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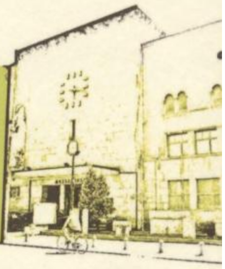

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GEOTECHNICAL HAZARDS AND RISKS: **EXPERIENCES** AND **PRACTICES**
GEOTECHNISCHE GEFAHREN UND RISIKEN: ***ERFAHRUNGEN*** *UND* ***PRAXIS***

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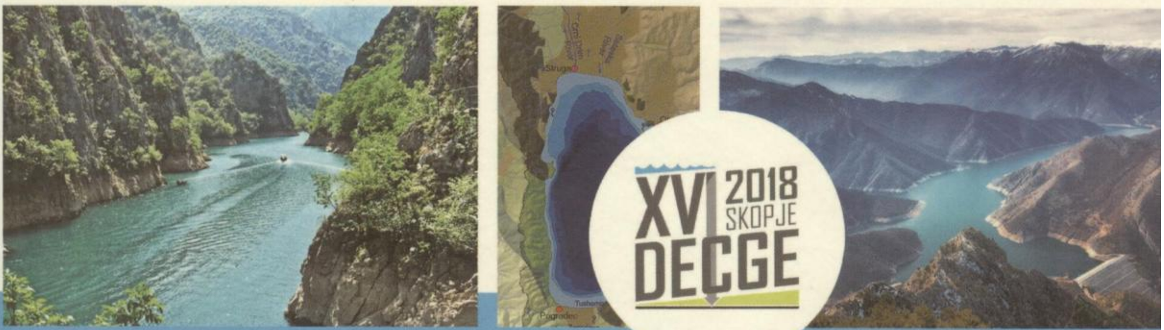

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GEOTECHNICAL HAZARDS AND RISKS: EXPERIENCES AND PRACTICES

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GEOTECHNISCHE GEFAHREN UND RISIKEN: ERFAHRUNGEN UND PRAXIS

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One approach in definition of acceptable level of risk for slopes in hard rocks

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Abstract. Slope stability analysis in hard rocks is one of the most complex tasks in geotechnical engineering. It requires application of specific design principles in order to find a way to incorporate all uncertainties coming from geological, geotechnical, economic and social aspects. In the frame of this article are presented the basics of one approach that shows how is possible to link the acceptable level of risk with the values of Factor of Safety or Probability of Failure. The methodology is supported with some results from stability analyses performed for slopes on the access road to dam “Sveta Petka” in R.Macedonia and some other case histories. Based on these analyses, the article gives some new proposals in definition of acceptable (tolerable) level of risks using also criteria of probability of failure, potential loss of life and economic impacts.

Keywords: Slopes; Hard rocks; Acceptable level of risks; Safety factor; Probability of failure

1 INTRODUCTION

The well known fact is that slope stability in hard rocks is extremely complex engineering problem which requires application of adequate analyses of technical, economic and social aspects. In past decades, numerous attempts are made in order to define a strategy for risk management with an idea to find an optimal compromise between a level of investments necessary to have safe structures and acceptable (tolerable) level of risks. In general, the term ‘tolerable’ means that some level of risks shall be accepted, but the real question is how to define it. General ideas are developed by the United Kingdom Health and Safety Executive (HSE 1988, 1992) in the form of Tolerability of Risk (TOR). Experience shows that rock engineering problems cannot be analyzed separately, and in the process of their solving it is necessary to observe factors in interaction from different aspects. At the moment, in geotechnics, there is still no clearly defined standpoint of what can be accepted as a tolerable level of risks. Some recommendations are given in references (Fell 1994, Fell and Hartford 1997), but still this is an widely open area for investigation. Based on practical experiences gained during working on number of large infrastructure projects in Republic of Macedonia, we are presenting one approach how to find a link between levels of Factor of Safety (SF), Probability of Failure (PF) as well as to define Acceptable Level of Risk (ALR). The explained methodology is related for stability problems for hard rocks, but with some adaptations, it can be also applied for other geotechnical problems.

2 IMPORTANT ELEMENTS IN THE METHODOLOGY

The presented methodology is based on the fact that all geotechnical structures involve a certain amount of uncertainty in the value of the input parameters, influenced by large variation of geological conditions, heterogeneity, anisotropy, discontinuity properties, rock mass strength, stress conditions, groundwater pressures etc. Additional uncertainties to be considered in design of slopes in hard rocks are complex loading conditions which affect reliability of the analysis procedure.

To incorporate all these uncertainties, in the engineering community is widely used the approach by definition of the Factor of Safety (FS). Adaptations to the Factor of Safety approach include sensitivity analysis, in order to investigate effect of variability in design parameters. Reliability analysis is another supporting method, expressed in probability density functions representing the range and degree of variability of the parameter. The definition of Probabilty of Failure (PF) is explained by (Hoek 2007), and it comes from defined statistical distribution and relative frequency of the SF. To explain the concept of Probablity of Failure one case history is presented in Figures 1 and 2.

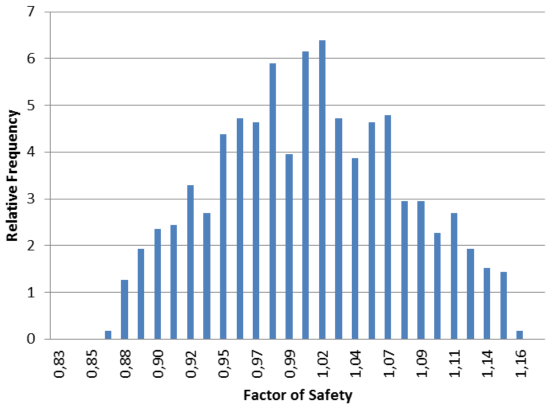

Figure 1. Output from analyses of one slope without protection with mean value of FS=1.008 and PF=44.8%.

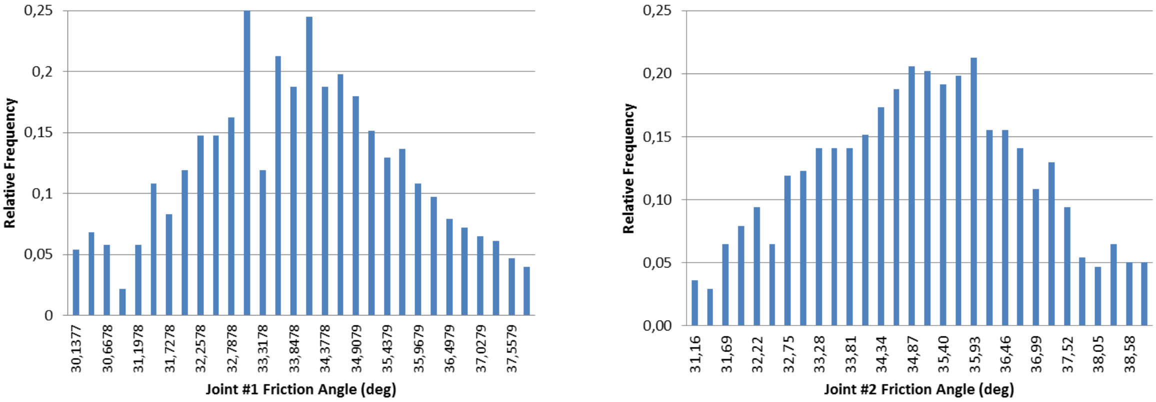

Figure 2. Statictical analyses of shear strentgh along joints forming kinematic mode for wedge failure analyses using software SWEDGE (case for one of the analysed slopes).

The given diagrams in Figure 1 and Figure 2 are connected with a case of slope protection analyses for access road to dam Sveta Petka in R. Macedonia (Jovanovski and Dimitrov 2010, and Jovanovski et al. 2017). The main input parameters for a case of wedge failure are presented in Table 1.

Table 1. Some geometric and input data for one case of wedge failure analysis using software SWEDGE (case history for an access road to arch dam Sveta Petka)

Data about analysis type and loading cases	Mean Wedge Data
Probabilistic analyses	Wedge height (on slope) =23 m
Sampling method=Monte Carlo	Wedge width (on upper face) =10.3005 m
Number of samples=1000	Wedge volume=1618.94 m^3
Number of valid wedges=1000	Wedge weight=4241.63 tones
Water Pressure Data: Percent Filled Fissures=30%	Wedge area (slope)=655.483 m^2
Seismic Data: Seismic coefficient=0.1	Wedge area (upper face)=268.177 m^2

When we come to the definition acceptable (tolerable) level of risk, we will illustrate concept trough the so called ALARP (As Low As Reasonably Practicable) method. The basics are developed by UK Health and Safety Executive in its regulation of the major hazardous industries, such as the nuclear, chemical and offshore oil and gas industries (Lee and Jones 2004), and beside that for slope stability and rock fall problems, as in Ho et al. 2000 (Figure 3).

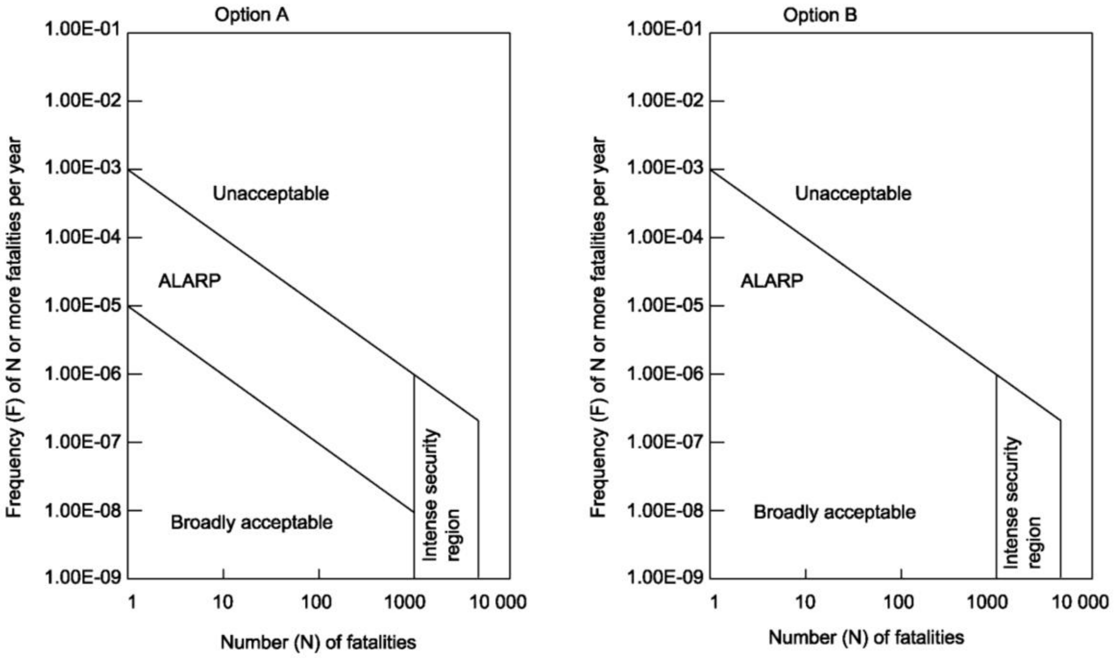

Figure 3. Proposed societal risk criteria for landslides and boulder falls from natural terrain in Hong Kong (Ho et al. 2000, taken from Lee and Jones 2004).

Analyzing zones in Figure 3, if the risk is unacceptable it must be avoided or reduced, irrespective of the benefits, except in extraordinary circumstances. If the risk falls within the ALARP or tolerability region, then cost may be taken into account when determining how far to pursue the goal of minimizing risk or achieving safety. Beyond a certain point, investment in risk reduction may be considered as inefficient use of resources (Lee and Jones 2004).

3 SUGGESTED METHODOLOGY TO LINK THE SAFETY FACTOR, PROBABILITY OF FAILURE AND ACCEPTABLE LEVEL OF RISK

Following the state of the art in this field, it can be noted that there is still not clearly defined what can be accepted as a tolerable level of risk. Based on ALARP concept, in the frame of this article we are suggesting some important steps that are necessary to be undertaken in detailed slope stability analyses in hard rocks, listed below:

- Analyses of possible kinematic modes of failure.
- Statistical analyses in order to define probability distribution functions for all input geotechnical parameters.
- Defining of Factor of Safety (FS).
- Defining of Probability of Failure (PF), expressed with probability distributions of Factors of Safety (SF).
- Definition of risk from sliding or rockfalls.
- Analyses of costs and benefits from using of some supporting mesaures for slopes.
- Definition of Acceptable Level of Risk (ALR).

Outcomes from analyses shall be analyzed with care, in order to assume possible risks. The conceptual diagrams that we are presenting can help in drawing final decisions (See Figure 4). We note that these diagrams should be considered as first idea to define acceptable levels of risk through the Probability of failure approach, and they should be further discussed and improved. Such diagrams may be even connected to hard rock slopes performed for specific cases of construction (roads, railways, settlements, mining, etc.).

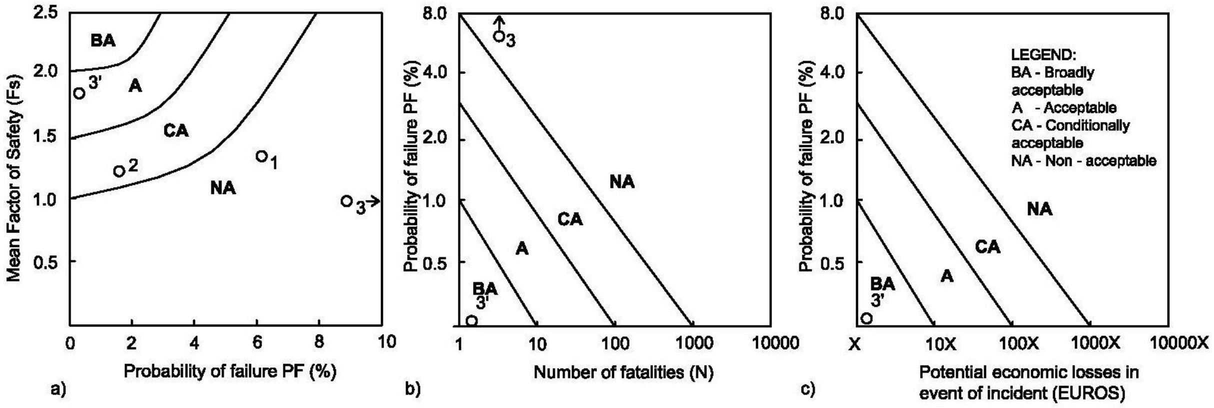

Figure 4. Concepts for defining an Acceptable Level of Risk; a-Mean Factor of Safety vs. Probability of Failure; b-Probability of Failure vs. Number of fatalities; c-Probability of Failure vs. Potential economic losses.

The first diagram on Figure 4 presents a combination of the mean Factor of Safety values with Probability of Failure, second diagram presents a combination of number of fatalities (N) with calculated probability of failure of some slope, while the last one presents relation between probability of failure and potential economic losses in event of incident.

In all diagrams, recommendations are given which zone can be considered as Broadly Acceptable (BA), Acceptable (A), Conditionally Acceptable (CA) and Non-Acceptable (NA). Risk level for zone NA is unacceptable and it must be avoided or reduced, irrespective of the benefits, except in extraordinary circumstances. For cases within CA region, the cost may be taken into account when determining how far to pursue the goal of minimizing risk or achieving safety. As also stated by others, beyond a certain point, investment in risk reduction may be an inefficient use of resources. Within the CA region, risks may be tolerated; however, same as in ALARP, tolerability does not mean ‘acceptability’. BA zone is from safety aspect in general acceptable, but here there are possibilities for some optimization of solutions. As it can be noted, in the diagrams, some marks from 1 to 3’ are given, and they are related to different cases (see Table 2).

Table 2. Illustration of concept with some case histories

No	Author	Value of Factor of Safety	Probability of Failure (%)
1	From Hoek E. 2000	Mean 1.34 (Max 2.33; Min 0.61)	6.40
2	From Poisel R. et al. 2017	Mean 1.3 (Max 2.0; Min 0.9)	1.90
3	Jovanovski et al. 2017 (case without support)	Mean 1.008 (Max=1.16; Min=0.81)	44.60
3’	Jovanovski et al. 2017 (case with support)	Mean 1.76 (Max=1.98; Min =1.46)	0.00

The potential economic losses estimation is also very important. Here, detailed analyses of costs for life, infrastructure and environmental protection, are necessary.

The value X in the third diagram can also be related to possible calculations related to loss of life estimation, as a problem that is heavy to define with one simple value. Some recommendations for 'value of life' estimates used by a range of countries are listed in Table 3. However, preparation and use of such diagrams will always remain questionable topic from many aspects.

Table 3. Typical 'value of life' figures (taken from ERM-Hong Kong 1998)

Sector	Country	Value of life: £ million	Year applicable
Transport	USA	1.67	1993
	New Zealand	0.75	1993
Railway industry	UK	2-5	1993
	France	4	1993
	Germany	1.3-2.1	1993
	Netherlands	0.30	1993
Dangerous goods transportation	UK	2.00	1991
	Hong Kong	2.00	1991

Just to give one example of the possible use of Factor of Safety and Probability of Failure as concepts in defining of acceptable risk, we are presenting case of analyses for access road to dam Sveta Petka marked with points 3 and 3' in Figure 4. In definition of tolerable level of risks, a very useful tool is considered to be the so-called Protection Effect (PE), defined with following formula:

$$PE = \frac{Fs(san) - Fs(prir)}{Fs(prir)} * 100(\%) \tag{1}$$

Where:
PE - Effect from applied measures in increasing of FS (%);
Fs (san) – Factor of Safety obtained with applied measure;
Fs (prir) - Initial Factor of Safety without applied measure.

Application of this concept for the case 3 from Table 2 is presented in Figure 5.

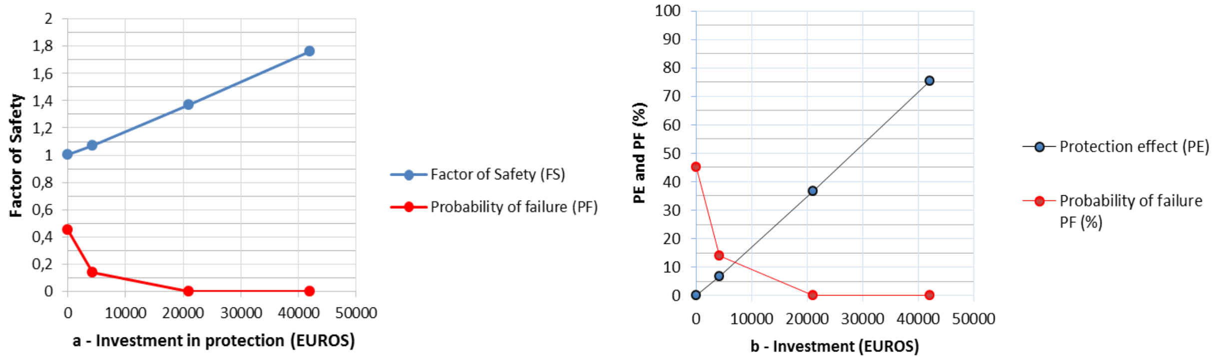

Figure 5. a-Diagrams presenting influence of investment on FS and PF, for the case 3 from Table 2; b-influence of investment (I) on increasing of PE and decreasing of PF.

From the given analyses, it is clear that all problems have to be considered in terms of the particular set of circumstances, as: rock types, design loads and end uses for which it is intended. The responsibility of the geotechnical engineer is to find a safe and economical solution which is compatible with all the constraints which apply to the project. Solutions should be based upon detailed analyses, but also on engineering judgement guided by practical and theoretical studies. These shall be combined with probability theories and risk assesment methods. Some reccomendations about acceptable relative Probabilities of Failure are presented in Table 4.

Table 4. Accepted relative probabilities of failure in percentage (modified from Gibson 2011)

Design Element	Sjoberg	Schellman	Pothitos	Kirsten	Recommended here
Bench	10	12	10-50	20 to 50	10 to 25
Inter-ramp	1 to 2	8 to 10	1 to 3 <1*	5 to 10	3 to 8
Overall Slope	0.3	<8	1 to 3 <1*	1.5 to 5	1 to 3

*Overall or inter-ramp including haul road or key infrastructure

4 CONCLUSIONS

Based on practical experiences and theoretical analyses, in a frame of the article, we are presenting one approach how to find a link between levels of Factor of Safety (FS), Probability of Failure (PF) as well as Acceptable Level of Risk (ALR). Getting the broad range of groups and interests that may be affected by slope stability problems in hard rocks to accept risk-based decisions is often critical to the successful implementation of some risk management strategies. The main conclusion is, there are is an need for improved communication between the geotechnical, traffic, blasting specialists and project managers, economists and social workers in order to find optimal solutions for these and other similar problems in rock engineering.

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