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Original Article

Back Analysis of Rock Support and Final-Lining Recommendation for Rock Class C1 of a Tunnel

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Abstract - *This paper provides recommendations for the rock support system and final lining of the tunnel along the Mumbai – Nagpur expressway using actual field data obtained from geotechnical investigation and PHASE2 software for numerical analysis and validation. Being a real-time study of an ongoing project, this may be a help to various researchers and consultants working in the field of tunnel support systems.Instrumentation data has been utilized for back analysis in order to determine the rock mass parameters to be considered in the numerical back analysis. The classification has been defined as per Class C1 with respect to the RMR value encountered at the site.Based upon the validated rock mass parameters, numerical analyses have been carried out for C1 for different rock covers using PHASE2 software. For Class C1, analysis has been carried out for rock cover of 12m and 25m min and max, respectively. It was observed that deformations in all the cases are small and are much smaller than the permissible convergence in the tunnel, which is taken as 0.5% of the tunnel span,i.e. 89.05mm. The maximum Axial force in a Rock bolt for a 25m cover is approximately 7% and for a 12m cover is approximately 30% of the capacity of a rock bolt. Also, the rock bolts are well outside the plastic zone in each case. Hence the provided rock bolts are safe and adequate for this case. The proposed final rock support is 25mm dia 4000mm long @ 2500mm c/c Rock bolt (Staggered)at the north end of the tunnel and 50 mm PFRS on the south end.*

Keywords - *Class C1, PHASE 2 software, RMR value, Rock class, Rock bolt.*

1. Introduction

Tunnels have been used since 2000-2100 B.C., through the stoneage. However,the popularity of the tunnel increased in the eighteenth century, and it was used for military, transportation, conveyance, mining, storage and flood control structures. With the increase in world population, industrialization and urbanization, underground tunnel constructionis preferred as they limit interferences with existing surface uses of water bodies and land. Although the construction of underground tunnels is the best alternative, they are very high-hazard risk structures. The risks are mostly related to poor ground conditions. Tunnels buried at depth disturb in-situ conditions, causing ground instability and, ultimately, failure (Claudio Oggeri, 2021).

The stability of the Tunnels is crucial to prevent various catastrophes, thereby reducing societal outcries. The permanency of underground structures is ensured by providing adequate resistance to any impending failure of the ground surrounding deep underground excavations (Abdullah, Vol 21-2016). The effectiveness of the ground-support interaction depends on geology, material properties and Geotechnical parameters, loads of the surrounding groundmass and mechanism of the interaction. In the present paper - using actual field data obtained from geotechnical investigation, PHASE2 software for Numerical analysis and validation using instrumental data and geological face logs, various recommendations are expressed for the primary support system and final lining of the tunnel along the Mumbai –Nagpur super communication expressway. Being a real-time study of an ongoing project, this may help various other researchers and consultants working in the field of tunnel support systems.

Plan & Profile of the tunnel cross-section per support design for various classes of rocks, 3D geological log of progressing tunnel and instrumentation data have been considered in this study. This study also contains geotechnical parameters of rock mass established by testing the rock samples done in the initial design stage, based on which the rock support design and drawings were issued for construction. At the onset of the design stage, three rock class categories (A, B & C) had been considered based on rock mass conditions present along the tunnel alignment. The rock support design had been accordingly designed for each Class A, B & C in 0 – 100m, 100m – 200m and 200m – 400m rock cover sectors. However, based on the execution experience as well as a review of geological face logs & instrumentation data of the tunneling done so far, three categories of Rock Class,i.e. C1, C2, and B, have been considered, out of which numerical analysis and support system design of Rock class C1 with 12m and 25 m rock cover are presented in this study.

2. Tunnel Alignment

The study is done on an ongoing real-time project of a Tunnel along the Mumbai –Nagpur super communication expressway of a total 13.1 Km length; the tunnel section comprises of LHS and RHS tunnel of 7780m and 7745m (The RHS portal in the South has been placed at Ch. 633+885 as against 633+880 shown in the portal drawing) length respectively. For the project area, refer to Figure 1.

Fig. 1 Project Area

The starting and end Chainages of the Twin Tube Three Lane Tunnel are as below:

2.1. LHS Tunnel

Km 626+140 (North-end) to Km 633+920 (South-end)

2.2. RHS Tunnel

Km 626+140 (North-end) to Km 633+885 (South-end)

The north end of the tunnel represents the Nagpur side, and the South end of the tunnel represents the Mumbai side. The tunnel has a downgrade slope of 2.49% from the North end to the South end.

The finished width of the main tunnel at spring and road level is 17.61m. The Typical Cross-section show-ing twin tubes of the tunnel are presented in Figure 2.

3. Geology of the Area

3.1. Regional Geology & Geology of the site

The project area represents the basalt lava flows of Deccan Trap. The project area falls in Igatpuri, taluka of Nashik and Thane districts of Maharashtra. The geological setting of the area is strikingly uniform, consisting of a sequence of Deccan Trap basalt flows (Upper Cretaceous to Lower Eocene age).The basalts are capped by lateritic soil mixed with alluvium of limited thickness varying from about 0.5m to 2m. Field studies show that the Deccan trap basalt flows can be divided into two major groups, viz. compact and amygdaloidal vesicular basalt.The amygdaloidal basalts contain vesicles and are filled with secondary minerals.The amygdaloidal varieties do not occur only as upper and lower portions of thick compact basalt flows but also as independent flows that are amygdaloidal throughout their thickness.

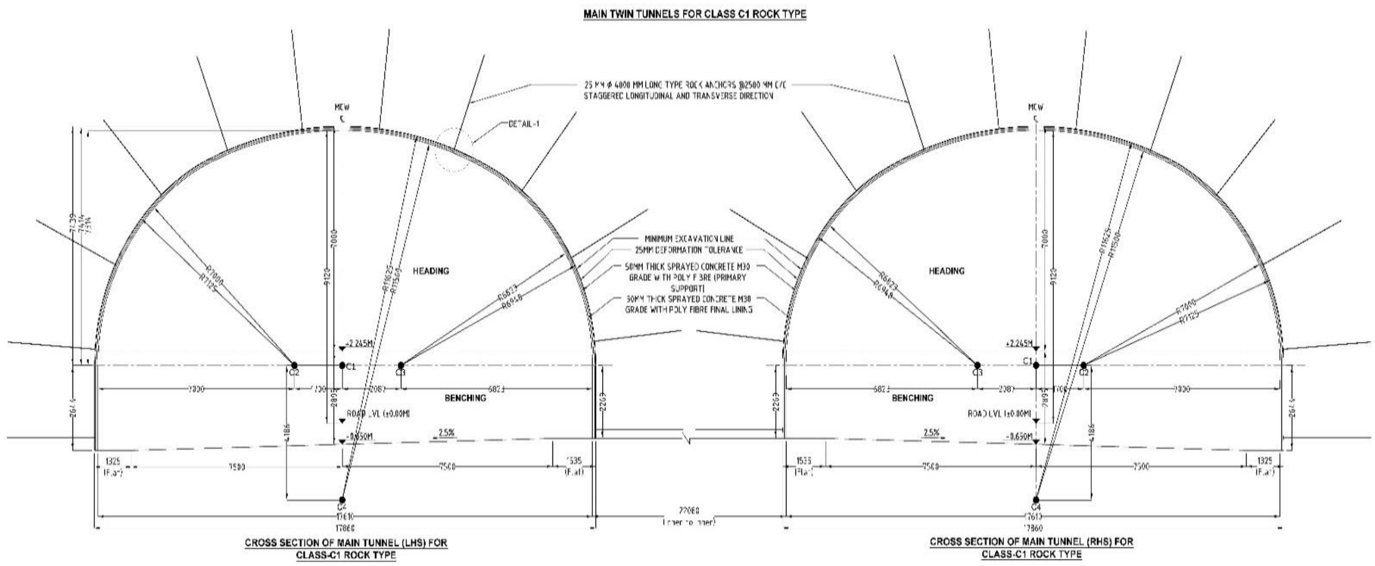


Fig. 2 Typical cross section showing twin tubes of the tunnel

The compact type of basalt is dense, hard, tough and fine to medium-grained. In contrast,the amygdaloidal vesicular type of basalt is comparatively soft and lighter; again, it depends on the vesicles' percentage, size and nature (Ajalloeian, Vol. 17 [2012]).

3.2 Geotechnical Investigation Program

Geological and Geotechnical assessment around the project area is essentially required for economic and safe design. The project data includes the geological set-up of the area, lithological characteristics and rock mass conditions. 15 numbers exploratory holes were carried out in subsurface exploration before the start of the execution of the tunnel excavation. The engineering properties of rock mass have been established by rock mechanic testing. In addition, a 3D geological and geotechnical face log was prepared during the tunnel excavation from both North and South, with details such as rock type, rock mass condition, and discontinuity characteristics.

Further rock mass classification, that is, rock mass rating (RMR), has been attempted to classify the rock. Exploration of the subsurface geological conditions has been carried out along the tunnel alignment at various locations, specifically at the portals and low-coverage areas. Core samples are obtained and tested in the laboratory to ascertain the physical and mechanical properties of the rock. At the onset of the design stage, the Geotechnical (GT) assessment of rock mass condition in the project area indicated that, in general, Class-B (RMR = 61-80) rock type category is envisaged to be encountered during the boring of the tunnel. As the RMR values assessed during surface mapping indicated Class-B rock type, hence it was inferred that the laboratory test results represent Class B Rock type. Rock parameter values for other rock types A (RMR = 81- 100) & C (RMR = 41-60) were improved or downgraded based on experience from similar projects or literature/ codes.

However, based on the execution experience as well as a review of geological face logs & instrumentation data of the tunneling done so far, Rock Class C has been further sub-divided into C1 (RMR = 41 – 50) and C2 (RMR = 51 – 60) in this report. Rock Class B (RMR = 61 – 80) and A (RMR = 81 – 100) have been kept unchanged. During execution, from North-end, Rock Class C1 has been encountered for approximately 250m. After that, Rock Class C2 has been encountered for approximately 350m with some sections of C1. Presently, the tunnel is being excavated in Rock Class B.

4. Data Analysis and Design Considerations

4.1. Data Analysis

Instrumentation & monitoring of the tunnel is integral to recording the rock mass's behaviour. It is being carried out in both tubes at regular intervals. Bi-reflex monitoring targets have been installed at approximately every 50m. The measurements are being carried out on a daily basis at points TP-1, TP-2, TP-3 and TP-4. Points TP-2 and TP-3 broadly represent the tunnel crown, while points TP-1 and TP-4 broadly represent the tunnel's walls. The points of measurement are shown in Figure 2.

It was observed that for a 13m rock cover, the maximum crown settlement is of the order of 4 – 5 mm.

For rock cover upto 25m, the maximum crown settlement is of the order of 5 mm with a variation between 2 mm to 7 mm, except for one stray value of 9 mm.

4.2. Design Considerations

Broadly, three methods are available for the design of Tunnel support as per IRC: SP: 91-2010 - Guidelines for

Road Tunnels (Section 4: Structural Design):
- Empirical methods (Barton Chart)
- Analytical methods/ IS Code Method
- Numerical methods

In the original report, the rock support design had been taken up by Empirical and Numerical methods. In this report, the rock support design has been validated using Numerical methods only, based on the instrumentation data and the geological face logs of the excavated tunnel.

The long-term safety of the tunnel is assured by considering the long-term loading, such as seismic effect and Factor of Safety as high as 1.7 for both seismic and non-seismic cases. The deformations in the tunnel should be within the acceptable range, the strength of shotcrete and rock anchors should not be exceeded, and the plastic zone around the tunnel should be generally small.

In the present report, we established that no rock load would act on the final sprayed concrete lining as the primary tunnel support has been provided with adequate margin and the sprayed concrete lining is done after the deformations in the tunnel have stabilized. The final sprayed concrete lining is provided as an added safety factor to enhance durability and the tunnel's aesthetic look.

5. Numerical Analysis and Validation

5.1. Back Analysis of Rock Support and Final Lining considerations for rock class C1

The process followed for back analysis is as below:

Step 1: Validation of Rock mass parameters using instrumentation data and Geological face logs through numerical analysis

Step 2: Revised numerical analysis for Rock Class C1 considering the validated rock mass parameters as determined in Step 1

Step 3: Establish the adequacy of primary rock support for the long-term requirement

Step 4: Considerations and Recommendations for the final sprayed concrete lining as a non-structural element.

5.2. Numerical Analysis

5.2.1. Loading Conditions

Rock at depth is subjected to stresses resulting from the weight of the overlying strata and locked-in stresses of tectonic origin. The magnitudes and directions of in situ and induced stresses is an essential component of surface excavation design since when the stresses exceed the strength of the rock, it results in instability, which can have severe consequences on the behavior of the excavations.

5.2.2. Design Assumption

- Two-dimensional sections are analyzed assuming plain strain conditions.
- It is assumed that rock is homogenous, isotropic and ideally elastic-plastic material.
- Excavation shall be performed systematically in Heading and Benching, along with providing proper support measures and drainage arrangement.

5.2.3. PHASE2 Software

Phase2 is a 2-dimensional elastoplastic finite element program from Roc Science, Canada, for calculating stresses and displacements around underground openings, which can be used to solve a wide range of mining, geotechnical and civil engineering problems involving- Excavations in rock, Elastic or plastic materials, Bolt support, Liner support (shotcrete/concrete/piles / geo-synthetics), Constant or gravity field stress, Jointed rock/construction joints.

5.2.4. Design Method

The Hoek–Brown failure criterion is an empirical relation that characterizes the stress conditions that lead to failure in intact rock and rock masses. In order to use the Hoek-Brown criterion for estimating the strength and deformability of jointed rock masses, three properties have to be estimated. These are:

- The Uniaxial Compressive Strength бci of the intact rock pieces,
- The value of the Hoek-Brown constant mi for these intact rock pieces, and
- The value of the Geological Strength Index GSI for the rock mass

For the linear analysis of underground excavation, the finite element model is formulated as two-dimensional, plane strain problems since the tunnel is very long compared to its other two dimensions. The generalized Hoek-Brown criterion has been used for this analysis.

5.2.5. Validation of rock mass parameters using instrumentation data and geological face logs through numerical analysis.

In the C1 rock class, a maximum and minimum rock cover of 25m & 12m have been considered, respectively.

A maximum crown displacement of 12mm was observed in the original analysis, which was done for a 100m rock cover. Using the above parameters, for a 25m rock cover, a maximum crown displacement of 2.3 mm has been calculated. The observed crown displacement through instrumentation data corresponding to the 25m rock cover in Class C1 is of the order of 5mm. The median total displacement of all four targets individually is also in the same range. Therefore, there is a need to re-adjust the rock parameters to get the numerical analysis results close to observed instrumentation results, which give a crown displacement of 5mm corresponding to a 25m rock cover in Class C1.

5.2.6. Modelling in PHASE2 Software

Tunnel excavation is analyzed using Phase 2, which is a finite element method-based, commercial software useful for geotechnical calculations. Multi-stage Sequential Modelling has been adopted to simulate the execution sequence of the tunnel.

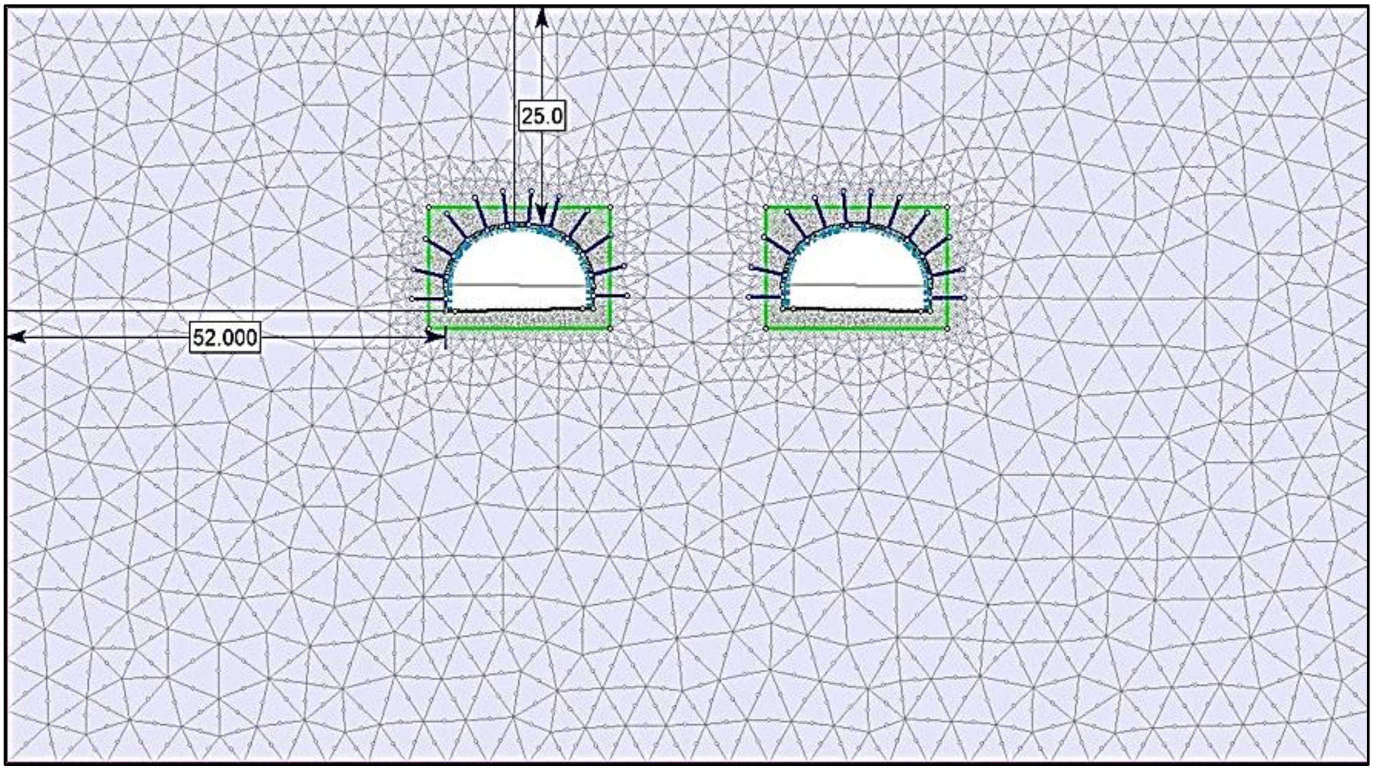


Fig. 3Phase 2 model for Support Class C1 with 25m rock cover

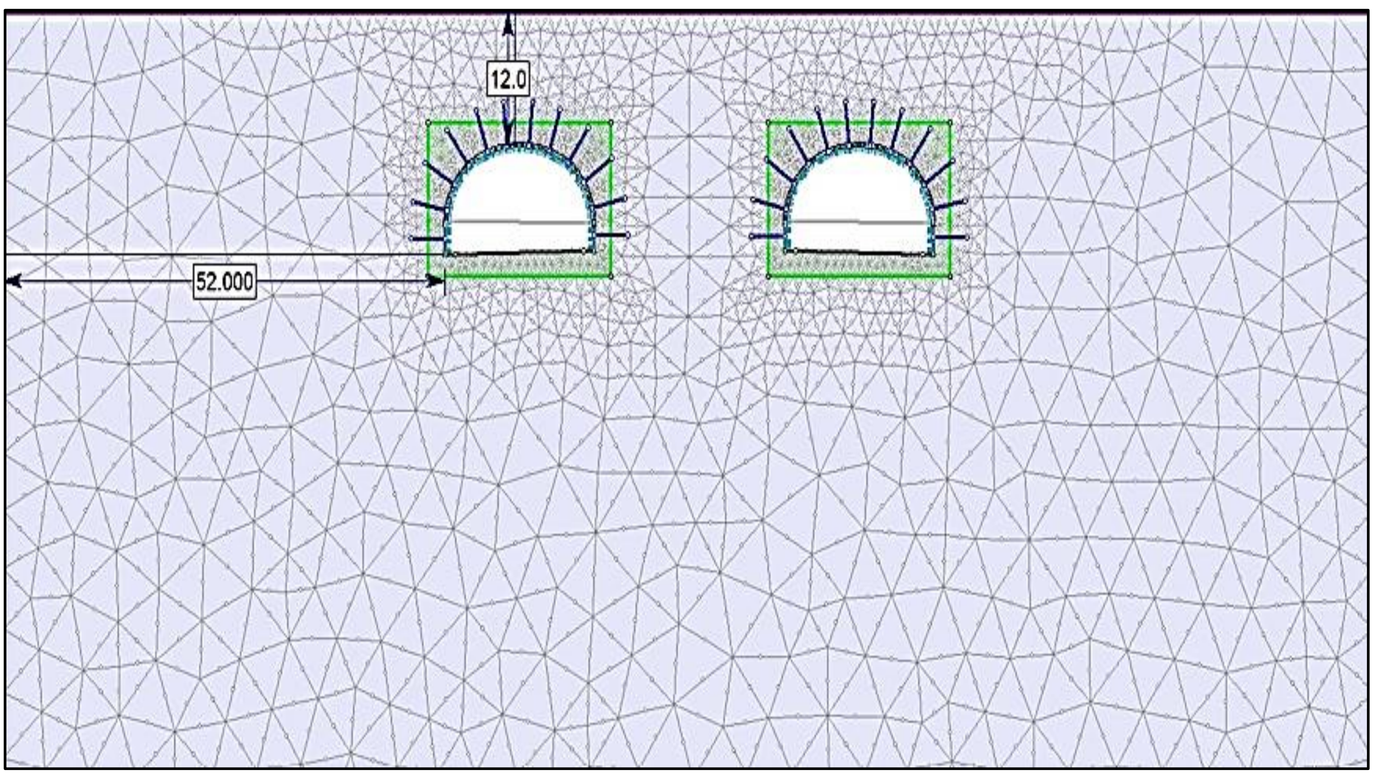


Fig. 4 Phase 2 model for Support Class C1 with 12 m rock cover

5.3 Numerical Analysis of rock Class C1 with a maximum rock cover of 25m

Numerical analysis is done with and without a support system, and their result is shown separately below the figures.

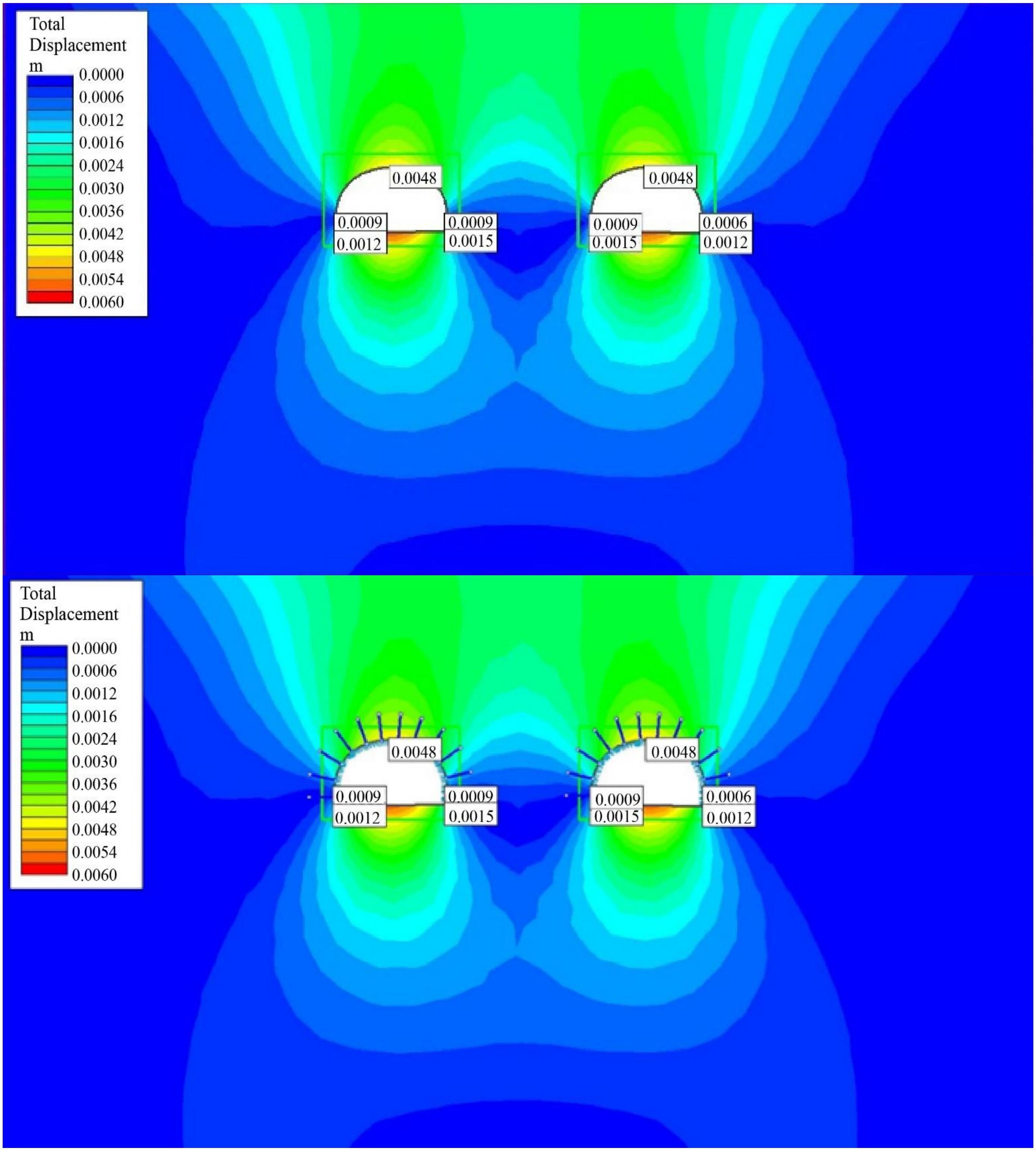
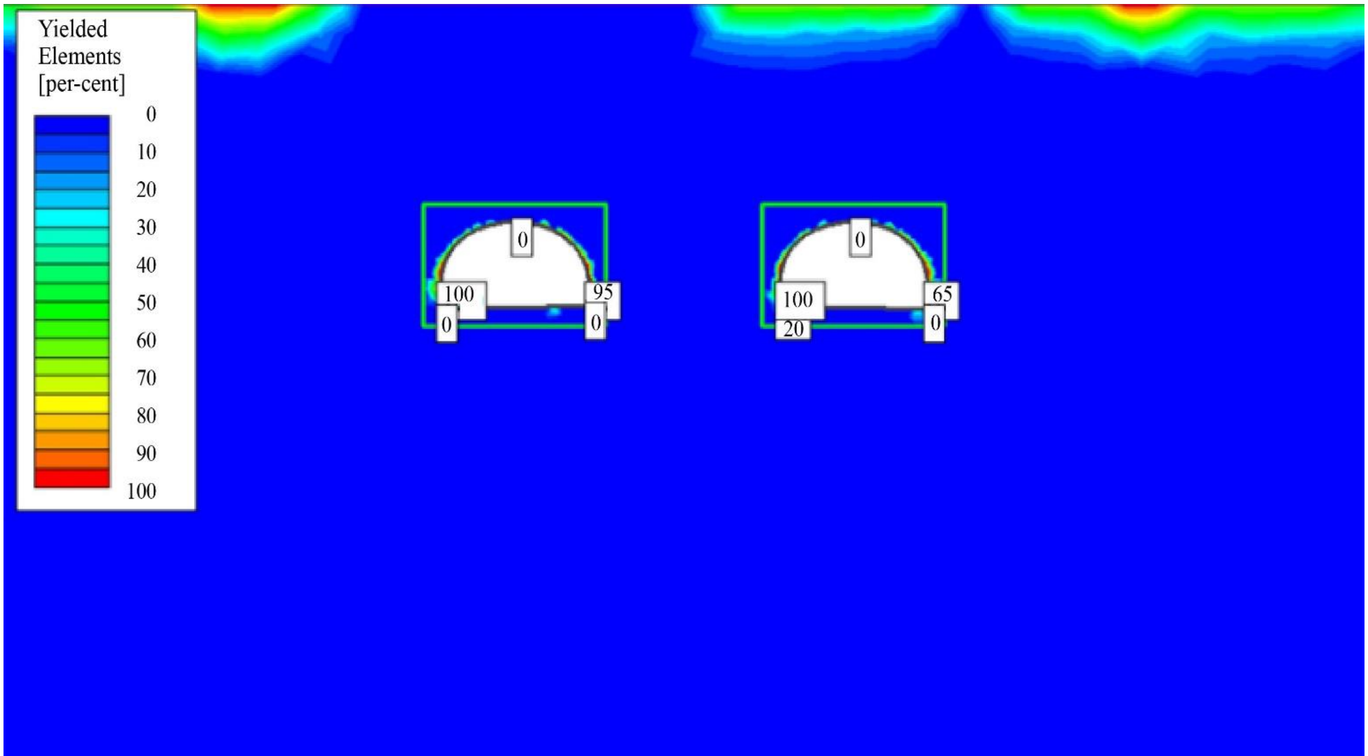


Fig. 5 a) Maximum total displacement is 4.8 mm



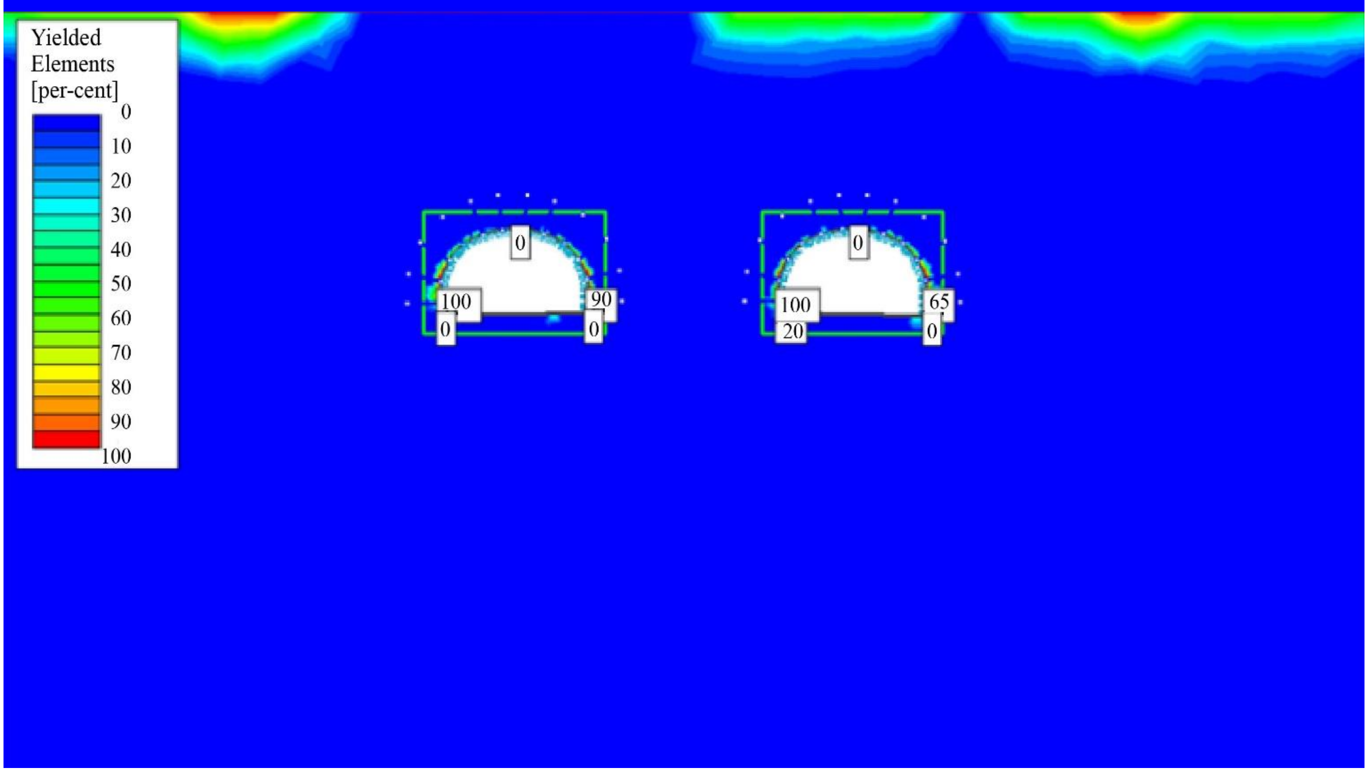


Fig. 5 b) Maximum Plastic zone around the tunnel

Fig. 5 a) and b) Analysis Result for 25m Rock Cover without Seismic Loading and Without Support

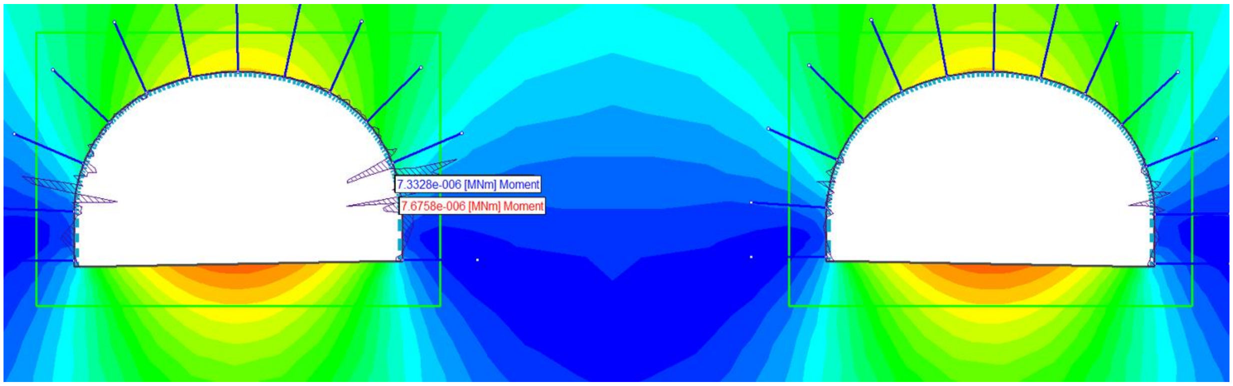


Fig. 6 a) Maximum Bending Moment in Shotcrete is 7.6758e-006MNm

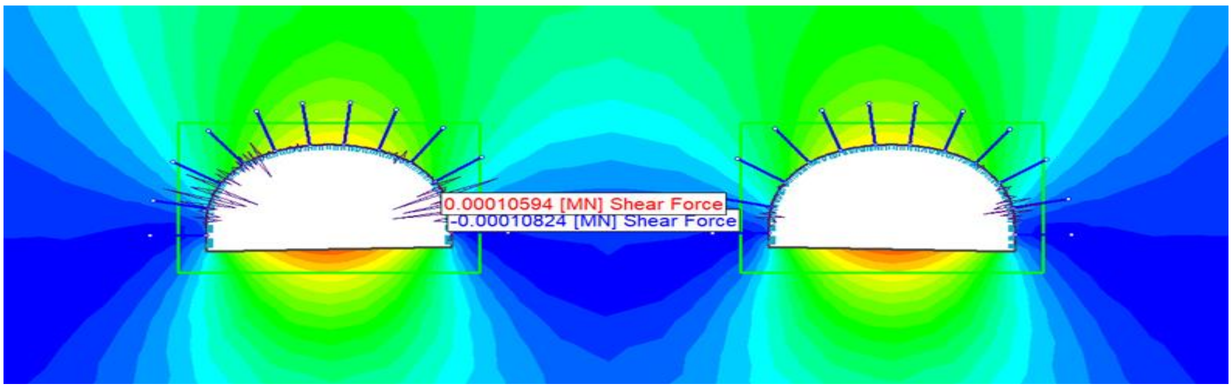


Fig. 6 b) Maximum Shear Force in shotcrete is 0.0001059MN

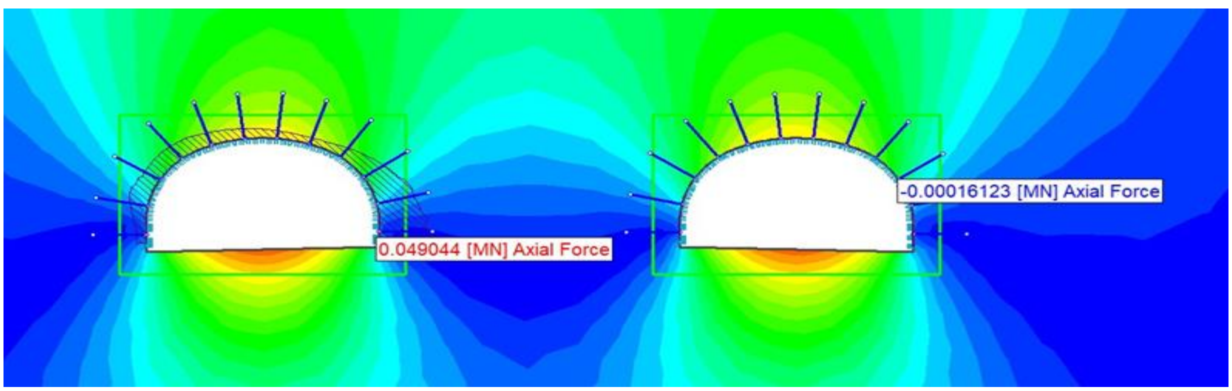


Fig. 6 c) Maximum Axial Force in Shotcrete is 0.0490 MN

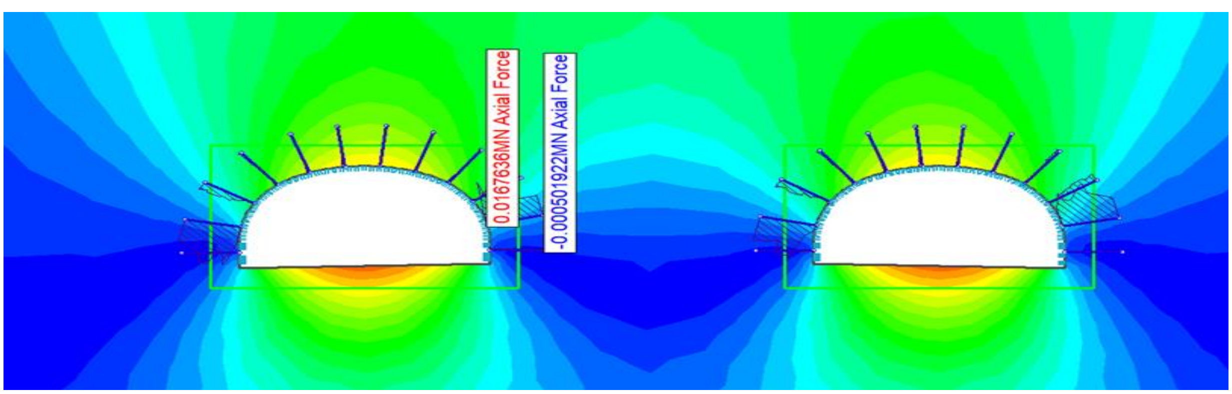


Fig. 6 d) Maximum Axial Force in Rock bolt is 0.0167 MN

Fig. 6 a, b, c, and d) Analysis Result for 25m Rock Cover without Seismic Loading and With Support.

5.4. Numerical Analysis of rock Class C1 with a maximum rock cover of 12m

Numerical analysis is done with and without a support system, and their result is shown separately.

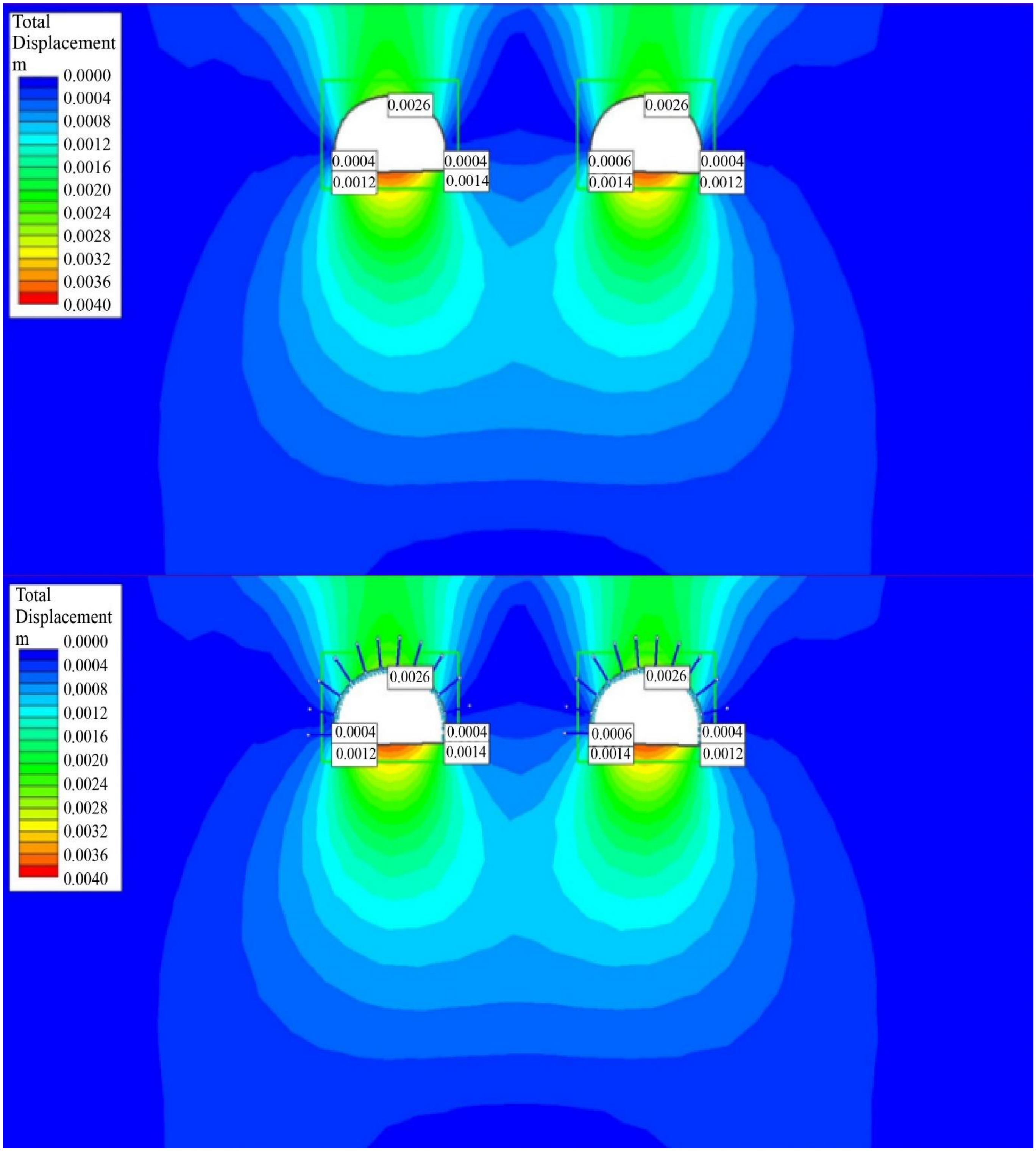
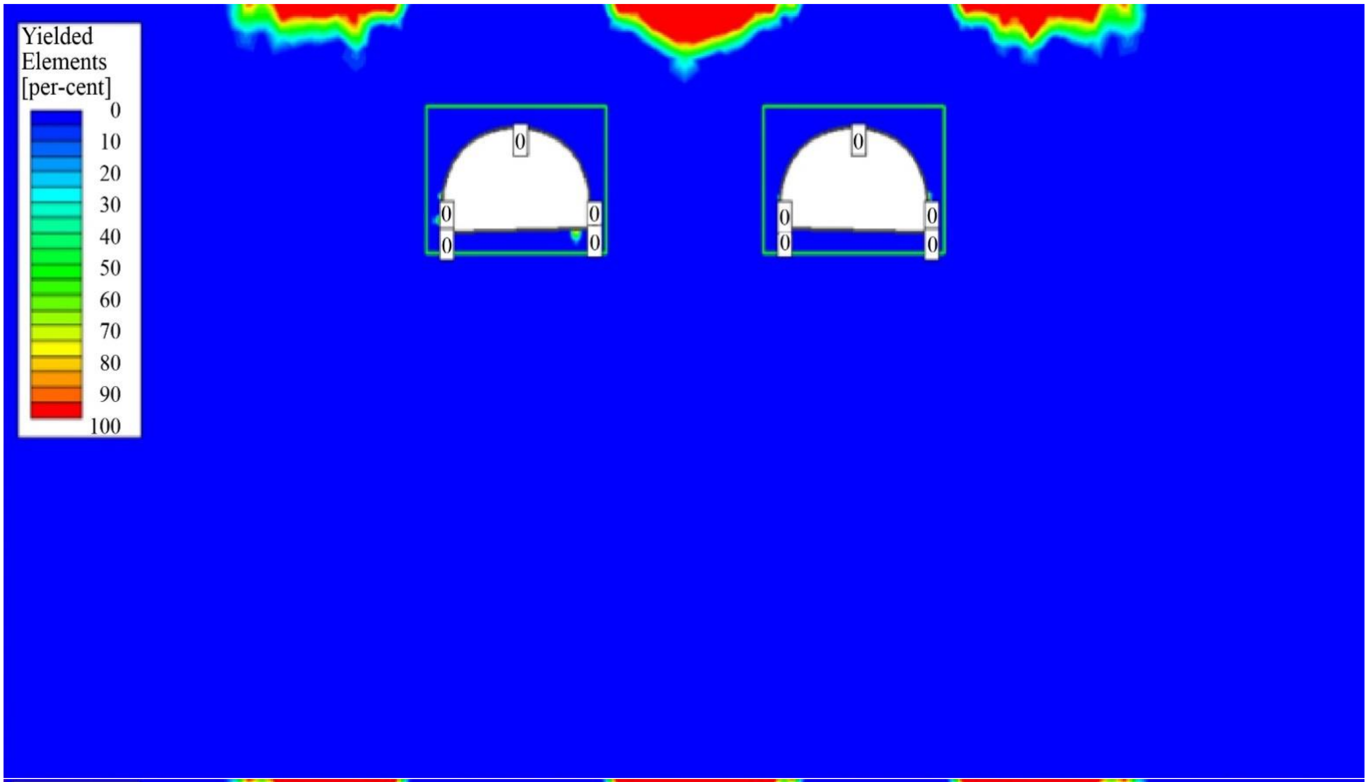


Fig. 7 a) Maximum total displacement is 2.6 mm



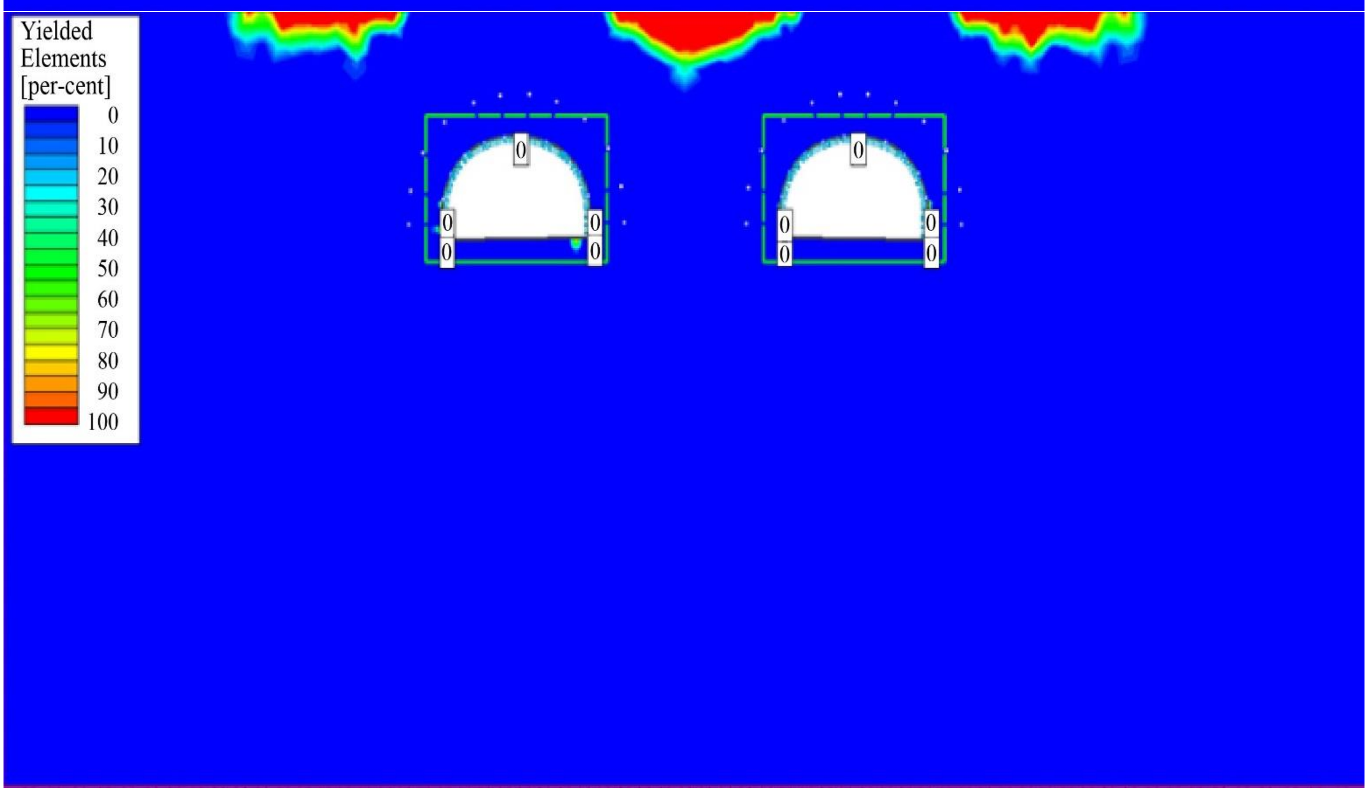


Fig. 7 b) Maximum Plastic zone around the tunnel

Fig. 7 a) and b) Analysis Result for 12m Rock Cover without Seismic Loading and Without Support.

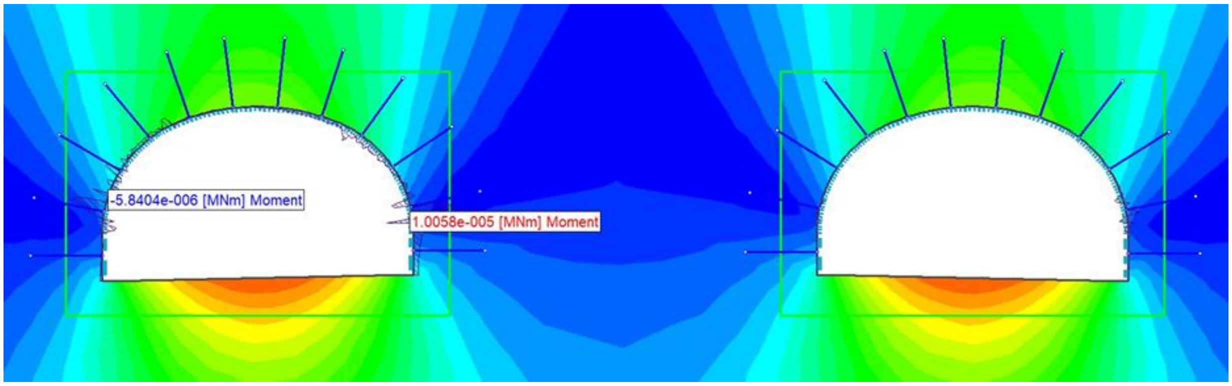


Fig 8 a) Maximum Bending Moment in Shotcrete is 1.0058e-006 MNm

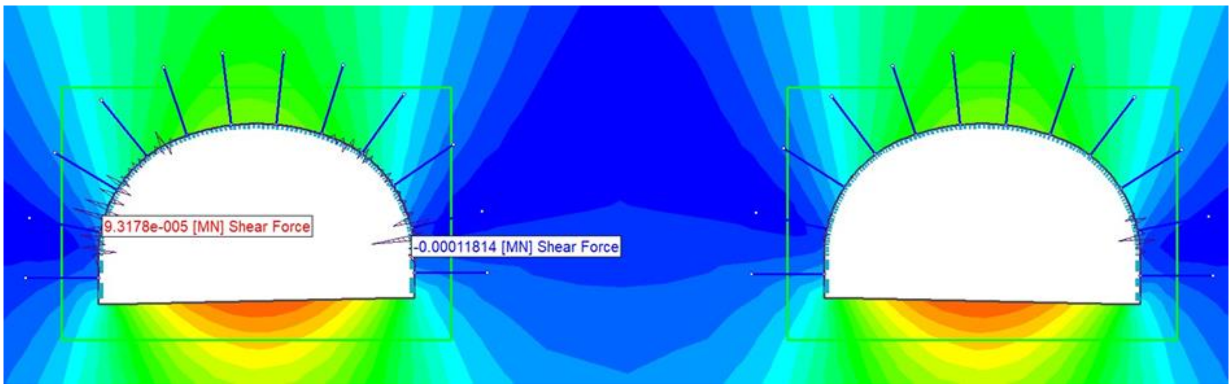


Fig. 8 b) Maximum Shear Force in shotcrete is 9.3178e-005MN

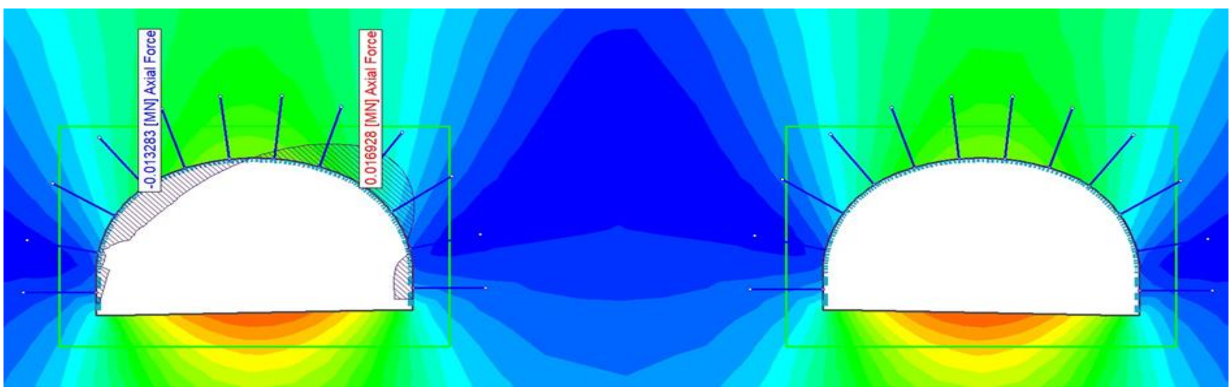


Fig. 8 c)Maximum Axial Force in Shotcrete is 0.016926 MN

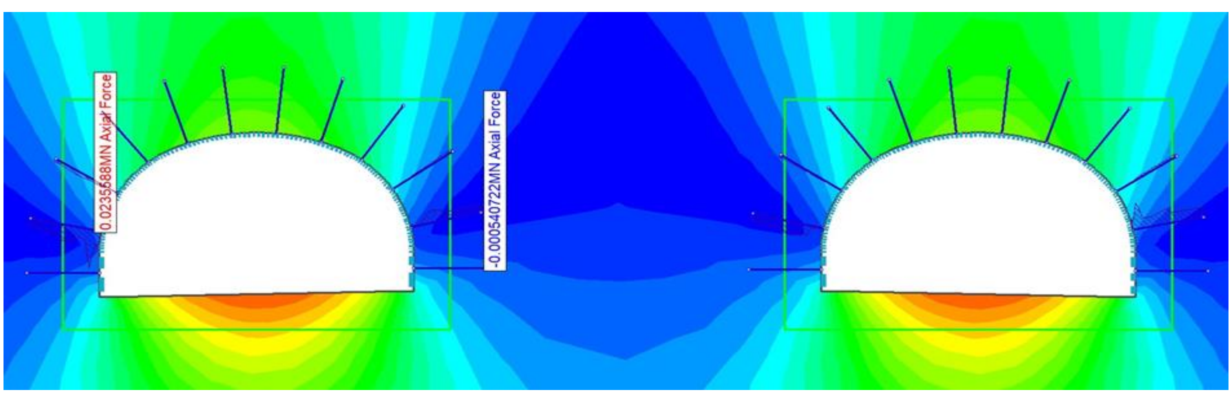
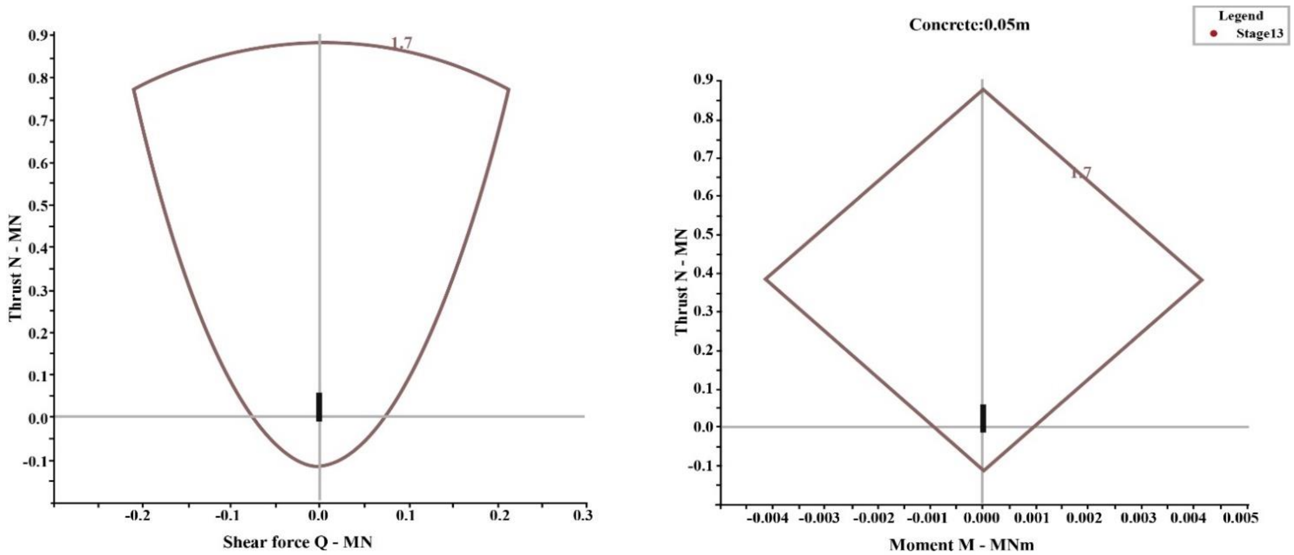


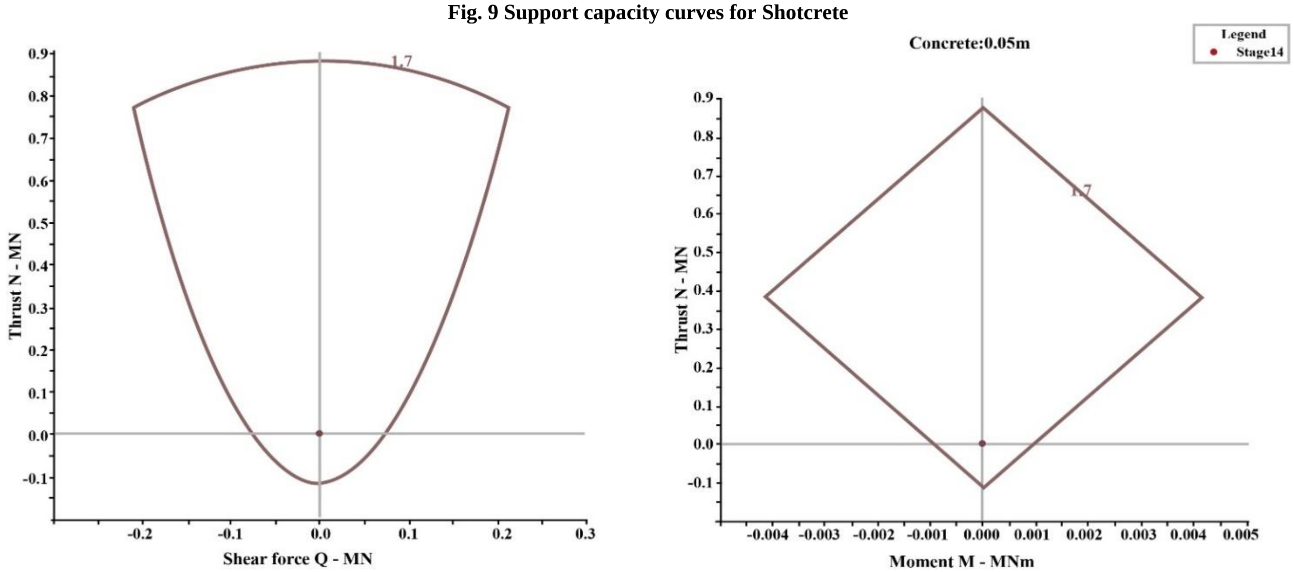
Fig. 8 d) Maximum Axial Force in Rock bolt is 0.02356 MN

Fig. 8 a, b, c, and d) Analysis Result for 12m Rock Cover without Seismic Loading and With Support.



Support Elemnet: Sprayed Concerte

Fig. 9 Support capacity curves for Shotcrete



Support Elemnet: Final Lining

Fig. 10 Support capacity curves for final lining

6. Results and Conclusion

6.1. Summary of Results for 25m and 12m Rock Cover

Table 1. Summary of Results for 25m and 12m Rock Cover

CASE	MAXIMUM DEFORMATION(mm)	MINIMUM AXIAL FORCE IN ROCK BOLT (MN)	MAXIMUM AXIAL FORCE IN ROCK BOLT (MN)
Without SeismicLoading and Without Support	4.8 (Figure 5)	-	-
Without SeismicLoading and With Support	4.8 (Figure 6)	0.0005	0.0167
Without Seismic Loading and Without Support	2.6 (Figure 7)	-	-
Without Seismic Loading and With Support	2.6 (Figure 8)	0.0005	0.0203

Table 2. Recommended Final Primary Rock Support for Class C1 Rock Type

S. No.	Location	Applicable Tunnel Length	Proposed Final Rock Support
1.	Main Twin Tunnels for Class C1 Rock Type	• North-end: initial 250m • South-end: initial 100m	• 25mm Dia 4000mm long @ 2500mm c/c Rock bolt (Staggered) • 50 mm PFRS

6.1.1. Deformation

From the above, it is seen that the deformations in all the cases are small and are much smaller than the permissible convergence in the tunnel, which is taken as 0.5% of the tunnel span, i.e. 89.05mm.

The deformation is small because the stresses due to rock cover are small, and the strength of the rock mass is significantly high.

6.1.2. Rock Bolts

For a 25mm dia rock bolt, the capacity of the bolt is as below:

Area of rebar = 490.625mm^2, Yield strength of bar = 500 N/mm^2,

Capacity of bolt = 490.625 x 500
= 245312.5 N
= 0.245 MN

The maximum Axial force in a Rock bolt for a 25m cover is approximately 7% of the capacity of a rock bolt in each case. Also, the rock bolts are well outside the plastic zone in each case. Hence the provided rock bolts are safe and adequate.

The maximum axial force in a Rock bolt for a 12m cover is approximately 30% of the capacity of a rock bolt in each case. Also, the rock bolts are well outside the plastic zone in each case. Hence the provided rock bolts are safe and adequate for this case also.

6.1.3. Shotcrete

As seen from the Support Capacity Curves of Shotcrete in each case, all the elements fall inside the Factor of Safety envelope of 1.7.

6.1.4. Final Sprayed Lining

As seen from the Support Capacity Curves of the Final lining in each case, all elements fall inside the Factor of Safety envelope of 1.7.

It is observed that the above recommended primary rock support meets the long-term support requirements, both for minimum cover (12m) and maximum cover (25m). The tunnel behaves well, and the maximum deformations are much below the maximum permissible deformation of 89.05mm.

The spacing of the rock bolts considered in the initial analysis was 3m, slightly modified to 2.5 m in the back analysis. Hence, additional spot bolting beyond what has been provided already be installed before spraying the final concrete lining of 50 mm. RCC lining may be required in the initial stretch of the tunnels in the portal areas, which is already been planned in the construction drawings and in areas where dripping water is encountered. . The location of those lining would be jointly decided before the work for the same is initiated.

6.2. Considerations and Recommendations for Final Sprayed Concrete Lining as a Non- Structural element

As evident from the above sections, for the long-term stability of the tunnel, the re-validated design supports match with the actual design supports and are sufficient to cater to the rock loads after considering the deformation that has already occurred and the reduction in the modulus of the rock mass. Therefore, the 50 mm sprayed concrete lining shall supplement and enhance the durability and aesthetics of the tunnel rock exposed face. Our recommendations for sprayed final lining in Rock Class C1 are as below:

Additional rock bolt support in the form of spot bolting is required between the already provided bolts @ 2.5 m c/c for long-term stability.

In C1 class, the provided support may be supplemented by an additional 50mm Sprayed concrete lining, as shown in the GFC drawings, which shall further enhance the durability and aesthetics of the tunnel structure, but it would have no structural function.

6.3. Conclusion

The back analysis and support design for twin tunnels is based on the field data supplied by the project team.

The field data utilized in the analysis are the geological face log of progressing tunnel, RMR value determined from tunnel geological data, rock cover along the tunnel alignment, engineering properties of rock mass determined by rock mechanics testing and instrumentation data etc.

Instrumentation data has been studied to consider the displacement in each rock class with varying rock cover. This has been utilized for back analysis in order to determine the rock mass parameters to be considered in numerical back analyses.

Table 3. The summary of numerical analyses results for Rock Class C1 is presented

CLASS	C1		C1	
ROCK COVER (m)	12	12	25	25
SUPPORTED/ UNSUPPORTED	Supported	Unsupported	Supported	Unsupported
MATERIAL PROPERTIES	D=0, EM= 3000 Mpa D=0.4, EM=1800 Mpa	D=0, EM= 3000 Mpa D=0.4, EM=1800 Mpa	D=0, EM= 3000 Mpa D=0.4, EM= 1800Mpa	D=0, EM= 3000 Mpa D=0.4, EM=1800Mpa
ROCKBOLTS	25mm dia, 4m long, 2.5m x 2.5m	-	25mm dia, 4m long, 2.5m x2.5m	-
SHOTCRETE THK. (mm)	50	-	50	-
DISPLACEMENT (mm)	2.6	2.6	4.8	4.8
MIN. AXIAL FORCE IN ROCK BOLTS (MN)	0.0005	-	0.0005	-
MIN. ROCKBOLT CAPACITY UTILIZATION (%)	0.25	-	0.25	-
MAX. AXIAL FORCE IN ROCK BOLTS (MN)	0.0203	-	0.0167	-
MAX. ROCKBOLT CAPACITY UTILIZATION (%)	10	-	8.23	-
PLASTIC ZONE (m)	0.1	0.1	0.15	0.7
SHOTCRETE SUPPORT CA- PACITY CURVE	All elements are within the limit	-	All elements are within FOS 1.7	-

The revised classification has been defined as per Class C1 regarding the RMR value encountered at the site.

Based on the validated rock mass parameters, numerical analyses have been carried out for C1 for different rock covers. For Class C1, analysis has been carried out for a minimum rock cover of 12m and a maximum rock coverof 25m. Additionally, the tunnel has been analyzed with and without support, along with the considered loading conditions and reduced deformation modulus, which has been obtained through back analysis in Class C1.

The summary of numerical analysis results for Rock Class C1 is presented in Table 3.

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