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Reliability Analysis for Tunnel Supports System by Using Finite Element Method

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ABSTRACT: *Reliability analysis is a method that can be used in almost any geotechnical engineering problem. Using this method requires the knowledge of parameter uncertainties, which can be expressed by their standard deviation value. By performing reliability analysis to tunnel supports design, can be obtained a range of safety factors and by using them, probability of failure can be calculated. Problem becomes more complex when this analysis is performed for numerical methods, such as Finite Element Method. This paper gives a solution to how reliability analysis can be performed to design tunnel supports, by using Point Estimate Method to calculate reliability index. As a case study, is chosen one of the energy tunnels at Fan Hydropower plant, in Rrëshen Albania. As results, values of factor of safety and probability of failure are calculated. Also some suggestions using reliability analysis with numerical methods are given.*
Keywords: *Finite Element Method, Reliability analysis, Tunnel design, PEM, Probability of failure.*

I. INTRODUCTION

The development of computational methods in the field of tunnel designs is constantly battling with difficulty to supply the relevant calculation models with representative and reliable data. The main difficulty relate to the large variation in the physic-mechanical properties of rocks as well as the presence on the field of a number of factors weakening the mechanical characteristics.

By using in calculation representative values, such as mean value of the parameters, gives usa quantitative result that can be expressed through the safety factor. However, the risk of failure of tunnel supports can varyfrom fairly wide limits depending on the degree in variation of the parameters to consider in the calculations. This situation of recognizing the risk of failure, which is not evidenced in the case of deterministic calculations, can be significantly improved using probabilistic methods which integrate elements of variability of the data to use in the design process. The results of the calculations are the reliability index associated with the probability of failure of tunnel supports.

By various methods of evaluating reliability index and probability of failure for tunnel supports, the following approach is selected, based on PEM (Point Estimate Method) [1]. Application of this method requires knowledge of the distribution type for each of the uncertain parameters, which corresponds to expectedvalue and standard deviation of these uncertain parameters.

Of particular importance is the choice of the computational method to use. Using numerical methods excludes some approximations which an engineer has to make, if analytical methods are used, but the computational time increases from the use of numerical methods. In this paper, calculation of factor of safety for tunnel supports is done by using FEM (Finite Element Method) and PEM is used to calculate reliability index.

II. CORE REPLACEMENT TECHNIQUE USED IN TUNNEL SUPPORTS DESIGN

Core replacement technique [2] is used to simulate three dimensional excavations of a tunnel by performing two dimensional analyses. Core replacement technique is very similar to convergence – confinement method [3], but in core replacement technique, is not the internal pressure that is changed from maximum value of p_o (initial geological stress) to zero, but is the value of Young modulus of rock mass that is lowered from maximum value represented by that of the rock mass around the tunnel (Erm), to a value of zero (excavated tunnel) Section A in figure 1 corresponds to the state of rock mass not influenced by tunnel excavation, and section C represents the situation when tunnel is fully excavated.Section B represents a state when value of Young modulus for rock mass is between zero and the maximum value of Erm. RS2 [4] is the software which is used to model and design the tunnel.

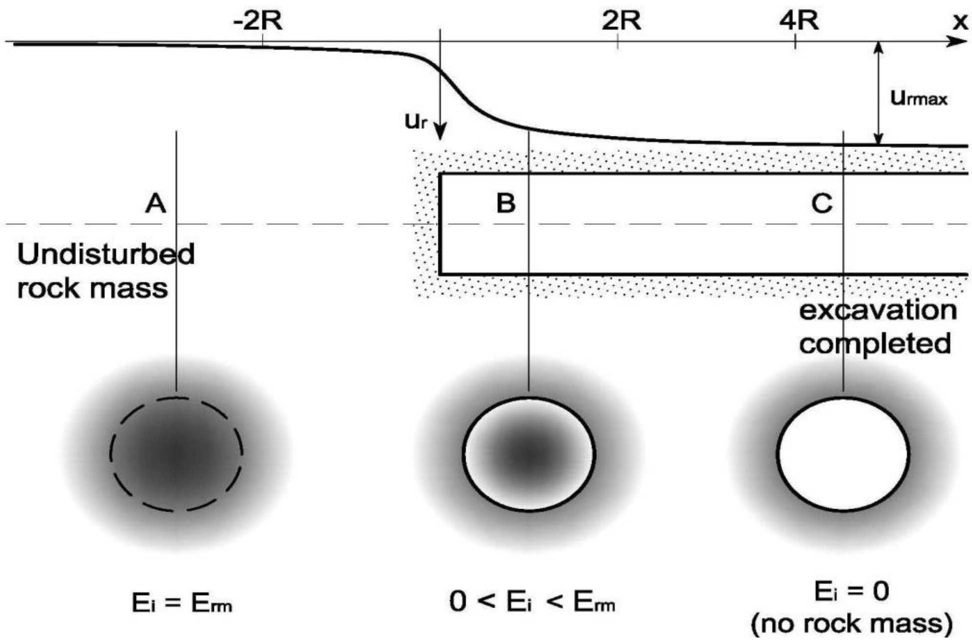

Fig. 1. Core replacement technique applied to sketch longitudinal deformation profile for tunnels excavated in rock mass.

Stage construction will be used to model different stages between sections A and B of figure 1. In these stages, value of Erm will change, and this will be represented by different materials for the rock mass inside the tunnel.

To design a supports system, firstly has to establish the amount of tunnel wall deformation prior to supports installation. In this paper this value will be established using Vlachopoulos and Diederichs empirical formulas [4]. Secondly, with this value and the graph of tunnel radial displacement vs. Young Modulus, is not difficult to establish value of Young Modulus for which the radial displacement is the same as that calculated by using Vlachopoulos and Diederichs formulas. Thirdly, build another model with an added stage where material inside tunnel will have Erm value calculated as described above. In this stage will be added the supports system and tunnel design can be acceptable if the tunnel is stable, the tunnel lining meets certain factor of safety requirements and the wall deformation meets the specified requirements.

III. RELIABILITY ANALYSIS FOR TUNNEL SUPPORTS SYSTEM BY USING POINT ESTIMATE METHOD (PEM)

To perform reliability analysis for a tunnel supports system, means that a method should be used to calculate mean value and standard deviation for the performance factor, in this case, for factor of safety, calculate reliability index and finally calculate probability of failure.

In this paper, Point Estimate Method will be used to calculate mean value and standard deviation for factor of safety. PEM was first introduced by Rosenblueth (1975) [1], and is a simple technique to estimate statistical moments for a performance function, by evaluating it in chosen different points. Original method proposed by Rosenblueth, requires 2N points to be evaluated, but recent modification [5], [6], [7], have lowered the number of points to 2N or 2N+1.

Factor of Safety for tunnel supports system should be a value bigger than one in order for the supports system to be stable. In this paper, factor of safety will be calculated directly by using RS2 and choosing envelope type of Carranza – Torrez & Diederichs [8]. Reliability index is calculated as below:

$$\beta = \frac{\mu_{FS} - 1}{\sigma_{FS}} \qquad (1)$$

Where:

μ_{FS} Mean value of Factor of Safety

σ_{FS} Standard Deviation of Factor of Safety β Reliability Index

Probability of failure will be calculated by accepting a Normal distribution for factor of safety and using NORMSDIST(-β) function in Excel.

IV. CASE STUDY. ENERGY TUNNEL 2 IN RRËSHEN HYDROPOWER PLAN, ALBANIA

Hydropower plant of Rrëshen is being built in Fan River, in Rrëshen, Albania.

Energy tunnel 2 has a length of 4027m, width and height of 4.5m and a maximum depth of 400m.Details are given in figures 2 and 3.

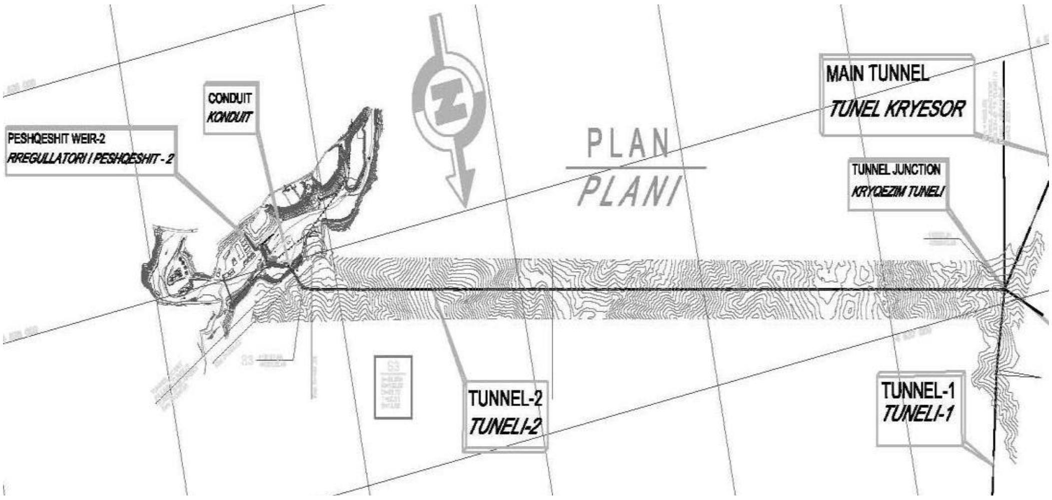

Fig. 2. Energy tunnel 2. (Fan River Hydro Power Project, published with consent of Aydiner Construction Co, Lezhe, Albania)

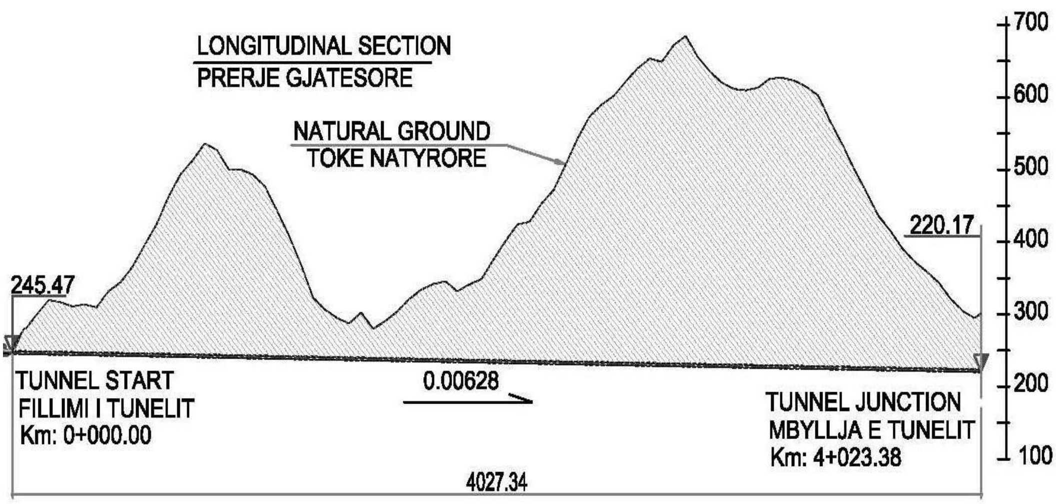

Fig. 3. Longitudinal profile of Energy tunnel 2. (Fan River Hydropower Project, published with consent of Aydiner Construction Co, Lezhe, Albania)

Tunnel excavation was performed by using explosive charge, and face advance was between 1.5 and 5 m, depending on the type of rock.

For every face advancement (in total 429 advances), has been made a face sketch and presented data for water, type of rock, joint number, joint alteration etc. By using this data, have been calculated RMR (Bieniawski), Q (Barton), GSI (Hoek & Brown). In Figure 4 is presented one of those tunnel face sketches at 62.5 m.

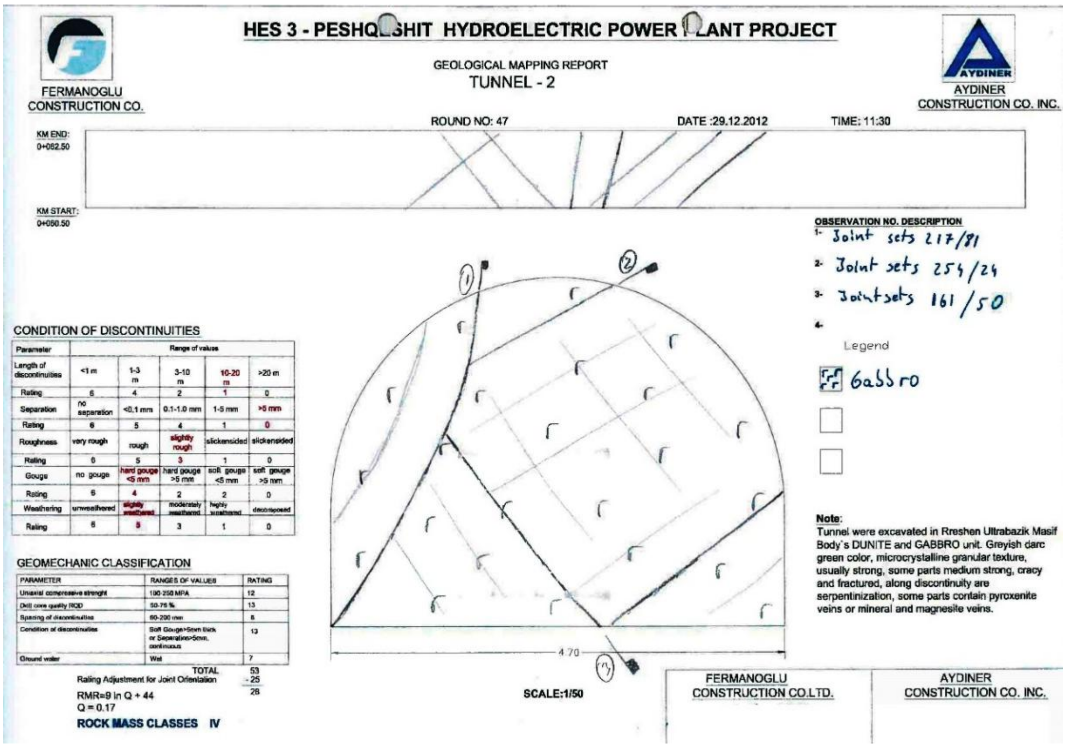

Fig. 4. Tunnel face sketch at 195.60 m. (Fan River Hydro Power Project, published with consent of Aydiner Construction Co, Lezhe, Albania)

By using boreholes near tunnel axis, rock samples have been taken and by using laboratory tests, is obtained the Uniaxial Compression Strength (UCS).Based on rock description made from the geological engineer in site, is approximated the value of intact rock mi to be used in Hoek – Brown failure criterion [9]

For 429 tunnel face advances, have been calculated 429 values of GSI, from which are evaluated mean value and standard deviation.

The same calculations are performed for UCS. 16 values of UCS were obtained from laboratory tests, from samples collected near tunnel axis, by using boreholes. Using Marinos & Hoek [10] table, value of mi has been chosen for basalt and is 20.

Table 1 gives a summary of the data collected.

Table 1: Mean values and standard deviation for UCS and GSI .

	Mean Value	Standard Deviation
UCS (MPa)	64.87	11.03
GSI	38.21	8.27

Blast damage factor D is taken zero, because tunnel blast will be controlled and the rock can be assumed undisturbed.

Tunnel supports chosen are steel ribs and shotcrete. Table 2 gives data for tunnel supports.

Table 2. Tunnel supports system data

Supports install distance from tunnel face	x = 1.5 m
Steel profile IPN 160 with area	A = 0.002280 m²
Distance between steel profiles	i = 1.5 m
Shotcrete thickness	d = 0.15 m
Young modulus for concrete	Ec = 2.5 * 10^7 kPa
Young modulus for steel	Es = 2.1 * 10^8 kPa
Steel yielding stress	fy = 5.4 * 10^5 kPa
Tunnel width	B = 4.5 m
Tunnel height	H = 4.5 m
Arch radius	R = 2.25 m

4.1 Energy tunnel 2 supports system design. Deterministic calculations.

By using deterministic calculations with mean values of input data, maximum radial deformation is Urmax = 0.0197 m and plastic radius Rpl = 3.775 m. Figure 5 shows the plastic zone around energy tunnel 2.

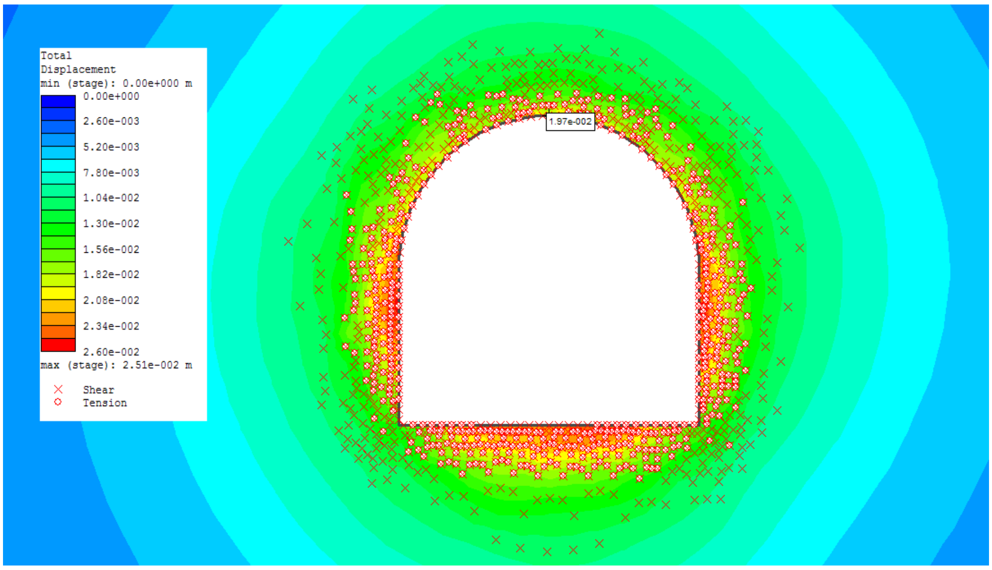

Fig. 5. Plastic zone around energy tunnel 2.

Radial displacement at the moment of supports installation have been calculated by using Vlachopoulos and Diederichs formulas [4], and results are ur(x=1.5m) = 0.0118 m.

Now is needed to determine the core modulus at the moment the supports system is installed, which can be determined by plotting radial displacement vs. Young Modulus, and finding the correspondent modulus of the radial displacement at the moment the supports system is installed, calculated by using Vlachopoulos and Diederichs formulas. Figure 6 shows the procedure described above.

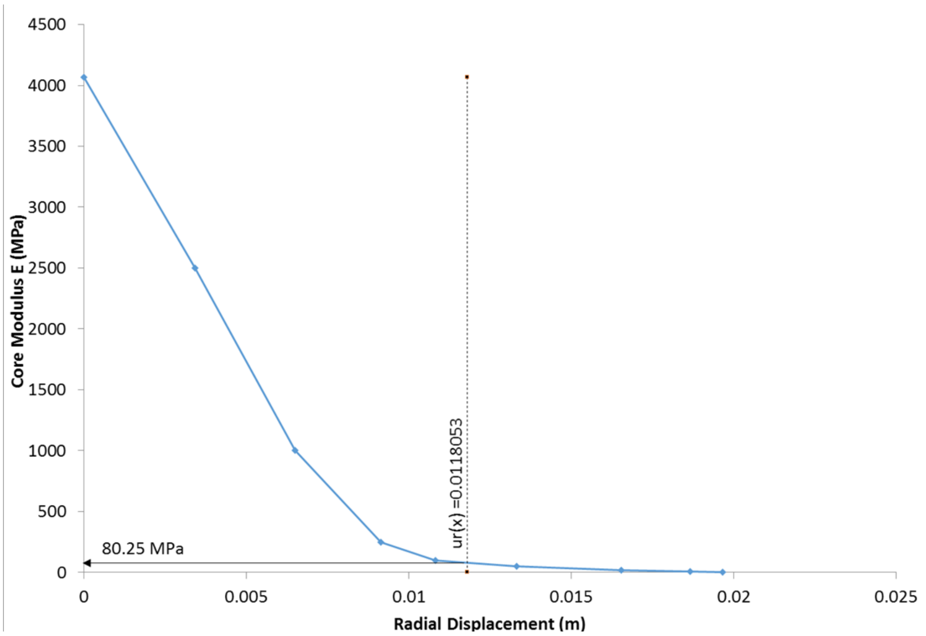

Fig. 6. Core Modulus (MPa) vs. Radial; Displacement (m), energy tunnel 2.

Calculated value for core modulus at the moment the supports system is installed is Erm = 80.25MPa.

Supports system will be added at a stage with Core modulus Erm = 80.25 MPa, and final phase will be tunnel excavation.

Figure 7 shows plastic zone around the tunnel when supports system is installed.

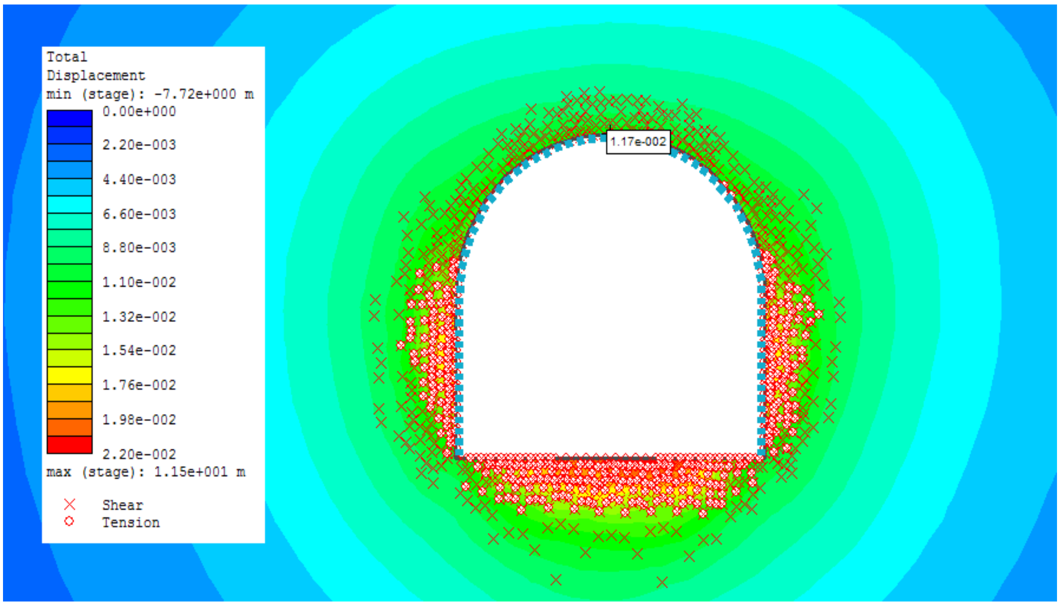

Fig. 7. Plastic zone with supports system installed, energy tunnel 2.

Capacity plots are given in figure 8.

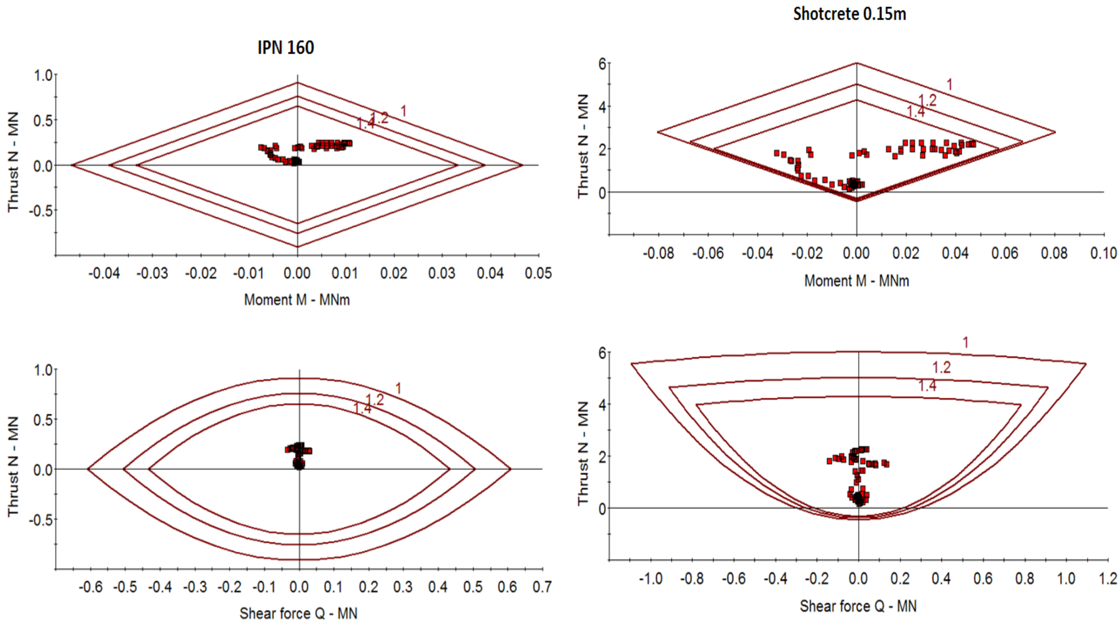

Fig. 8. Capacity plots for supports system used for energy tunnel 2
(IPN 160/1.5 m and 15 cm shotcrete)

Is noticed that all data points fall within a factor of system = 1.4 envelope, on all plots. This means that the supports system chosen has a factor of safety greater than 1.4.

4.2 Energy tunnel 2 supports system design. Reliability analysis.

RS2 does not have the capability to perform reliability analysis for tunnel supports system. To make this possible, for each discrete point in the PEM method, has to be build a model and calculate factor of safety, as shown in the deterministic analysis performed in paragraph 4.1. With four Factors pf Safety (because there are two uncertain parameters), using PEM, is easy to calculate reliability index and probability of failure, as shown in paragraph 3.

Reliability analysis will be performed for points 1 and 2, shown in figure 9.

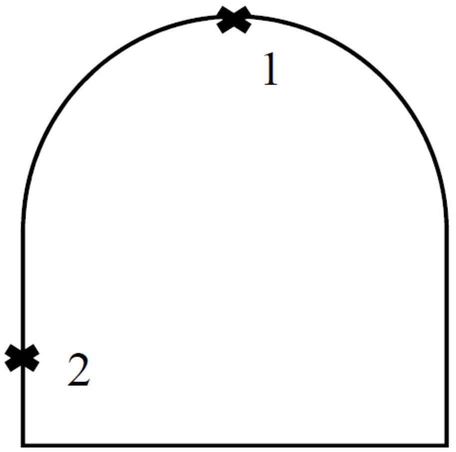

Fig. 9. Points used to perform reliability analysis.

Result taken by using reliability analysis are given in table 3.

Table 3. Reliability analysis results for tunnel supports system used in Energy tunnel 2.

	Energy tunnel 2			
	Point 1		Point 2	
	IPN160	15 cm concrete	IPN160	15 cm concrete
μ(FS)	14.5	9.625	2.3375	1.4125
σ(FS)	0.866	0.65	0.3698	0.4904
β	15.588	13.28	3.6173	0.8412
p_f	4E-55	2E-40	0.0001	0.2001

Point 1, which corresponds to tunnel roof crown has a safety factor bigger than 9 and zero probability of failure. Point 2, lower side of tunnel, has a safety factor of 1.4 and 20 % probability of failure for concrete lining. Probability of failure of steel ribs is 0.01 %.
Plastic radius calculated by using reliability analysis is 4.85 m, as shown in figure 10.

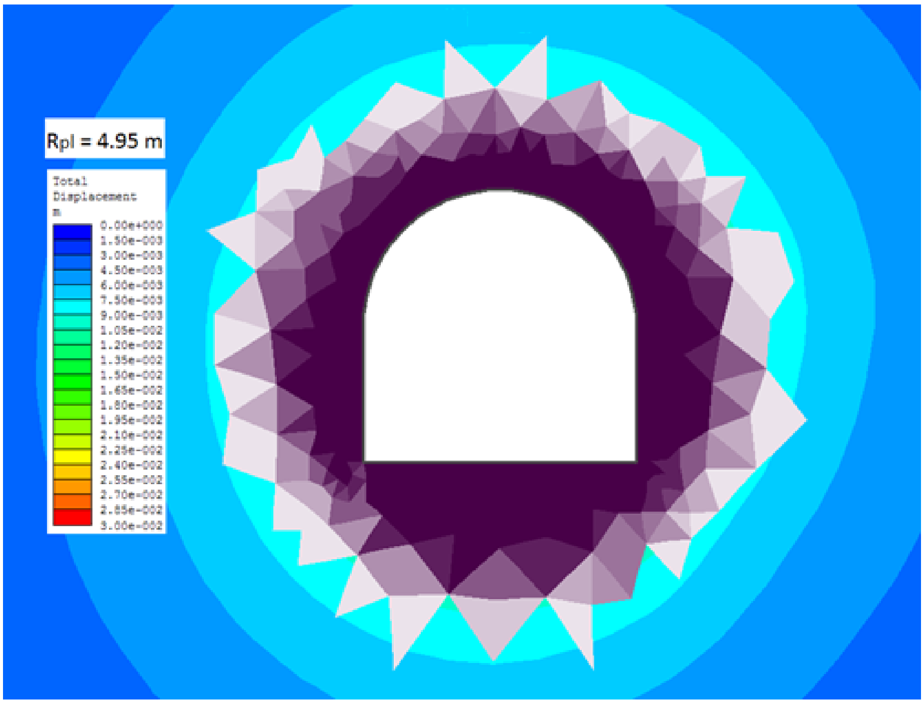

Fig. 10. Plastic radius envelope obtained by using reliability analysis for energy tunnel 2.

V. SUMMARY AND CONCLUSIONS.

Reliability analysis was applied in this paper to resolve a probabilistic analysis of the tunnels supports system consisting of steel ribs and shotcrete. The uncertain parameters considered in this analysis were GSI and UCS of rock mass. A Finite Element analysis was used for the deterministic model. PEM was the approach used to determine reliability index for the tunnel supports system. It was shown that:

Result taken by using deterministic analysis gives safety factors larger than 1.4 and after tunnel lining is installed, plastic zone for tunnel roof crown is almost zero.

Results taken by using reliability analysis, gives safety factors larger than 1.4, as in the deterministic analysis, but probability of failure for tunnel lining in the lower side of the tunnel is 20 %, so there is 20% chance of failure for tunnel lining. Probability of failure for steel ribs is 0.01%.

Plastic radius calculated by using reliability analysis is 31% larger than that calculated by using deterministic analysis.

PEM used to perform reliability analysis in this paper is a discrete method. More exact solutions may be obtained by using stochastic methods, such as FORM, SORM, Monte Carlo Simulation, etc. PEM was chosen for the only reason that was possible to simplify the complex reliability analysis as a sum of four deterministic analysis performed for each discrete point calculated by using PEM.

This paper shows that with little effort, reliability analysis can be used in conjunction with Finite Element Method, to resolve a probabilistic analysis of the tunnel supports system.

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