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Hazard and Risk Analysis in the Design and Construction of Tunnels in Carbonate Rock Mass of the Adriatic Area

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Summary

An extensive data base has been formed during the design and construction of six tunnels in Croatia (Hrasten, Tuhobić, Vrata, Sljeme, Sopač and Vršek) whose total length amounts to approx. 5 km. The tunnels were excavated in rock carbonate formations formed of limestones (dating back to the Lias and Dogger) and, less often, dolomitic limestones from the Jurassic period and dolomites from the Upper Triassic period [Garašić, 1995].

Taking into account all elements specified in the paper, it is possible to pinpoint all significant factors that had to be dealt with when defining hazards and specific risks occurring during design and construction of tunnels in carbonate rock formations of the Adriatic coastal area.

1. Introduction

The paper starts with the generally accepted definition that the *natural hazard* is the probability of occurrence of a potentially harmful phenomenon (event) in a particular area and within a defined space frame, while *risk* is an expected level of loss (loss of human life, damage to materials) due to occurrence of a hazard.

An extensive data base has been formed during the design and construction of six tunnels in Croatia (Hrasten, Tuhobić, Vrata, Sljeme, Sopač and Vršek) whose total length amounts to approx. 5 km. The tunnels were excavated in rock carbonate formations formed of limestones (dating back to the Lias and Dogger) and, less often, dolomitic limestones from the Jurassic period and dolomites from the Upper Triassic period [Garašić, 1995].

Caverns encountered in the studied tunnels are mostly located in fault zones, or next to fault paraclases, or in top parts of anticlines, or in zones characterized by frequent occurrence of bedding joints. Out of 58 caverns explored during excavation of these tunnels, 90% are of vertical type (pits) [Garašić, 1995].

A regularity in cavern occurrence was observed within relatively sound rock categories (II and III) as well as within worse rock categories (IV and V) next to fault zones filled with clayey material and some rock fragments, locally with the presence of ground water.



Investigations performed so far in these tunnels have shown that there are 58 caverns corresponding to 3 to 18 percent of the total tunnel length. The greatest cavern depth is 126 m and an average depth of other caverns ranges from 25 and 35 m, while their length varies from 15 to 25 meters [Garašić, 1995].

The preparation of final designs for these tunnels was preceded by appropriate engineering geological surveys, trial boring, geophysical and geotechnical testing, all that with the purpose of preparing an engineering geological and geotechnical profile or model. Based on these investigations, experts proceeded to classification and categorization (K_D) of rock mass along the tunnel axis, to the level of detail required for the tunnel design preparation.

During tunnel excavation according to NATM method (tunnel driving in two stages), a detailed engineering geological mapping and a limited geotechnical testing in laboratory and in situ was conducted for the purpose of rock mass classification and categorization (K_{is}).

Based on appropriate analyses, the following relationship was established :

$$K_{is} = a \cdot K_D^b \quad (1)$$

It was determined that, in addition to lithogenetic properties of rock mass, the value of K_{is} is also influenced by discontinuities (which can not easily be taken into account by any classification), rock mass fragmentation (which is very hard to define at the stage of preliminary investigations), technology used in excavation and primary support work (whose influence on classification and categorization can not readily be estimated).

This paper also analyzes the existing classifications (**RMR** and **Q**) as well as the new **JAK** classification (earlier known as "**n**" classification) which was developed during the study of carbonate rock formations in the coastal area of the Adriatic [Jašarević, Kovačević, 1996].

Taking into account all elements specified in the introductory part of the paper, it is possible to pinpoint all significant factors that had to be dealt with when defining hazards and specific risks occurring during design and construction of tunnels in carbonate rock formations of the Adriatic coastal area (Table 1).

2. Analysis of suitability and applicability of rock mass classifications

Very extensive hazard and risk investigations were undertaken in carbonate rock formations in which the studied tunnels are situated, for the purpose of designing and building two concrete arch dams each about 50 m in height [Jašarević et al, 1997]. These investigations consisted of engineering geological, geophysical and geotechnical (laboratory and in situ) surveys, and included realization of a number of boreholes and six prospection galleries each about 50 meters in length. On the basis of results obtained during these investigations, classifications were made according to "**RMR**", "**Q**" and "**JAK**" methods. The classification results are given in Figure 1.

The following relationships [Jašarević, Kovačević, 1996] were taken into account in the preceding Figure:

$$RMR = 9 \ln Q + 44 \quad (2)$$

$$RMR = 110 - 20 JAK \quad (3)$$

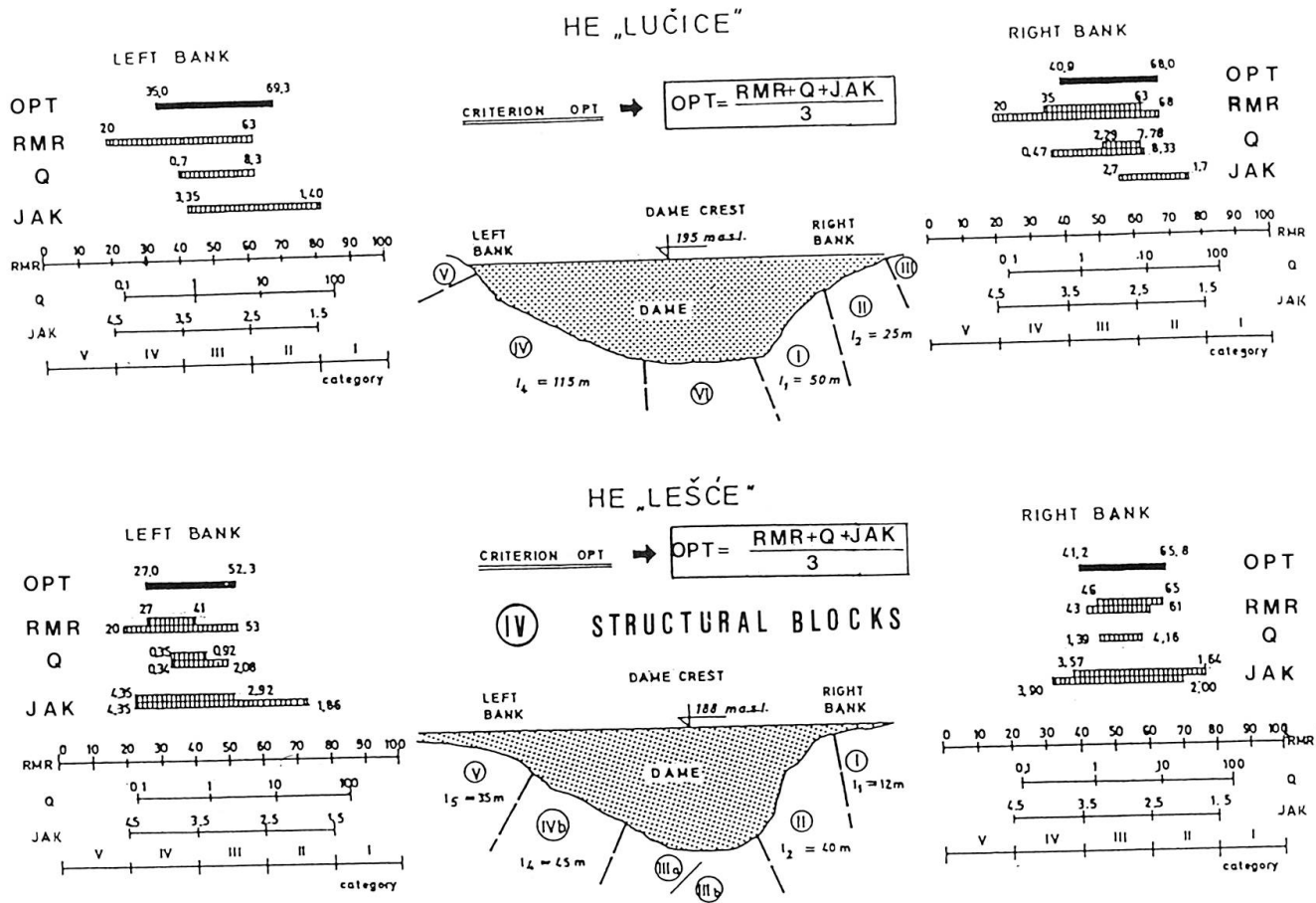


Figure 1 Results of "RMR", "Q" and "JAK" classifications for hydroelectric power plants "Lučice" and "Lešće"

The following conclusions can be made after analyzing RMR, Q and JAK values (which are partly presented in Figure 1) :

- maximum values obtained by JAK classification are up to 15% higher than the "opt" value
- minimum values obtained by RMR classification are up to 25% lower than the "opt" value
- classification provides a more restricted range, both in the minimum and maximum, when compared to the "opt" value.

In addition, the following was established through analyses conducted on these dams:

- in the maximum range (best categories), the $(RMR+Q)/2$ is lower by 8% than the $(RMR+Q+JAK)/3$,
- in the minimum range (worst categories), the $(RMR+Q)/2$ is lower (i.e. it provides a lower category) by 6% with respect to $(RMR+Q+JAK)/3$.

This analysis leads to the conclusion that it would be advisable to conduct classifications according to all three procedures ("RMR", "Q" and "JAK") and to calculate an average value for maximum and minimum values (marked in Figure 1 as "opt").



3. Analysis of engineering geological and geotechnical parameters indispensable in tunnel design

Many earlier studies as well as those undertaken in recent times [Einstein, 1993], [Yufin, 1993], point to the necessity of applying usual and standard procedures [ISRM, Suggested Methods, 1981] when performing engineering geological and especially geotechnical investigations.

When assessing rock mass "behavior" Einstein emphasizes the importance of knowing the position of joints and joint systems. Stochastic modeling of joints enables presentation of data about geometry of discontinuities as well as a *more reliable formulation* of engineering geological models and their insertion into reliability models. When arriving at the final conclusion, this author introduces the *risk analysis* and points to the permanent problem of measurement errors in data collection, namely :

- inadequate geological models (three-dimensional scale models based on one-dimensional and two-dimensional information)
- unsatisfactory approximation due to the lack of knowledge about mechanical effect of rock bridges (break in the continuity of joints), their deformation and fracturing
- formulation of engineering geological and geological model based on an acceptable risk

In case of underground structures, it is extremely significant - more than in any other structures - to identify and analyze risk dependent on natural conditions, i.e. on geological structure and geotechnical properties, according to the following expression :

$$R_u = R_c = R_{GE} \cdot R_{GT} \quad (4)$$

where

- R_u - total risk dependent on natural conditions,
- R_c - classification risk,
- R_{GE} - geological risk (probability of occurrence of fault zones, caverns, caves, etc.)
- R_{GT} - geotechnical risk (probability of occurrence of specific geotechnical properties)

As the procedures currently used for the classification and categorization of rock mass along an underground structure ("RMR", "Q" and "JAK") take into account engineering geological conditions and geotechnical properties, it can be stated that classification risk (R_c) is best expressed with the general equation presented under (4) above.

Based on experience gained in Germany and Austria, M. John emphasizes in his paper [M. John, 1997: Sharing of risks under changed ground conditions in design/build contracts] the significance of the following elements from the owner/contractor agreement:

1. Distribution of Excavation Classes: The geotechnical risk is borne by the owner.
2. Dimensioning of the Primary Support: Provisions are made that permit the quantitative and qualitative adjustment of the primary support (cf. Introduction, item 3).
3. On-Site Adjustments: Since the risk of changed ground conditions is borne by the owner, it is the owner who refines the design by adjusting it to the conditions actually encountered.

4. Recommendation regarding methodology for hazard and risk evaluation during tunnel construction in carbonate rock formations

The hazard and risk evaluation and categorization was performed using data base created from 1990 to 1996 during design and construction of six tunnels (total length: about 5 km) situated in carbonate rock formations of the coastal region of the Adriatic.

The hazard and risk was evaluated by appropriate use of IT (information technology). At that, individual terms were associated with quantified values based on the methodology for evaluating hazard and risk of landslides [Fell, 1993].

The study of engineering geological elements (bedding plane, discontinuities, speleological structures, occurrence of water, etc.), as well as geotechnical testing in laboratory and in situ (PLT, RQD, axial strength, geophysical surveys - SASW, weathering) served as the basis for performing the technical rock mass classification according to methods "RMR" and "Q".

Based on the analysis of the data base and engineering classifications, the following parameters were established: magnitude (M), probability of occurrence (P), hazard (H), vulnerability (V) and specific risk [R_s], as shown in Table 1.

5. Practical application of hazard and risk evaluation

As emphasized in section 2, in order to increase the level of reliability it is advisable to perform the engineering classification based on all three procedures ("RMR", "Q" and "JAK") and then to calculate an average value "opt" for both maximum and minimum values.

If only one engineering classification is performed according to equations (2) and (3), then the "JAK" value is calculated as shown in Table 1, because it also represents the magnitude M. The subsequent procedure is presented in Table 1.

The engineering classification (K_D) according to "Q" and "RMR" procedures and the K_{is} classification (rock classification during tunneling) were performed for the Vršek tunnel, as presented in Figure 2. The same figure shows estimations of hazard and specific risk along the tunnel axis.

Based on the detailed monitoring of tunneling works along the Rijeka - Karlovac highway route, it was established that the advance rate is 12 m/day depending on the rock-mass category, for round the clock work (24 hours a day) and 350 working days in a year [Brnčić, 1995], [Balen, 1995] and [Garašić, 1995]. The tunneling technology consisted in tunnel profile excavation in two stages with primary support.

Further to investigations [Jašarević, 1996] conducted in 1995 and 1996 for Rijeka - Karlovac motorway tunnels built in carbonate massif (limestones, dolomites, and dolomitic limestones) in order to determine rationality of excavation and primary support, the following correlation (Fig. 3) was established:

$$K_{is} = a \cdot K_D^b \quad (5)$$

where: K_D ... rock category determined on the basis of investigations for final design.
K_{is} ... rock category determined during tunneling works.



Classif. proced.	“RMR”	0	20	40	60	80	100			
	“Q”									
	RMR=9lnQ + 44	0.1	0.7	6.6	54.6	503.8				
	“JAK”									
	JAK=(110-RMR)/20	4.5	3.5	2.5	1.5					
Rock Mass Category		Very poor V	Poor IV	Fair III	Good II	Very good I				
Magnitude [M]		> 4.5	3.5 - 4.5	2.5 - 3.5	1.5 - 2.5	< 1.5				
Cleft Area - Fault zone [m ³]		Very large > 10000	Large 1000-10000	Medium 100-1000	Small 10-100	Very small < 10				
Proba bility	Descr.	Extrem. high	High	Medium	Low	Very low				
	[P]	8	6.5	5	4	3	2.5	2	1.5	1
	Annual prob. [P _{an}]		1		0.1		0.01		0.001	
Hazard [H]=[M]·[P]			29.25	14	6.25	2.25				
		> 29.25	14 - 29.25	6.25 - 14	2.25 - 6.25	< 2.25				
Vulnerability [V]			0.90	0.50	0.10	0.05				
[R _s]=[P _{an}]·[V]			0.10	0.05	0.001	0.000005				
Border values [R _s]		> 10 ⁻¹	10 ⁻¹	5·10 ⁻²	10 ⁻³	10 ⁻⁵	< 5·10 ⁻⁵			
Descr.		Extrem. high	High	Medium	Low	Very low				

Table 1 Risk and hazard evaluation for underground structures built in carbonate rock formations

Hazard [H] is a danger affecting humans and material goods.

Risk [R] is an evaluated level of danger from a particular hazard

Vulnerability [V] is an evaluated loss of stability at the excavation contour or primary lining, and it may range from the total loss of stability (failure - cave-in) $V \geq 0.9$ to the very low vulnerability $V \leq 0.05$.

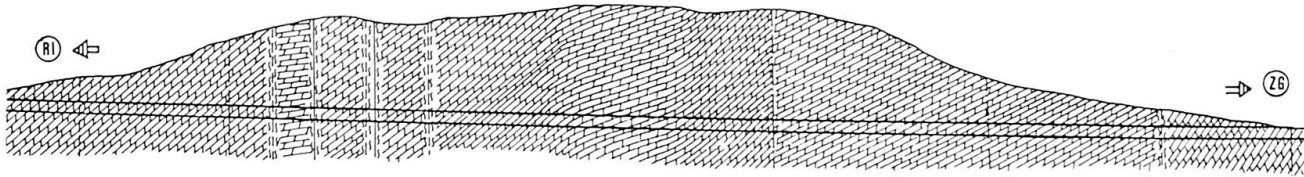
By analyzing this diagram (Fig. 3), we can note an increase in K_{is} category as related to K_D which is probably due to scale effect, i.e. to insufficient massif investigations at the stage prior to final design. Based on information gathered through on-site surveys presented in [Brčić, 1995], the following correlation between the advance rate (V_n) and rock-mass category (K_{is}) was established:

$$V_n = a + b \cdot K_{is} \quad (6)$$

This correlation is presented in Figure 4.

TUNNEL "VRŠEK"

l = 867 m



CHAINAGE	980.00	990.00	1045.00	1135.00	1200.00	1225.00	1240.00	1320.00	1365.00	1530.00	1665.00	1730.00	1750.00	1847.97	
TERRAIN LEVEL	810.10	823.58												795.14	802.41
GRADE LEVEL															
ENG. - GEOLOGICAL CLASSIFICATION [K]	RMR _D		23	42	54	23-8	54	23-8	44	54	78	63	23		
	ROCK MASS CATEGORY [K]	V	IV	III	III	IV-V 60/40%	III	IV-V 60/40%	III	III	II	II	IV	V	
	Q _D	0.139	0.28	1.25	3.89	0.28 -0.02	3.89	0.28 -0.02	1.25	3.89	14.2	7.78	0.28	0.139	
	CATEGORY OF SUPPORT	31/31	31/27	23/22	22/17	31/27 35/35	22/17	31/27 35/35	23/22	22/17	14	18/13	31/27	31/31	
CATEGORY "IN SITU" [K _{IS}]	V	IV	V	IV	V	V	V	V	IV	IV	V	IV	III	IV	V
HAZARD (ALLORING TO TABLE 1) [H]	>10	>29	≈ 26	≈ 14	≈ 7	26-23	≈ 7	26-23	≈ 13	≈ 7	≈ 24	≈ 6	≈ 26	>29	>29
SPECIFIC RISK [R _S]			≈ 10 ⁻¹	≈ 5·10 ⁻²	≈ 10 ⁻³	≈ 10 ⁻¹	≈ 10 ⁻³	≈ 10 ⁻¹	≈ 5·10 ⁻²	≈ 10 ⁻³	≈ 5·10 ⁻²	≈ 10 ⁻³	≈ 10 ⁻¹	>10 ⁻¹	>10 ⁻¹

Figure 2 Estimated longitudinal profile of the Vršek tunnel with separate presentation of hazard and specific risk

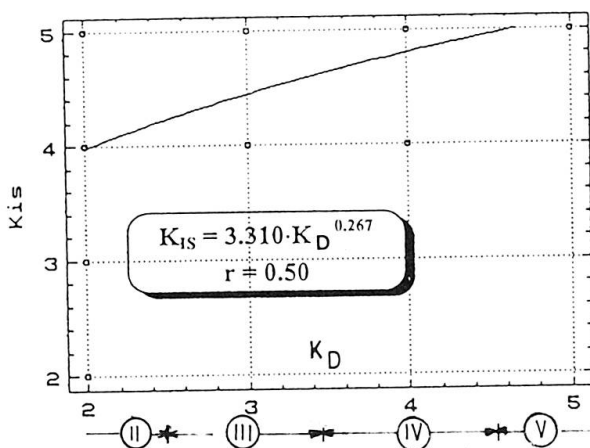


Figure 3. Correlation between the category determined in situ and the one anticipated at the design stage

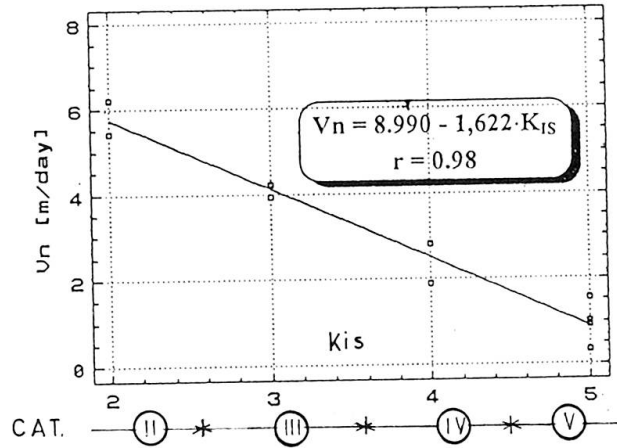


Figure 4. Correlation between the advance rate (Vn) and the rock mass category (K_{IS})

6. Conclusion

The following conclusions can be derived from analyses focusing on the evaluation of hazard and risk levels during tunnel construction in carbonate rock formations :

1. The proposed methodology for the hazard and risk evaluation during design and construction of tunnels is based on the methodology used for evaluating hazards and risks concerning landslides [Fell, 1993]. The proposed methodology should therefore be checked on a number of underground structures in carbonate rock formations.



2. The proposed methodology for evaluating hazards and specific risks along the tunnel axis enables builders to keep funding allocated for tunnel construction within the planned limits, while also helping them to avoid unwanted extensions in construction time.
3. In addition, for sections presenting an increased level of specific risk, the methodology is conceived in such a way that the contractor is warned to pay a special attention during excavation and selection of an appropriate primary support.
4. Based on the analyses performed in the scope of this research, it may be concluded that the increase in hazard between neighboring categories results in an exponential (10^{-11}) increase in specific risk and hence in similar increase in the cost of construction (Fig. 4).
5. It may finally be concluded that the prognostic longitudinal profile with a rock category estimate (K_p) - which is usually regarded as a basic technical document for the procurement of tunnel excavation work - is now complemented by hazard and risk evaluation by individual sections. This enables a more precise distribution of responsibilities between the client and tunneling work contractor.

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