



Петти симпозиум на ДГМ

Специјализирана конференција на ISRM

Втора конференција на регионалните геотехнички друштва

Инженерски проблеми во меки карпи

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ISRM Specialized Conference
2nd Conference of regional geotechnical societies
Engineering problems in soft rocks



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One approach for design and construction of slopes in andesitic rocks prone to deterioration

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ABSTRACT

This paper presents an approach applied in the design and construction of one cut at the section km 24+740 - km 24+960 from the expressway A4, section Stip – Radovich, a part of the Macedonian road network in construction. The road in some zones is constructed in hydrothermally modified rock mass of andesitic type, with complex geological structure and alternation of different zones within the massif, prone to deterioration. In the frame of this article, the approach based on the integral application of empirical – analytical, and observational methods during the design and construction is presented. Some results from investigations and correlations between the investigated parameters necessary to define optimal elements of the slope are also given. The complexity of the problem, requiring consideration and inclusion of many factors in the analysis and the degree of uncertainty of the input parameters, especially in zones of rock masses prone to weathering and deterioration, is pointed out. The example indicates that sometimes it is almost impossible to fully predict all geotechnical and construction aspects in the initial stages of research and design. It is noted that every engineering problem is a unique challenge, which requires the cooperation of all parties involved in investigation, design, and investment in capital projects. In this regard, some recommendations on the acceptable values of the factor of safety and probability of failure, in the context of the rank of the object are presented.

KEYWORDS

Andesite; Acceptable level of risk; Weathering; Rock Slope Engineering.

1. INTRODUCTION

The practice in Rock Engineering shows that slope design and construction in rock masses is an extremely complex task, which requires an adequate methodology of analysis. Overall management of such problems requires an ongoing assessment where all known methods of analyses (empirical, analytical, numerical, and combined approaches) should be related to the Observational Method (OB) implemented in the phase of construction (Eberhard E., 2011, Boguszh and Goblewski, 2019). The quality of the conceptual geological models and the geotechnical information available has primary importance in all phases, and the reliability of such model shall be improved from phase to phase.

Sometimes, accumulated experience and application of empirical methods have the primary role in decision making during construction. This comes from the fact that...” it is practically impossible to assess the stability of rock slope cuttings and benches in real-time, using analytical approaches such as kinematics, limit equilibrium, or FEM/DEM modeling...” (Barton and Bar, 2017).

Related to this article, several approaches are important. For example, empirical methods are important because they incorporate in implicit manner experiences from numerous cases of construction in a variety of complex geological conditions. Over 100 classification systems have been developed. These include the RMR (1973) and Q (1974) systems, the Slope Mass Rating (SMR)

system proposed by Romana (1993), the GSI system by Hoek (1997), Sonmez and Ulusay modification of the GSI system (1999), the SSR (Taheri et al., Slope Stability Rating system, 2006), Bar and Barton's Q-slope system (2015), and others.

A particular problem can occur in certain types of rocks, which when exposed to atmospheric influences quickly lose their physical-mechanical properties, i.e. are prone to weathering and deterioration. Neglecting this phenomenon can lead to numerous problems such as instability of the slopes, the occurrence of landslides, and the need for expensive slope protection. These aspects were analyzed by many authors, for example, Dearman and Fookes, 1974, Dearman 1976, Martin and Hencher 1986, Ansari et al. 2012, Gupta 2006, Ahmad et al. 2013, resulting in different classifications describing the weathering grade of rocks. The quantification of weathering grades is also presented in The ISRM Suggested Methods for Rock Characterization, Testing and Monitoring (1981). Rock deterioration assessment (RDA) has been developed in the UK, and extensive work has been done considering all types of rock slopes by Nicholson, while the development of geoengineering classification related to deterioration assessment is presented by Niyogi et al. (2020). Interesting analyzes are also shown by Huisman (2006), where the importance of the so-called primary relaxation of the material after excavation, when the properties and conditions of the rock mass are rapidly changing, being even more emphasized by the atmospheric influences.

According to these analyzes, it may be assumed that to properly assess the impact of the atmospheric influences on the rocks, it is necessary to conduct field exposure of the material near the location where the construction will take part. Hence, the material will be affected by the same atmospheric and climatic conditions. The weathering intensity should be monitored over time by examining the decay strength should be determined with a slake durability test (Angelova et al., 2017). This kind of degradation of rock materials exposed to changing atmospheric influences is especially noticeable in regions with rocks rich in ore minerals, the presence of fault structures, alterations, etc.

This leads to the concept that a final decision shall be based on some element of probability and reliability concepts analyzed by several authors (for example Peshevski et al. (2018), Bogusz W., Godlevski T., 2019, etc.).

2. ANALYZED AREA

The area of analysis is related to the SE part of Macedonia, i.e. the region from the cities of Stip to Radovich, where an expressway with a length of about 30 km is in the final phase of construction. During the construction, several cuts where rocks prone to weathering, such as shales, sandstones, serpentinites, and andesites were noted.

A typical representative is the cut at km 24+740 - km 24+960 in andesites, which will be discussed in this paper. These andesites were created in the past under complex genetic-geological conditions with the existence of fault structures and joints that served as supply channels for hydrothermal influences that decompose the rock. Thereby, generally, two types of andesites were created, older with weaker, and younger with better geotechnical properties. They gradually move from one type to another or alternate between certain joint systems, which significantly complicates the geological composition of the terrain of the micro-location. Besides them, on some zones along wider faults, the alterations are also present, which leads to the approach to divide them as "separate" quasi-homogeneous zones. It can be underlined, that until the start of the excavation, it was very difficult to estimate the extent to which atmospheric influences would affect all separate zones without special testing. Also, the presence of many geological phenomena such as hydro-thermal changes, fault structures, filled joints, etc., has a significant impact on accelerating the weathering process. So, some conclusions from the construction phase are briefly presented here.

3. METHODOLOGY OF WORK

The excavation of the cut started with an inclination of 4:1 and berms 3 meters' width on every 8 meters of height. This produced a general slope angle of about 70 degrees, for a maximal height on some sections of about 20 meters. During the construction, the method of controlled blasting with a combination of mechanical excavation was used. The excavation of this cut started in May 2019, and in the following summer months, the slopes maintain their stability, the berms keep the designed width, with no significant problems visible. With the advent of autumn, changing weather conditions, and exposure of the rock to atmospheric influences, in November 2019 the first occurrence of a rockfall from the second slope was recorded (Figure 1).



Figure 1. Appearance of a local rock fall (left up), typical picture of relatively fresh jointed andesite (left right), typical picture of altered andesite (down left) and a view on fault zones with higher level of alteration (down right).

After the first rockfall, a detailed prospecting of the condition of the cut was carried out. It was determined that atmospheric influences and temperature oscillations led to a surface decomposition and deterioration of some zones in the andesites. During the winter months, additional and accelerated degradation of the rock, under the influence of the above factors, but additionally the appearance of ice, was observed. In a short period, several smaller rockfalls and leaching of the degraded material appeared, which in some parts led to a local loss of the berms (Figure 2).

Figure 2 shows that the rockfalls occurred mainly on the contact zone between the hydrothermally altered and solid andesites. The negative atmospheric impact by expanding the hydrothermally altered zone in the central part of the incision is noticeable as well. The surface decomposition of andesite is

expressed along the entire length of the open slope. Its intensity is lower at the contact of fresh andesite with hydrothermally altered andesite and is significantly higher in the zones of hydrothermally altered types.



Figure 2. A look on the excavated part of the slope in the period from November 2019 (up) till September 2020 which indicates possible extension of deterioration phenomena's (down).

Based on these observations, and applying the principle of active cooperation between the teams of the investor, the supervisor, the contractor, and the designer, using knowledge from the project Technical Assistance preparation of climate resilience Design Guidelines for the Public Enterprise for roads in Macedonia, World Bank (2019), it was decided to adjust some of the slope designs to reduce the risk to the lowest possible level.

4. METHODS FOR GEOTECHNICAL CHARACTERIZATION OF ROCK MASSES

To find an optimal solution, and to reduce future risks and maintenance cost to a minimum, the following main steps are applied in the analyses:

- Analyses of existing documents;
- Detailed engineering geological mapping, including simple field rock mechanics;
- Laboratory test on rock samples;
- Analyses of relevant geotechnical parameters;
- Defining of Factor of Safety (FS) and Probability of Failure (PF);
- Defining the probability of failure;
- Definition of an acceptable level of risks.

In the first place, parameters of intact parts were analyzed, using numerous results from Point Load Strength (J_s-50) and Schmidt Hammer Rebound Value (SHRV). Their distribution is presented in Figure 3.

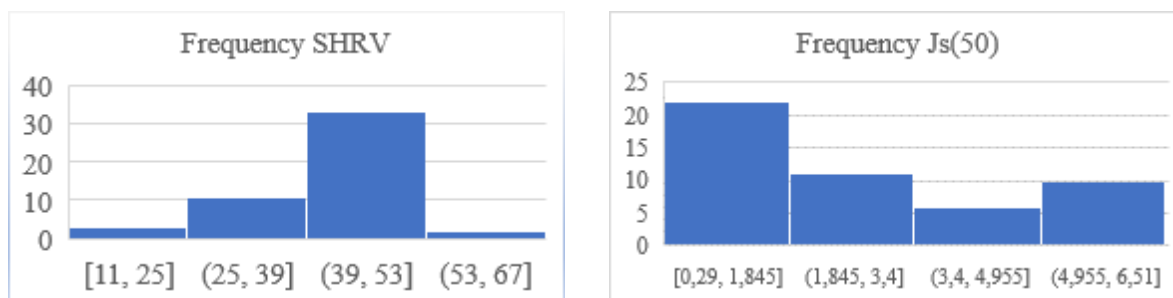


Figure 3. Diagram of distribution of values for SHRv and Js-50.

After dividing main ranges for altered and fresh varieties of andesites, the established correlations between main intact rock mass parameters are presented in Figure 4, Figure 5, and Figure 6.

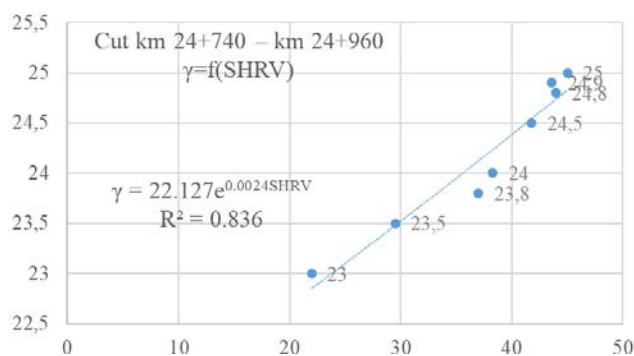


Figure 4. Correlation between Unit weight (γ) and SHRv value for divided classes of parameters.

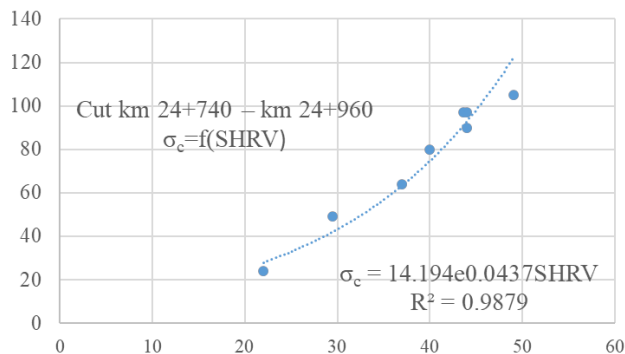


Figure 5. Correlation between Uniaxial Compressive Strength (σ_c) and SHRv.

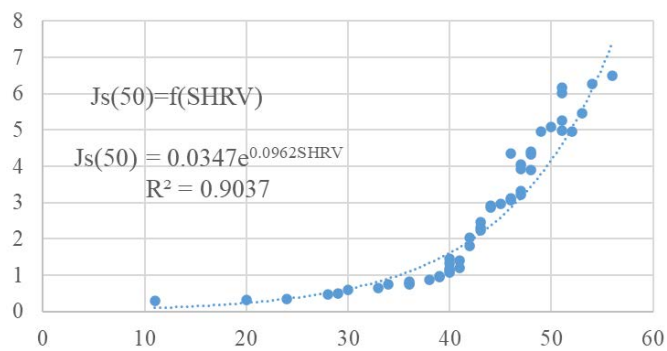


Figure 6. Correlation between Js (50) and SHRv.

It may be mentioned that the hydrothermally altered andesite, in some parts, is almost completely grussified and altered to the extent of coarse-grained soil. The examination of the residual strength of grussified material shows that the residual friction angle has values from $\phi=29$ to $\phi=35.7^\circ$. This indicates that this composition of the material has quite high friction.

The second step in the analyses, was the extrapolation of data from the intact parts, to the level of rock mass parameters. Only a brief form of the results is given in Figure 7.

The presented curves in Figure 7, are obtained by using the empirical failure criterion of Barton and Chobeau (BC) for typical joint surfaces and Hoek and Brown criteria (HB) for rock mass. It is visible, that the shear strength of the fault zone (Fz) and the altered andesite (a) is in the same range as for joint surfaces. This indicates that a global failure should not be expected, and some local wedge failures shall be the dominant failure mode.

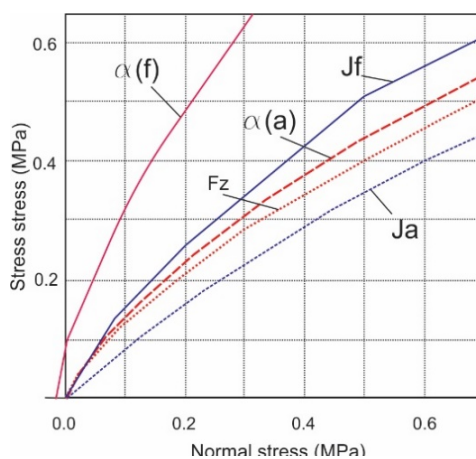


Figure 7. Presentation of typical curves normal stress – shear stress for typical rock mass zones and joint surfaces: $\alpha(f)$ - fresh andesite; $\alpha(a)$ - altered andesite; Fz (fault zone) using HB empirical criteria; Jf - joints in fresh andesite's and Ja – joints in altered andesite's using BC criteria.

An important step is the definition of the possible deterioration and the degree of weathering using some known parameters because this has profound effects on the physical and mechanical properties of rock material and the development of further instabilities. The main equations are presented below.

$$Vr = \frac{Gh - G_o}{Gh - G_a} \quad (1)$$

where Vr is the degree of weathering by Zolotarev, Gh is the value of a chosen parameter for fresh rock, G_o is the value of the analyzed zone and G_a is the value for altered rock.

$$K_t = \frac{V_u - V_m}{V_u} \quad (2)$$

where K_t is the coefficient of weathering by the modification of Iliev's method (1966), V_u is the value of the chosen parameter for fresh rock and V_m for altered rock.

$$Rs = \frac{\sigma_c(\text{weathered})}{\sigma_c(\text{fresh})} \times 100 \% \quad (3)$$

where Rs is the strength ratio according to Gupta and Rao (1996), σ_c is the value of compressive strength for weathered or fresh intact rock samples.

It should be noted, that primary, the expression in equation 2 was developed by Iliev using values of sonic velocities of samples, but in this case, we modified it by using values for the parameters presented in Table 1.

Table 1. Some data about weathering or alteration parameters and coefficients using different methods.

Zone in rock mass	Unit weight γ (kN/m ³)	SHRV	σ_c (MPa)	Vr cases for γ , SHRV and σ_c	Kt cases for SHRV and σ_c	Rs (%)
Fresh andesite	25-25.5	45-50	80 - 105	0 – 0.25 0 - 0.16 0 - 0.27	0.1 0 - 0.24	95- 100
Altered andesite	24-24.5	25- 30	30-35	0.4-0.75 0.66- 0.83 0.83-0.88	0.4 - 0.5 0.71 - 0.76	33-37
Fault zone	23 – 23.5	15-20	15-20	1	0.6 - 0.7 0.90	18 - 19

In Zolotarev's original classification, the values $Vr = 0.9 - 1$ are for highly weathered (altered) rocks, $Vr=0.7-0.9$ for weathered rock, $Vr = 0.3 - 0.7$ for moderately weathered rocks, and $Vr = 0 - 0.3$ for slightly weathered rocks. The suggested range of weathering indices is presented in Table 2 (based on Gupta and Rao, 1996, Iliev and Zolotarev indices, classes are partially modified).

Table 2. Suggested range of analysed weathering indices in correlation with ISRM classes.

Weathering grade (ISRM,1981)	Rs	Ku	Vr
I (Fresh)	80-100	0	0-0.1
II (Slightly weathered)	50-80	0-0.4	0.1- 0.3
III (Moderately weathered)	25-50	0.4 -0.7	0.3-0.7
IV (Highly weathered)	10-25	0.7-0.8	0.7-0.9
V (Completely weathered)	<10	0.8-1.0	0.9-1

Based on these analyses, without details, a typical range of values for the three main quasihomogeneous zones, according to several different rock mass classification methods, are given below. Namely, Rock Mass Rating (RMR 89' version), modified GSI value (Sonmez & Ulusay, 1999), Slope Stability Rating (Tahery et al., 2006), and Rock Slope Deterioration Assessment – RDA (Nicholson and Hencher, 1997) are presented.

Typical for the RDA assessment is that the weathering indices are included in the classification and several-step analyses. The values of RDA serve as a guide for the necessity of slope protective measures.

SSR assessment has been proposed to study the stability of fractured rock slopes with non-structurally controlled failures. In this method, the GSI value, uniaxial compressive strength, rock type, excavation method, groundwater influences, and the expected horizontal earthquake accelerations are included.

Table 3. Some data about weathering or alteration parameters and coefficients using different methods.

Zone in rock mass	RMR	GSI	SSR	RDA1
Fresh andesite	51-59	45-55	84- 86	38
Altered andesite	24-29	19-25	40-44	69
Fault zone	18-22	17-20	25- 29	81

In table 4, analyses for Qslope values, based on Bar and Barton methodology defined with equation 4, are presented.

$$Q_{slope} = \frac{RQD}{J_n} x \left(\frac{J_r}{J_a} \right) x \frac{J_{wice}}{SRF_{slope}} \quad (4)$$

Where *RQD* is Rock Quality Designation, *Jn* is Joint sets number, *Jr* is Joint roughness number, *Ja* is Joint alteration number, *Jwice* is Environmental and geological condition number and *SRF* is strength reduction factor.

Table 4. Some data about weathering or alteration parameters and coefficients using different methods.

Zone in rock mass	RQD/ <i>Jn</i>	<i>Jr</i> / <i>Ja</i>	<i>Jwice</i> / <i>SRF</i> _{slope}	<i>Q</i> _{slope}
II	82/12	2/2	0.7/2.5	$6.83 \times 1 \times 0.28 = 1.93$
III	56/12	1/3	0.6/5	$4.66 \times 0.33 \times 0.12 = 0.185$
IV	25/12	1/4	0.6/10	$2.77 \times 0.06 \times 0.25 = 0.042$

Without going into details, it may be noted that according to the RMR system (Bieniawski, 1989) fresh andesites have a rating between RMR= 51 – 59 or class III, for altered andesites, RMR =24 – 29 or class IV, while fault zones belong to class V. The classification methods are further used in the estimation of rock mass parameters in the stability analyses, or in the final selection of design solution. For example, from the *Q*_{slope} system, the angle of stable slope (β) without application of supporting measures can be assumed. RDA approach suggests the relationship between deterioration mechanisms involved for specific rock type and stage three, i.e., RDA3 helps design site-specific remedial measures (Niyogi et al., 2020). The details overcome the goals of this paper.

5. STABILITY ANALYSES AND SELECTION OF SOLUTION

To confirm the stability conditions of the cut, first, detailed analyses of the kinematic conditions defining the possible mode of failure are carried out. Stability analyses for a case of global failure are excluded even for the design case of slope angles of 4:1, but there are several combinations of joint sets, slope angles and orientation that indicate a possible development of wedge failures. Details are given by Petkovski et al. 2020 in the design document, and here we are presenting only one case of the analyses using the software SWEDGE (Figure 8).

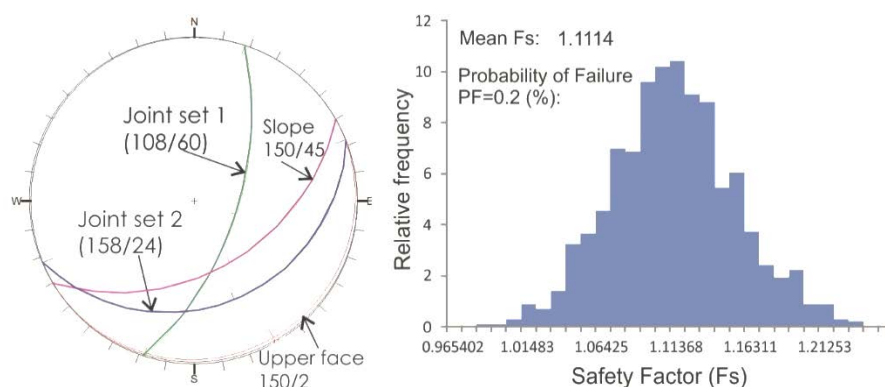


Figure 8. Left – Stereographic plot of joints and slope elements used for wedge analyses; Right - Diagram presenting distribution of Safety Factor (*F_s*) and Probability of Failure (*PF*) for a case of wedge analyses with applied horizontal acceleration *a_h*=0,1g and 30% infilling of joints with water mean value of *S_f*=1,11, probability of failure *P_f*=0.2% (Note: for same wedge in static conditions and without groundwater influences *S_f*=1.57 while *P_f*=0).

The values of the internal friction angle for joints (ϕ) in the range from $\phi=30-35^\circ$ and the unit weight $\gamma=23.5-25 \text{ kN/m}^3$ are used in the analyses. It should be noted, that on some sections, for the initial design of slope elements with an inclination of 4:1, there are cases with $F_s < 1$ and a high probability of failure, which is confirmed by the occurrences of local rockfalls presented in Figure 1 and Figure 2. By lowering the slope inclination in 1:1, the risk of wedge failures is reduced i.e. the prerequisites for wedge forming are not fulfilled. Analytical solutions show that not only the global but also the local stability is on the safe side, with a very low risk of occurrence of local instabilities (see Figure 9). The

diagram is constructed according to the ALARP concept, modified by Peshevski et al. (2018), where besides technical costs and benefits, the analyses shall assume costs for possible life loss prevention.

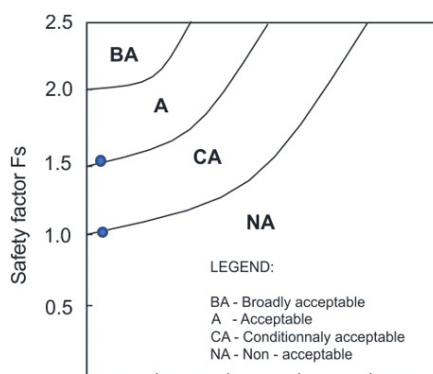


Figure 9. Diagram for defining an Acceptable Level of Risk with several zones based on combination of F_s and PF , illustrating the position for the case from Figure 8 with blue circles.

It is visible that for the given case in Figure 9, the values of F_s and PF are in the acceptable (A) zone for static loads and conditionally acceptable (CA) zone in case of earthquake influences.

To compare the results with other approaches, in Figure 10, the Bar - Barton Q_{slope} diagram is used.

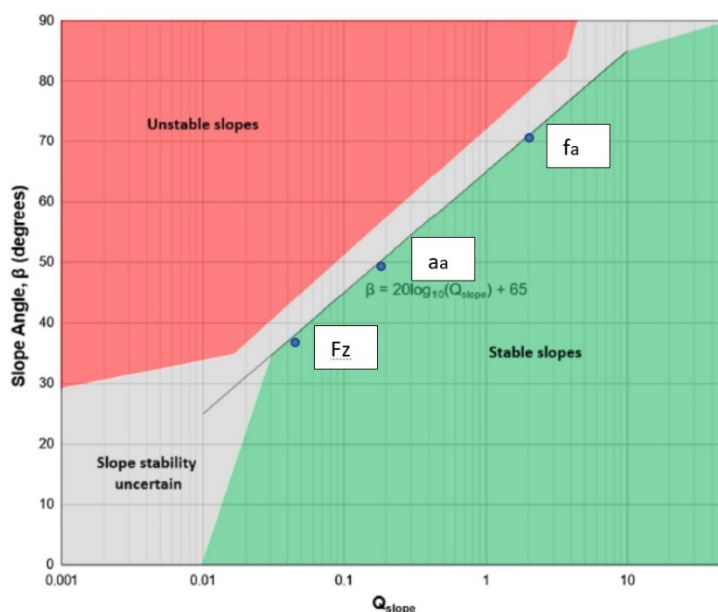


Figure 10. Q-slope stability chart with a presentation of the position of points for cases of fresh (fa), altered (aa) andesite, and fault zone (Fz), where the stable slope angle β without application of special protective measures is visible.

Finally, to choose the most optimal solution, four alternatives were analyzed. Variant 1 and 2 included moving the slope's toe 3m/4m from the road, lowering the inclination in 1:1 and construction of berm at 15m height with 5m width. Variant 3 and 4 included keeping the originally designed slope but protected with shotcrete with 15cm thickness and different anchors combinations. Techno-economic analyses indicate that it is optimal to choose safe, maintenance-free, and reinforcement free solution (Figure 11). Installation of protective wire mesh on the entire slope and locally horizontal/inclined drainage pipes at an angle of 5-10° is also recommended.

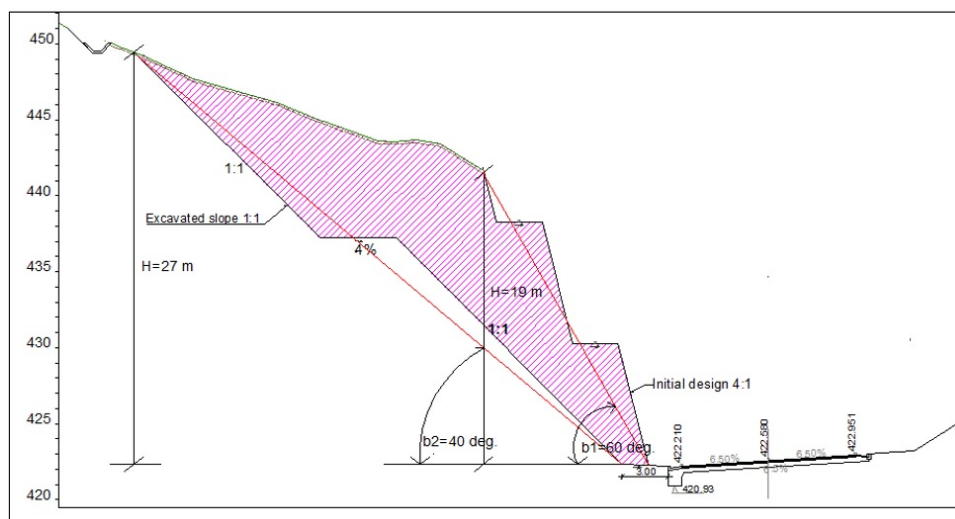


Figure 11. Presentation of solution for the cut on the km 24+740 - km 24+960

6. LESSONS LEARNED AND CONCLUSIONS

In the traditional geotechnical design practice, there is a multitude of methods that enable the design of complex structures, but this is a field that still has scope for further development. For the reasons stated in the article, it is important to note that the geological interpretation of materials in terms of their geological past is very important in assessing the mechanical properties of rocks, and therefore geology as science is of great importance in geotechnics (Wood, 2004). According to the analysis in the paper, it follows that on the stability of the cuts that are made in rocks prone to degradation, there are many challenges, which should be considered in terms of an acceptable level of risk to the object and traffic safety. It seems that the application of the observational design method is inevitable in the design and construction of roads. This approach certainly carries some risk of slowing things down and is usually difficult for investors to accept. This is related to the contractual aspects, but in the long term, the changes made on time, before the completion of the object, bring a conditional gain on the part of minimizing maintenance costs, and the most important aspect, safe and secure operation of the facility. The need for active communication of all parties involved in the decision-making process is obvious.

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