Virtual reality based uncertainty assessment of rock mass characterization of tunnel faces

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ABSTRACT: Rock mass characterization has a high degree of uncertainty due to difficulties in capturing the heterogeneity of the rock mass, and due to human subjectivity and biases while mapping. Since classification systems are often used as a tool to decide rock support design, misinterpretation of the rock mass can lead to an inadequate support design. In this study, 3D-scans of tunnel faces are implemented in virtual reality (VR) to investigate the uncertainty of tunnel face mapping. A VR-mapping survey is conducted where 14 professional and experienced engineering geologists have performed Q-system based tunnel face mapping and the results allow to quantify the uncertainty related to that process, as well as investigating the different psychological aspects that influence engineering geologists in the mapping process. The paper closes with a discussion about what this VR-study's results mean with respect to rock mass classification and possible future applications for VR in rock engineering.

Keywords: Rock mass characterization, tunnel face mapping, virtual reality (VR), rock mass classification systems, Q-system, uncertainty.

1 BACKGROUND AND MOTIVATION

Lord Kelvin once said, “When you can measure what you are speaking about, and express it in numbers, you know something about it”. This quote summarizes the main principle in classifying and characterizing rock masses: Based on given parameters or characteristics defined within a classification system, the user can give a quantitative rating to an arbitrary rock mass, which reflects the quality of the rock mass. In rock engineering, however, the people that perform these measurements with their eyes and other senses, introduce uncertainty to the obtained knowledge. Given that the quantitative rating from rock mass classification is – in some systems - used as a support design basis, insight into the uncertainty of rock mass characterization is imperative.

Engineering geological mapping and rock mass characterization are mostly done directly by human observations (visual, tactile etc.), often guided by utilizing a classification system, e.g. the Q-system (Barton 1974 and NGI 2015), RMR (Bieniawski 1989), or GSI (Hoek 1994). The founders of these classification systems all emphasize the importance of having basic geological knowledge to use the system. However, a rock mass is an intricate material due to its complexity and the inherent natural geological variability, making it impossible to have complete knowledge of the material. The process of attempting to describe the rock mass is therefore subjected to a degree of uncertainty, related to the subjective interpretations influenced by e.g., previous mapping experiences and human factors such as degree of risk aversion and cognitive biases (e.g., Wilson et al. 2019, or Elmo and Stead 2021). It has been argued that the understanding of uncertainty and sources of errors in rock engineering has not received the same attention as further development of design procedures and inclusion of new technology (Elmo et al. 2022).

A quantitative uncertainty assessment of the rock mass characterization of a tunnel face is often difficult due to the practical difficulties in bringing a lot of people to the same tunnel face. However, modern mapping technology (e.g., laser-scanning, photogrammetry) provides high-resolution 3D models of tunnel faces, thus making it possible to present the tunnel conditions in virtual reality (VR). Hence, it is possible to bring the same tunnel faces to a lot of people by use of VR. This allows for studying the degree of uncertainty related to tunnel face mapping and examining the different psychological aspects that may influence the mapping result.

Integration of VR in rock engineering is in an early stage. In current literature only one article was found that uses VR for uncertainty assessment of engineering geological mapping (Uotinen et al. 2019). The study presented in this article contributes to investigating the application of VR in rock engineering and provides new insights about the uncertainty related to tunnel face mapping.

2 VR SET-UP AND TUNNEL FACE MAPPING SURVEY

High-resolution, colored LiDAR point clouds of tunnel faces were used to create the VR scenes. The point clouds of the selected tunnel faces were collected using Leica RTC360 LiDAR scanner, right after machine scaling of the blasted rock surface. To collect a colored scan, the tunnel faces were illuminated by the tunnel construction machines (e.g., rock scaling-, or grouting rig). Each point cloud consists of two to three scans automatically aligned by the Leica Cyclone software.

The point clouds were further processed and triangulated in the software CloudCompare. Triangulated meshes of the scans were then imported into Unity to develop a VR model of the tunnel faces. In Unity, rendering and light conditions were optimized to display the rock mass as detailed as possible when seeing it with VR goggles. The VR headset HTC Vive Focus 3 was used for the tests. The VR set-up for the survey consisted of the tunnel faces, two virtual 2 m scale bars (Figure 1) and virtual look-up tables of the Q-system as an aid for the participants.

Tunnel faces with varied rock mass quality are selected from the new Skarvberg tunnel, located in northern Norway. The tunnel has a width of appx. 12,5 m and was mainly excavated through a metasandstone with a distinct sub-horizontal foliation.

For the survey, a total of four different tunnel faces were selected. One of these four faces was used as an "accommodation face" that was not included in the survey and only had the purpose of helping participants to accommodate to the VR world. The remaining three faces that were used in the survey were selected according to their originally mapped RQD and/or GSI provided by the contractor's mapping geologist and Bøgeberg & Skretting (2021). Mapping data from the selected tunnel faces are shown in Table 1. Tunnel faces 1 and 4 are the same, but face 4 is a mirrored version of face 1 which was done to add an additional investigative feature to the survey. Comparing the RQD and GSI values, the tunnel faces were originally categorized into relatively poor, medium and good quality. A front view of the four tunnel faces in VR is shown in Figure 1.

Table 1. Mapping data from contractor (Q-system) and Bøgeberg and Skretting (2021) (GSI).

Tunnel face	RQD	J_n	J_r	J_a	Q_{base}	GSI
1 & 4 (medium)	40	12	1	4	0,83	45-50
2 (good)	55	12-15	1	2-4	0,92-2,29	-
3 (poor)	10-15	15	1	8-12	0,06-0,13	22-27

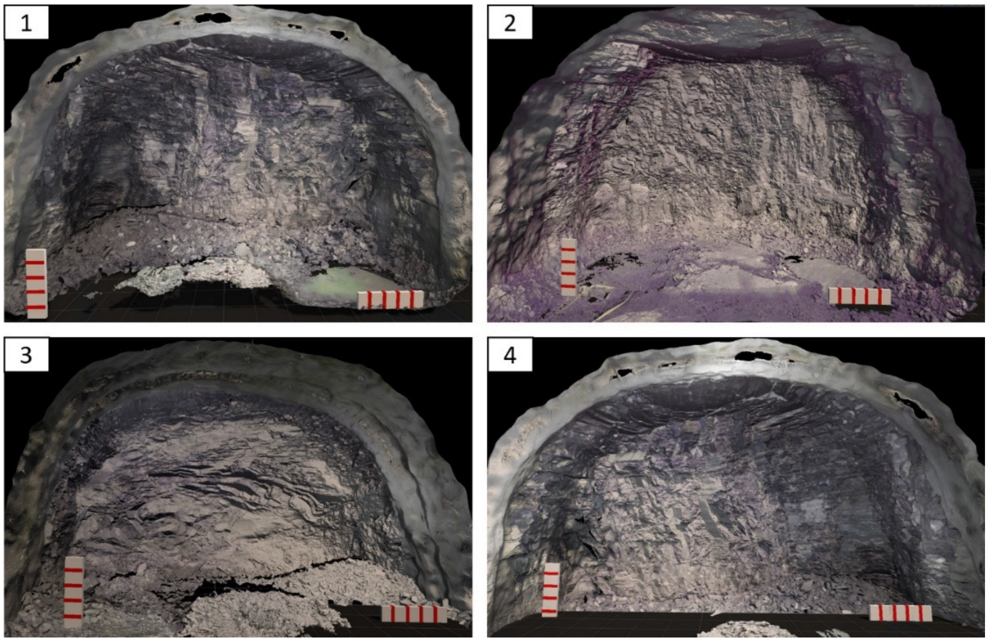

Figure 1. Front view of the four tunnel faces used in the study from the VR model, with varied rock mass quality based on existing RQD and GSI values from tunnel face mapping.

To quantify the uncertainty of the rock mass characterization in the tunnel face mapping, the Q-system, which is the most utilized classification system in Norway, was used in this study. Participants consisted of 14 engineering geologists with finished studies and various amounts of professional experience (between 1 year and several decades). All of them characterize themselves as "familiar with the Q-system". Additionally, three participants with a strong geotechnical background (i.e., predominantly concerned with soil mechanical topics) were also included in the study to see how people who are not frequent users of rock mass classification systems perform in comparison. The Q-system is given in equation 1 (NGI 2015):

$$Q = \frac{\text{RQD}}{J_n} \times \frac{J_r}{J_a} \times \frac{J_w}{\text{SRF}} = Q_{base} \times \frac{J_w}{\text{SRF}} \quad (1)$$

where RQD = Rock Quality Designation; J_n = Joint set number; J_r = Joint roughness number; J_a = Joint alteration number; J_w = Joint water reduction factor; and SRF = Stress reduction factor. For this survey, only the first four Q-parameters were evaluated, known as Q_{base}. RQD and J_n relates to the rock mass' degree of jointing. Thus, the two parameters can be sufficiently evaluated only by visual observation. J_r and J_a reflects the joint friction, and is therefore, to some extent, dependent on tactile assessment. In a real tunnel face mapping, the two parameters are, however, often evaluated based on only visual observation, due to the risk of assessing an unsupported tunnel face. Thus, it was decided that J_r and J_a also were included in the VR mapping. Participants were generally encouraged to only give single value answers, but if they insisted on giving parameter ranges, the average of the range was used for further analysis which is also in accordance with NGI (2015).

After showing participants the "accommodation face" (see above), the same succession of tunnel faces was shown to them, from face 1 to 4 (see Figure 1). Each face was shown for max. 5 minutes to each participant. The participants did not get any information about the tunnel or the geology prior to the survey, except that the faces were from the same tunnel. However, the participants got different information regarding the location/succession of the tunnel faces and were split into two equally sized groups, "group 0" and "group 1". Dividing the participants in two groups and including a mirrored tunnel face (nr. 4) was done to investigate the independence of each tunnel face mapping.

- "Group 0" was told that the scans where consecutive tunnel faces that are 6 meters apart, and that the order the faces are shown is the same as the tunnel was excavated.
- "Group 1" was told that the scans were from random tunnel faces from one tunnel.

3 RESULTS

The survey showed that the individually mapped parameters are generally subjected to a considerable variability. Different amounts of variability are however observable for different faces and parameters, as can be seen in Figure 2. The largest spread was observed for the RQD on tunnel face 3 (i.e., the face with the poorest rock mass quality acc. to the original mapping) which has a range of 30-75 and 35-80 for groups 0 and 1, respectively. The spread of J_n from 6 to 12 for most faces is also considerable since this causes a halving of the resulting Q-value. Also J_r shows a high variability for face 3 (esp. in group 1 – random) and so does J_a for face three, but here it has a higher spread for the results of group 0 – consecutive. The other faces show smaller, but yet existing variabilities, and it can be observed in both groups that face 2 was generally perceived as the one with the lowest rock mass quality (i.e., lowest RQD, highest J_n, lowest J_r (on average)). From the original mapping, this tunnel face has the highest RQD and Q_{base} (see Table 1). During the survey, participants expressed repeatedly that they struggle most with the assessment of J_r and J_a which highlights the limitations of VR mapping (see discussion).

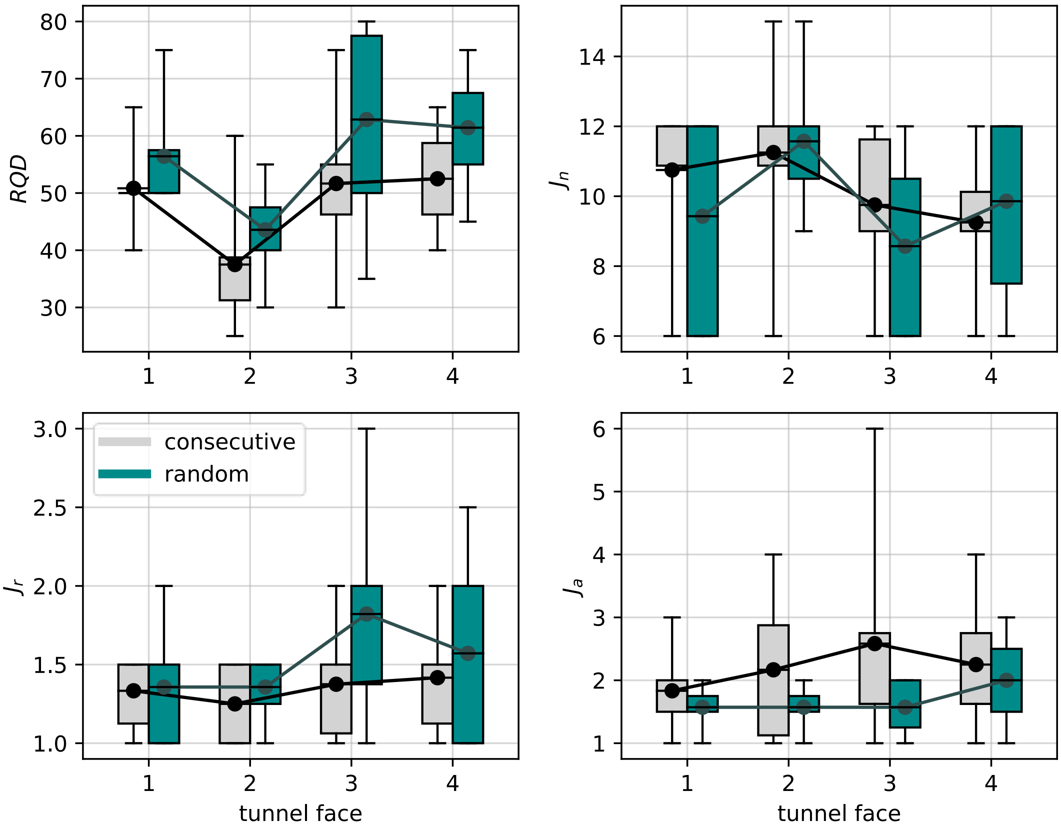

Figure 2. Box plots showing the spreads of the four Q-base parameters RQD; J_n, J_r and J_a for the two participant groups (group 0, consecutive, grey; group 1, random, cyan) and the four different tunnel faces.

Although none of the participants recognized that face 1 and face 4 are the same (only one mentioned that "this rock mass feels familiar"), the mapping results between the two faces are also not very pronounced (see Figure 2). The participants of group 0 - consecutive faces -, however, show a tendency to also give values closer to the previous face (face 3) than the participants of group 1.

An analysis of the Q_{base} that results from the assessed parameters acc. to equation 1, shows that also this final number – which is in many cases decisive for the tunnel support design – is subjected to a large spread. Assessing tunnel face 1 alone (Figure 3, left), for which most results are available since groups 0 and 1 can be combined, show a spread of the Q_{base} between 1.8 (i.e. Q-class D – poor) to 12.5 (i.e. Q-class B – good) with a median of 4.2 (i.e. Q-class C-fair). With a Q_{base} between 2.9 and 4.2, the results from the three participating geotechnicians (who have little experience with rock mass classification) are located well within this distribution.

Looking at consecutive faces, it can be seen that the Q_{base} from group 1 – random faces – indeed shows a higher variability from one face to another than the Q_{base} from group 0, who believed that they see consecutive tunnel faces (Figure 3, right). During the survey it was also observed that participants from group 0 frequently asked for which values they have mapped on previous faces, to get a hint for the current face.

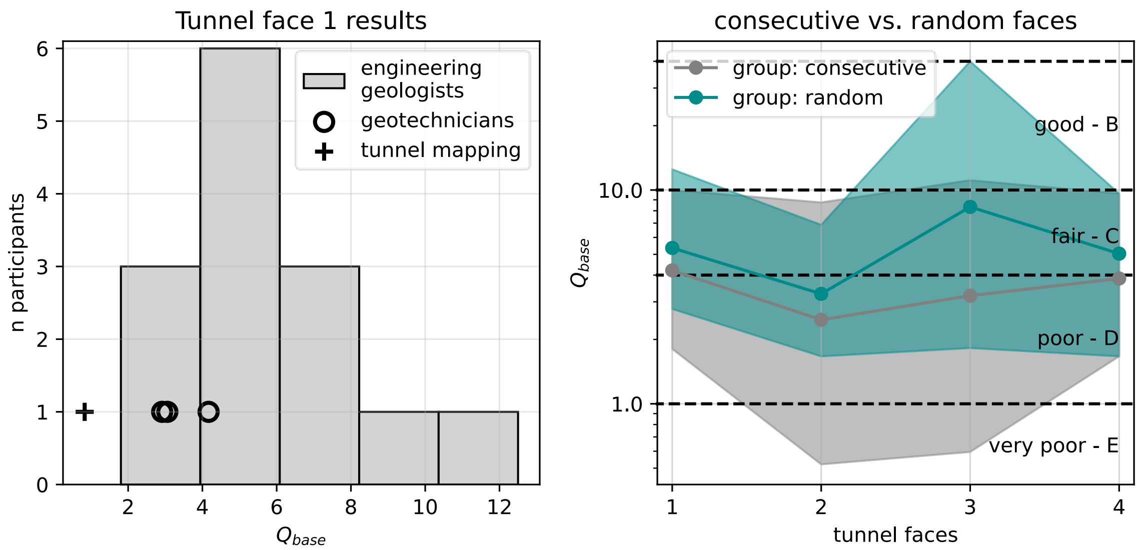

Figure 3. Left: Histogram showing the variability of resulting Q_{base} for tunnel face 1 alone including results of the three participating geotechnicians and the original mapping. Right: The average Q_{base} per face for group 0 (consecutive) and 1 (random) respectively. Colored areas in the background show observed minimum and maximum values, and the dashed black lines mark the different Q-classes acc. to NGI (2015).

4 DISCUSSION AND OUTLOOK

It is recognized that a VR mapping is not ideal for capturing all the details and elements of a rock mass, and that lack of background information prior to the mapping affect the evaluation of the rock mass. This is evident from the results by comparing the "real" mapped Q_{base} to the VR mapped Q_{base}. E.g., the results show the lowest Q_{base} for tunnel face 2, which is the face with the highest Q_{base} acc. to the original mapping. It is, however, emphasized that an in-depth discussion of the VR-results vs. the "real" mapping is seen as pointless since both observations were collected under completely different circumstances. Neither geological background information nor physical observations from scaling or tactile assessment of the rock mass were available for the participants, and lack of such information brings an uncertainty to the assessment which results in a lower degree of knowledge (Bedi & Harrison 2013). However, the spread in the results indicates the degree of uncertainty which is related to the subjective interpretation of visual observations to a rock mass characterization, which is a critical element of uncertainty in rock engineering considering that engineering geologists will, in many cases, be asked to evaluate a situation based on photographic evidence and/or digitally mapping technology (based on photogrammetry and laser scanning data, for example).

RQD and J_n, which are believed to be sufficiently evaluated only by visual observation, shows the overall largest spread in the results. The spread is in accordance with previous uncertainty studies where professionals have assessed the same rock face and quantified the rock mass' jointing conditions (GSI: Elmo et al. 2022, and RQD: Torres et al. 2014). The spread in J_r and J_a is also prominent, but from the survey it was evident that the participants to a higher degree "guesstimated" on these parameters (especially on J_a) due to lack of tactile information. Thus, it is recommended that evaluation of joint friction solely in VR or any other 3D models should be done with great care.

The results from this survey also indicate a larger variability from face to face from group 1 (random) compared to group 0 (consecutive), which can be explained by the human tendency to make decisions based on what is most dominant or accessible in memory (Wilson et al. 2019). One could argue that this type of bias is relevant for tunnel face mapping in general, as previous mapping experiences will lead to differences in the individual basis of empirical knowledge, which drives our decisions. However, rock mass classification is not intended to be the definitive solution with respect to stability and rock engineering design. Analytical studies, field observations, measurements and engineering judgement should also be a part of the decision basis (Bieniawski 1989). Especially engineering judgement is important to validate whether the drawn conclusion is correct or not (Elmo & Stead 2021). From a rock engineering point of view, this can refer to whether the obtained recommendations on rock support from a classification system seem reasonable or not. In this survey, the participants were only told to quantify the four former Q-parameters, and not to estimate a support design. It can be argued that this may cause a lack of engineering judgement in the mapping process, which further leads to a less careful consideration in the decision making.

Rock mass characterization in VR can, however, be a good tool for validating real life tunnel face mapping and consultancy on rock engineering evaluation, where background information is given prior to the mapping. It is believed that VR mapping gives better spatial awareness compared to pictures and 3D-models on a computer. Therefore, VR mapping can also be used for training purposes in a realistic tunnel environment. The results from this study show, however, that the rock mass quality was overestimated in VR compared to real life, highlighting that decision making based on solely a VR mapping or mapping from other 3D models should be avoided.

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