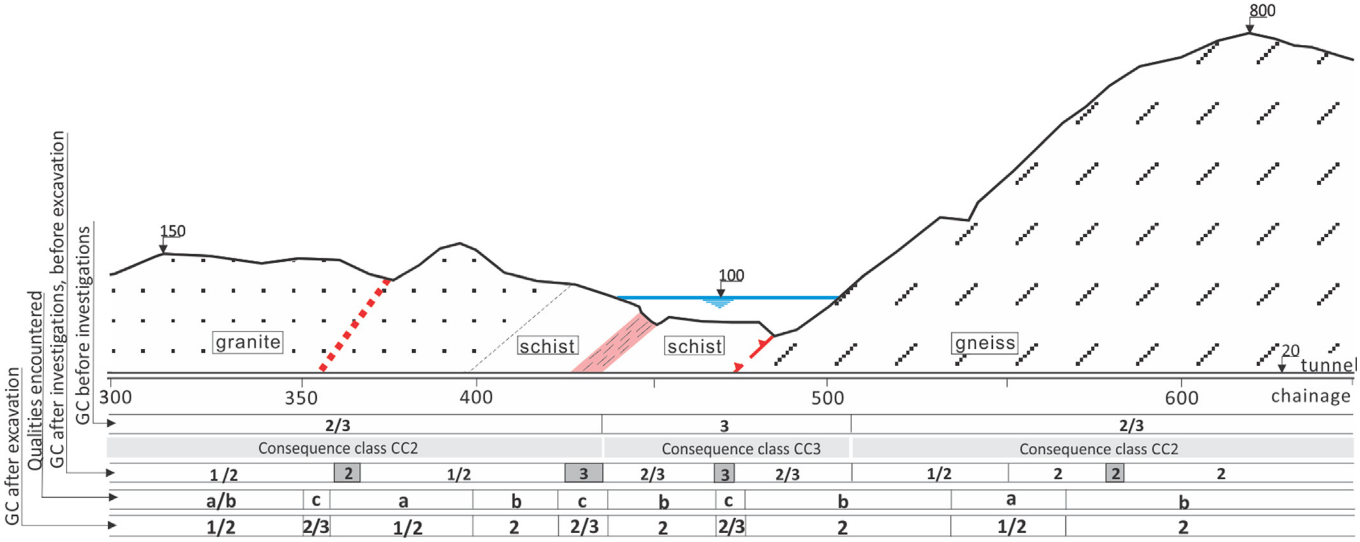

Fig. 4. After excavation. The GC classes after the tunnel excavation has revealed the ground conditions along the tunnel (quality a (good) to c (poor)). The GC is based on the ground stability (quality) conditions which form the basis of the permanent support to be designed.

by (1) combining the consequences of a failure to the geological uncertainties before excavation, and (2) combining the consequences and the ground quality found after excavation. The GC classes may vary along the rock excavation and during various stages of a project in relation to different risk situation and risk level.

The geological risks incorporated in the Geotechnical Category (GC) also influence the types of control, inspection and supervision to be applied during design and construction. An example is presented showing how the GC can be determined at various stages of rock constructions.

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