Systematic errors in the characterization of rock mass quality for tunnels

a comparative analysis between core and tunnel mapping

MARÍA DOMINGO SABUGO
Abstract
This thesis analyzes the potential systematic error in the characterization of the rock mass quality in borehole and tunnel mapping. The difference when assessing the rock mass quality refers to the fact that the characterization performed on drilled rock cores are commonly done on-meter length, while the tunnel section can be up to 20-25 m wide. At the same time, previous studies indicate that the engineering geologist tends to characterize the rock mass quality during tunnel excavation with a conservative estimation of the parameters defining the rock mass quality to ensure a sufficient rock support. In order to estimate this possible systematic error produced by the size difference when assessing the rock mass quality, a simulation was performed within a geological domain, representative of Stockholm city. In the simulation, each meter of the tunnel section was given a separate value of the rock mass quality, randomly chosen from a normal distribution representative for the studied geological domain. The minimum value was set to represent the characterized rock mass quality for that tunnel section. The results from the simulation produced a systematic error due to the difference between the geological domain, reproducing the borehole mapping, and the simulated values, representing the tunnel mapping. The results showed a systematic error in the RMR_{basic} index around 15 points in average, which compared to the difference of 5-7 points obtained in Norrström and the Norrmalm tunnels in the Stockholm Citylink project recently constructed, are found to be excessive. However, in the simulation, it was assumed that (1) the results obtained were the same in the borehole mapping and in the tunnel mapping, (2) with the only difference of the engineer geologist assigning to the tunnel section the lowest RMR_{basic} value, and (3) that there was no spatial correlation between the quality RMR_{basic} index. After analyzing the three assumptions the simulation was based upon, the absence of spatial correlation was found to be the most significative, which indicate that spatial correlation in rock mass quality needs to be included if a more correct value should be obtained.

Keywords
Rock mass classification, scale effect, RMR, tunnel mapping, borehole mapping, systematic error.
Stockholm, June 2018

María Domingo
Acknowledgements

First and foremost, I would like to thank my thesis supervisor, Mr. Fredrik Johansson. Without his assistance and dedicated involvement through the process, this thesis would have never been accomplished. I would like to thank you also the KTH Royal Institute of Technology for giving me the opportunity to study in this university and perform my bachelor thesis.

Most importantly, none of this could have happened without the love and support of my family and friends. My father Amador Domingo for his support with whatever I pursue, my supportive sister Clara Domingo for helping me with the correction of the report and my Fermin Mallor who encouraged me and helped me with whatever I needed. And finally, thanks to my mum who always loved me and believed in my ability to be successful. You will always be in my heart.
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1. Introduction

1.1. Background

As in many other infrastructure projects, one of the main issues of tunnel construction is the increase of cost during the planning phase. Focusing in the cost increase based on the unique features of tunnel construction, Lundman (2011) concluded that changes in the rock support during construction phase frequently leads to higher costs.

Initial support is based on the geological prognosis, whereas the final reinforcement is modified after mapping the tunnel. This difference between both prognoses (initial and final) leads to an increase in cost, which in some cases can be quite large. Finally, Lundman (2011) concluded that large cost increases are generated due to optimistic prognoses, as well as cognitive bias, and cautious choices in the tunnel mapping.

Kjellström et. al (2015) studied and quantified the aforementioned discrepancies analyzing the differences between forecasts and tunnel mapping on the Norrströms and Norrmalms tunnels, data obtained from drill holes, engineering geological forecast and tunnel mapping. Kjellström (2015) found that differences in scale in testing can be decisive when assessing lower rock mass quality in tunnel mapping.

The scale effect is caused by assessing the rock mass quality with a lower grade because the worst part of the section being judged will define it. Another reason is that the engineering geologist can conservatively set a lower rock mass quality than he/she thinks it really has, for safety purposes. Therefore, a systematic error is made in rock mass characterization between borehole mapping and tunnel mapping. As a result, a stronger tunnel reinforcement will be used leading to costs increase compared to the initial prognosis.

In addition, Kjellström (2015) specified that one of the causes of this systematic error is that for bore mapping, an average of the fracture
properties of the assessment parameter (i.e. strength, joint spacing) used for
the section is calculated - which is mostly 1-meter long. By contrast, in
tunneling, only visual assessment is used, and critical values are obtained for
a large proportion of the tunnel cross section, where sections of 10 meters are
commonly used in Sweden.

1.2. Aim

The principal aim of this thesis is to investigate if the scale effect is the reason
why a systematic error is produced during rock mass characterization between
the borehole mapping and tunnel mapping.

In order to achieve this, this work aims to (1) select the most appropriate
parameter in current classification systems for the assessment of rock mass
quality that may have been influenced by the cross-section size and (2)
simulate the rock mass quality obtaining a systematic error between borehole
mapping and tunnel mapping, studying in which size the cross-section width
influences the systematic error. The ultimate objective is to gain a more
complete understanding of how these discrepancies are produced to
ultimately identify potential solutions for the increase of project cost due to
changes in the tunnel support.

1.3. Disposition

This bachelor thesis begins with an introduction to the purpose, background
information and limitations.

The second chapter is a summary of the literature study to acquire
knowledge on the subject as well as to evaluate the state of the art techniques in
tunnel rock quality prognoses. Information about the site investigations
performed for tunnel construction purposes, the rock mass definition and the
characterization and classification systems used for the assessment of rock mass quality. Three of the most currently used classification systems in construction are examined and explained in this chapter.

In chapter three, the methodology used in this work is presented. The input data used to define the geological domain, the assumptions made to perform the study, and the steps followed to find the systematic error performed during tunnel mapping due to the scale effect.

Chapter four summarizes the results obtained. Firstly, the representation of the random values simulated are plotted and the selection of the minimum values. Then, the normal distributions of the parameter and the systematic error made in tunnel mapping in comparison with borehole mapping is presented, all performed for varying tunnel widths.

Chapter five consist of the discussion of the results followed by conclusion in chapter six.
2. Literature study

In any kind of civil engineering project, it is necessary to study and determine the ground characteristics where the construction will take place. These studies will determine the design size of the project. Borehole drilling is the most important method in the geological investigation phase, since it provides tangible and direct information about the rock mass.

2.1. Site investigations

The main ground investigations should obtain as much information as possible. These investigations should not be constrained to obtain only the information needed by the design engineer (e.g. for the location and design of the tunnel, shafts and portals), but it should also provide the necessary information for the contractor (e.g. for planning and carrying out the construction). The site investigations are performed taking into account the preliminary ground investigation report, from which a provisional line and depth of the tunnel can be set.

Site investigations are carried out to determine the geological and engineering properties of the soil and/or rock and to know about the existence of groundwater. It is also important to know if the rock mass is consistent or if there is spatial changes in the properties.

Rock samples are generally obtained by core drilling the in-situ rock. The location of borehole is selected for the interpretation of the geological structure. They should be sited in each shaft and portal position and in key positions (West, Carter, Dumbleton, & Lake, 1981). The samples are tested to render a practical identification of rock mass quality and to determine the probable resistance of the material.

At the same time, a borehole mapping needs to be drawn to record the different types of rock or soil encountered in the tunnel path, indicating the
rock mass quality and properties. Later on, an engineering geological forecast will be established, which describes the rock and ground properties that can be expected along the tunnel alignment (Kjellström, Johansson, Swindell, & Larsson, 2015).

2.2. Tunnel mapping

It is never possible to fully know the type of material that will be encountered by a tunnel or anticipate its behavior despite the accuracy of the predictions. For this reason, observations and investigations must be performed during construction. In this way, a modification in the design of tunnel reinforcement can be carried out as necessary in the light of ground conditions and structural behavior during this stage. A continuously updated geological section should be drawn as tunnel moves forward, named tunnel mapping.

Detailed information is obtained by probing ahead of the tunnel face. This technique involves drilling short distances ahead of the tunnel. It may be possible to obtain cores, but in practice it is more usual that a responsible observer records the geological and groundwater conditions encountered and reports any significant information (West, Carter, Dumbleton, & Lake, 1981).

2.3. Scale effect

Scale effect is the result of measuring constitutive properties of rocks in different scales of testing. Specifically, in rock mass quality assessment for tunnel construction purposes, the scale effect refers to the differences generated from the assessment of different size samples in borehole and tunnel mapping, in addition to the intrinsic differences of each mapping type.

In borehole mapping, usually a drilled rock core is characterized in one-meter long sections, whereas in tunnel mapping the rock mass quality is usually assessed through visual examination by the engineer geologist, who rates the rock mass in a more cautious way (this means assigning the lowest
local value found within the cross section), and consequently, a stronger tunnel support will be later used. In addition, the engineering geologist map the tunnel with a width larger than one meter and might define the rock mass quality of that section based on the part of the tunnel section with the poorest quality.

2.4. Rock mass

2.4.1. Definition

In rock mechanics, intact rock is defined as an element of rock which does not present any observable discontinuity. Whereas a rock mass refers to the in situ rock with its discontinuities, understood as stratification, schistosity, folds, faults and joints, and weathering profile (Singh & Goel, 1999) (West, Carter, Dumbleton, & Lake, 1981).

2.4.2. Characterization and classification of rock mass quality

A variety of systems have evolved, especially during the latter part of the 20th century. The international systems are in many cases associated with what is called “rock mass classification”. In the classification, the rock mass quality is based on a score system for different parameters, which is a numeric value corresponding to its quality or strength. Then, it is inserted in a predefined class or interval defined by a lower and upper numeric limit. Theses classes are associated with a verbal description of the rock quality and in most of the cases a recommended rock support based on experience from case studies.

The characterization of rock quality is a method in which the rock mass is described in a systematically and measurably manner in terms of quality. A simple characterization of rock quality can be based on a single parameter (eg RQD), while more sophisticated multi-parameter systems are based on several components deemed to be relevant to the purpose. Characterization can take into account external factors such as tension conditions, groundwater conditions and cracks orientation in relation to driving direction. In case the characterization takes into account these external factors are called character-
rization with full index value. There is also the possibility to characterize without considering the external factors, what is called “characterization with base index value”.

Rock mass characterization defines the pure rock mass with respect to its strength and quality. On the contrary, the discontinuities and the context of the rock mass are also accounted in rock mass classification. Furthermore, the tunnel design, its position and its possible interaction with the discontinuities play a big role in rock mass classification, as well as the presence of caves and cavities.

2.4.3. Classification systems

Currently, the three geomechanics classifications most used are: the Geomechanics Classification or RMR of Bieniawski (1973), the Q-system by Barton, Lien and Lunde (1974) and the GSI (Geological Strength Index) by Hoek (1994). These classifications were created for underground excavations and the main application is the selection of the tunnel support. The two first classifications use the parameter RQD (Rock Quality Designation) introduced in 1964 by Deere (Ramírez Oyanguren & Alejano Monge, 2004).

2.4.3.1. RQD (Rock Quality Designation)

The RQD by Deere (1964) is the percentage of core pieces (see Figure 1) that are equal or greater than 10 cm in length and allows to measure the degree of jointing or fracture in a rock mass.

\[
RQD = \frac{\text{sum core pieces } \geq 10\text{cm}}{\text{total drill run}} \cdot 100\% \tag{1}
\]

When cores are not available, RQD may be estimated from number of joints (discontinuities) per unit volume \(J_v\). A simple relationship which may be used to convert \(J_v\) into RQD for clay-free rock masses is (Palmström, 1974):
where $J_v$ represents the total number of joints per cubic meter or the volumetric joint count.

The volumetric joint count (Palmström, 1982) is defined by $J_v = \sum_{i=1}^{j} \frac{1}{S_i}$, where $S_i$ is the average jointing space in meters for the joint set and $J$ is the total number of joint sets (except the random joint sets).

\begin{equation}
RQD = 115 - 3.3 J_v
\end{equation}

Figure 1. Drilled rock cores. (SWAS Water Surveys, 2013)

2.4.3.2. RMR (Rock Mass Rating)

Today, there are two versions of the Rock Mass Rating (RMR) system in general use: RMR$_{76}$ (Bieniawski, 1976) and RMR$_{89}$ (Bieniawski, 1989). Trafikverket (2105) recommends using the later version, RMR$_{89}$, when generating both the base index value and the full index value. In the future, the term "RMR" is used as a synonym for RMR$_{89}$ system.

To determine the rock mass quality with the RMR classification, a given site is divided into structural domains, in other words, in zones limited by geologic discontinuities within which the structure is almost homogeneous. The RMR (Rock Mass Rating) is the index used to classify the rock mass, which evaluates it by meaning of the following parameters:
Uniaxial compressive strength should be obtained from core rocks in accordance with site conditions. The joint spacing is the mean distance between discontinuities. The rock mass resistance decreases with increasing of number of joints, that is, when the spacing of each family of joints decrease. The rating should be obtained for the most critical distance. Joint condition regards to some physical characteristics as, for example, continuity of the joint depending on course and dip, roughness and joint filler. The presence of water is assessed estimating the water flow in litres/min every 10 m of tunnel. The description is completely dry, wet, moderate water pressure and high-water pressure.

The RMR is the addition of the above parameters, and its range varies from 8 to 100. Additionally, the classification system considers one correction factor related to the relative disposition between the discontinuities and the tunnel axis (classification part), distinguishing from highly favourable and highly unfavourable, with a constant that varies from 0 to -12.

\[ RMR = RQD + \sigma_{ci} + J_{\text{spacing}} + J_{\text{cond}} + \text{GW}_{\text{cond}} + J_{\text{orientation}} \]  

(3)

There is also the possibility of characterizing the rock mass using the RMR system, using the RMR base index value, denoted as \( \text{RMR}_{\text{basic}} \). It is defined in the handbook of design of tunnels and rock caverns construction” by Trafikverket, the Swedish transport administration (2015). In this handbook, it is recommended to characterize the rock mass quality in a variety of situations, e.g. at surface hills, mountain slopes and underground
installations, when drilling cores and during mapping during construction time.

In characterization no account is taken of:
- In-situ stresses
- orientation of cracks in relation to the orientation of the tunnel
- tunnel design
- And water pressure or flows into the intended tunnel, i.e. dry conditions should be assumed

Table 1. RMR classification parameters and their values (Ramírez Oyanguren & Alejano Monge, (2004) based on Bieniawski Z. T. (1989)).

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Scale values</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Intact rock strength</td>
<td>Under point load</td>
</tr>
<tr>
<td>Value</td>
<td>15</td>
</tr>
<tr>
<td>2 RQD</td>
<td>90-100 %</td>
</tr>
<tr>
<td>Value</td>
<td>20</td>
</tr>
<tr>
<td>3 Joint spacing</td>
<td>&gt;2 m</td>
</tr>
<tr>
<td>Value</td>
<td>20</td>
</tr>
<tr>
<td>4 Joint condition</td>
<td>Very roughs, with no continuity, closed, joint walls slightly meteorized.</td>
</tr>
<tr>
<td>Value</td>
<td>30</td>
</tr>
<tr>
<td>5 Ground water condition</td>
<td>Flow in each 10 m tunnel</td>
</tr>
<tr>
<td>Joint water pressure</td>
<td>0</td>
</tr>
<tr>
<td>General conditions</td>
<td>Completely dry</td>
</tr>
<tr>
<td>Value</td>
<td>15</td>
</tr>
<tr>
<td>RMR total value</td>
<td>81-100</td>
</tr>
<tr>
<td>-----------------</td>
<td>--------</td>
</tr>
<tr>
<td>Class number</td>
<td>I</td>
</tr>
<tr>
<td>Description</td>
<td>Very good</td>
</tr>
</tbody>
</table>

2.4.3.3. Q-system

The classification suggested by Barton et al. (1974), the rock mass is classified by the rock mass quality index Q, based in the following 6 parameters:

- RQD “Rock Quality Designation”
- J_n Joint set number
- J_r Joint roughness
- J_a Joint alteration number
- J_w Joint water reduction factor
- SRF “Stress Reduction Factor”, factor mainly dependent on the existent stresses in the rock mass.

The aim of the Q-system is to classify the rock mass and provide a preliminary empirical design of the support systems for tunnels and caverns (even though the last application is not going to be explained in this project as it is focused in rock mass characterization and classification).

Barton’s classification assigns an index of quality to each zone, where higher values represent better quality. Its variation is not linear as RMR is, but it is exponential, and oscillates between Q=0.001 for very poor rock masses to Q=1000 for very good rocks.

The rock mass quality is defined as:
The fist coefficient, \( R_{QD} \), represents the block size.

\( J_n \) enables to estimate the inter-block shear strength.

\( J_r \) indicates the active effective stress state in the rock mass.

The above included parameters in equation (4) are briefly described.

- **RQD** is explained in section 2.3.3.2.
- **J\(_n\)**, Number of joint sets. It is approximately equal to the square of the number of joint sets. It varies from 0.5 for massive or few joints to 20 for crushed rock.
- The parameters \( J_r \) and \( J_a \) represent roughness and degree of alteration of joint walls or filling material. \( J_r \) varies from 0.5 for planar rock contacts to 4 for discontinuous joint. \( J_a \) varies from 0.75 for unaltered joint walls to 20 for bands of clay with no rock wall contact. These parameters should be obtained for the weakest critical joint-set or clay-filled discontinuity in a given zone. If the selected one is favourably oriented for stability, then a second less favourably should be used.
- **J\(_w\)** is a measure of water pressure (MPa), which has an adverse effect on the shear strength of joints due to reduction in effective normal stress. Adding water causes softening and possible outwash in clay-filled joints. The value varies from 0.05 for high inflow to 1 for dry excavation.
- **SRF** is a measure of loosening pressure during excavation through shear zones and clay-bearing rocks; rock stress in competent rocks and squeezing pressure in plastic incompetent rocks. (Total stress parameter). It goes from 0.5 for very tight structures to 400 for heavy rock burst and immediate dynamic deformations in massive rock.
The rock mass quality is prone to change in all directions. It varies from $Q_{\text{min}}$ to $Q_{\text{max}}$, so the average rock mass quality may be used in design calculations. The rock masses are classified into nine categories (see Table 3).

### Table 3. Classification of rock mass based on Q-values.

<table>
<thead>
<tr>
<th>$Q$</th>
<th>Classification</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.001-0.01</td>
<td>Exceptionally poor</td>
</tr>
<tr>
<td>0.01-0.1</td>
<td>Extremely poor</td>
</tr>
<tr>
<td>0.1-1</td>
<td>Very poor</td>
</tr>
<tr>
<td>1-4</td>
<td>Poor</td>
</tr>
<tr>
<td>4-10</td>
<td>Fair</td>
</tr>
<tr>
<td>10-40</td>
<td>Good</td>
</tr>
<tr>
<td>40-100</td>
<td>Very Good</td>
</tr>
<tr>
<td>100-400</td>
<td>Extremely good</td>
</tr>
<tr>
<td>400-1000</td>
<td>Exceptionally good</td>
</tr>
</tbody>
</table>

### 2.4.3.4. GSI (Geological Strength Index)

The Geological Strength Index (GSI), introduced by Hoek (1994), to solve the problems detected using the RMR index to assess the rock mass strength by the generalized criterium of Hoek-Brown. It is determined based on two parameters which define the strength and deformability of the rock mass: (1) the RMS, which is the structure of the rock mass, defined by its blockiness and its workability and (2) the joint condition of the discontinuities. It ranges from 0 for low rock mass quality to 100 for high quality rock mass, and it is essentially a qualitative procedure whose accuracy depend on the level of experience and judgement of the observer directly involved in field mapping (Morelli, 2015). To improve the objective assessment of the GSI, quantitative charts based on a numerical quantification of the parameters have been presented by several authors. In the last version of the GSI Chart,
two simple linear scales have been found to be suitable to consistently present the discontinuity conditions on the horizontal axis and blockiness of the rock mass on the vertical axis. It uses the \( J\text{Cond}_{89} \) parameter from Bieniawski (1989) and \( \text{RQD}/2 \) (see Figure 2). The final value of the GSI is given by the sum of the two scales (Hoek & Brown, 1997):

\[
\text{GSI} = 1.5 \times J\text{Cond}_{89} + \text{RQD}/2
\]  

Hoek (1997) recommends referring to a numerical range rather than a unique value because it is more realistic.

Figure 2. Chart for determining GSI of jointed rock mass (Hoek & Brown, 1997).
3. Methodology

This chapter presents the methodology used to estimate the systematic error made in rock mass quality assessment between borehole mapping and tunnel mapping due to the effects derived from using different scale.

The following issues are addressed in order to achieve the aforementioned aim:

1. Identify the assessment parameter of the rock mass classifications to focus on.
2. Choose a geological domain that characterizes the Stockholm city area for each selected parameter.
3. Simulate the rock mass data obtained during tunnel excavations for different tunnel sizes.
4. Assume the engineer geologist selects the minimum value of the one-meter sections in the tunnel cross section for safety reasons to define rock mass quality.
5. Find the systematic error between the simulated values obtained in tunnel mapping and the ones obtained in borehole mapping.
6. Analyse the results and perform a parameter sensitivity analysis.
7. Compare the simulated results against observed discrepancy between core and tunnel mapping in the Stockholm City Link project.
3.1. Parameter selection

Different characterization systems have been presented in the previous chapter and, in this section, the choice of the most suitable parameter to simulate the systematic scale error will be assessed. The choice of the parameter will be first done by choosing an appropriate classification system and then by selecting a rock mass quality parameter associated with such classification system.

The RMR system uses the RMR index to assess the rock mass quality, which is in decimal scale, whereas the Q-system uses the Q-index which is in logarithmic scale. Hence, the reason for choosing the RMR system is the simplicity in terms of scaling. Then, once the classification system has been chosen, the relevant rock mass-quality parameters must be selected. In order to make a comparison between the two different prognoses (borehole mapping and tunnel excavation results), the parameters selected must be applicable to both cases (i.e. the
parameter should be such that it can be computed with the information available in each phase. This translates into comparing the rock mass characterization and not the classification. When classification is compared, external factors only known during the excavation phase, such as tunnel design or crack orientation relative to driving direction, must be considered. The RMR classification index is a result of two values, the RMR_{basic} (Trafikverket, 2015) related to the rock mass characterization, and the Joint orientation with respect to the direction of the tunnel, related to the classification. As the exact joint orientation cannot be determined with the borehole mapping, only the RMR_{basic} value will be used in this study in order to determine the systematic error, in which the ground water condition is set to be in dry conditions, so with a score of 15.

\[
RMR = RQD + \sigma_{c_i} + J_{spacing} + J_{cond} + GW_{cond} + J_{orientation}
\]  

(6)

\[
RMR = \underbrace{RMR_{basic}}_{\text{characterization}} + J_{orientation}
\]  

(7)

### 3.2. Assumptions

To perform this study, in which the finding of the systematic error related to scale effect is the aim, the following assumptions were made:

- The engineering geologist who carries out the mapping of the tunnel during excavation is assumed to use the RMR index where the obtained value is based on the area in the tunnel section with the poorest quality for security reasons, whereas in core testing, the mean value is considered.
- The quality registered is the same in both geological investigations. The engineering geologist maps the rock cores and the tunnel in the same way, with the same values.
- The parameters are randomly distributed spatially within a geological domain. No spatial correlation is introduced when simulating the RMR basic parameter.
3.3. Geological domain

The same geological domain is going to be used to assess the RMR$_{\text{basic}}$ for both mappings. First, the normal distribution of borehole mapping is determined from available data, and then, using the same domain, the tunnel excavation data is simulated. As it was previously mentioned, the values obtained in both tunnels of the Stockholm Citylink define the geological domain used to perform this study. Tables 3 and 4 show the mean values, the standard deviations and the coefficients of variance obtained from borehole mapping presented in the pre-investigation report (Kjellström et al. 2015).

Table 3. Data collected in the Norrström tunnel (Kjellström et al. 2015).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>µ</th>
<th>σ</th>
<th>COV</th>
</tr>
</thead>
<tbody>
<tr>
<td>RMR$_{\text{basic}}$</td>
<td>78,10</td>
<td>9,11</td>
<td>11,66</td>
</tr>
<tr>
<td>Uniaxial compressive stress</td>
<td>11,44</td>
<td>1,63</td>
<td>14,24</td>
</tr>
<tr>
<td>RQD</td>
<td>19,14</td>
<td>2,25</td>
<td>11,78</td>
</tr>
<tr>
<td>Joint spacing</td>
<td>11,09</td>
<td>3,03</td>
<td>27,29</td>
</tr>
<tr>
<td>Joint condition</td>
<td>21,44</td>
<td>5,05</td>
<td>23,54</td>
</tr>
</tbody>
</table>

Table 4. Data collected in the Norrmalm tunnel (Kjellström et al. 2015).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>µ</th>
<th>σ</th>
<th>COV</th>
</tr>
</thead>
<tbody>
<tr>
<td>RMR$_{\text{basic}}$</td>
<td>75,96</td>
<td>11,70</td>
<td>15,40</td>
</tr>
<tr>
<td>Uniaxial compressive stress</td>
<td>10,78</td>
<td>2,05</td>
<td>18,99</td>
</tr>
<tr>
<td>RQD</td>
<td>18,70</td>
<td>3,09</td>
<td>16,51</td>
</tr>
<tr>
<td>Joint spacing</td>
<td>11,27</td>
<td>3,59</td>
<td>31,82</td>
</tr>
<tr>
<td>Joint condition</td>
<td>20,21</td>
<td>6,20</td>
<td>30,68</td>
</tr>
</tbody>
</table>
In accordance to the RMR classification system, values of RMR basic between 61-80 rating are associated to a good rock mass class. Table 5 presents the geological domain obtained by taking the average values of both tunnels.

Table 5. Geological domain.

<table>
<thead>
<tr>
<th>RMR basic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu$</td>
<td>77.03</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>10.4</td>
</tr>
<tr>
<td>COV</td>
<td>13.53</td>
</tr>
</tbody>
</table>

3.4. Simulation of the rock mass data in tunnel mapping

The main aim of this project is to find the possible systematic error in the step between the borehole mapping and the tunnel mapping related to the so called scale effect. In order to do so, different tunnel sections, ranging in width from 5 up to 25 meters, are used. Then, a Monte Carlo simulation is performed using the data from the borehole mapping studies. This allows to obtain random inputs which are then used as if they were taken during real in-site investigations in tunnel excavations. This chapter will explain all the procedure followed to obtain the simulated normal distributions and the systematic errors.

3.4.1. Normal distribution

The normality of RMR distribution has been verified using various graphical and statistical tests, such as Shairo-Wilk test and Kolmogorov-Smirnov test with Lilliefors corrections. The Gaussian distribution can be extended to the other rock mass characterization parameters since its validity has been plenty of times verified.
The Normal or Gaussian distribution is a probability distribution of a continuous variable in the domain \([-\infty, +\infty]\). It is dependent of the mean, \(\mu\), and the standard deviation, \(\sigma\). The probability density function (PDF) of a Gaussian distribution, expressed like \(X \sim N(\mu, \sigma^2)\) is given by (8).

\[
f(x) = \frac{1}{\sigma \sqrt{2\pi}} \exp\left(-\frac{(x - \mu)^2}{2\sigma^2}\right)
\] (8)

The function curve is symmetric, and bell shaped so that the mean, median and mode fall together. The value of the mean fixes the location of the normal curve and the value of the standard deviation determines the spread; the bigger \(\sigma\), the more spread out or flat is the curve.

### 3.4.2. Monte Carlo simulation

The distribution is obtained using a geological domain, which indicates the mean and the standard deviation. The method used for simulating the distributions is the Monte Carlo method. A two-step method is followed: (1) random variables normally distributed between 0 and 1 are generated, and (2) the values of the normal distribution obtained in step 1 are transformed to the values with the mean and the standard deviation given by the borehole mapping data.

1) There are several arithmetic random-generators developed for computer-based random generation. Matlab allows to obtain normally distributed random numbers using the function \(\text{randn}\). This function returns a sample of random numbers from a normal distribution with zero mean and variance equal to one.

2) The next step is to shift and scale. The general theory of random variables states that if \(x\) is a random variable whose mean is \(\mu_x\) and whose standard deviation is \(\sigma_x\), then the random variable, \(y\), defined by \(y = ax + b\), where
\( a \) and \( b \) are constants, has mean \( \mu_y = a\mu_x + b \) and variance \( \sigma_y^2 = a^2\sigma_x^2 \) (Matlab, 2005). The expressions result as follow:

\[
y = \sigma_x \ast x + \mu_x \tag{9}
\]

3) Create a matrix which contains the simulated random values as if they were taken from the tunnel. A matrix with the random values placed in \( n \) rows, where \( n \) are the meters of the tunnel section (width), and \( m \) the columns, where \( m \) is the length of the tunnel.

\[
\text{Matrix random} = \begin{bmatrix} n, m \end{bmatrix}, \\
\text{where } n = \text{tunnel width and} \tag{10}
\]

\[
m = \frac{\text{tunnel length}}{\text{tunnel progress}} \tag{11}
\]

4) Create a vector with the minimum values of each column, that is, the minimum values of each tunnel progress, and compute its mean, \( \mu_y \), and its standard deviation, \( \sigma_y \).

5) Calculate and plot the probability density function stated above.

Figure 4 shows a 20 m wide and 50 m long tunnel section, in which the random values generated with Matlab were mapped. The different colours represent 5 different categories based on the RMR system classification of rock mass quality. Figure 5 shows the location (coloured in red) of the minimum RMR\(_{\text{basic}} \) values obtained at each one-meter depth cross-section, in the same 20 by 50 m tunnel section.

3.4.3. Systematic error

Once the simulated distribution with the minimum RMR\(_{\text{basic}} \) values has been obtained, the next step is to calculate the systematic error. A systematic error implies that all measurements in a set of data taken with the same instrument or technique are shifted in the same direction, the same amount (a systematic or bias
error is a non-zero mean event, compared to a random error, which has zero mean). In this case, where normal distributions are considered, it is obtained simply by

Figure 4. Random values representation of RMR\textsubscript{basic} values in tunnel mapping in a 20x50 m section of tunnel.

Figure 5. Location of the minimum RMR\textsubscript{basic} value at each one-meter depth cross-section of a 20x50 m section of tunnel.
computing the difference of the means in borehole mapping, which is defined by the geological domain (see Table 5) and the minimum values simulated for each tunnel width. Therefore, 25 systematic error will be analysed, and the effect of the scale of the tunnel (i.e. its width) will be investigated.

3.4.4. Sensitivity analysis

In principle, two possibilities can lead to the scaling effect:

- The engineering geologist takes the minimum rock mass quality assessment to map the tunnel, that in the rock mass rating system is the RMR index mapping.
- The engineering geologist takes the minimum rating of one or more parameters that compose the RMR index.

The sensitivity analysis, which considers the second option, has been performed in the same way as the RMR \textit{basic} simulation, assuming that the engineering geologist only maps the parameter with the lowest value in each section. In this way, the importance of each four parameters in the estimation of the rock mass quality using the RMR system is observable. Looking separately into these components will help to better understand the causes of the scaling effect.

Recovering its definition, the RMR index was the addition of: $\sigma_{el}$, RQD, $J_{\text{spacing}}$, $J_{\text{cond}}$, $GW_{\text{cond}}$, $J_{\text{orientation}}$. As explained before, in this work the focus is placed only on the rock mass characterization, which is given by the index RMR\textit{basic}. Thus $GW_{\text{cond}}$ was assumed to be 15, that is in dry conditions, in both the core and the tunnel for the RMR \textit{basic} to be comparable and $J_{\text{orientation}}$ was not included because it is part of the classification, and not the characterization (Trafikverket, 2015). The other values for the parameters were selected from the Stockholm City Link tunnels (Kjellström et al. 2015).
Table 6. Mean, standard deviation and variance coefficient of the RMR system parameters in characterization (Kjellström et al. 2015).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$\sigma_{c_1}$</th>
<th>RQD</th>
<th>$J_{\text{spacing}}$</th>
<th>$J_{\text{cond}}$</th>
<th>GW</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu$</td>
<td>11,11</td>
<td>18,92</td>
<td>11,18</td>
<td>20,83</td>
<td>15</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>1,84</td>
<td>2,67</td>
<td>3,31</td>
<td>5,63</td>
<td>0</td>
</tr>
<tr>
<td>COV</td>
<td>16,62</td>
<td>14,15</td>
<td>59,11</td>
<td>27,11</td>
<td>0</td>
</tr>
</tbody>
</table>
4. Results

This chapter summarises the results obtained for tunnel widths from 5 to 25 m. The normal random distribution was produced for each tunnel section and the systematic error was generated by selecting the lower rate of the RMR\textsubscript{basic} index.

The minimum RMR\textsubscript{basic} values obtained by the simulation range from rates of 42.3 to 71.4. The mean, the standard deviation and the systematic error are compiled in Table 7 for five different widths.

Table 7. Mean, standard deviation and systematic error of RMR\textsubscript{basic} obtained for each tunnel width.

<table>
<thead>
<tr>
<th>Width (m)</th>
<th>$\mu$</th>
<th>$\sigma$</th>
<th>Systematic error</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>65.4</td>
<td>6.4</td>
<td>11.6</td>
</tr>
<tr>
<td>10</td>
<td>62.2</td>
<td>5.5</td>
<td>14.8</td>
</tr>
<tr>
<td>15</td>
<td>59.6</td>
<td>5.4</td>
<td>17.4</td>
</tr>
<tr>
<td>20</td>
<td>58.6</td>
<td>5.1</td>
<td>18.5</td>
</tr>
<tr>
<td>25</td>
<td>57.3</td>
<td>4.9</td>
<td>19.7</td>
</tr>
</tbody>
</table>

The results show that the mean decreases with the width. This is because increasing the size section will allow the compilation of more data leading to a lower RMR\textsubscript{basic} value. Regarding the dispersion of the values, the wider the tunnel is, the lower the standard deviation becomes. This is because increasing the number of values and choosing the minimum one implies the results being closer to the mean; whereas when only 5 choices are available, the difference between these is bigger when selecting the lower one. This can be appreciated in Figures 6.a and 6.b, where the wider the tunnel is, the narrower the normal distribution curve becomes.
Figure 6. a) Both borehole and tunnel mapping probability density functions for randomly normally distributed RMR basic values in a 5 m wide tunnel a) and in a 15 m wide tunnel b).
Finally, it can be observed an increase in the systematic error, from 11.6 in a 5 m wide tunnel to a 19.7 in a 25 m wide tunnel. Such a large systematic error leads to ask which of the terms that compose the RMR index takes a bigger role in its outcome. The results of the sensitivity analysis are plotted in Figure 7. It depicts how the systematic error in the RMR\textsubscript{basic} index, obtained by taking the lowest value of one parameter in each case, varies with tunnel width.

The analysis illustrate that the joint condition is by far the most important parameter, graded from 6.39 in the 5 m wide tunnel to 10.94 for the 25 m wide tunnel points lower. It is followed by joint spacing, RQD and uniaxial compressive strength in order of influence.

![Sensitivity analysis](image)

Figure 7. Sensitivity analysis of the parameters that compose the RMR\textsubscript{basic} index; $\sigma_c$, RQD, $J_{\text{spacing}}$, $J_{\text{condition}}$, $GW_{\text{cond}}$. 
5. Discussion

A second-order polynomic function was found to be the function that better describes the $RMR_{\text{basic}}$ systematic error (see Figure 7). Errors between 12 to 20 are too big when comparing them to the ones obtained in the Norrström and Norrmalm tunnels, assessed with 5.03 and 7.53 units lower when compared to borehole mapping (Kjellström, 2015). Such a big difference between realistic and simulated results indicate that some assumption may be not correct. Next there are some discussions about the assumptions made, and their consequences in the results.

![Graph](image)

Figure 7. Systematic errors obtained with the simulation of the $RMR_{\text{basic}}$ values in tunnel mapping varying the tunnel width.
5.1. The engineering geologist maps core and tunnel in the same way

The first assumption was that the engineering geologist maps the rock cores and the tunnel in the same way, with the same quality values. However, it is more likely to assess some of the parameters in a different way in the tunnel mapping compared to a drill core.

In the uniaxial compressive strength, $\sigma_{ci}$, no change is expected. The rock strength is not going to change because of the tunnel excavation. However, the other three parameters are expected to be assessed different. RQD will increase due to the difficulty in observing cracks in tunnel walls compared to doing it on drilled rock cores. Joint spacing and RQD will decrease because more or wider cracks appear when blasting the rock. Joint condition may be as well lowered due to assessing the roughness in distance during tunnel driving, for instance, is more difficult and less accurate that in rock cores. The rock will appear to have less roughness, so the joint condition will be set lower.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$\sigma_{ci}$</th>
<th>RQD</th>
<th>$J_{spacing}$</th>
<th>$J_{condition}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rock core</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Tunnel</td>
<td>x</td>
<td>↑</td>
<td>↓</td>
<td>↓</td>
</tr>
</tbody>
</table>

It can be concluded, that joint condition and joint spacing are the rock mass parameters that can variate more. On the contrary, uniaxial compressive strength could be neglected as it is a property of the rock, which is not influenced by any external factor. It is also noticeable that RQD may increase and partly counteract the decrease of the joint parameters. So, in a real scenario, following Table 8 as a rough estimation, the curve obtained in Figure 7 will be lowered somewhere around the middle since the systematic error will be reduced because the joint parameters will decrease.
5.2. The rock quality is assessed with a minimum value.

The second assumption made was that the engineering geologist, who carries out the mapping during the tunnel excavation, assess the rock mass with the lower RMR value for security reasons. But, in real projects, how this minimum value is being chosen? Is she or he taking all the minimum values of the four parameters or only a few of them? And, is all of the section being considered?

The engineering geologist will probably not take all the parameters with the minimum value. As it can be seen in Table 8, not all of them are planned to vary in the same quantity, so the engineering geologist may choose the parameters that are most likely to change, i.e. joint spacing and joint condition. Furthermore, he or she may be only considering the tunnel ceiling, because is the most critical part. This reduction in the tunnel section considered implies a reduction in the systematic error.

5.3. The parameters are randomly distributed spatially

The third assumption made was that the parameters were randomly distributed spatially. This assumption is most likely wrong, obviously the rock mass is not changing every meter. It probably exists a spatial correlation that should have been taken into account.

In order to estimate how the systematic error will be, if spatial correlation was used, the extreme case of the spatial correlation being equal to the width is presented. The result would be no difference with borehole mapping, because the minimum value is equal in all the width. So, it can be extracted that the real systematic curve is between the line y=0 and the curve obtained in the simulation. This is clearly the assumption that most affects the results.
6. Conclusion and further discussion

The scale effect is proved to happen because in the Stockholm Citylink project, the rock mass quality was assessed to be lower (5-7 points) in the tunnel mapping, compared to borehole mapping and the prognosis, which affected the tunnel support used in the tunnel construction, and resulted in cost increases (Kjellström et al. 2015). The attempt through Monte Carlo simulations to estimate the systematic error produced between borehole and tunnel mapping doesn’t fit with real results, obtained for the tunnels constructed in Stockholm city, Norrström and Norrmalm tunnels. The reason might be due to the assumptions made to simulate the quality of the rock mass in the tunnel mapping. No spatial correlation was introduced in the simulation, so the systematic error might be exaggerated. In addition, no difference in assessment was also assumed but, blasting and other unexpected geological events may lead to changes in the results.

Finally, it should be noted that tunnel mapping is an assessment performed by an engineer geologist most of the times based only on visual judgement. This assessment is also subjective and varies between different engineering geologists. Therefore, the systematic error is riddled with uncertainty and is difficult to predict. In addition, it can be concluded that special attention must be done in the assessment of joint condition and joint spacing, because these parameters are the ones in the characterization system that could be expected to vary the most between core and tunnel mapping.

Further investigations could apply some scale factor in the rock mass quality obtained during tunnel excavation, to mitigate the lower quality designated and reduce the increase of costs due to the redesign of the tunnel support. These investigations should be taken into account all the previous remarks. Also, one way to minimize the systematic error could be to investigate the spatial correlation in drill cores that has been mapped. In this way, a better forecast can be done, and the lowest values can be expected.
7. References


