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# FINITE ELEMENT STUDY OF PRELIMINARY DESIGN OF TUNNEL SUPPORT BASED ON RMR AND Q-SYSTEM

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**Abstract:** The main purpose of a tunnel design is to use the rock itself as the principal structural material with little disturbance during the excavation and to provide as little support system as possible. Therefore, the determination of geological and geotechnical conditions in a project area is necessary as to provide the preliminary design of support system. For purpose of this research, secondary data from an island in Singapore were collected. The assessment on the rock mass classification and tunnel support system has been carried out using Rock Mass Rating (RMR) and Q-Index (Q) systems. These two sets of support systems obtained from the RMR and the Q systems will be compared and analyzed using the numerical analysis of Phase2 software. The stress conditions and resulting deformations around the tunnel were monitored to identify the workability of the proposed support system. It was found that, at depth of 50m, the RMR support system appeared to be conservative. However, at the depth of 145m, where the stress is almost three times at which, the proposed of RMR support system provide a satisfactory result compared to the Q system. It is also appeared that total displacement of the tunnel boundary is quite sensitive to the UCSi value. Further parametric study should be carried out on other rock mass parameters to monitor the tunnel behavior.

**Keywords:** *RMR, Q-system, tunnel support systems, Phase$^2$*

## 1.0 Introduction

The informative data when dealing with rock mass are discontinuities. These discontinuities represent a wide variety of surfaces which geological identification conveys important information on some of their geometrical and mechanical parameters. Other parameters such as degree of weathering, strength of intact rock and water flow are also important in the process of classifying the rock mass condition. For example, the water seepage in these discontinuities has softening effect on the excavated rock surface and caused weakening of the rock. The knowledge of these conditions are of a great assistance in the classifying the rock mass condition and identification appropriate supporting system.

The two commonly used rock mass classification systems are Q and RMR, they have been successfully applied to estimate stability conditions and determination of support systems for many underground constructions (Bieniawski and Benjamin, 2007 and Barton, *2002*). Such empirical approaches have normally been used in mining. In order to confirm the empirical results obtained and hence the decision taken as a solution for a particular problem, a reliable estimates of the strength and deformation characteristics of the rock masses require numerical approach. The trend is towards the use of numerical analysis techniques in order to model and estimate the stresses and strains around tunnel supports. They are either used to specify the support system or to check the appropriateness of the support system empirically chosen (Gadde *et al*., 2007).

## 2.0 Rock Mass Classification

### *2.1 Rock Mass Rating (RMR)*

Classification of rock masses utilizes the following six parameters, all of which are measurable in the field and some of them may also be obtained from the borehole data (Bieniawski, 1989):

1. Uniaxial compressive strength of intact rock material (UCS),
2. Rock quality designation (RQD),
3. Spacing of discontinuities,
4. Condition of discontinuities,
5. Groundwater conditions and
6. Orientation of discontinuities.

The first five parameters (1 to 5) represent the basic parameters ($RMR_{basic}$) in the classification system. Each of these parameters is given a value. All the values are algebraically summed for the first five given parameters and then adjusted by the sixth parameter depending on the joint and tunnel orientation as shown in the following equations:

$$RMR_{basic} = \Sigma \text{parameters } (1+2+3+4+5) \quad (1)$$

$$RMR = RMR_{basic} + \text{adjustment for joint orientation.} \quad (2)$$

### *2.2 Q-System*

Barton *et al.* (1974) at the Norwegian Geotechnical Institute (NGI) proposed the Q-system of rock mass classification on the basis of about 200 case histories of tunnels and caverns. It is a quantitative classification system, and is an engineering system that enables the design of tunnel supports. The Q-system depends on three fundamental requirements:

1. Classification of the relevant rock mass quality,
2. Choice of the optimum dimensions of the excavation with consideration given to its intended purpose and the required factor of safety,
3. Estimation of the appropriate support requirements for that excavation.

The Q-System is based on a numerical assessment of the rock mass quality using six different parameters:

$$Q = (RQD/J_n) \,.\, (J_r/J_a) \,.\, (J_w/SRF) \tag{3}$$

Where:

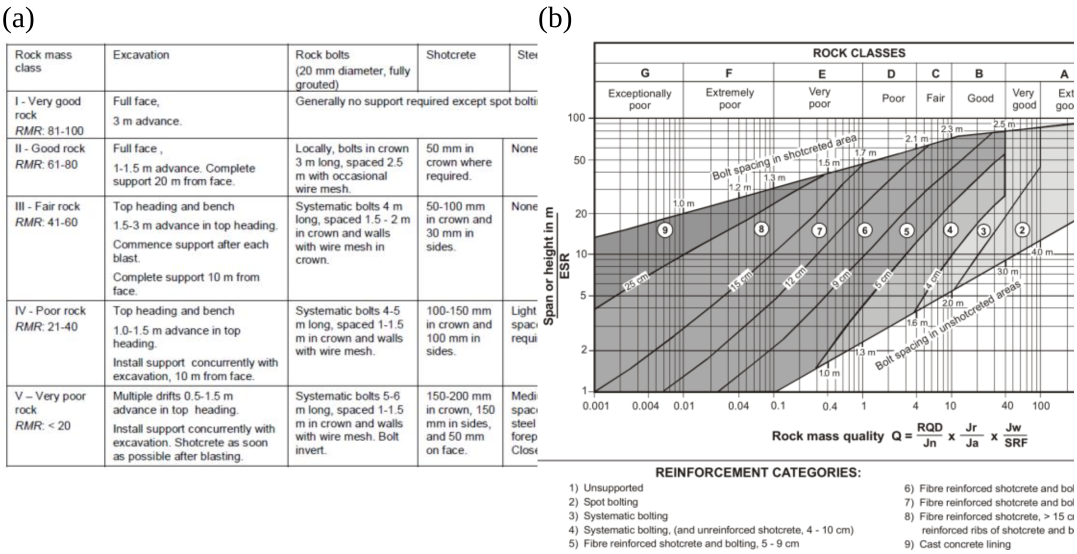
| | |
|---|---|
| RQD | is the Rock Quality Designation |
| $J_n$ | is the joint set number |
| $J_r$ | is the joint roughness number |
| $J_a$ | is the joint alteration number |
| $J_w$ | is the joint water reduction factor |
| SRF | is the stress reduction factor |

The numerical value of the index Q varies on logarithmic scale from 0.001 to a maximum of 1000. The numerical values of each of the above parameters are interpreted as follows (Barton *et al.*, 1974): The first quotient ($RQD/J_n$), representing the structure of the rock mass, is a crude measure of the block or particle size. The second quotient ($J_r/J_a$) represents the roughness and frictional characteristics of the joint walls or filling materials. The third quotient ($J_w/SRF$) consists of two stress parameters. The parameter $J_w$ is a measure of water pressure. The quotient ($J_w/SRF$) is a complicated empirical factor describing the active stress.

Barton *et al.* (1974) considered the parameters, $J_n$, $J_r$ and $J_a$, as playing a more important role than joint orientation, and if joint orientation had been included, the classification would have been less general. However, orientation is implicit in parameters $J_r$ and $J_a$, because they apply to the most unfavorable joints.

## 3.0 Design Support System.

Both RMR and Q systems provide the support system which reflect to the given quality rock mass condition (Figure 1). However the RMR support is only applicable for the 10m span of tunnel, while the Q system provides more option in span length.



| Rock mass class | Excavation | Rock bolts (20 mm diameter, fully grouted) | Shotcrete | Ste |
|---|---|---|---|---|
| I - Very good rock<br>*RMR*: 81-100 | Full face,<br>3 m advance. | Generally no support required except spot bolti | | |
| II - Good rock<br>*RMR*: 61-80 | Full face ,<br>1-1.5 m advance. Complete support 20 m from face. | Locally, bolts in crown 3 m long, spaced 2.5 m with occasional wire mesh. | 50 mm in crown where required. | None |
| III - Fair rock<br>*RMR*: 41-60 | Top heading and bench<br>1.5-3 m advance in top heading.<br>Commence support after each blast.<br>Complete support 10 m from face. | Systematic bolts 4 m long, spaced 1.5 - 2 m in crown and walls with wire mesh in crown. | 50-100 mm in crown and 30 mm in sides. | None |
| IV - Poor rock<br>*RMR*: 21-40 | Top heading and bench<br>1.0-1.5 m advance in top heading.<br>Install support concurrently with excavation, 10 m from face. | Systematic bolts 4-5 m long, spaced 1-1.5 m in crown and walls with wire mesh. | 100-150 mm in crown and 100 mm in sides. | Light spac requi |
| V – Very poor rock<br>*RMR*: < 20 | Multiple drifts 0.5-1.5 m advance in top heading.<br>Install support concurrently with excavation. Shotcrete as soon as possible after blasting. | Systematic bolts 5-6 m long, spaced 1-1.5 m in crown and walls with wire mesh. Bolt invert. | 150-200 mm in crown, 150 mm in sides, and 50 mm on face. | Medi spac steel forep Close |

Figure 1: Charts to determine support need for different values of (a) RMR and (b) Q (Hoek *et al.*, 2005)

## 4.0 Methodology

This study was carried out in two stages, which are (1) classification of rock mass condition and proposed of support requirement using empirical approaches of RMR and Q systems and (2) the verification of the proposed support was performed in the numerical model of Phase$^2$.

### *4.1 Secondary Data Collection*

This study made used of secondary data obtained from soil investigations carried out in an Island of Singapore. In the study, data from seven boreholes, namely BH10-BH14, IBH2 and IBH3 were gathered. Rock mass classification using the RMR and Q system has been carried out in the investigation. The preliminary design was carried out on 10m diameter tunnel at depths of 50m and 145m. Tables 1 and 2 summarized the data collection and support system based on the RMR and Q.

The UCS values were obtained from the soil investigation report. Average Young's Modulus of rock (intact) $E_i$ = 34641MPa and the Residual Young's Modulus, $E_r$ = 12000MPa were used in the analysis. For the modeling purpose, the General Hoek-Brown (GHB) constitutive model was used in the numerical analysis. The Geological Structural Index (GSI) was computed from RMR values. The GHB constitutive model parameters $m_b$, *s* and *a* were generated from GSI values with D assumed as 0. As the rock in the area was made up of siltstone, $m_i$ = 9 was adopted to compute $m_b$ (Hoek and Brown, 1997).

Table 1: Tunnel support design from RMR and Q system guidelines for tunnel at 50m depth

| Bore Hole | RMR | GSI | UCSi (Mpa) | Class | Quality | Length of Rock Bolt (20mm Dia Fully Grouted) (m) | Rock Bolt Spacing (m) | Shotcrete Thickness (mm) |
|---|---|---|---|---|---|---|---|---|
| BH10 | 24 | 19 | 25 | IV | POOR | 4.9 | 1.1 | 100 |
| BH11 | 27 | 22 | 25 | IV | POOR | 4.7 | 1.2 | 100 |
| BH12 | 27 | 22 | 50 | IV | POOR | 4.7 | 1.2 | 100 |
| BH13 | 15 | 10 | 5 | V | V. POOR | 5.3 | 1.4 | 150 |
| BH14 | 39 | 34 | 25 | IV | POOR | 4.1 | 1.5 | 100 |
| IBH02 | 28 | 23 | 25 | IV | POOR | 4.6 | 1.2 | 100 |
| IBH03 | 27 | 22 | 25 | IV | POOR | 4.7 | 1.2 | 100 |

|  |  |  |  | ESR =1 |  |  |  |  |
|---|---|---|---|---|---|---|---|---|
| Bore Hole | Q | GSI | UCSi (Mpa) | Category | Quality | Length of Rock Bolt (20mm Dia Fully Grouted) (m) | Rock Bolt Spacing (m) | Shotcrete Thickness (mm) |
| BH10 | 19 | 19 | 25 | 3 | GOOD | 3 | 2.4 | 40 |
| BH11 | 22 | 22 | 25 | 3 | GOOD | 3 | 2.4 | 40 |
| BH12 | 22 | 22 | 50 | 4 | FAIR | 3 | 1.95 | 45 |
| BH13 | 10 | 10 | 5 | 4 | FAIR | 3 | 2 | 45 |
| BH14 | 34 | 34 | 25 | 2 | V. GOOD | 3 | 3 | 40 |
| IBH02 | 23 | 23 | 25 | 3 | GOOD | 3 | 2.2 | 40 |
| IBH03 | 22 | 22 | 25 | 3 | GOOD | 3 | 2.7 | 40 |

Table 2: Tunnel support design from RMR and Q system guidelines for tunnel at 145m depth

| Bore Hole | RMR | GSI | UCSi (Mpa) | Class | Quality | Length of Rock Bolt (20mm Dia Fully Grouted) (m) | Rock Bolt Spacing (m) | Shotcrete Thickness (mm) |
|---|---|---|---|---|---|---|---|---|
| BH10 | 35 | 30 | 25 | IV | POOR | 4.3 | 1.4 | 100 |
| BH11 | 46 | 41 | 25 | III | FAIR | 4.0 | 1.6 | 50 |
| BH12 | 46 | 41 | 25 | III | FAIR | 4.0 | 1.6 | 50 |
| BH13 | 38 | 33 | 50 | IV | POOR | 4.1 | 1.4 | 100 |
| BH14 | 45 | 40 | 50 | III | FAIR | 4.0 | 1.6 | 50 |
| IBH02 | 43 | 38 | 25 | III | FAIR | 4.0 | 1.6 | 50 |
| IBH03 | 47 | 42 | 50 | III | FAIR | 4.0 | 1.7 | 50 |
|  |  |  |  | ESR =1 |  |  |  |  |
|  | Q | GSI | UCSi (Mpa) | Category | Quality | Length of Rock Bolt (20mm Dia Fully Grouted) | Rock Bolt Spacing | Shotcrete Thickness |
| BH10 | 30 | 30 | 25 | 3 | GOOD | 3 | 2.8 | 40 |
| BH11 | 61 | 41 | 25 | 2 | V. GOOD | 3 | 3.4 | 40 |
| BH12 | 64 | 41 | 25 | 2 | V. GOOD | 3 | 3.5 | 40 |
| BH13 | 30 | 33 | 50 | 4 | GOOD | 3 | 2.8 | 40 |
| BH14 | 68 | 40 | 50 | 2 | V. GOOD | 3 | 3.6 | 40 |
| IBH02 | 38 | 38 | 25 | 3 | GOOD | 3 | 3 | 40 |
| IBH03 | 70 | 42 | 50 | 2 | V. GOOD | 3 | 3.7 | 40 |

## 4.2 *Phase$^2$ Modeling*

The proposed support designs have been verified using the finite element software, Phase$^2$ by Rocscience (Rocscience, 2013). The soundness of the design was determined in terms of deflection consideration, anchor and liner yielding. Comparison was made on the two sets of design based on the above criteria. The GHB constitutive model was used in the analysis. Based on GSI computed, values of $m_b$, $s$ and $a$ are generated to formulate the GHB failure criterion constitutive model. The rock parameters like $m_b$, $a$ and $s$ can be computed from Geological Strength Index (GSI). For the generally competent rock masses with GSI > 25, the value of GSI can be related to Rock Mass Rating RMR value as:

$$\text{GSI} = \text{RMR} - 5 \qquad \text{Equation 4}$$

$$\sigma'_1 = \sigma'_3 + \sigma_{ci}\left(m_b \frac{\sigma'_3}{\sigma_{ci}} + s\right)^a \qquad \text{Equation 5}$$

$$m_b = m_i e^{\left(\frac{GSI-100}{28-14D}\right)} \qquad \text{Equation 6}$$

$$s = e^{\left(\frac{GSI-100}{9-3D}\right)}$$ Equation 7

$$a = \frac{1}{2} + \frac{1}{6}\left(e^{-GSI/15} - e^{-20/3}\right)$$ Equation 8

The values of $m_i$ are given in Heok and Brown (1997), the $\sigma_{ci}$ is the intact uniaxial compression strength of rock and D is the disturbance factor, taken as zero if there is no impact or damage, disturbance and relaxation from blasting. The above relationship will account for fractures or discontinuities in the rock (Hoek and Brown, 1997).

Far field stresses around the tunnel were generated assuming hydrostatic load condition around the tunnel taking density of rock as 27 kN/m$^3$. Horizontal K (horizontal stress/vertical stress) factor was taken as two. Hydro-fracturing tests in the rock of this area yielded values of 2-2.4 for horizontal stress/vertical stress ($\delta h/\delta v$) ratios. Hence K factor of two was a reasonable assumption. At 50m depth, Phase$^2$ was carried in one stage in view of the low loading environment. Meanwhile, at 145m depth, the numerical analysis was carried out in three stages. Stage 1 was the excavation of tunnel with 30% relaxation before installation of rock bolts in Stage 2. Stage 3 was the laying of tunnel liner after a further 30% relaxation in the tunnel support system. To represent this in Phase$^2$, the load split technique was employed. The load split factors were 0.3:0.3:0.4 for Stages 1-2 respectively. This would imply that the load capacity was distributed to the rock, rock bolts and tunnel liner in this proportion.

Field stress in the rock around the tunnel was taken as hydrostatic. Horizontal stress of two times vertical stress was adopted based on Sheorey (1994) and the hydro-fracturing test results in the soil investigation report. Model of the design support system adopted in Phase$^2$ numerical analysis is shown in Figure 2.

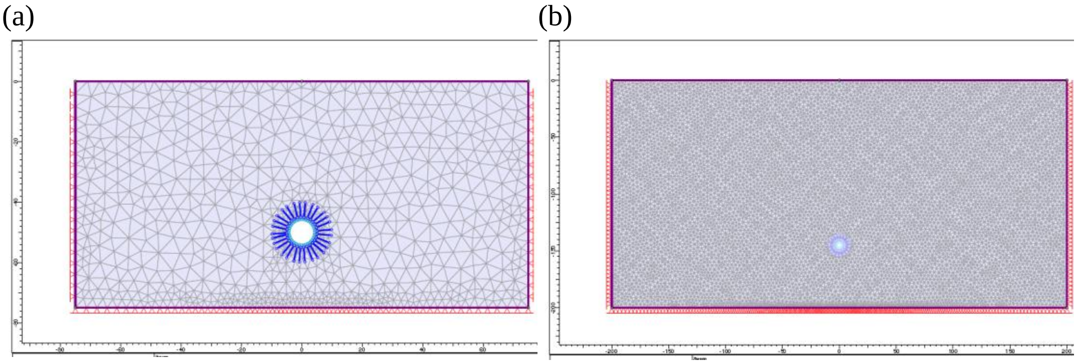


Figure 2: Phase 2 models, tunnel at (a) 50m depth and (b) 145m depth

Then, the comparative study was made to identify the better support system for the tunnel in terms of the total displacement. A parametric study of varying the UCSi has also been performed as to represent the different rock strength.

## 5.0 Results and Discussion

Results of the numerical analysis are shown in Figures 3 and 4. They are shown in in different color contours. At depth of 50m, for a 10m diameter tunnel, both empirical designs based on RMR and Q systems are sound as seen in Figure 5 and Table 3, except in one case of low Q value (Q=10). Figure 5 which shows the total deflections of the tunnel boundary indicates that at Stage 2, the deflection was less than 12mm and 6mm for Q and RMR systems respectively. The Q-system support design was found to be less conservative and hence the total deflections were higher than the RMR support system. However, as the total deflections were small, lower stress was induced in the rock bolt system and tunnel liner. Hence, there was hardly any yielding in the rock bolt and liner support, except for one case in the Q system was found to be partial yielding of the rock bolt system due to higher total deflection in the system. Comparing the designs obtained from the two systems, RMR system would result in a more conservative design.

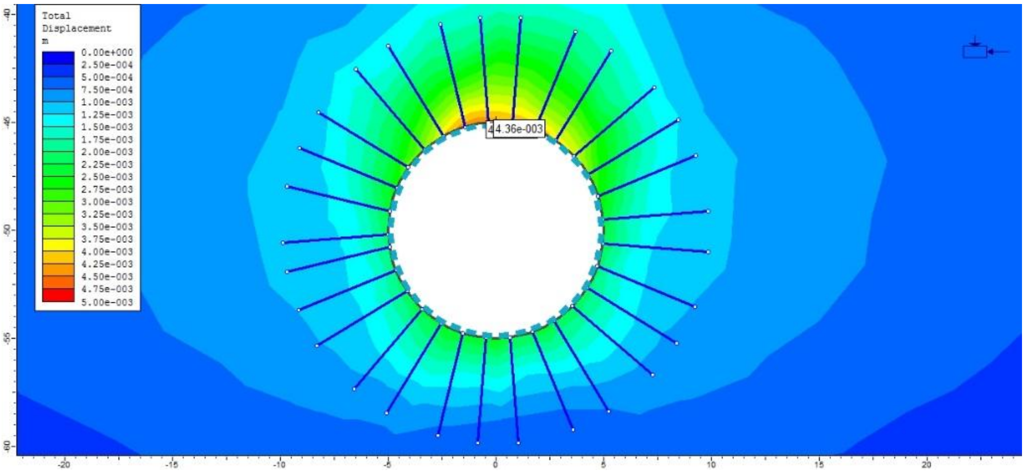


Figure 3: Phase 2 – Total displacement contour of the tunnel at 50m depth

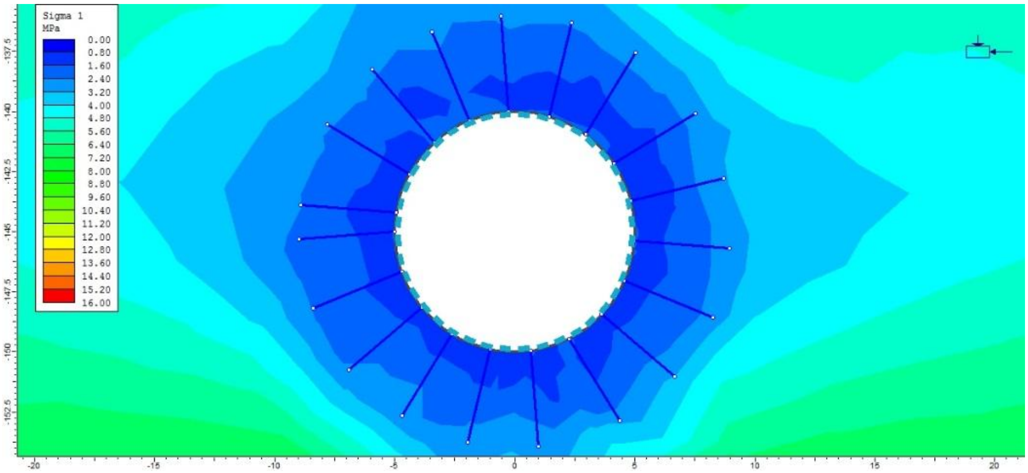


Figure 4: Phase 2 – Total displacement contour of the tunnel at 145m depth

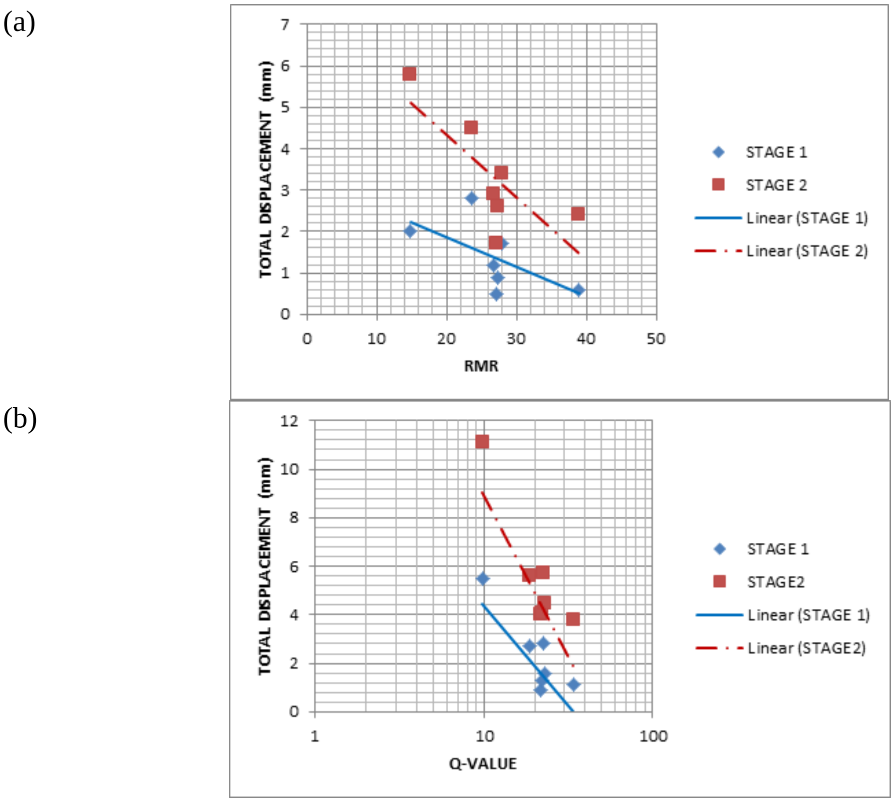


Figure 5: Maximum total displacement of tunnel for (a) RMR and (b) Q support design system at tunnel depth of 50m

Table 3: Total displacements at various stages and rock bolt and liner condition for support system for (a) RMR and (b) Q system guidelines for tunnel at 50m depth

(a)

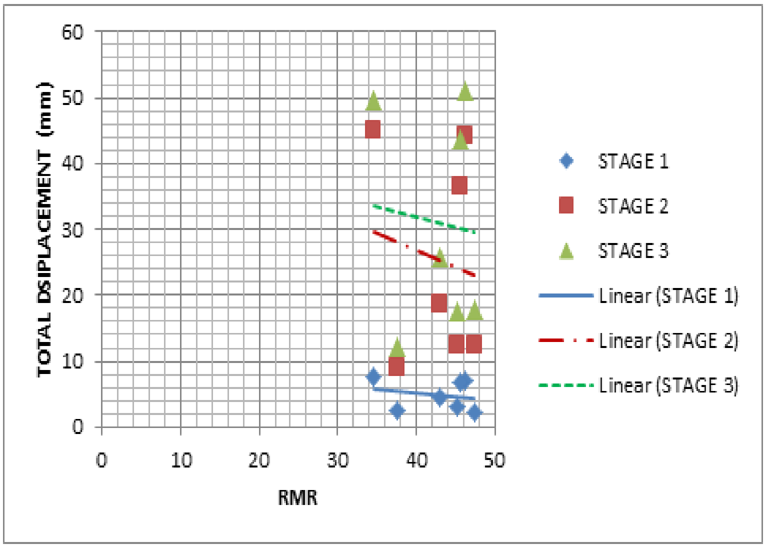
| Bore Hole | RMR | GSI | UCSi (Mpa) | Stage 1 Displacement | Stage 2 Displacement | Rock Bolt 20mm Dia Fully Grouted | Liner |
|---|---|---|---|---|---|---|---|
| BH10 | 24 | 19 | 25 | 2.8 | 4.5 | OK | OK |
| BH11 | 27 | 22 | 25 | 1.2 | 2.9 | OK | OK |
| BH12 | 27 | 22 | 50 | 0.5 | 1.7 | OK | OK |
| BH13 | 15 | 10 | 5 | 2 | 5.8 | OK | OK |
| BH14 | 39 | 34 | 25 | 0.6 | 2.4 | OK | OK |
| IBH02 | 28 | 23 | 25 | 1.7 | 3.4 | OK | OK |
| IBH03 | 27 | 22 | 25 | 0.9 | 2.6 | OK | OK |

(b)

| Bore Hole | Q | GSI | UCSi (Mpa) | Stage 1 Displacement | Stage 2 Displacement | Rock Bolt 20mm Dia Fully Grouted (m) | Liner (m) |
|---|---|---|---|---|---|---|---|
| BH10 | 19 | 14 | 25 | 2.7 | 5.6 | OK | OK |
| BH11 | 22 | 17 | 25 | 0.9 | 4.0 | OK | OK |
| BH12 | 22 | 17 | 50 | 1.3 | 4.1 | OK | OK |
| BH13 | 10 | 5 | 5 | 5.5 | 11.1 | OK | Marginal |
| BH14 | 34 | 29 | 25 | 1.1 | 3.8 | OK | OK |
| IBH02 | 23 | 18 | 25 | 1.6 | 4.5 | OK | OK |
| IBH03 | 22 | 17 | 25 | 2.8 | 5.7 | OK | OK |

Figure 6 and Table 4 show the total displacement for RMR and Q system at 145m depth. It was found that, the total deflection of up to 51mm at Stage 3 for RMR system and 55mm for Q. Due to this large total deflection, at this depth, both systems of rock classification did not give a satisfactory support design. However, the RMR design appeared to better in terms of bolt and liner yielding. RMR design resulted in three cases of bolt yielding (BH10-12) and four cases of partial yielding (BH13, BH14, IBH02 and IBH03). Meanwhile, the Q system produced four cases of bolt yielding (BH10, BH11, BH 12 and IBH02) and three cases of partial yielding (BH13, BH14 and IBH03). For liner, the difference was even more. RMR design resulted in three cases of liner yielding and one case of partial yielding while Q system produced four cases of liner bolt yielding and one case of marginal yielding. RMR resulted in three cases of satisfactory liner while Q-system produced only two cases of satisfactory liner. These results are tabulated in Table 4. Again, the reason lies in the conservative design of the RMR system. Figures 7 and 8 show the yielding of the liner support system and rock bolt system respectively.

(a)



(b)

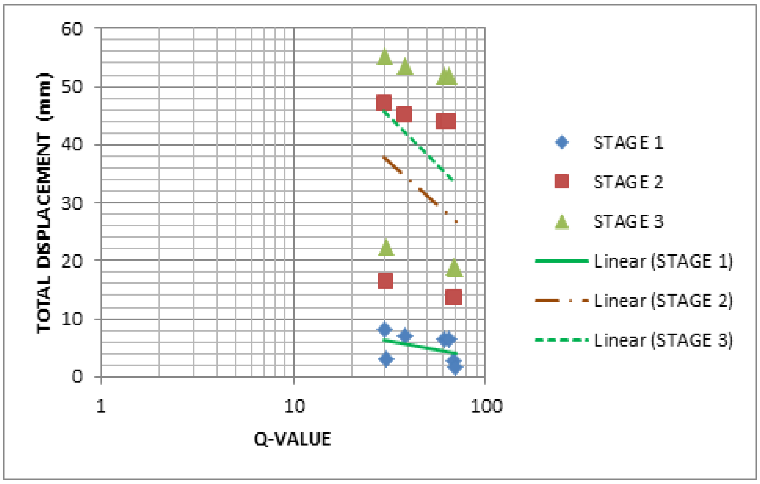


Figure 6: Maximum total displacement of tunnel for (a) RMR and (b) Q support design system at tunnel depth of 145m

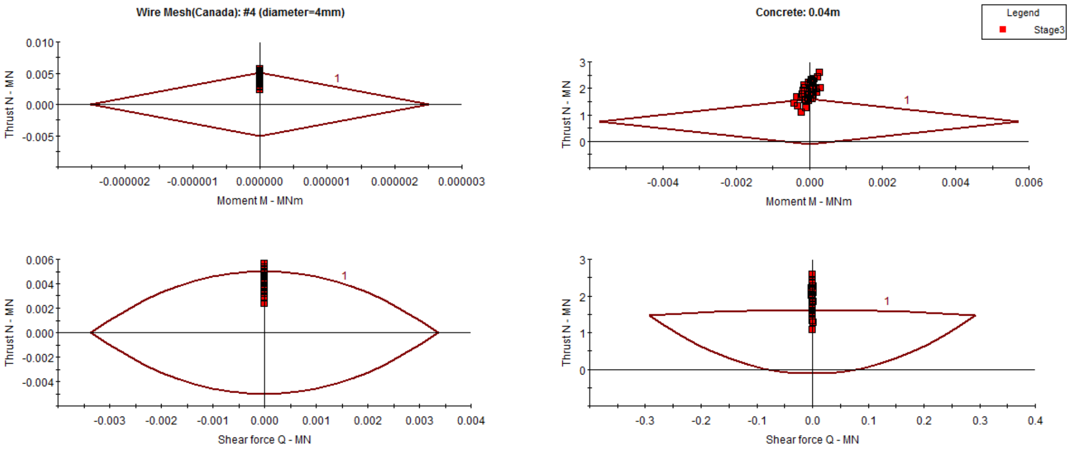
Table 4: Total displacements at various stages and rock bolt and liner condition for support system from (a) RMR and (b) Q system guidelines for tunnel at 145m depth

(a)

| Bore Hole | RMR | GSI | UCSi (Mpa) | Stage 1 Displacement | Stage 2 Displacement | Stage 3 Displacement | Rock Bolt 20mm Dia Fully Grouted | Liner |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | | |
| BH10 | 35 | 30 | 25 | 7.6 | 45.1 | 49.7 | YIELD | OK |
| BH11 | 46 | 41 | 25 | 6.9 | 44.1 | 51 | YIELD | YIELD |
| BH12 | 46 | 41 | 25 | 6.7 | 36.5 | 44 | YIELD | YIELD |
| BH13 | 38 | 33 | 50 | 2.5 | 8.9 | 12 | Partial | OK |
| BH14 | 45 | 40 | 50 | 3 | 12.4 | 18 | Partial | OK |
| IBH02 | 43 | 38 | 25 | 4.5 | 18.6 | 26 | Partial | YIELD |
| IBH03 | 47 | 42 | 50 | 2.1 | 12.5 | 18 | Partial | OK |

(b)

| Bore Hole | Q | GSI | UCSi (Mpa) | Stage 1 Displacement | Stage 2 Displacement | Stage 3 Displacement | Rock Bolt 20mm Dia Fully Grouted | Liner |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | (m) | (m) |
| BH10 | 30 | 30 | 25 | 8.1 | 46.9 | 55.3 | YIELD | YIELD |
| BH11 | 61 | 41 | 25 | 6.4 | 43.8 | 51.9 | YIELD | YIELD |
| BH12 | 64 | 41 | 25 | 6.5 | 43.8 | 51.8 | YIELD | YIELD |
| BH13 | 30 | 33 | 50 | 3.1 | 16.4 | 22.4 | Partial | Marginal |
| BH14 | 68 | 40 | 50 | 2.9 | 13.6 | 19.0 | Partial | OK |
| IBH02 | 38 | 38 | 25 | 7.1 | 45 | 53.5 | YIELD | YIELD |
| IBH03 | 70 | 42 | 50 | 1.7 | 13.5 | 18.8 | Partial | OK |



Support Element: Liner 1

Figure 7: Phase 2 – Yielding of liner at 145m depth

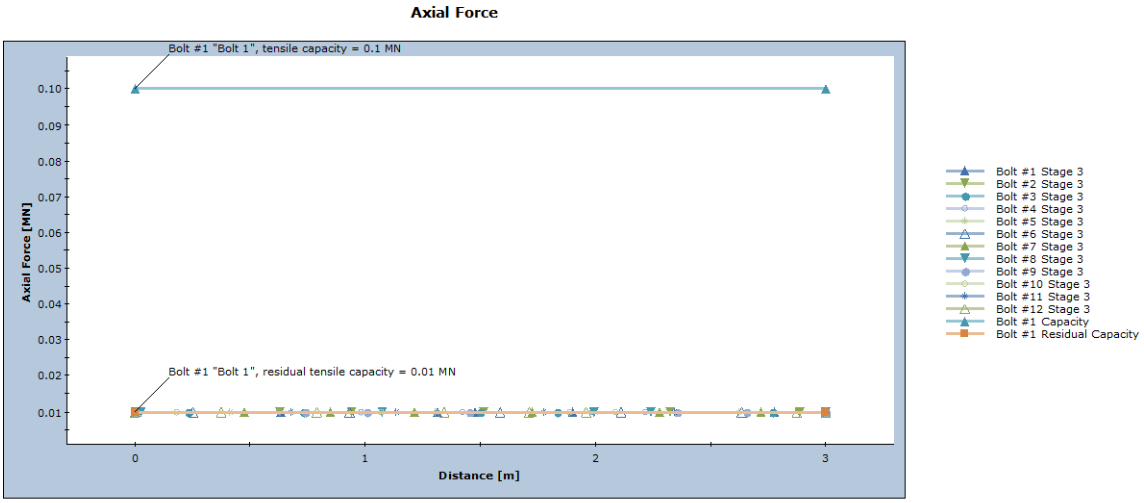


Figure 8: Phase 2 – Failure of the rock bolt system at 145m depth

Figure 9 shows the total deflection of the tunnel with regards to the variation of UCSi at 145m depth. It was found that, the RMR support design system seems to perform better than Q-system support design system as seen by the trend line. The trend lines of RMR support system for both rock bolts and liner are a generally above that of the Q-system support indicating better performance. This may be expected as the RMR design support system required rock bolts of longer length and smaller spacing and at the same time calls for thicker tunnel liner.

Rock bolt system yielding may not be as serious as to treat it as tunnel failure. For tunnel excavation in rock, we can explore the concept of standup time. Tunnel displacement does not take place instantaneously but over time and hence the concept of standup time, i.e., the time window after excavation before the excavation starts to cave. Installation of rock bolts will increase this time window and as long as a strong liner is installed in time, therefore there will be no collapse.

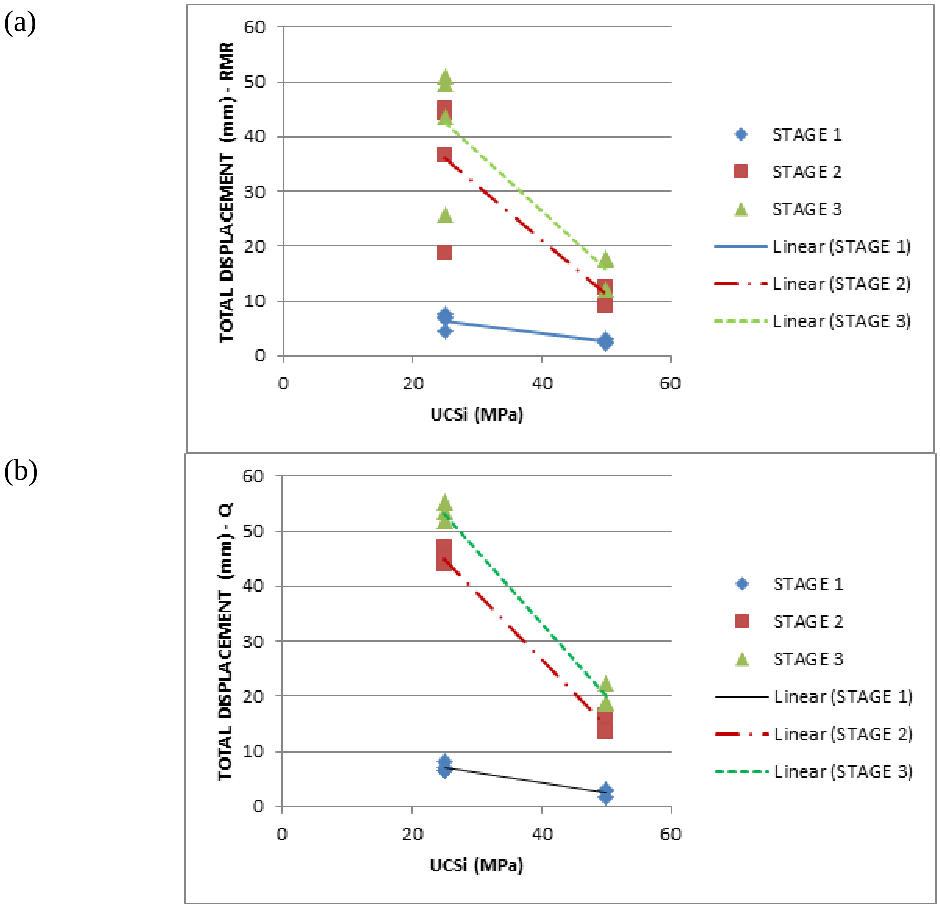


Figure 9: Variation of maximum total displacement of tunnel for (a) RMR and (b) Q support design system at tunnel depth of 145m with different UCSi of rock

In addition, an interesting observation is that, the total deflection in the tunnel was quite sensitive to the UCSi of the rock around the tunnel. The graph shows that total deflection was greatly reduced when the UCSi of the surrounding rock was high. Hence, despite the discontinuities in the rock which is accounted by $m_b$, s and to a small extent a in the GHB constitutive rock model, UCSi of the rock plays an important role in the total displacement of the rock in the tunnel.

## 6.0 Conclusion

At shallow depth and low field stresses, Q support design system appeared to work quite well, while the RMR system of support design appeared to be a conservative approach. However, at greater depth of 145m at which the far field stresses was almost three times at much, the both support systems design began to experience problems. From the numerical analysis of Phase$^2$, there was not a single case in which both rock bolt and liner supports were performing satisfactorily, in which, both may failing or yielding.

In all cases, the rock bolt systems were either yielding or partially yielding. This could be attributed to the large displacement experienced at greater depth due to higher field stress. A larger strain was exerted on the rock bolt support system, inducing higher stress causing the support to yield. On the other hand, four cases out of seven of the tunnel liner was satisfactory for the RMR design support system whereas three cases out of seven for the Q-value design system was performing satisfactorily. This could result from the fact that the RMR design support system requires generally thicker tunnel liner. Furthermore, the circular shape of the tunnel liner would generate largely compressive stress in the liner but relatively less bending and shear stresses. In other words, a satisfactory tunnel liner design could be easily achieved by just increasing the liner thickness to take the compressive force with minimal consideration for flexural and shear forces as these are likely to be small in the circular tunnel liner.

From the parametric study if $UCS_i$, it is appeared that total displacement of the tunnel boundary is quite sensitive to the $UCS_i$ value. It is recommended that, since the tunnel behavior depends on many other's rock mass parameters, further parametric study should be carried out and the instrumentation should also be installed on site during the excavation as to determine the in-situ displacement.

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