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Integral approach in stability analyses for weak anisotropic rocks

Milorad Jovanovski[(1)]*, Bojan Janevski[(2)], Igor Peshevski[(3)]

1) University Ss. Cyril and Methodius, Faculty of Civil Engineering, Skopje, blvd. Partizanski odredi 24, MKD, +38970236962 jovanovski@gf.ukim.edu.mk

2) Civil Engineering Institute "Makedonija", Skopje, Drezdenska 52, MKD

3) University Ss.Cyril and Methodius, Faculty of Civil Engineering, Skopje, blvd. Partizanski odredi 24, MKD

Abstract Slope stability in weak rock masses is a practical problem where the anisotropy, weathering, and inhomogeneity must be incorporated adequately in geotechnical models for stability analyses. Such media are susceptible to local or global instabilities expressed as wedge, planar, or rotational mode of failure, depending on combinations of slope elements, discontinuity orientation, block sizes, and other factors in the rock masses. Often, even in cases with extensive field investigations, some uncertainties still exist, thus it is a challenging task to compromise between the economy and the reliability of the solution. With an idea to underline some open questions, we are presenting experiences gathered through phases of investigation, design, and construction for several large infrastructural projects on the Macedonian road network. An extensive data basis is collected for weak rock mass parameters, modes of failure, and methods for rock mass stabilization for over 80 deep cut sections. The well-known limit equilibrium, kinematic, and empirical methods are used in certain analyses. Some of the results are presented in partially modified diagrams from known Q-slope in correlation with the Slope Mass Rating method. Some diagrams with values from calculations of the factor of safety and probability of failure are also presented. An attempt is made to incorporate also some findings related to different design approaches. Analyses indicate that it is necessary to combine results from stability analyses with tolerable levels of risk. Here, consequence classes and geotechnical categories defined in Eurocode 7 are correlated with values of the so-called reliability index. The findings lead to the conclusion, that interaction and integration of technical, economic, and social aspects as well as involving different perspectives are necessary in the process of rock slope risk management. Some arising open questions and some recommendations for further development of the methodology are also presented.

Keywords anisotropic rocks, analytical methods, integral approach, empirical methods, slope stability, reliability index

Introduction

There are many guidelines for design of cut slopes in rocks, but rarely do they anticipate the material anisotropy and discontinuity. It is a well-known fact that weak rock masses are complex media, where anisotropy and inhomogeneity often play an important role in forming geotechnical and calculation models. ISRM (1981) classified the weak rock mass in categories: R0 when Uniaxial Compressive Strength (UCS) has values UCS<1, R1 when UCS = 1-5 MPa and R2 for a range of UCS = 5-25 MPa. Usually, weak rocks are also highly anisotropic. In practice, for intact rocks, several classes of index of anisotropy Id are defined (Saroglou et al., 2007). Such media are susceptible to local or global instabilities expressed in different modes of failure depending on combinations of two main elements in interaction – rock mass states and properties (especially discontinuity orientations and block sizes) in relation to artificial engineering structures and their elements. When dealing with slope stability problems in weak rock masses, this problem becomes very complex, because there are a lot of uncertainties even in cases with extensive field investigations, problems of relaxation because of excavation influences etc.

With an idea to underline some important questions and dilemmas, experiences gathered from several large infrastructural projects on the Macedonian road network are presented. Namely, in the past decade, the A2 motorway from Kicevo-Ohrid, the express road near the town Kriva Palanka to the Bulgarian border, and express roads from town Stip to Kocani and to Radovis were in construction, in a heavy geological environment with impressive cut heights. An extensive database is collected for weak rocks for physical and mechanical properties, rock mass classes, modes of failure, methods for stabilization and other problems from over 80 deep cuts.

The authors believe that a presentation of observed phenomena and problems in construction can be interesting for the scientific community, with an idea of some of the findings, to be incorporated in practice in future projects.

Analysed area

The presented case histories are in different areas of the country. The position of the analysed cases is presented in Fig.1. from where it is visible that the subject road sections are located in different geotectonical units. The geological conditions of the areas certainly influenced a lot on the stability conditions in specific ways during the construction phases.

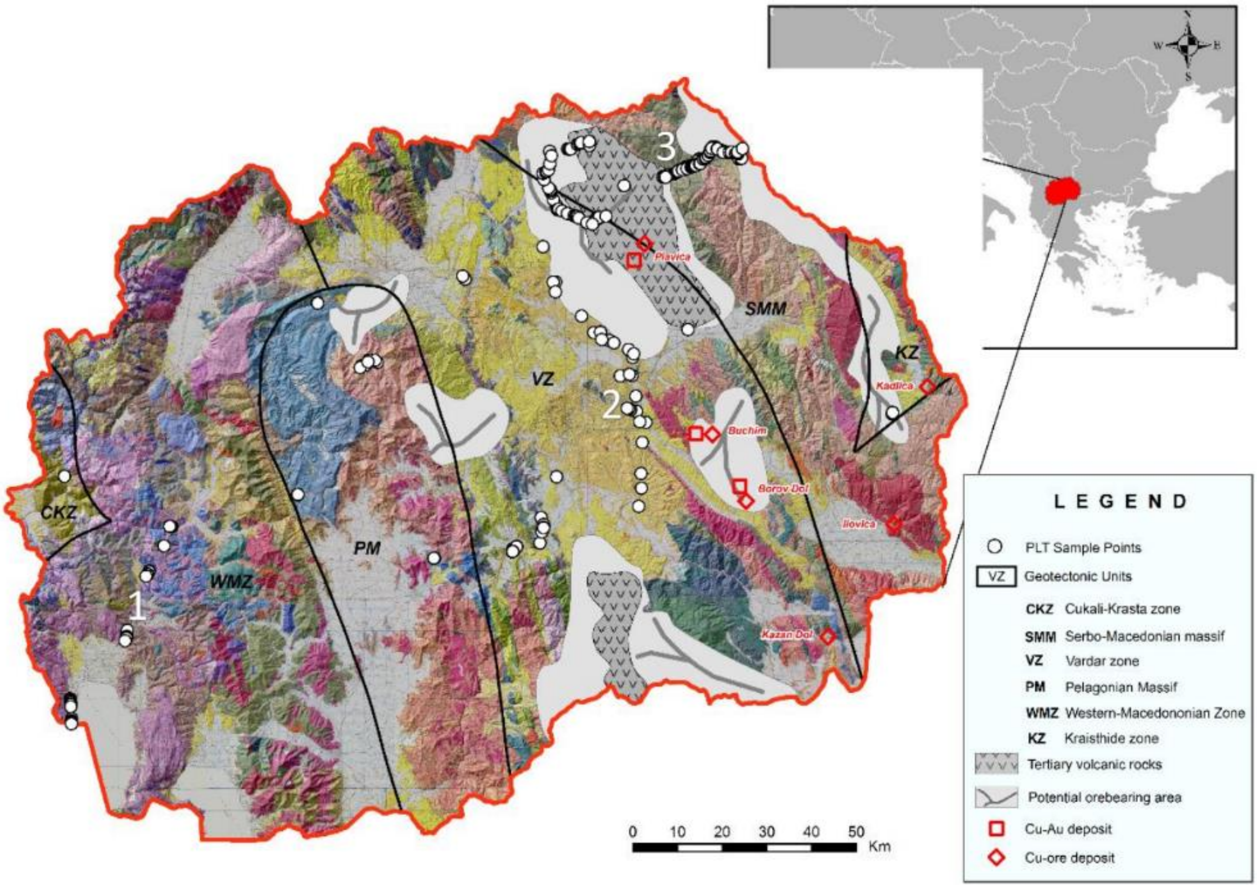

Figure 1.Main geotectonic units in the country and schematical position of the analysed infrastructural projects. 1 –area of highway from Kicevo to Ohrid; 2 – area of express roads from Stip to Kocani and Stip to Radovis; 3 – area of express road from Kriva Palanka to the Bulgarian border.

The Section for the highway from Kicevo to Ohrid is placed in the so-called Western-Macedonian zone (WMZ in Fig.1). It is represented by very complex tectonics, with a multitude of folded and faulted structures. It is mostly composed of a phyllitic low-grade metamorphic complex. Its lower parts are dominated by volcanic sedimentary rocks and its upper part by a terrigene-carbonate formation. Along the highway route, about 53 cut slopes are analysed. The majority of the cuts are with heights of more than 30 m and several of the cuts are even higher than 100 m. The terrain predominantly consists from phyllites and schists (sericite, quartz-sericite and graphitic). The anisotropic rocks are low-grade metamorphic rocks of Palaeozoic age, folded, tectonically disturbed and affected by the processes of surface degradation. The heterogeneity of the rock formations is manifested through often transformation from one rock type to another, both in horizontal and vertical direction. The positive aspect in terms of stability is the foliation dip angles, which vary in the range from 10^0–50^0, with predominant dipping into the hill slope.

The express roads from Stip to Kocani and from Stip to Radovis are placed in the Vardar zone (VZ). This zone is also known as an area with complex tectonic structure, that includes fragments from the Precambrian Earth crust, Palaeozoic volcanic-sedimentary complexes, Mesozoic magmatism and in the areas of roads, Eocene flysch complexes. Along the express roads route, about 17 cut slopes are analysed. Some of them are constructed in areas of the Eocene flysch complex, built up dominantly from marles and sandstones in rhythmic sequences. Some of the cuts are with heights of more than 20 m. The main element of anisotropy is related to properties parallel and perpendicular to sedimentary planes.

The Serbian-Macedonian massif (SMM) is an area, where the construction of the express road Kriva Palanka to the Bulgarian border takes place. It is characterized by the presence of Precambrian and Riffey-Cambrian complexes. In the area of the road, quartz–sericite shist formations are dominant. The anisotropy is mainly connected with foliation, but very often, along the route of 10 higher cuts, the changes in rock mass properties and weathering state are expressed on short distances.

It should be considered, that as a result of the various changes in each stage of geologic development, the rocks will exhibit very variable behaviour during the construction, especially related to the rock mass parameters. Fig. 1 also shows the approximate spatial distribution of analysed intact rock samples in total, around 1200 samples have been analysed (Peshevski et al., 2019). Just to illustrate the effect of anisotropy even at the range of volume for intact rocks, some correlations obtained from testing of the Point Load Strength Index perpendicular and parallel to main structural planes, are presented in Tab. 1.

Table 1. Correlations of the point load index for samples tested parallel and normal to foliation/bedding for some dominant rock types (part of the table from Peshevski et al.,2919).

Established correlation	Project	Rock type
Js(n)=1.4127*Js(p)+1.4169 r^2=0,8083	Zones of highway Kicevo-Ohrid	Quartz-sericite schists
Js(n)=2,7199*Js(p)+0.6445 r^2=0,915	Cuts in Flysch	Marls are dominant
Js(p)=0.4382Js(n)+0.3931 r^2=0,8266	KrivaPalanka – Deve Bair	Albite-sericite schists

From Tab. 1 it can be seen that the coefficient of correlation r^2 has usually high values, but the correlations vary a lot depending on the rock type. This certainly has an effect on the anisotropy of the shear strength at the rock mass level.

Applied methods in the stability analyses

In the slope stability calculations, the intention shall be to apply adequate geotechnical models when choosing the most appropriate method for the analysis. In the selected sections, based on local conditions, all main known approaches are used, depending on kinematic conditions at certain zones, scale effect, orientation of the main structural elements and slope dimensions.

As a supporting empirical method, in some cases, the Slope Mass Rating System – SMR (Romana, 1995) and/or the Q-slope system, developed by Barton and Bar (2015) are used. The Q-slope method is presented in Eq. 1.

$$Q_{slope} = \frac{RQD}{Jn}\left(\frac{Jr}{Ja}\right)_O \frac{Jwice}{SRF_{slope}} \qquad [1]$$

The first four parameters (RQD, J_n, J_a, and J_r) in the equation remain unchanged from the original Q-system (Barton, Lien and Lunde, 1974), while important changes are related to the discontinuity orientation factor (O), environmental and geological condition number (J_{wice}), and the strength reduction factor (SRF_{slope}).

Global stability analyses are prepared using the Limit Equilibrium Methods (LEM) i.e. the methods of Bishop, Spencer and Morgenstern-Price in the program Slide.

Methods developed for the analyses of planar or wedge failure type by E. Hoek and J.W. Bray 1974 are also used, combining them with kinematic analyses, when slope and discontinuity elements produce such conditions.

In some cases, the Finite Element Method (FEM), or Eurocode 7 suggested approaches are also used, but detailed explanations overcome the frame of this article.

The concept of the traditional factor of safety definition is extended whenever possible using the theory of probability and reliability with approaches of Reliability-Based Design (RBD). The fundamental difference between the RBD and the deterministic approach is in the fact that the uncertainty of parameters can be quantified through their probability distribution function. The benefit of this type of analysis is in cases when some of the material parameters cannot be precisely defined or they vary within some range. This is often a case when, the rock mass is highly weathered and fractured, characterized with anisotropy and discontinuities. The probability of failure (PF) is defined by the relation shown in Eq. (2).

$$PF = \frac{Nf}{Ns} * 100\% \qquad [2]$$

Where N_f is the number of analyses with a safety factor less than 1.0 and N_s is the total number of samples defined before the calculation.

The reliability index is another commonly used measure of slope stability. This index is an indication of the number of standard deviations which separate the mean factor of safety from the critical factor of safety (FS=1.0). It can be calculated assuming either a normal or log-normal distribution of the results. If the factors of safety are normally distributed, then the following equation is used to calculate the reliability index (β), as shown in Eq. (3).

$$\beta = \frac{\mu - 1}{\sigma} \qquad [3]$$

Where μ is the mean factor of safety and σ represents the standard deviation of the factor of safety. There are options to calculate the Reliability Index also with a log-normal distribution.

Shortly, it can be noted, that there are a variety of methods available. They can be used with adequate success and they can give a reliable result if only they are applied to models that present the physical conditions in the field, which are always expressed in a unique way.

The presentation of different modes of failure for the analysed cases is illustrated in Fig. 2, Fig. 3 and Fig. 4.

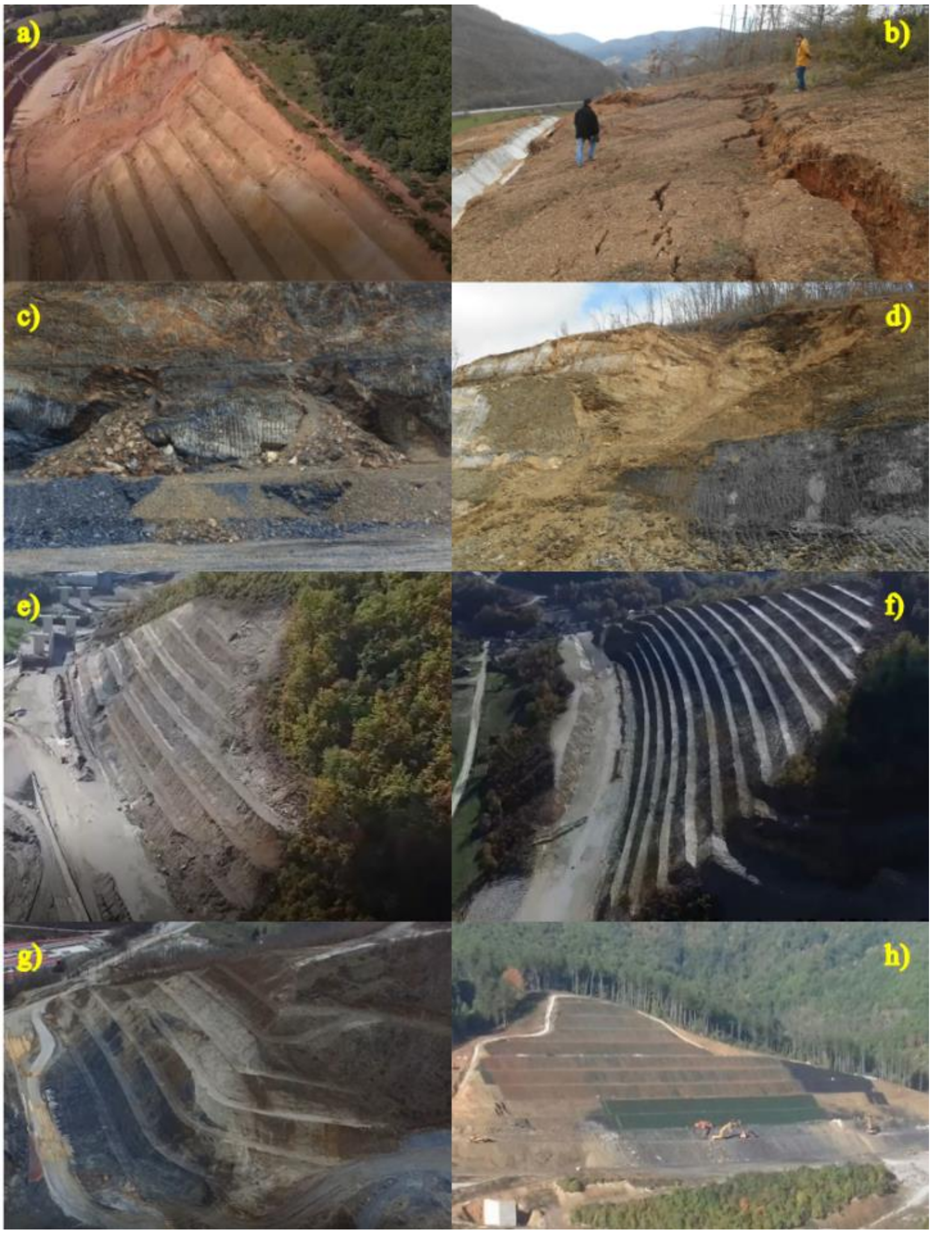

Figure 2.View of some of the representative cuts, along the route of the A2 motorway, section Kicevo – Ohrid: a) 3+400 – 3+961; b) 14+990 – 15+310 c) 11+745 – 12+140; d) 12+340 – 12+600; e) 13+327 – 13+576; f) 15+690 – 16+114; g) 13+770 – 14+000; h) 17+740 – 18+200.

In Fig. 2, several cases from the highway Kicevo to Ohrid are presented, and each of them has some specifics. The global failure occurred on the first two cuts (Fig. 2a, Fig. 2b), local failure on the second two cuts (Fig. 2c, Fig. 2d), the next two cuts (Fig. 2e, Fig. 2f) have only minor (local) deformations and the last two cuts (Fig. 2g, Fig. 2h) have no deformations. The instabilities on the first two cuts (Fig. 2a, Fig. 2b) occurred a few months after excavation, while the local failures (wedges) on the second two cuts (Fig. 2c, Fig. 2d), occurred a few weeks after excavation of the subject berms.

In Fig. 3a and 3b, several cases from expressways from Stip to Kocani and from Stip to Radovish are presented. Here, the dominant role in slope stability is the orientation of the bedding planes in relation to the slope elements. In every case, when the slope has a higher dip angle, typical planar failures occur often, even in a case when some anti-erosion measures are applied (Fig 3b).

In Fig. 3c and 3d typical examples of several cases from the express road from Kriva Palanka to the Bulgarian border show, that failure mechanisms depend not only on the orientation of planes of weakness but also on the zones with different grades of weathering. It can be concluded, that a lot of cases and variations of problems are possible, and to solve them, a high level of theoretical and practical knowledge is essential in the formulation of reliable calculation models. The key element in the analyses is that a multi-disciplinary approach and step-by-step procedures are always necessary, with a main point, that the geotechnical and calculation model must be based on conceptual geological and engineering-geological models. Several typical examples are presented in Fig. 4, Fig.5, Fig.6, Fig. 7 and Fig. 8.

Figure 3. a) Cut it Eocene flysch deposits with kinematic conditions for plane failure along bedding planes at the express road from Stip to Radovish; b) cut at km 2+700 at express road Stip-Kocani; c) and d) Different types of failure at cuts along route of express road from Kriva Palanka to the Bulgarian border: upper section – rotational failure in soil debris at cut 5+900 – 6+100.

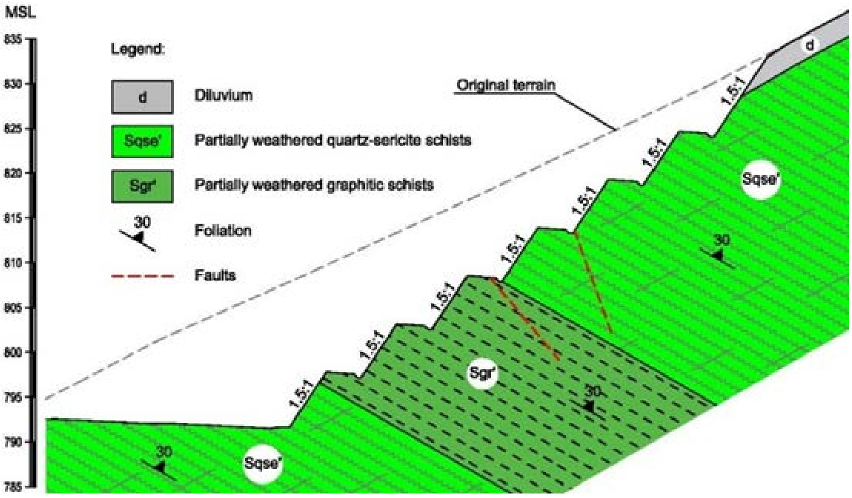

Figure 4.Geological model for one of the cuts at the highway from Kicevo to Ohrid in highly anisotropic weak rocks with favourable foliation orientation.

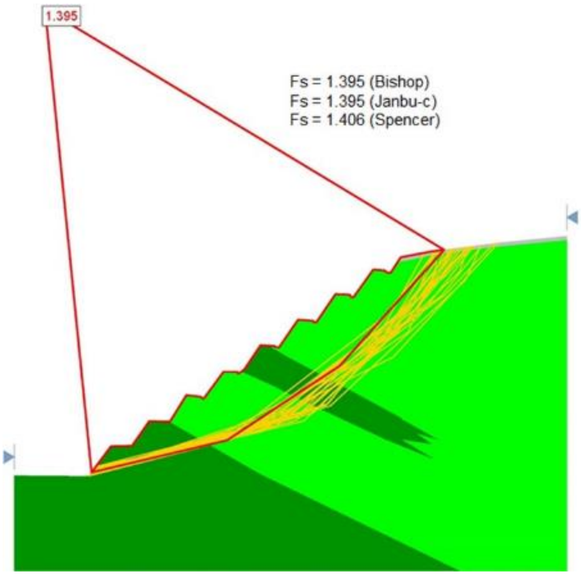

Figure 5. Calculation model for stability analyses with LEM for one of the cuts from Kicevo to Ohrid, which is appropriate for such cases in order to define global stability.

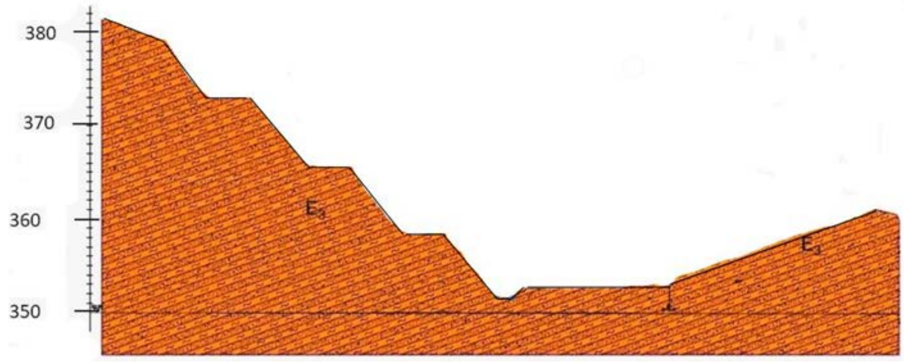

Figure 6.Geological model for a cut at km 2+700 (section from Stip to Kocani) in weak anisotropic Eocene flysch deposits, illustrating a case with favourable orientation of bedding planes at the left side and unfavourable bedding planes orientation for the right side that produces kinematic conditions for planar failure.

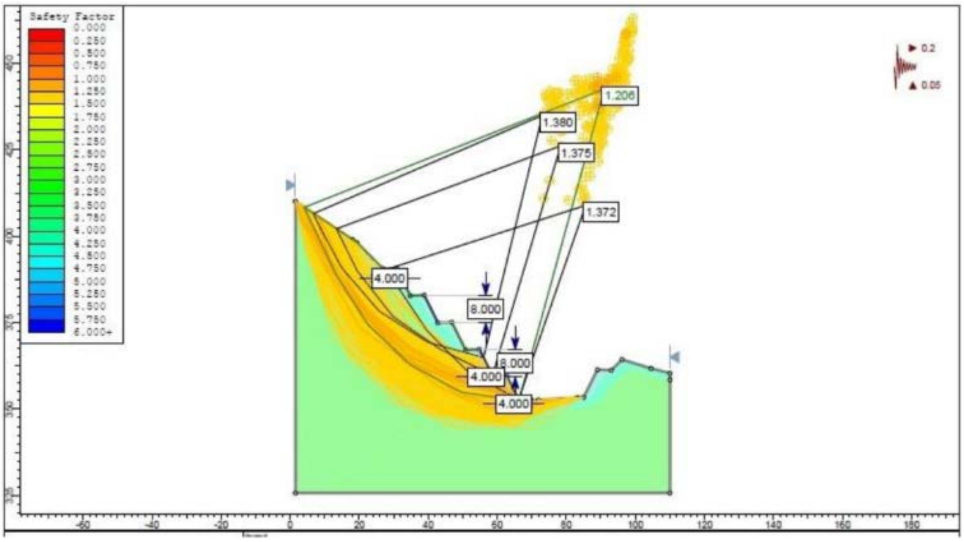

Figure 7. Calculation model for stability analyses with LEM method for left side of the cut at km 2+700.

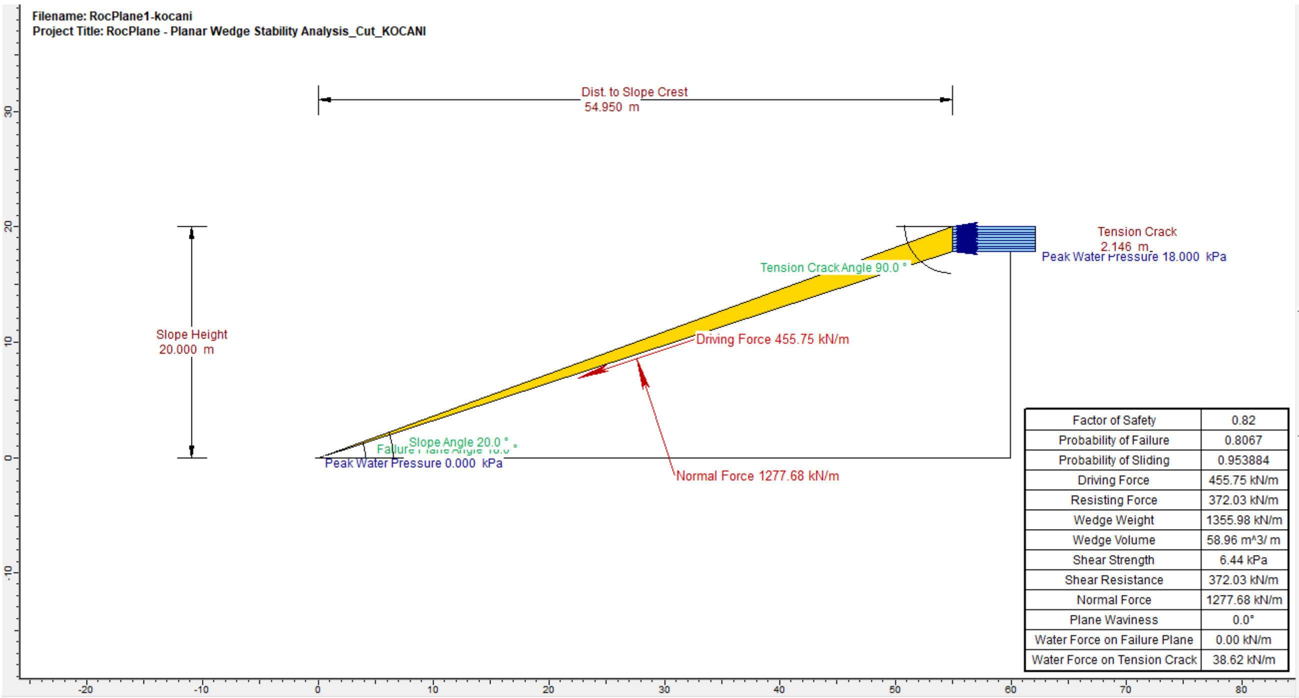

Figure 8.Calculation model for planar failure at the right side of the cut at km 2+700 using Eurocode 7, Design Approach 3.

Suggested methodology for integral approach

The presented results indicate that, in practice, every case is unique, and needs adequate attention in model preparations. The fact is that there are many guidelines for the design of slopes in rocks, including weak rock masses. Anyhow, there are still a lot of open questions to be analysed. The difficulty in determining the long-term stable slope geometry arises from the geological uncertainties within the rock mass. Although some methodological approaches can take into account these uncertainties, a major drawback that remains is the difficulty in defining an acceptable (adequate) level of risk.

This can be solved if only we use some integration of knowledge from several engineering and other disciplines. The integrated approach assumes that the problem shall be analysed from several perspectives, not always strictly related to geotechnical engineering. For example, in rock engineering problems, input from structural geology in rock mechanics is very important.

It is very obvious that the main step is to produce reliable geological and engineering-geological models, where the separation of quasi-homogeneous zones per necessary parameters for analytical or numerical analyses is necessary. The design model should incorporate slope protection methods, actions and resistance. All elements shall be analysed by an adequate geotechnical calculation model. After problem definition in critical zones, typical phases of the slope stability and slope protection program based on adequate investigation and design process shall be applied. Methodology must include a back-analysis of the past failures, prognosis failure modes, estimation of rock strength along joints etc. In brief, the methodology is based on the application of several interrelated phases, using the following approaches (Jovanovski et al, 2017):

- Analyses of possible kinematic modes of failure;
- Statistical analyses in order to define the probability distribution functions;
- Defining the factor of safety (Fs), probability of failure (PF) and reliability index (RI);
- Analyticaland/or numerical analysis;
- Definition of the risk from sliding or rockfalls;
- Cost-benefit analyses;
- Definition of the acceptable level of risk (ALR);

Integration of all findings.

For example, the risk level can be proposed using ideas presented in Fig. 9. The upper portion of the diagram presents a combination of the values of mean factor of safety and the probability of failure. The down portion presents a combination of the probability of failure and the potential economic losses in the event of an incident. In the diagrams, there are zones considered with broadly acceptable (BA), acceptable (A), conditionally acceptable (CA) and non-acceptable (NA) level of risk. The zone NA indicates an unacceptable level of risk and must be avoided or reduced, irrespective of the benefits.

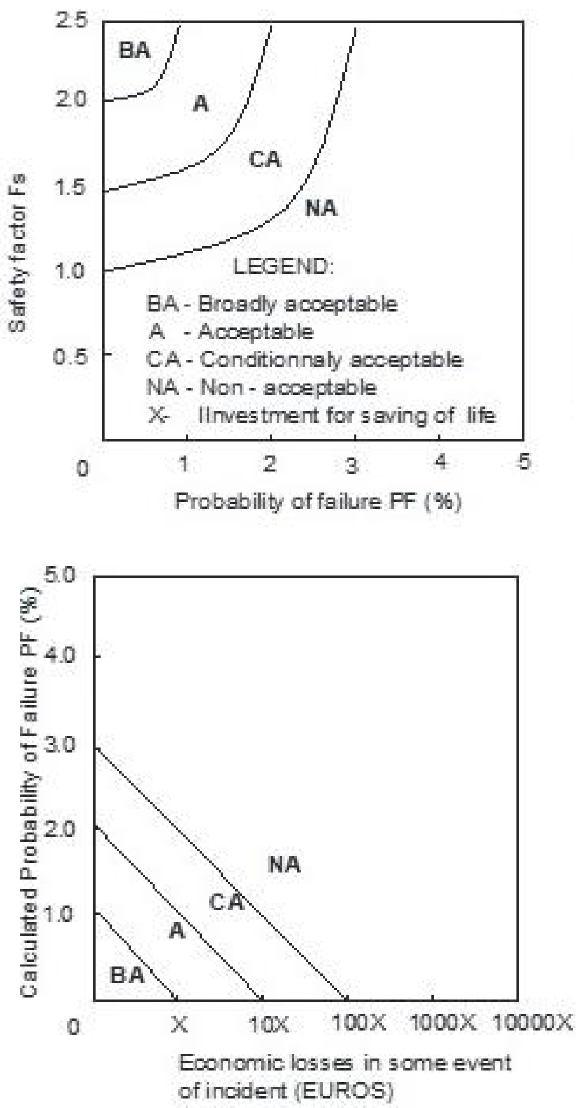

Figure 9.One concept for defining an acceptable level of risk. Upper section: mean value for the factor of safety vs. probability of failure; down section: probability of failure vs. potential economic losses in the event of incidents (Jovanovski et al,2017).

Within the CA region, the risks may be tolerated, but here there are possibilities for some optimization of solutions. The value X in the right diagram portion includes possible economic and life loss impacts. In different countries, such values can be adopted using the country's GDP, values from insurance companies and other specifics in each country, but explanations overcome the frame of this article.

Every time when possible, it is good to combine methods and not to use only one approach. For example, in Fig. 10, a correlation is established between the results from Q-slope and SMR analyses. In Fig. 11, a combination of empirical and analytical methods is presented. Such combinations can give us the possibility to find some „weak points" or confirmation approaches with cross–checking of findings.

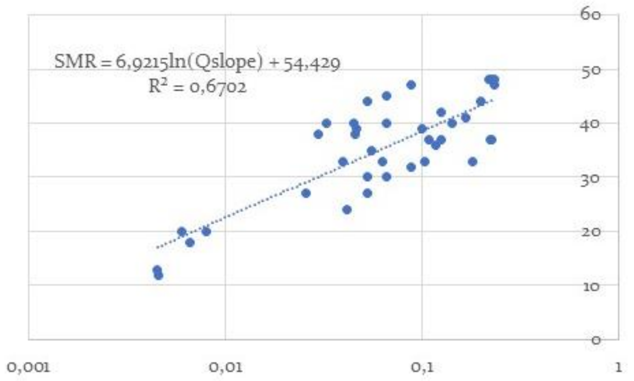

Figure 10.Correlation between the values of SMR and Q-slope for a cut at the express road from Kriva Palanka to the Bulgarian border.

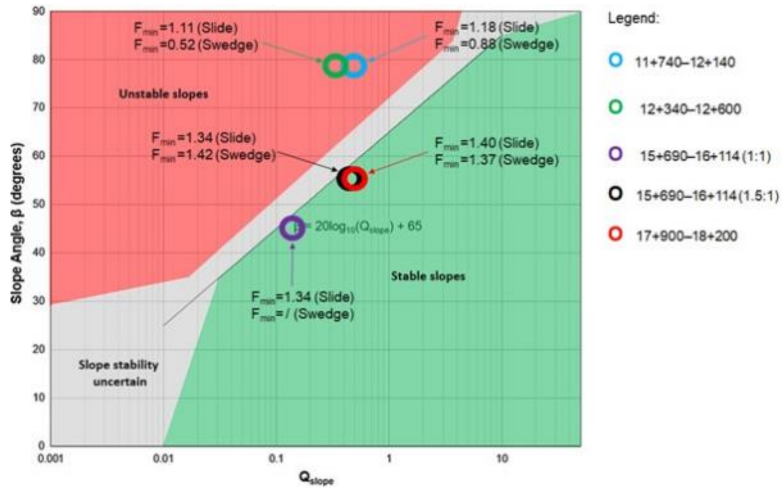

Figure 11. Q-slope stability chart (Barton and Bar 2015, 2017) for the subject cut slopes and their corresponding factors of safety obtained with LEM in Slide and Swedge (Janevski et al.,2020).

If we compare the correlation from Fig. 10, we can only underline, that recommendations from Q-slope methods are usually related to stable slope angle, but without supporting structures, while SMR for categories with lower values typical for weak rock masse, usually suggests applying some protective measures.

The circles in Fig. 11 represent the Q-slope value and obtained factors of safety in the software package Slide in a parallel way. Circles refer to the global stability and the factors of safety obtained with Slide software, or results for local instabilities defined for wedge mode of failure with software package Swedge. According to the results, it is clear that the cuts with failures are quite deep in the unstable zone of the Q-slope stability chart. Also, for these two cuts, the values of the factor of safety against forming surface wedges are smaller than 1.0 which confirms the failures. The global factor of safety does not indicate a failure (which in rock slopes is not common) but it is not satisfactory either.

Some additional ideas in the methodology are based on the findings from the highway from Kicevo to Ohrid. The summary of the results from the deterministic and probabilistic slope stability analyses for all of the cuts is shown in Tab. 2.

Table 2. Summary of the slope stability analyses (Janevski et al,2021).

Cut information	No. of cuts	Safety factor	Reliability index	Probability of failure [%]
Failure occurred	15	1.06 – 1.26	1.27 – 1.98	1.5 – 9.8
Minor deformation	15	1.08 – 1.43	1.71 – 3.05	0.3 – 4.9
No deformation	23	1.39 – 1.69	2.40 – 5.50	0.0 – 1.0

The results for the cuts with failure which initially were considered to be stable, show a factor of safety greater than 1.0, reliability index less than 2.0 and probability of failure less than 10%. Hence, this can be a motivation for further improvements of the methodology and redefine the possible uncertainties of the cut slopes in weak rocks.

Some open questions

Presented findings show that the problem of stability in weak rocks is very complex, and needs a lot of attention. In fact, newer approaches related to the reliability design methods and the probability analyses, indicate that there are still some open questions.

New trends that should be followed in the near future in preparation for the next Eurocode 7 generation shall also incorporate term consequence classes CC [10]. In Table 3, we present ideas for further analyses, in the form of recommended values for weak rock slopes. A summarised simple diagram is presented in Fig. 12. If we want to reach the acceptable zone (A) defined in Fig. 9, and if we want to achieve the desired value of RI=5, we must invest more resources in the remediation of the slopes. Some additional open questions can arise, related to values of Disturbance factor D in analytical and numerical analyses (Fig.13 and Fig.14).

Table 3.Authors suggestions for a value for Reliability Index and Probability of Failure for rock slopes in weak rocks related to Consequence's Classes in Eurocode 7.

Consequence Class	Reliability index	Probability of failure [%]
Lower CC1	1.27 – 1.98	1.5 – 9.8
Normal CC2	1.71 – 3.05	0.3 – 4.9
Higher CC3	2.40 – 5.50	0.0 – 1.0

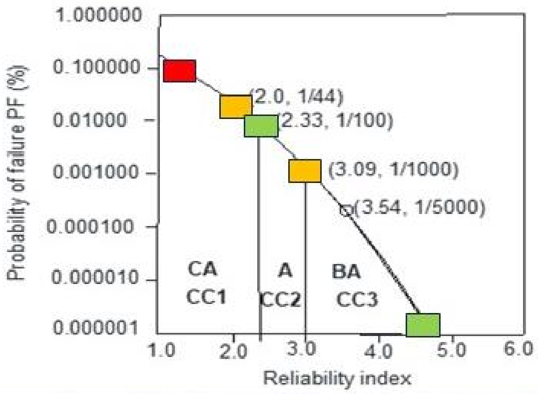

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Figure 12. Diagrams presenting consequence classes from Eurocode 7, reliability index and value for the probability of failure and the level of risk from Fig.9.

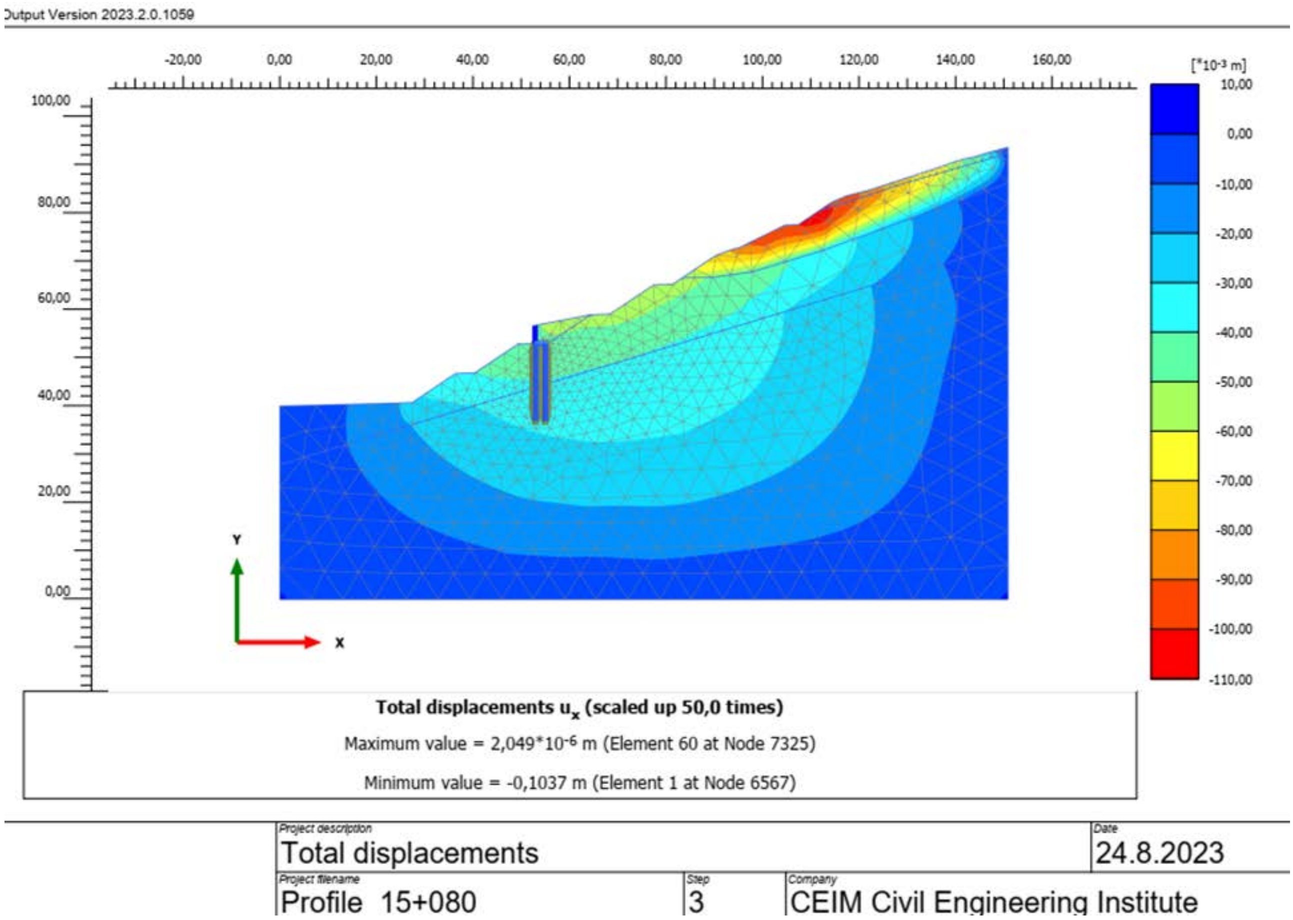

Figure 13.Numerical analyses for a cut slope at highway from Kicevo to Ohrid using the Plaxis software.

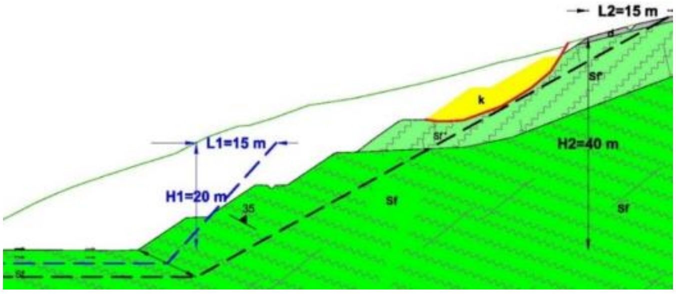

Figure 14.Geological section illustrating two possible solutions for the cut presented in Fig. 13, using reinforced concrete structure (blue colour) or unloading of slope and delineation of disturbance zone (blue for the first solution, black for the second solution).

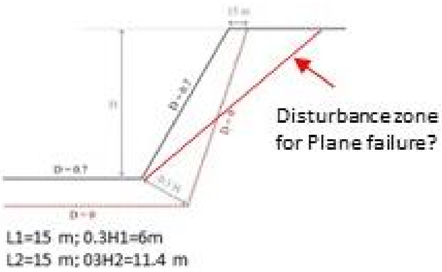

Figure 15.Diagram for defining the disturbance zone of slopes.https://www.rocscience.com/help/slide2/tutorials/tutorials-overview/damage-regions-generalized-hoek-brown

A lot of discussions can be opened if such recommendations for disturbance factor D and if the interpretation of disturbance zone for different slope heights can be similar for slope crest. Certainly, such recommendations cannot be valid when planar failure is the dominant failure mode (Fig. 15).

Finally, as an idea for further analyses, in weak rock mass media, we can underline a problem in the interpretation of rock bridge influences in assuming shear strength and coefficients of normal (K_n) and shear stiffness (K_s) along sliding surfaces, in a process of relaxation of rock mass during excavation, etc. These aspects are highlighted as an area for further scientific analyses, with one main goal – to get closer to the real mechanical behaviour of weak rocks during construction.

Conclusions

The article highlights some specific aspects of the stability behaviour of weak rock masses. The main conclusion is that the optimal way to assess the stability condition of slopes is to combine different tools and techniques and to choose which one suits best for the selected case. The given analyses show that all experiences and practices can be useful in developing some new ideas, despite the fact that each case is unique and has to be considered in terms of a particular set of circumstances. Solutions should be based upon detailed analyses, but also on engineering judgement guided by practical and theoretical studies of rockfall risks and stability of the slopes. The authors believe that the presented experiences can help in establishing an effective way for the protection of rock slopes susceptible to different modes of failure.

Acknowledgements

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