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ONE METHOD FOR DEFINING AN ACCEPTABLE LEVEL OF RISKS IN TUNNELING

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Abstract. *This article presents one method for defining an acceptable level of risks in tunneling. The analyses are based on a simple analytical method for definition of tunnel stability using appropriate software in order to define the stability of excavations with and without protection. These analyses helped to find an approach on how to link the Acceptable Level of Risks with values of the Safety Factor (SF) and the Probability of Failure (PF). The explained methodology is related mainly to tunnels constructed in soft rocks or fault zones, but with some adaptations, it can be applied to other tunneling problems and other engineering structures. The case history used to test the methodology is a diversion tunnel at Hydro System "Sveta Petka" near Skopje. Based on these analyses, one proposal to define an acceptable (tolerable) level of risks using the criteria of the probability of failure and potential economic costs is presented.*

Key words: *acceptable level of risk; the probability of failure, safety factor, stabilization, tunneling.*

1. INTRODUCTION

It is well known that tunneling is a very complex engineering discipline important for civil and mining engineering since constructing tunnel structures comes with a high level of different risks. Designing underground structures, including hydrotechnical tunnels, is a particularly complicated procedure, because of the need to know a large number of engineering and economic factors that in one way or another affect the risks involved in their implementation. The technology of construction should take into consideration several important factors as:

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- The stability of rock mass during excavation,
- Stability of individual large blocks,
- Stability problems due to swelling,
- Resistance to digging, mining, and drilling,
- Conditions for protection from groundwater,
- Conditions for protection against high temperatures and gases,
- Conditions for loading and transportation,
- The impact of working operations on the natural environment, etc.

When performing work, stability in hard rocks is treated in one, and in low-quality rocks in another way, therefore during the construction stage, a large number of specific cases are possible. To overcome this, it is necessary to apply different technical and economic analyses in order to reduce all risks to a tolerable level. The strategy for risk management should represent an optimal compromise between the level of investments necessary to construct safe structures and the acceptable level of risks during or after the construction. At the moment, in tunneling and also in geotechnics, the level of tolerable risks is still not clearly defined. Some recommendations for slopes and tunnels are given in [1], [2], [3], but still this is an open area for investigation. The general concept for the tolerability of risks is developed by the United Kingdom Health and Safety Executive in its regulation of the major hazardous industries, such as the nuclear, chemical, offshore oil and gas industries [4], [5].

Based on this concept, later, the so-called ALARP concept (from as Low as Reasonably Practical) is developed in order to define a tolerable level of risks, and it is explained in [6] and [7]. This is an interesting method which presents the possibility to connect some engineering problems with the tolerable risk level. Based on these approaches, in the frame of this article, we are presenting further possibilities, with an intention to show that it is possible to link the Safety Factor (SF) as a measure of the stability of a tunnel structure, Probability of Failure (PF) and Acceptable Level of Risk (ALR). This is presented through a case of the hydrotechnical tunnel "Sveta Petka" in the Republic of Macedonia, but with some modifications, it can be applicable for other engineering problems.

2. THE BASIC THEORETICAL BACKGROUND OF THE PROBLEM

The presented methodology is connected to the fact that construction of tunnels, slopes, and other underground structures involves a certain amount of uncertainty in input parameters as a result of the complex geological nature and different loading combinations, which affects the reliability of the analysis procedure. To cover uncertainties, in most cases Factor of Safety analysis (SF) is widely used in engineering analyses. Reliability analysis is another supporting method, expressed in probability density functions representing the range and degree of variability of the parameter. An important step is to analyze the Probability of Failure (PF) for rock masses in interaction with the primary and secondary lining (support) defined with an appropriate statistical distribution functions and relative frequency of SF.

The methods mentioned above, are more on the technical side of the problem, which in some way should be connected to the risk assessment methods. From the practice, it is evident that all risks cannot be completely eliminated, and therefore the concept of an acceptable level of risk has been introduced. The essence of the concept is to make a decision that determines the extent to which a certain risk can be accepted when analyzing

a number of factors. At the moment there are a number of concepts related to the topic, such as:

- ALARP (As Low as Reasonably Practicable)
- ALARA (As Low as Reasonably Achievable)
- BACT (Best Available Control Technology)
- RACT (Reasonably Achievable Control Technology)

In order to define the acceptable (tolerable) level of risk, we will illustrate the concept through the so-called ALARP method. The method is applied for problems in hydrotechnical engineering, slope stability, rock fall, and other engineering problems. The basics of the concept are presented in Figure 1.

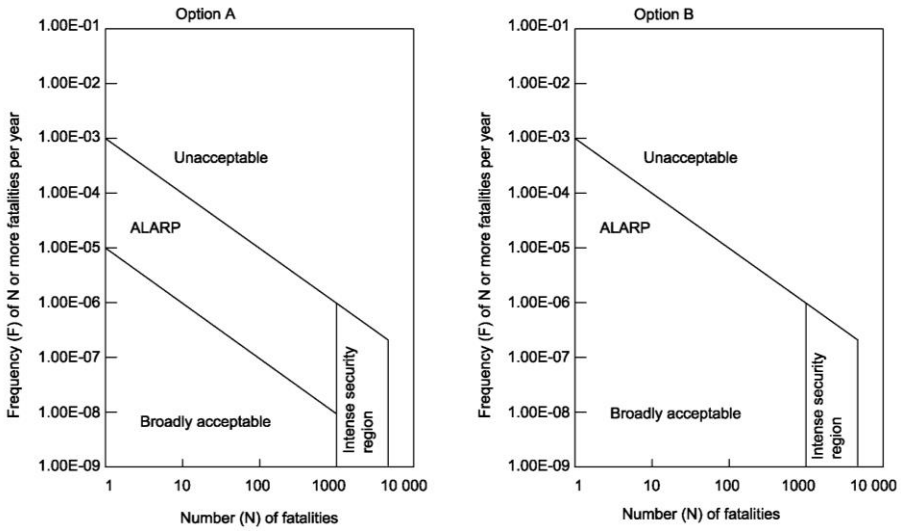

Fig. 1 Proposed societal risk criteria for landslides and boulder falls from natural terrain in Hong Kong [8]

If the risk falls into the unacceptable zone (Figure 1), 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 the 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 an inefficient use of resources. Some analyses in this sense are presented in the frame of this article.

3. ANALYSES

The proposed methodology for connecting the Factor of Safety and the Probability of Failure, with the level of acceptable risks, is presented on the case for a diversion tunnel at "Sveta Petka" dam, near the capital of Skopje, The Republic of Macedonia."Sveta Petka" is a thin concrete arched dam, with a double curvature in the horizontal and vertical direction. The total height of the dam is 64.0 meters, not counting the fencing. Its body has

varying thickness and length- at an altitude of +364.00 m thickness -2.0 m, length- 10.0 m, and in the lower part at an altitude of +300 m - thickness 10.0 m, length 25.0 m. The length of the analyzed tunnel is 360 m., the diameter is 10 m, and the cross-section is circular. It was built in gray-white marbles, with an average compressive strength of 44 MPa, with variations from zone to zone. The main geological and geotechnical data are presented in Figure 2. According to these data, the tunnel is divided into 6 quasi-homogeneous zones with defined values for the deformation modulus (D), elasticity modulus (E), values of propagation velocity of longitudinal seismic waves (Vp), obtained from geophysical investigations, and parameters of rock mass quality based on Bieniawski Rock Mass Rating (RMR) and Barton Quality (Q) systems.

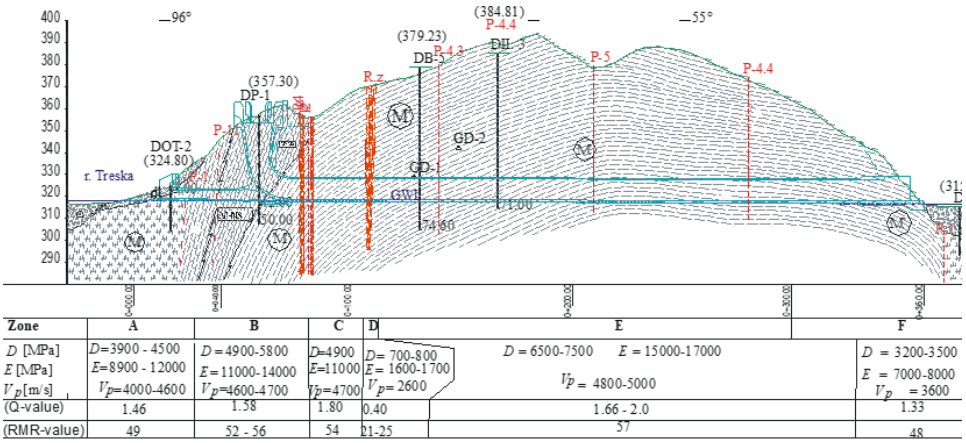

Fig. 2 Longitudinal geotechnical profile of „Sveta Petka“ hydrotechnical tunnel

In order to adequately illustrate the probabilistic analysis procedure, Zone D is used as a testing sequence. This zone is connected with a fault zone that intersects the tunnel. The rock mass in this zone has low quality, according to the RMR value of 21-25. Table 1 shows the input parameters for the zone D when analyzing an unsupported tunnel, using software RocSupport.

Table 1 Input parameters for zone D when analyzing an unsupported tunnel

Property	Distribution	Mean value	Standard Deviation	Rel. Min	Rel. Max
1 Tunnel Radius (m)	Normal	5	2	1	1
2 In-Situ Stress (MPa)	Normal	2.04	1	0.5	0.5
3 Poisson Ratio	None	0.3	0	0	0
4 Dilation Angle (degrees)	None	0	0	0	0
5 Compressive Strength of Intact Rock (MPa)	Normal	25	2	1	1
6 GSI (peak)	None	21	0	0	0
7 mi (peak)	None	10	0	0	0
8 Disturbance Factor (peak)	None	0.5	0	0	0

The following Figure 3 presents the results from the initial case of analyses of the unsupported tunnel opening.

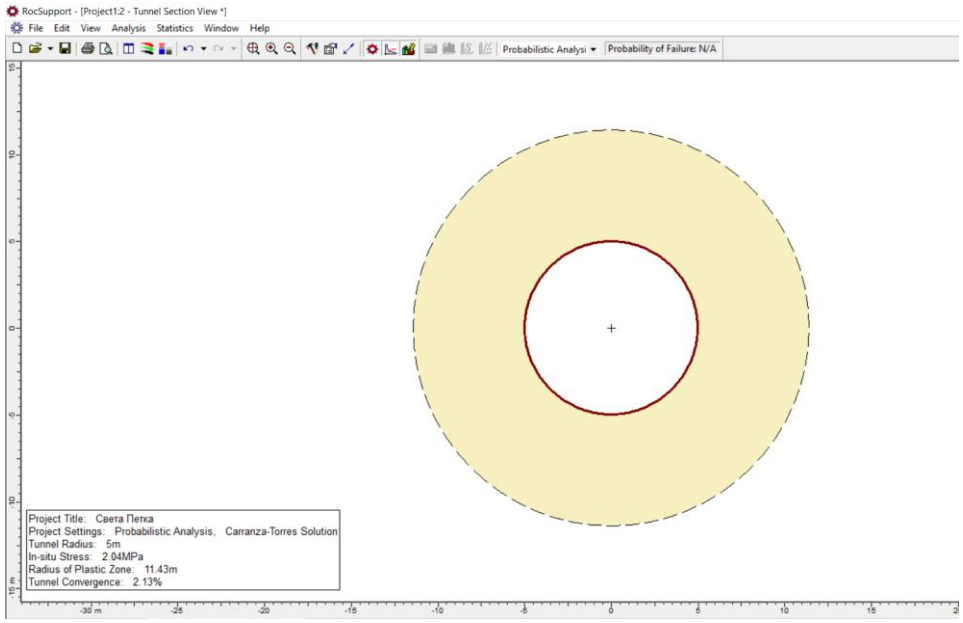

Fig. 3 Plastic zone radius for the unsupported tunnel for zone D

When analyzing the unsupported tunnel, it was concluded that the radius of the plasticization zone is 11.43 m. The excavation, in this case, is unstable and, it is necessary to immediately put primary lining support. Concrete support, with 5 cm thickness, 6 MPa compressive strength, reachable after 12 hours, was analyzed. Results show that the radius of the plastic zone, in this case, is 9.49 m, the safety factor (SF) is 0.45, and the probability of failure (PF) is 100%.

This means that measures need to be taken to increase the safety factor and reduce the probability of failure. Next, an analysis was made for the same concrete support and anchors with diameter Ø25, placed at 2m. After 12 hours, when the concrete reaches a compressive strength of 6 MPa, the safety factor (SF) was 0.75, and the probability of failure (PF) was 100%. After 3 days, with concrete compressive strength of 11 MPa, the safety factor (SF) was 1.02, and the probability of failure (PF) was 47.7%, and after 28 days, when the concrete reaches its maximum strength of 35 MPa, the safety factor (SF) was 2.28 and the probability of failure (PF) is 0%. The results for this case are presented in Figure 4.

It can be noted that the concrete support has a small effect on the radius of the plastic zone, but a significant effect on the safety factor, and the probability of failure decreases rapidly with the increase of concrete strength.

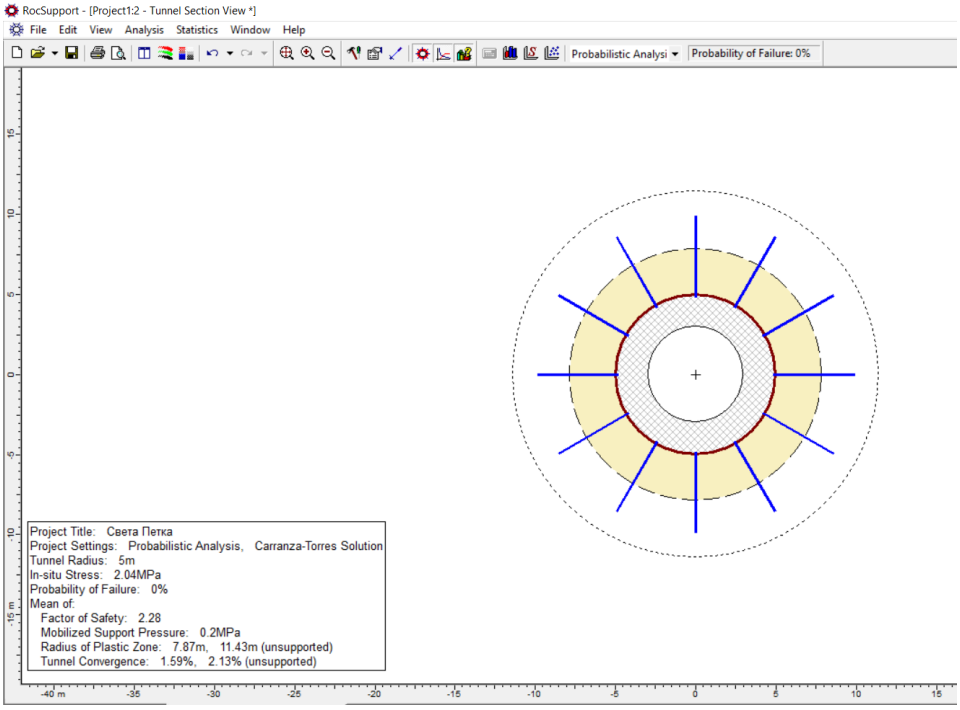

Fig. 4 Tunnel with concrete support 5 cm thick, after reaching a compressive strength of 35 MPa and Ø25 anchors

The logarithmic dependence of the probability of failure on concrete age is presented in Figure 5.

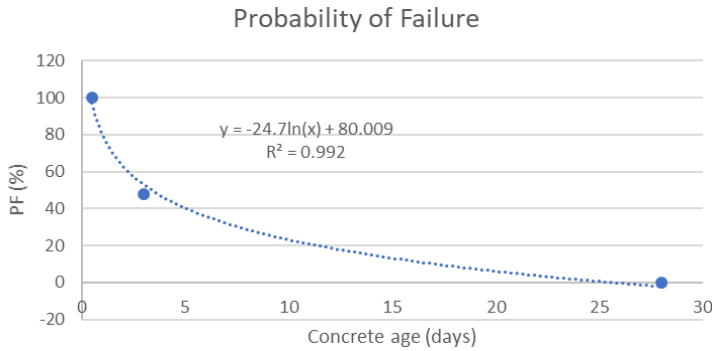

Fig. 5 The dependence of the probability of failure and the concrete age

From the obtained dependency, it can be calculated that the probability of failure will be zero, only after 25.5 days. It should be noted that after 25.5 days, the curve shows that the probability of failure will be less than zero, which does not have engineering logic.

This means, that after this period, the concrete gains the necessary strength and it can be assumed that there will be no failure. The dependence of the safety factor on concrete age is given in Figure 6.

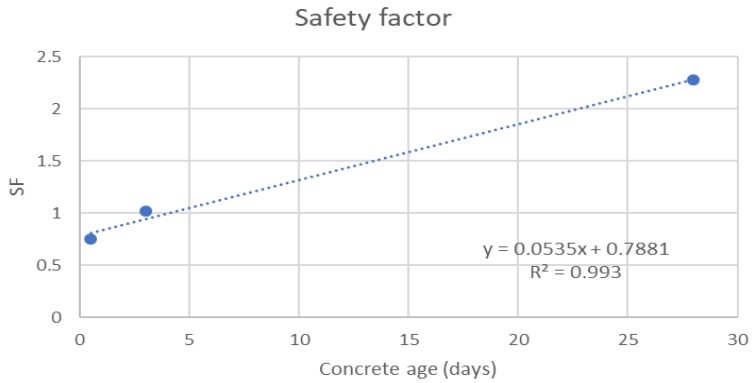

Fig. 6 The dependence of the safety factor on concrete age

Based on the analysis of the unsupported tunnel, it is obvious that some investments are necessary, in order to reduce the risk to an acceptable level, so in Figure 7, the relation between the costs for primary support, increasing of the safety factor and decreasing of the probability of failure for the analyzed section are presented.

Table 2 Input parameters for zone D when analyzing an unsupported tunnel

Support type	Cost for support (EUR/m')	PF (%)	SF
Shotcrete 5 cm	550	100	0.45
Shotcrete 5 cm +wire mesh Q221	770	47	1.02
Shotcrete 5 cm + anchors +wire mesh Q221	2695	0	2.28

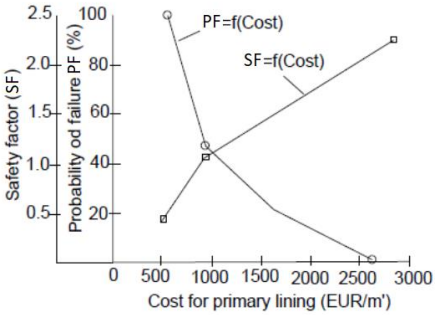

Fig. 7 Diagrams presenting the influence of investments on the SF and the PF based on data shown in table 2

4. PROPOSED METHOD

The presented analyses represent the base for the next step, which consists of proposing a method similar to the ALARP concept. In order to explain the concept further here, we present some charts in Figure 8. and Figure 9, which were given by [8].

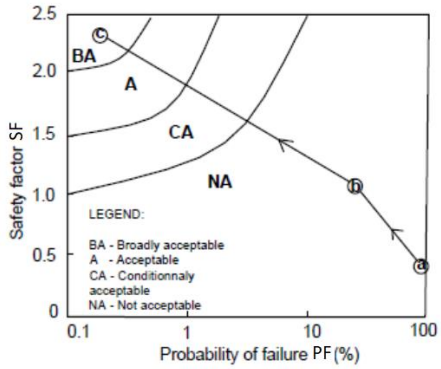

Fig. 8 Concepts of determining the acceptable level of risk with a combination of the safety factor and the probability of failure – a), b) and c) combinations from table 2

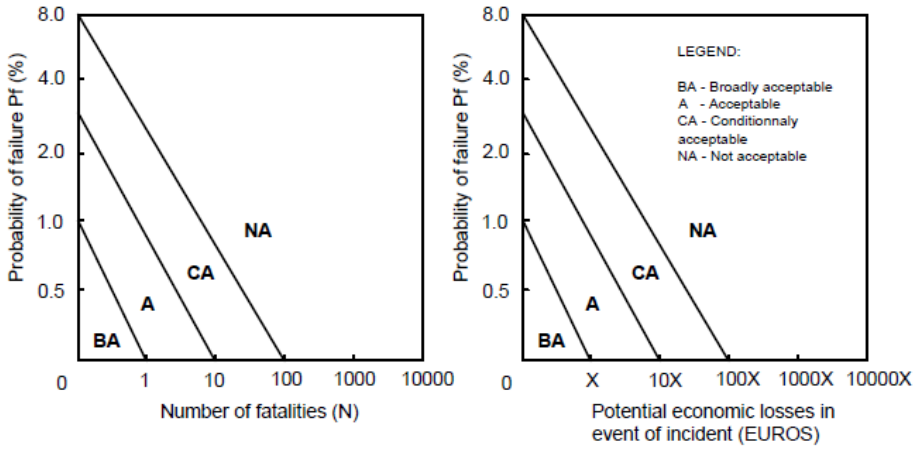

Fig. 9 Concepts of determining the acceptable level of risk a) Probability of failure - Number of deaths b) Probability of failure - Potential economic costs [8]

The value of X in Figure 9, is a variable related to estimated values that insurance companies shall pay for the possible loss of life, which as a problem is very difficult to determine with one simple value. Some recommendations for the "value of life" used by a number of countries are listed in Table 3.

Table 3 Typical "value of life" figures [9]

Country	Value of life (million £)
USA	1.67
New Zealand	0.75
Great Britain	3
France	4
Germany	2.1
Netherlands	0.3

The table shows that the “value of life” varies from country to country. This parameter is very difficult to determine. In Figure 10, we are presenting the possible cost of the loss of people in the above countries.

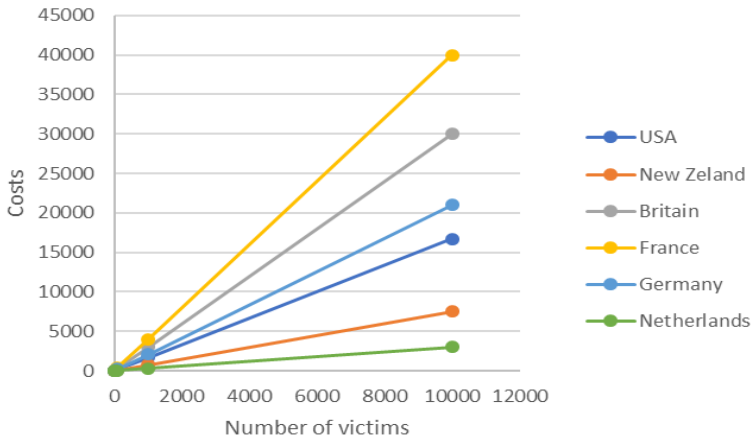

Fig. 10 The increase in costs for the loss of life for different countries according to Table 3

The value of X in Figure 9, can also be related to economic costs and loss in a case delays in the traffic because of accidents, remediations of the tunnel or other structures because of some unplanned event, etc., but this is a field for authors’ further investigation.

Finally, in Table 4, we are presenting some ideas to define some acceptable risk levels according to [8], modified slightly by the authors of this article. The motivation for this modification was the fact that the existing recommendations take into consideration only temporary mine openings, but not the unsupported temporary excavations for other structures presented in Table 4. The author's recommendation for tunnels is added according to the ESR (Excavation Support Ratio) parameter. The ESR indicator is selected depending on the type of object. The Q-value is related to tunnel support requirement by defining the equivalent dimensions of the underground opening. This equivalent dimension, which is a function of the size and type of the excavation, is obtained by dividing the span, diameter or wall height of the excavation (Dt) by a quantity called the excavation support ratio (ESR), given as:

$$De = Dt/ESR \tag{3.1}$$

Table 4 Ratings of the excavation support ratio (ESR) (modified from [10]).

Type or use of underground openings	ESR	The acceptable level for Probability of failure PF (%)
Temporary mine openings	3.5	5-8
Temporary unsupported excavations in tunnels under pressure, pilot tunnels and excavations short time before installation of the primary lining	**3**	4-7
Vertical shafts, rectangular and circular	2-2.5	3-6
Water tunnels, permanent mine openings, adits, drifts	1.6	2-3
Storage caverns, road tunnels with little traffic, access tunnels, etc.	1.3	1.5- 2
Power stations, road and railway tunnels with heavy traffic, civil defense shelters, etc.	1	0.5-1.3
Nuclear power plants, railroad stations, sports arenas, etc.	0.8	0.1- 0.5

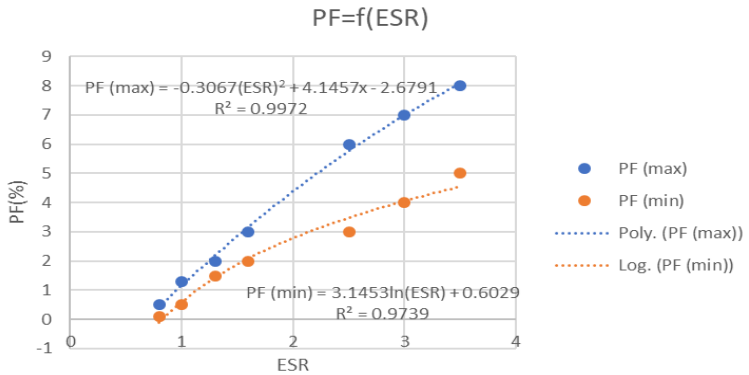

Fig. 11 Dependence of the acceptable probability of failure on the ESR value according to table 4

It should be noted that these charts should be considered as a first idea to determine an acceptable level of risk, and they should be additionally reviewed and improved. It is clear that all problems should be considered in terms of the specific set of circumstances, such as types of rock mass, design loads and the intended use of the future construction. Based on these concepts, in addition, we can underline some important steps that are necessary for the suggested method:

- Analyses of possible kinematic modes of failure along the tunnel section.
- Statistical analyses in order to define probability distribution functions for all input geotechnical parameters.
- Definition of Factor of safety (SF)
- Defining of the probability of failure, expressed with probability distributions of the Safety Factors SF.
- Analyses of costs and benefits from using some supporting measures for tunnels
- Definition of the acceptable level of risks.

These "simple" analyses give a clear view of the complexity of the problem. This is a subject for further occupation and development by the authors in the future.

5. CONCLUSION

Based on the presented analyses, it can be concluded that each design is unique and has to be considered in the terms of the particular set of circumstances, as rock types, design loads and the intended use of the future construction. The responsibility of the geotechnical and civil engineers is to find a safe and economical solution which is compatible with all the constraints that apply to the project. Solutions should be based on accurate analyses, and on engineering logic guided by practical and theoretical studies. The presented experiences are a good illustration, which shows that the knowledge of geological, tectonic and structural geological conditions is the basis for all analytical and numerical analyses and supporting measures design.

Based on the aforementioned, we can conclude that there are many possibilities for further researches in this area. The purpose is to improve and confirm methodologies suggested in this article and not only when it comes to tunneling but also for other types of structures.

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JEDAN METOD ZA DEFINISANJE PRIHVATLJIVOG NIVOA RIZIKA U GRADNJI TUNELA

U ovom radu je prikazan jedan pristup za definisanje dozvoljenog nivoa rizika u gradnji tunela. Prikazane analize su zasnovane na jednostavnim metodama i procedurama koje pomažu da se definiše stabilnost tunela sa ili bez podgradbe. Ove analize su od pomoći kako da se poveže nivo dozvoljenog rizika sa faktorom stabilnosti (SF) i verovatnoćom loma (PF). Prikazani postupak se odnosi uglavnom na tunele koji se grade u stenske mase slabog kvaliteta i u rasednim zonama, posebno za slučajeve za vreme nepodgradjenog iskopa i potrebnog vremena da se instalira privremena podgradba, ali sa određenim adaptacijama, moze da se iskoristi i za druge probleme u gradnji tunela i za druge inžinjerske probleme. Primjer na osnovu koji se prikazuje metodologije je razradjen za optocni tunel za branu Sveta Petka u R.Makedoniji. Na osnovi analiza, prikazani su mogući načini povezivanja rizika, dozvoljene verovatnoće loma i potrebna sredstva da se postigne dozvoljeni nivo rizika.

Ključne reči: *dozvoljeni nivo rizika, verojantost loma, faktor sigurnosti, stabilizacija, gradnja tunela*