Rock-Engineering Design and NTC2018: Some Open Questions

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Abstract. The Italian technical standard of construction (NTC-2018) defines the standards for designing, building and testing all kinds of constructions, considering their performances in terms of mechanical resistance, stability and durability. These standards give us the general safety criteria, stating that the effect of actions and material characteristics must be included in the design. Moreover, NTC-2018 transposes requirements suggested in the EN Eurocodes (EN 1990 - EN 1999). For what it concerns geotechnical structures, since 2010, EN-1997 Geotechnical Design (EC7) has been the reference design code for construction in the EU. What about rock engineering designs? Since rock mechanics is a branch of geotechnics, rock-engineering constructions should be designed following EC7 and NTC-2018 requirements. However, their applicability is not obvious, since the use of partial factors in design calculation is not allowed due to lack of proper partial factors or since there are no precise indications about the processing of data coming from new analysis techniques (e.g. remotely sensed data). For rock masses, partial factors may be applied to joint strength but they cannot be used for joint orientation or spacing. As a consequence, statistical approaches, together to detailed geomechanical surveys (traditional and/or non-contact) are more suitable for these parameters. In this paper, the authors analysed some open questions in national and European regulations related to rock-engineering design.

Keywords: Rock-engineering design · NTC2018 · Eurocode 7

1 Introduction

NTC-2018 is the Italian technical standard for the design of common civil and industrial engineering works and it implements requirements suggested by the EN Eurocodes (EN 1990 - EN 1999). It contains principles referring to various types of structures, providing common rules for their design, for checking their strength, stability and durability against actions (Dimova et al. 2014).

Chapter 6 of NTC-2018 refers to the geotechnical design dealing with foundations, underground constructions, man-made soil structures, excavation faces and slope stability. In particular, it deals with constructions in or on the ground, which is defined as

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“soil, rock, fill in place prior to the execution of the construction works”. As it will be discussed hereinafter, NTC-2018 and EC7 requirements are suitable for problems that involve interaction between structure and soil but their applicability is debatable concerning rock mechanics.

NTC-2018 is based on the limit state design (LSD) approach that requires the application of partial safety factors to characteristic parameter values for considering parameter uncertainty and achieving designs with a certain target reliability. For what concerns geotechnical problems, the possible relevant failure mechanisms have to be identified in order to forecast the structural adequacy and the ground capacity and resistance.

The geotechnical design requires a proper reconstruction of the geological model and the definition of physical and mechanical properties of the ground. The latter requires performing in situ surveys and laboratory tests for defining characteristic parameters and, in relation to the type of construction, the geotechnical model. Geological and geotechnical models have to be coupled for helping designers in the choice of the best technical solution and the executive plan.

According to the code, geological model has to “identify and describe geological factors inducing instability processes”. The standard also requires that “stability analysis of ground and structures have to be based on data acquired with geotechnical surveys”. Each parameter has to be pertinent to failure mechanism and properly reduced or increased with partial coefficients. The magnitude of these coefficients is governed by the probability of failure: at present, their applicability to rock mechanics parameters is unproven. In fact, nor NTC-2018 neither EC7 present any factors for rock mechanics parameters (Bedi and Orr 2014; Harrison 2014).

In contrast to soil, in which the particles are very small in comparison with structure dimension, rock masses are typically jointed. As a consequence, their representative elementary volumes (REV) are greater than soil particles and vary in size. The strength, shape, orientation and magnitude of REV dictate the response of the rock mass (Ferrero et al. 2014). By considering various scales of loading to which a rock mass may be subjected in construction practice, the size of REV also affects rock mass resistance. Generally, REV cannot be tested, disallowing for the direct determination of engineering parameters in laboratory (Harrison et al. 2015).

NTC-2018 provides a general description and just states that “in case of rock masses and complex formations, it is necessary to take into account the nature, the geometric characteristics and the resistance of the discontinuities”. Moreover, it reminds that “the geomechanical characterization of the rock mass must include type of joint, orientation, continuity, spacing, roughness, strength, aperture (if opened), fill width and nature (if filled), weathering level and water” and adds that “representative values should be quantified starting from a considerable number of joint data”.

All these aspects undoubtedly have a huge impact on the analysis of rock masses susceptible to rockfall phenomena especially for the evaluation of the representative rock block and its dynamic along the slope. In the design of protection structures against rock fall phenomena, the definition of rock mass characteristics and the statistical treatment of these parameters become of the utmost importance for the definition of the related probability of failure.

In this paper, the authors want to focus on the previous open questions related to rock mechanics in NTC-2018 providing two illustrative examples to better explain these limitations and how to overcome them. In particular, concerning the uncertainties in rock mass characterization, the case study of Rovenaud (Ferrero et al. 2016) has been used as an example for highlighting how the choice of REV could influence the definition of maximum impact energy. Finally, the findings of this study have been used for performing reliability-based analysis (Vagnon et al. 2018), here proposed as a possible approach for the evaluation of probability of failure of structures and for overcoming the LSD limitations, widely discussed in the following.

2 Rock Engineering Design

In rock engineering design, the choice of the best design approach is governed by geometrical and physical characteristics of the rock mass in relation to the engineering problem size.

One of the main questions in rock mechanics is the definition of the rock mass strength. Since the rock mass is defined as an assembly of intact rock blocks separated by geological discontinuities and the action of tectonic forces plays a decisive role in its behaviour (displacement take place primarily along these planes of weakness), the combined influence of joints, their configuration and the strength along them are the first aspects to be taken into account. They define the failure mechanism and influence the choice of modelling scheme to be adopted in any design operation.

Depending on the rock mass degree of fracturing, continuum or discontinuum models can be used for the analysis of rock mass behaviour. Continuum approach is applied to weak rock masses or if there isn't any macro-structure governing the medium strength behaviour. On the contrary, if the stress-strain behaviour of rock mass depends mainly on the discontinuity sets, the discontinuum approach is more suitable in defining rock mass behaviour.

For what concerns a continuum or pseudo-continuum medium, the evaluation of intact rock characteristics (peak and residual friction angles, cohesion, bulk density) by performing laboratory tests may be enough for defining the whole rock mass behaviour. Continuum or pseudo-continuum approaches allow for the use of rock mass classifications, since the effect of discontinuities can be spread over the whole rock volume, defining a 'homogenized' medium with global values of deformability and resistance. For these reasons, in engineering practice, empirical relationships, developed over the last decades by several authors, have been applied correlating the characteristic parameters of the mechanical behaviour with the quality indexes of the rock mass.

On the contrary, for a discontinuum medium, rock mass properties should not be based only on laboratory and/or in situ testing, but also on a thorough characterization of the rock mass. The concept of homogenized medium is theoretically wrong since failure mechanisms depend on the discontinuity features. Thus, a considerable number of joint data representative of the site and including type of joint, orientation, continuity, spacing, roughness, strength, aperture if opened, fill width and nature if filled, weathering level and water (Ulusay and Hudson 2007) should be acquired. Their quality and quantity should be related to the rock mass quality for reducing the design uncertainties coherently with the limit state approach (Bedi and Harrison 2013). Moreover, the amount of data depends on the geotechnical model to be adopted and the possible failure mechanisms involved.

In fact, fracturing rules the possible failure mechanisms and an effort must be made to characterize discontinuities both by the geometrical and the mechanical point of view.

Summarizing, if the fracturing leads to rock block of negligible size compared to problem scale, the rock mass can be assumed as an equivalent medium and the discontinuity effects can be distributed over the whole rock mass. In this case, the partial safety factor approach may be useful. For what concerns discontinuum models, the rock block volume and discontinuity properties rule the definition of possible failure mechanisms. Unfortunately, NTC-2018 suite never deals with these aspects and no recommendations are given regarding the percentage to be considered in the relative frequency distribution or partial factors to be applied.

Moreover, for defining the frequency distribution of rock block volumes, a large amount of data on spacing, orientation and, possibly, persistence should be necessary; NTC-2018 and EC7 suites do not provide any suggestions on the number of data and/or on the definition of reference block dimension.

The increase of analysed data requires a distinction between epistemic and aleatory uncertainties in measurements: epistemic uncertainties depend on characteristics of the survey method and aleatory uncertainties one the natural variability of discontinuities. As stated by Bedi and Harrison (2013), aleatory variability can be invoked only when there are enough measurements that are sufficiently precise to objectively fit a probability distribution to the data using statistical methods.

In the following, two examples for highlighting the actual problems related to rock mechanics in national NTC-2018 suite.

3 Discontinuity Data Obtained with Remote Sensing Tools

Rock fall phenomenon is a good example to highlight the complexity of the identification of design parameters: in fact, uncertainties are involved in slope characterization (geometry, restitution coefficients), in discontinuity survey method, in the definition of the design block volume and in the simulation of block trajectories along the slope. As previously remarked, for reconstructing a reliable statistical distribution of block volumes a huge dataset of rock discontinuity characteristics in terms of orientation, spacing and persistence is required. Traditional surveys are not always feasible due to rock face accessibility, safety conditions and time limits. Non-contact surveys are a good alternative for obtaining information about discontinuities characteristics, allowing for statistical analyses and therefore for uncertainties evaluation.

NTC-2018 and EC7 do not provide yet a standardization of the requirements about the acquisition and processing of the products of remote sensing techniques, such as Digital Surface Models (DSM), in order to generate input for the design of protection works. Lato et al. (2010) performed tests concerning point density as a function of the look angle of the laser scanner and its distance from the object. A discussion concerning quality and quantity of DSM points in order to be suitable for different kinds of analysis is included for example in Ferrero et al. (2016).

Discontinuity data obtained from the analysis of a DSM need to be reliable and representative of the considered rock mass, therefore great attention must be paid to their accuracy and completeness.

Hereinafter, a discussion regarding the development of advanced survey methods for the geometrical characteristics of rock discontinuities is proposed: since neither NTC-2018 nor EC7 contain references to these methods, the authors want to highlight the great gap between the state-of-the-art of research and the actual regulations.

3.1 Orientation

Ferrero et al. (2009) performed tests concerning the accuracy of dip and dip direction of discontinuity planes fitted on point samples of a DSM and inferred that it mainly depends on two factors: the ratio between the point accuracy and their average distance, and the roughness of the actual rock surface. Based on these tests they developed a guide in survey design to determine the minimum number of points to be acquired in order to obtain a certain accuracy in the dip and dip direction estimation.

3.2 Spacing

Spacing, coupled with orientation, can be surveyed with non-contact methods: manual or automatic measurements can be performed on the DSM reproducing the outcrop surface, with the great advantage of acquiring data on the whole surface and have all the input data to obtain true spacing values.

3.3 Persistence

Persistence, defined as the ratio between the total discontinuity area and a reference area, controls the stability of blocks; however, direct measurements of discontinuity area are quite impossible to obtain, and therefore many researchers (Kulatilake and Wu 1984; Zhang and Einstein 1998; Mauldon 1998) proposed method for inferring discontinuity area and degree of fracturing based on trace lengths. Thanks to the development of non-contact survey techniques, different methods were proposed to automatize trace identification and measurement on DSM (i.e. Gigli and Casagli 2011; Umili et al. 2013), allowing for the creation of a complete database of trace lengths and directions.

3.4 Roughness

Joint Roughness Coefficient (JRC) (Barton, 1973) value of a rock joint is traditionally estimated by visibly comparing it to the ten standard profiles (Barton and Choubey 1978). The development of objective methods for a quantitative estimation of JRC has been the research topic of many authors in recent years (for a review of the state-of-the-art see Li and Zhang 2015; Li and Huang 2015): regression correlations between JRC and geometrical, fractal, and geostatistical descriptors were proposed. Research was also focused on significant aspects that influence roughness quantitative estimate, such as the anisotropy of the discontinuity surface, the scale effect and the sampling interval.

3.5 Block Volume

The definition of the design block in rockfall events is strictly influenced by discontinuities orientation and spacing in the originating rock mass, as defined by the well-known relation by Palmström (1996). As previously reported, the higher level of completeness of databases of these two parameters acquired with non-contact methods allows for the definition of their statistical distributions. Therefore block volume frequency distribution can also be inferred, with the advantage of including uncertainties related to the original data and of relating probability of exceeding with a certain block volume. This aspect is fundamental for properly choosing the design block for a barrier.

The study by Ferrero et al. (2016) performed on a rock face characterized by rockfall events located at Rovenaud, in the Gran Paradiso Park area (Valsavaranche, Aosta, Italy), is an attempt to cover the previously mentioned gap between research and regulations in rock mechanics.

Following charts presented in Ferrero et al. 2009, the epistemic and aleatory uncertainties were evaluated on each discontinuity set. As expected, the aleatory components, namely that related to the natural variability of discontinuity characteristics inside the rock mass, is one order of magnitude greater than the epistemic one. Consequently, this variability in defining discontinuity orientation reflects on rock volume estimation. Monte Carlo analysis was performed in order to reproduce the cumulative distribution of detached block: for validating the goodness of this process, the estimated frequency distribution was compared with the real block distribution evaluated at the base of the rock face. Variability in rock block volume defines a great variability in total kinetic energy on a hypothetical barrier. Figure 1 shows the cumulative distribution of total kinetic energy evaluated at a certain location considering three different volume blocks. It is evident the influence of the choice of the design block volume on the evaluation of kinetic energy and on the definition of barrier resistance.

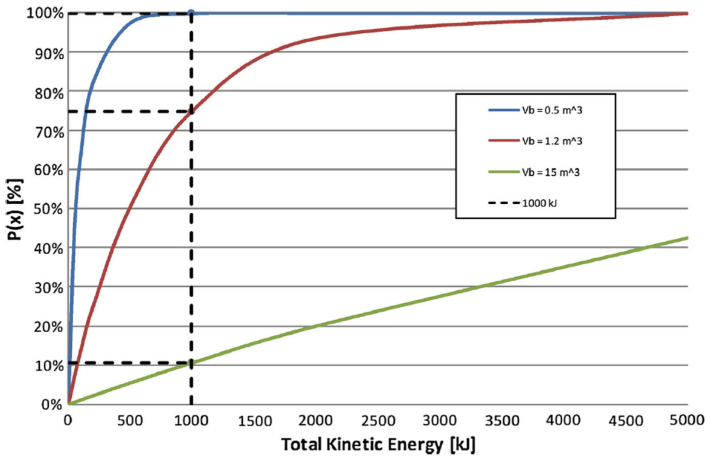

Fig. 1. Cumulative distribution of total kinetic energy evaluated considering three different volume blocks (from Vagnon et al. 2017). This kinematic analysis was performed for highlighting how the uncertainties related to spacing and joint orientation measuring have a huge impact on the evaluation of REV and consequently on kinetic energy.

Summarizing, rock block volume is the dominant parameter for a proper design of rockfall barrier, but unfortunately the NTC-2018 and EC7 never deal with this aspect and no indications are given on the possibility of applying partial safety factors.

4 Rock Fall Barriers

For the design rock fall protection barriers the partial safety factor approach cannot be applied since partial factors have still to be proposed (by EC7 and NTC-2018) to cover involved uncertainties on design parameters (block volume, block velocity etc.). Thus, to overcome these limitations a design approach based on a target reliability index (Duncan 2000; Baecher and Christian 2003) could be a useful tool to provide geotechnical structures with a uniform probability of failure.

Statistical analyses should be performed for identifying the rock block volume frequency on the basis of orientation, spacing and persistence of discontinuity sets.

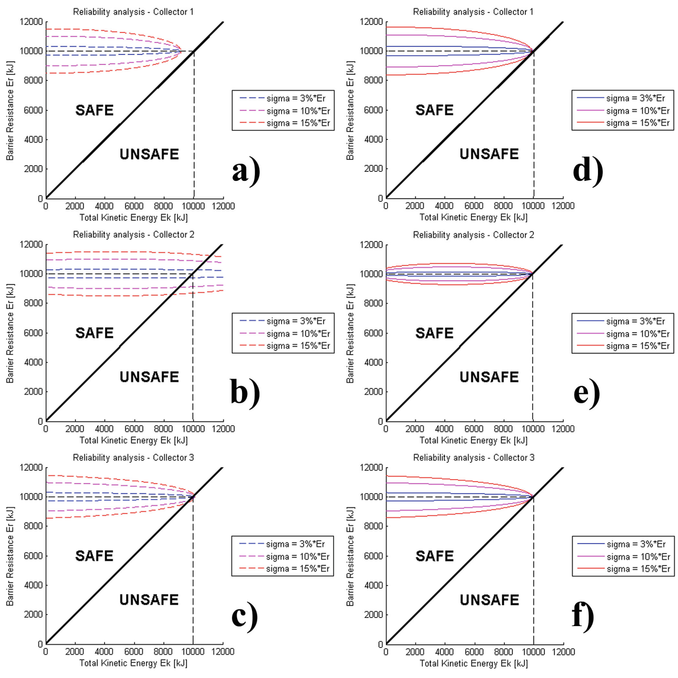

Fig. 2. Graphical representation of the RBD approach for rock fall problems (from Vagnon et al. 2018). Dotted lines (a, b and c) represent the ellipsoids generated by barrier resistance and kinetic energy with three level of standard deviation, associated to barrier resistance, for three rockfall barrier located in different position along the slope. Continuous lines (d, e and f) represent the ellipsoids tangent to failure domain evaluated using RBD approach. The figure highlights that barrier resistance for collector 2 and 3 is insufficient to guarantee an acceptable level of safety, independently of standard deviation values; thus, an increase in barrier resistance is highly recommended.

This aspect requires an accurate knowledge of the rock slope fracture structure and, consequently, a thorough definition of the geological model.

To illustrate these aspects, the reliability-based design (RBD) has been applied to a flexible rockfall barrier (Fig. 2) located at the base of the rock face presented in the previous section.

The complete description of the performed procedure is presented in Vagnon et al. 2018: the main results of the study can be summarized as follows:

- The target reliability index is independent from the variability of barrier resistance but it mainly depends on rock block dimension and impacting kinetic energy.
- RBD approach allows for the evaluation of the probability of failure of the designed structure. Consequently, it becomes immediate the choice of the best strategy for reaching the expected target probability of failure.
- The main limitation is the availability of wide dataset of real events for performing solid statistical analyses.
- For rock mechanics problems, the use of probability of failure as an indicator for calculating the residual risk should be preferred to the use partial safety factor. In fact, by moving upwards the ellipses generated by average values and standard deviation of design parameters it is possible to reduce the associated probability of failure.

5 Conclusions

NTC-2018 and EC7 are mandatory for civil engineering geotechnical design, including rock-engineering design. However, even though both the codes requires design to adhere to the principle of limit state design, as highlighted in the presented examples, it is not completely clear if current design practise can satisfy these requirements.

Moreover, actual EC7 and NTC-2018 are suitable only for the characterization of continuous media, where particle scale is completely negligible, but not for jointed media. Thus, rock mass characterization, failure mechanisms, how to quantify the degree of fracturing and taking into account anisotropy are all aspect not mentioned in the codes.

The codes should also suggest remote sensing techniques as tools for improving the quality and quantity of data, useful for performing robust statistical analyses.

In rock mechanic problems, probability of failure should be used as an indicator for evaluating structure residual risk and going beyond a single factor of safety.

References

Baecher GB, Christian JT (2003) Reliability and statistics in geotechnical engineering. J. Wiley, Chichester, West Sussex, England, Hoboken, NJ

Barton N (1973) Review of a new shear-strength criterion for rock joints. Eng Geol 7:287–332

Barton N, Choubey V (1978) The shear strength f rock joints in theory and practise. Rock Mech 10:1–54

Bedi A, Harrison JP (2013) Characterisation and propagation of epistemic uncertainty in rock engineering: A slope stability example. In: Kwasniewski and Łydzba (eds) Rock Mechanics for Resources, Energy and Environment (2013) Taylor & Francis Group, London, ISBN 978-1-138-00080-3

Bedi A, Orr TLL (2014) On the applicability of the Eurocode 7 partial factors method for rock mechanics. In: Alejano, Perucho, Olalla and Jimenéz (eds). Proc. EUROCK European Reg. Symp. – Rock Engineering and Rock Mechanics: Structures in and on Rock Masses, Vigo, Spain, 27–29 May 2014. London: Taylor & Francis Group

Dimova S, Nikolova B, Pinto A, Bond A.J. (2014) – Eurocode 7: Geotechnical Design Worked examples. In: Dimova, Nikolova, Pinto, Bond (eds). Workshop "Eurocode 7: Geotechnical Design", Dublin, Ireland, 13–14 June 2013. JRC research centre.

Duncan JM (2000) Factors of safety and reliability in geotechnical engineering. J Geotech Geoenviron Eng 126(4):307–316

EN 1997-1. (2004) – Eurocode 7: geotechnical design - part 1: genetal rules - Brussels, Belgium, CEN

Ferrero AM, Forlani G, Roncella R, Voyat HI (2009) Advanced geostructural survey methods applied to rock mass characterization. Rock Mech Rock Eng 2(4):631–665

Ferrero AM, Sofianos AI, Alejano LR (2014) Critical review of Eurocode-7 regarding rock mass characterization. In: Alejano, Perucho, Olalla and Jiménez (eds) Rock engineering and rock mechanics: structures in and on rock masses – Taylor & Francis Group, London, 978-1-138-00149-7

Ferrero AM, Migliazza MR, Pirulli M, Umili G (2016) Some open issues on rockfall hazard analysis in fractured rock mass: problems and prospects. Rock Mech Rock Eng 49(9):3615–3629

Gazzetta Ufficiale della Repubbòica Italiana (2018) Norme tecniche per le costruzioni. Ministero delle infrastrutture e dei trasporti (in Italian)

Gigli G, Casagli N (2011) Semi-automatic extraction of rock mass structural data from high resolution LIDAR point clouds. Int J Rock Mech Min Sci 48(2):187–198

Harrison JP (2014) Eurocode 7 and rock engineering: current problems and future opportunities. In: Alejano, Perucho, Olalla and Jimenéz (eds) Proc. EUROCK European Reg. Symp. - rock engineering and rock mechanics: structures in and on rock masses, Vigo, Spain, 27–29 May 2014. London: Taylor & Francis Group

Harrison JP, Alejano L, Bedi A, Ferrero AM, Lamas L, Mathier JF, Migliazza R, Olsson R, Perucho A, Sofianos A, Stille H, Virely D, Wittke M (2015) Rock engineering design and the evolution of Eurocode 7: the critical six years to 2020. In ISRM Congress 2015 Proceedings - Int'l Symposium on Rock Mechanics - ISBN: 978-1-926872-25-4

Kulatilake PHSW, Wu TH (1984) Estimation of mean trace length of discontinuities. Rock Mech Rock Eng 17(4):215–232

Lato MJ, Diederichs MS, Hutchinson DJ (2010) Bias correction for view-limited lidar scanning of rock outcrops for structural characterization. Rock Mech Rock Eng 43:615–628

Li Y, Huang R (2015) Relationship between joint roughness coefficient and fractal dimension of rock fracture surfaces. Int J Rock Mech Min Sci 75:15–22

Li Y, Zhang Y (2015) Quantitative estimation of joint roughness coefficient using statistical parameters. Int J Rock Mech Min Sci 77:27–35

Mauldon M (1998) Estimating mean fracture trace length and density from observations in convex windows. Rock Mech Rock Eng 31(4):201–216

Palmström A (1996) Characterizing rock masses by the RMi for use in practical rock engineering. Tunnel Underground Space Tech 11(2):175–188

Ulusay R, Hudson JA (2007) The complete ISRM suggested methods for rock characterization, testing and monitoring: 1974–2006. In: Ulusay R, Hudson JA (eds) Commission on testing methods. International Society of Rock Mechanics.

Umili G, Ferrero AM, Einstein HH (2013) A new method for automatic discontinuity traces sampling on rock mass 3D model. Comput Geosci 51:182–192

Vagnon F, Ferrero AM, Umili G, Seglini A (2017) A factor strength approach for the design of rock fall and debris flow barriers. Geotech Geol Eng 35(6):2663–2675

Vagnon F, Harrison JP, Ferrero AM, Umili G (2018) Reliability based design for rockfall barriers. Geomech and Geodyn Rock Masses 2:1543–1548

Zhang L, Einstein HH (1998) Estimating the mean trace length of rock discontinuities. Rock Mech Rock Eng 31(4):217–235