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Probabilistic Rock Mass Classification from Prior Construction for the Future Extension of a Tunnel

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Abstract – This paper presents a procedure to re-analyze the original design of the Eisenhower-Johnson Memorial Tunnel (EJMT), which opened in 1973 and 1979 when rock mass classification systems were being introduced. The re-analysis used a new probabilistic approach to rock mass classification and stochastic representation of ground and support parameters. The results will be used to select the alignment of future extensions of the EJMT. Rock mass classification systems using Q and RMR were applied probabilistically in the back analysis of the tunnel design. Distributions of Q and RMR were developed for discrete points along the tunnel for prior and future tunnel alignments. Based on the probabilistic rock mass classifications, installed support systems were compared to actual support systems. Important differences between deterministic and probabilistic results were observed, including bias of deterministic results away from peak probabilistic results. Numerical models using rock mass properties based on probabilistic rock mass classifications were found to provide a good match to rock loads recorded during tunnel construction. This result suggests that forward modeling of tunnels using probabilistic rock mass classifications may provide a more realistic estimate of tunnel support requirements, costs, and risks. Current deterministic geotechnical baseline reports may be inadequate to provide a complete picture of a proposed project and may bias design towards a sub-optimal solution.

***Keywords*:** tunneling, rock mass classification, back analysis, case study, probabilistic analysis

1. Introduction

Rock mass classifications are a common empirical basis for the design in the tunneling industry. Systems such as the Rock Mass Rating (RMR) and the Q rock mass value are based on several component parameters developed from available geologic data, such as joint frequency and intact unconfined compressive strength ([1], [2], [3]). The resulting rock mass classification score is then correlated to suggested support systems, such as a certain shotcrete thickness or a rock bolting pattern. Rock mass classifications are also commonly correlated to material parameters such as rock mass deformation modulus. Rock mass classification systems have been calibrated against many years of tunnel construction experience across various geologic conditions. The suggested lining design should be applied to a specific project carefully and validated by other design methods. Still, rock mass classification-based designs represent a useful starting point for many projects.

Many of these rock mass classification systems have been applied deterministically. However, given underlying data with significant uncertainty or variability, a distribution of rock mass classifications can be developed, i.e., a probabilistic rock mass classification. Such a probabilistic approach is demonstrated by re-analyzing the original design of the Eisenhower-Johnson Memorial Tunnel (EJMT) in Colorado, USA. The updated rock mass classifications will be applied to the selection of tunnel alignments for the planned future extension of the tunnel.

2. Case Study

The Eisenhower-Johnson Memorial Tunnel (EJMT) is a pair of dual-bore, four-lane automobile tunnels located approximately 97 km west of Denver, Colorado. They are some of the highest highway tunnels in the world at 3400 m (11,155 ft) above mean sea level and carry Interstate 70 (I-70) from one side of the continental divide to the other. Above the east portal is the Loveland Ski Area, and several ski runs are directly above the tunnel alignment. To the west of the tunnel are several world-class ski resorts. The first bore, named after Dwight D. Eisenhower, the U.S. President for whom the Interstate system is also named, opened in 1973. The second eastbound bore, named for Edwin C. Johnson, former Colorado Governor and U.S. Senator who lobbied for an Interstate Highway to be built across Colorado, was completed in

1979. The EJMT is the main thoroughfare for vehicles traveling between Denver and the major cities in the west. The tunnel greatly reduced the travel time over the Continental Divide and the hazard of attempting to cross mountain passes in winter [4].

The tunnels were excavated by the drill-and-blast (D&B) technique through the Silver Plume Granite (SPG) and the Idaho Springs Formation (ISF). The ISF is a Precambrian-age meta-sedimentary formation that grades from gneiss to schist. On the west side of the tunnel, the rock is extremely massive and hard, and the tunnel was advanced rapidly without significant issues. At the east side of the tunnel, the rock is heavily fractured and presented some problems with excavation, leading to the use of a top-heading and bench excavation method. Near the center of the ridge, the tunnels pass through the inactive Loveland Fault. Rock in this area became progressively more fractured until the rock was almost entirely decomposed to fault gouge for a portion in the middle. This squeezing material presented extreme excavation difficulties.

The EJMT was very thoroughly studied and documented. The proximity of the tunnel to the Colorado School of Mines (Mines), the United States Geological Survey (USGS), and the United States Bureau of Reclamation (USBR) made it convenient for all these organizations to use the construction of the tunnel as a laboratory and case study, while at the same time providing useful information to the designers and contractors. In addition, researchers from the South Dakota School of Mines (SDSM) contemporaneously studied the construction of the pilot bore. They documented their findings on the in-situ stress field around the EJMT. The most heavily documented portion of the tunnel is the pilot bore.

As constructed, the EJMT bores are 35 m (115 ft) apart at the east portal, 37 m (120 ft) apart at the west portal, and 70 m (230 ft) apart at the widest point of separation. The westbound tunnel curves to the left, while the eastbound tunnel is approximately straight. Each tunnel is approximately 2.7 km (1.7 mi) long; about 335 m (1,100 ft) of this distance is ventilation equipment, portal structures, and cut and cover tunnel at each portal. The Continental Divide above the tunnels is approximately 3843 m (12,608 ft) above mean sea level or approximately 450 m (1500 ft) above the tunnel roadway elevation where the tunnel alignment crosses the divide. The western approach to the tunnel has a grade of approximately 7%, while the eastern approach has a grade of approximately 6%. These steep approaches also contribute to traffic issues near the tunnel, especially when heavier trucks have difficulty climbing the approach grades. The passage through the tunnel has a shallow grade of 1.6% as the tunnel climbs slightly from east to west. This grade was useful during construction as it allowed groundwater flowing into the tunnel during construction to flow out to the mouth of the tunnel as the boring proceeded from east to west [4], [5].

The EJMT carries a large volume of traffic that continues to increase yearly. The traffic through the EJMT has consistently exceeded traffic flows estimated before construction [6] since 1974, the year after the first tunnel opened, and today traffic far outstrips any traffic volume that could be imagined in 1960. Long traffic delays at the tunnels are common, and CDOT enforces a metering system for safety reasons. In 2018, the daily vehicular count ranged from about 29,000 in October to more than 44,000 in July. Due to the increased traffic congestion, a plan is now to build new tunnel bores close to the existing tunnels. This plan brought the need to re-analyze the analysis and design of the original tunnel bores considering the more updated current rock mass classification systems, which were not available during the original tunnels. The updated rock mass classifications can then be used to select the most appropriate tunnel alignments and preliminary support designs for additional tunnel bores.

Steel sets supported the EJMT pilot bore. These supports were originally designed using a version of Terzaghi's empirical support design method [7]:

$$P = C(b + h)\gamma \tag{1}$$

where P is the rock load in pressure units, C is an empirical constant depending upon rock conditions found to vary between 0.35 to 1.6, b is the tunnel width, h is the tunnel height, and γ is the unit weight of overburden.

The pilot bore was approximately 12 ft wide and 12 ft high (3.6 x 3.6 m^2). Tunnel supports were either 4-in (10.16 cm) wide flange or 6-in (15.25 cm) H-section steel beams. A curved invert strut was also used in high ground load conditions, e.g., crossing the Loveland Fault.

3. Rock Mass Classification

Based on data provided in a contemporaneous construction report, a geologic report by [5], and a USGS professional paper by [4], which included extensive laboratory data, the authors estimated various geologic properties along the pilot bore bore alignment. These data include joint spacings, joint conditions, intact rock strength and stiffness properties, groundwater groundwater flow rates, and discontinuity orientations. The authors estimated the distribution and uncertainty of the reported reported data using normal, triangular, and uniform distributions.

Rock mass classification systems included RMR and Q. Both RMR and Q values for a given point along the pilot bore are continuous random variables. Each variable represents several underlying data, which are themselves continuous random variables that have been transformed via linear, power, and exponential functions and then combined arithmetically to produce a composite distribution representing the total RMR or Q score. In the case of RMR, the components are summed and multiplied by several factors. In the case of Q, each pair of the six components is combined in a ratio, and the three ratios are multiplied by each other to produce Q. In general, algebraic operations on random variables, both functional transformations as well as compositions of multiple variables, do not produce distributions that have closed-form definitions ([8], [9]). It is commonly necessary to resort to non-closed-form representations of the distribution to adequately represent such distributions. For this study, the Monte Carlo method was adopted. The authors took many random samples (N = 2,000) from each underlying data distribution. They carried each sample through estimating the components of RMR and Q and the combination of these sub-components into the total score. This process was automated in MatLab. This process produces a distribution of possible RMR and Q values at each station and for the pilot bore, as shown in Fig. 1.

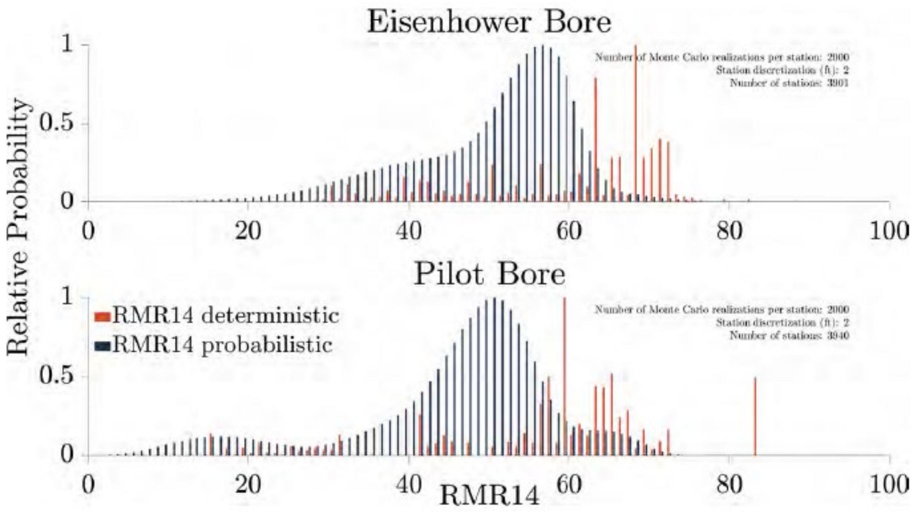

Fig. 1: Histogram of Monte Carlo RMR and Q values along the EJMT pilot bore.

Note that simply taking the best estimate of each underlying data distribution and performing a deterministic calculation neglects the interaction of peak and non-peak parameters. Such a deterministic estimate does not necessarily return the peak value from the probabilistic histogram. Thus, a deterministic estimate is not equivalent to a peak probabilistic estimate. This behavior is demonstrated in Fig. 2, which shows deterministic and probabilistic RMR scores along the EJMT pilot bore. Note that the deterministic estimate consistently overpredicts the RMR value along the pilot bore alignment, which would lead to an unconservative design.

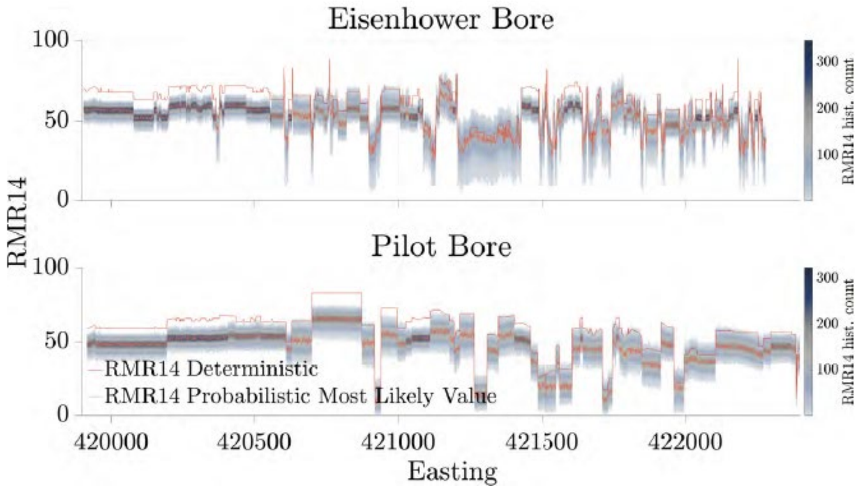

Fig. 2: Probabilistic and deterministic RMR estimates along the EJMT pilot bore.

4. Rock Mechanical Properties

From the distribution of rock mass classifications and available laboratory and in situ test data from current and historical laboratory testing, the authors estimated rock mass properties including strength and stiffness. These parameters are summarized in Table 1.

Table 1 Summary of Material Modelling Parameters.

Parameter	Silver Plume Granite	Idaho Springs Formation
Young's modulus E	55 GPa	14 GPa
Distribution of E	normal	lognormal
E Dist. Param.	$\mu = 55$, $\sigma = 16$	$\mu = 9.94$, $\sigma = 0.632$
E Truncation	20 and 80 GPa	3 and 80 GPa
Poisson's ratio υ	0.22	0.18
Hoek-Brown m_i	22.6	5.48
Hoek-Brown σ_{ci}	180 MPa	97 MPa
Std. Dev. of σ_{ci}	56 MPa	47 MPa
Truncation of σ_{ci}	100 and 230 MPa	30 and 120 MPa

Distributions of intact unconfined compressive strength (*UCS*) and Young's modulus E were truncated at bounds representing the limits of laboratory data, which are assumed to represent the credible bounds of the material properties. The intact rock Hoek-Brown strength envelopes were also based on laboratory testing of 27 SPG specimens and 24 ISF specimens. The in-situ Hoek-Brown envelope was estimated based on [10] methodology using an estimated GSI.

The in-situ rock mass modulus around the pilot bore was tested during construction by flat jack tests conducted by the South Dakota School of Mines [11]. Hoskins [11] reported Young's modulus of 130 MPa in the "softest, most unstable, squeezing ground that we could find in the pilot bore." USBR [12] reported the results of plate jacking tests in the fault gouge materials of the Eisenhower bore of approximately 11 MPa, suggesting a fault gouge material that had decomposed to stiff clay. Rock mass modulus was also estimated by correlation to the estimated rock mass classifications RQD, RMR, Q, and GSI. Several correlations were applied to get a range of plausible moduli ([2], [10], [13]). The moduli suggested by these correlations are presented in Figure 3. Note that the plate jack test results by [12] are well below the rock mass moduli estimated by correlation to rock mass classifications, and the flat jack test results by [11] are at the lowest end of even the softest empirical estimates.

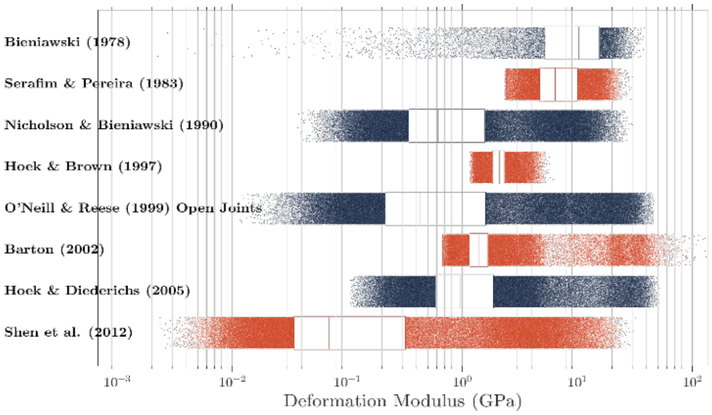

Fig. 3: Rock mass moduli estimated along the EJMT pilot bore by various empirical correlations to rock mass classifications.

5. Back Analysis

A two-dimensional (2D) finite difference model (FDM) using the estimated engineering properties discussed above was created of the pilot bore representing a slice through the tunnel perpendicular to the tunnel axis using FLAC software [14]. An initial elastic FLAC model experiment was carried out by varying several input parameters and comparing output crown deformation results to the reported deformations in the EJMT pilot bore squeeze zone. This calibration suggested that a rock mass modulus of approximately 38 MPa most accurately reproduced the reported squeeze zone crown deformations. Note that this modulus is between the USBR and Hoskins in-situ testing results but well below the empirical modulus estimates by every method except by [15].

More varied load data are available in the pilot bore from load cells installed at the base of 33 steel support sets. Six locations also installed load cells in the invert struts and at the crown of the steel sets. The 33 stations in the pilot bore with load cell data were modeled in FLAC with elastoplastic properties, as shown in Table 1, and reduced to in-situ values by correlation to rock mass classifications. The rock mass Poisson's ratio was assumed to be equal to Poisson's ratio of the intact material as there is no scientific consensus on the best methodology for estimating rock mass Poisson's ratio. Rock mass deformation modulus was estimated for each Monte Carlo realization based on the intact modulus, the estimated rock mass classification for that Monte Carlo realization, and the mean of the seven empirical correlations listed in Figure 3. A Hoek-Brown yield criterion was similarly estimated for each Monte Carlo realization. For each of the 33 stations with load cell data, 200 Monte Carlo realizations of the 2D elastoplastic FLAC model were run.

As shown in Figure 4, median axial thrust from FLAC models in the legs of the EJMT pilot bore steel sets generally overpredict the effect of rock load on the tunnel supports, with a few notable exceptions (e.g., Station 4384). However, as shown in Figure 5, the histogram of FLAC-calculated axial thrust in the steel support legs agrees relatively well with the measured data in the EJMT pilot bore.

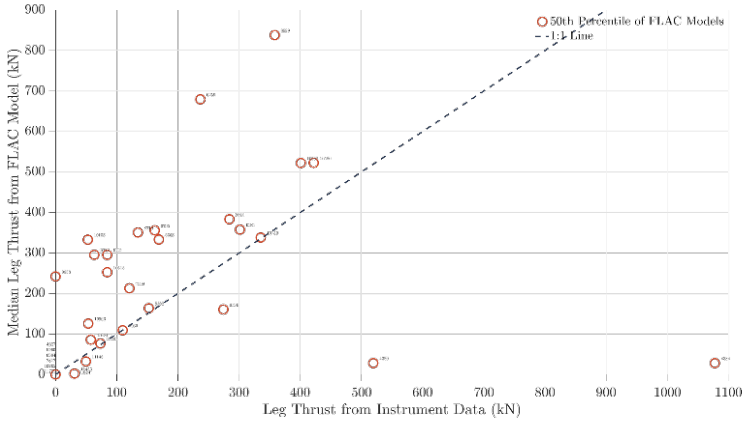

Fig. 4: Median FLAC modeled axial thrust in EJMT pilot bore steel set legs versus instrumentation data for 33 instrumented stations.

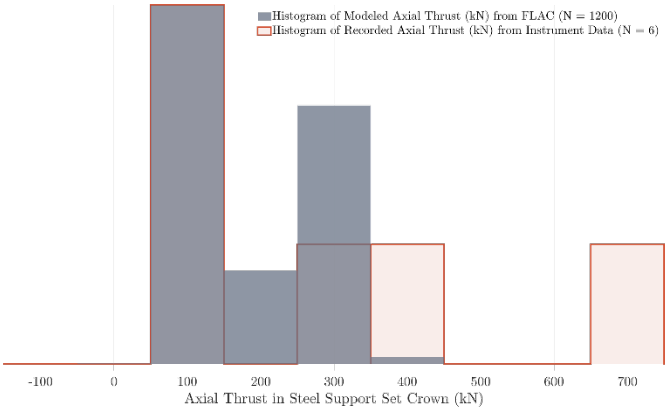

Fig. 5: Histogram of FLAC-calculated axial thrust at crown of EJMT pilot bore steel sets versus recorded crown thrust at the same stations.

Although the horizontal load data are sparse (six instrumented stations), there is some agreement between axial thrust at the crown of the FLAC-modelled tunnel liner and instrumentation data, as shown in Figure 6. While the FLAC model reasonably approximates the tunnel support loads, the tunnel deformations are not. The tunnel closures predicted by FLAC are approximately an order of magnitude smaller than the instrumentation data (e.g., 3 mm vs. 30 mm). This under-prediction is likely a shortcoming of the continuum modeling approach, suggesting that two sources of deformation neglected by this model may be controlling much of the deformation observed in the EJMT pilot bore. These sources of deformation are discontinuous displacement of rock mass blocks along joints in the rock mass and long-term creep deformation of the rock mass. The rock mass structure in the EJMT vicinity does have a blocky structure in many areas. The portion of the EJMT through the Loveland fault contains significant fault gouge and clay minerals, which are susceptible to long-term creep deformation. Construction reports noted deformations as large as 2 feet (0.6 m) in the tunnel through the Loveland Fault zone. It is noted that many areas had to be trimmed and re-supported approximately two weeks after initial excavation and support were installed.

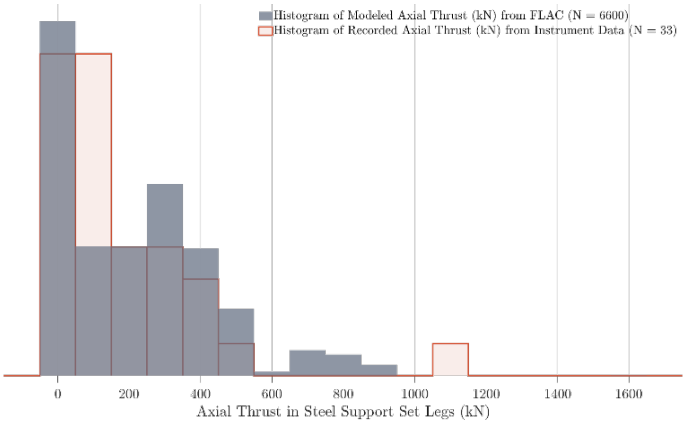

Fig. 6: Histogram of FLAC-calculated axial thrust in the legs of the EJMT pilot bore steel sets versus histogram of recorded axial thrust at the same stations.

6. Conclusions

The data and analysis presented here demonstrate a fundamental feature of probability distributions: carrying a deterministic estimate through functional transformations and convolutions of probability distributions does not necessarily replicate the same results as carrying the random variable distribution through the same mathematics. A deterministic estimate may be biased away from the most likely probabilistic estimate. The consistent disagreement between the deterministic and most likely probabilistic estimate of rock mass classifications shown here is a feature of the interaction of the underlying asymmetric probability distributions for each parameter of each rock mass classification. In this case, probabilistic modeling has revealed an inherent bias to the RMR and Q-systems when applied deterministically. This bias can be either high or low, though in this case, the bias is more often on the high side. Thus, a tunnel design based on a deterministic rock mass classification estimate is likely unreliable. A tunnel design based on the most likely probabilistic estimate is a more realistic portrayal of the ground conditions than a deterministic estimate. This inherent deterministic bias may significantly contribute to the relatively frequent failure of tunnel construction cost estimates to match actual project costs. A probabilistic modeling approach using Monte Carlo simulation of data, intermediate interpretations, and modeling may improve the reliability of preliminary tunnel designs.

There is a disagreement between the median FLAC model results with instrumentation data, but an agreement of the FLAC model histogram of results with instrumentation histogram suggests that the simplistic elastoplastic model used here may not accurately represent a specific cross-section of the tunnel. However, the Monte Carlo realization of many slices may accurately represent the range and distribution of likely results for the tunnel. This representation suggests that applying many simple models in a Monte Carlo analysis may be an effective strategy for preliminary design studies. Many iterations of a simple model with probabilistic parameters may more accurately represent tunneling conditions than a single (or few) iterations of a more complex model with deterministic parameters.

The model discussed here fails to capture discontinuous and creep deformation of the EJMT pilot bore. A more complex creep deformation model may be capable of capturing this behavior. However, for this research project, i.e., the probabilistic estimation of likely excavation and support conditions in new tunnels adjacent to the existing tunnels to support early-stage project feasibility studies, the simplistic model presented here may be a sufficient and efficient path forward.

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