Finite Element Analysis of Twin Tunnels in Granitic Rock

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1 Introduction

Tunnels are essential since they made transportation simpler. Due to the lack of available land in emerging nations like India due to rapid urbanization, development, industrialization, and civilization, tunnels are crucial. It may be built underground in the event of a metro tunnel. Additionally, tunnels can be used for economic activity, water conductor systems, shelters, relaxation, and defense in developing nations [1]. During the construction of a tunnel, the rock's stability is crucial. Selecting the right excavation techniques in accordance with the grade of the surrounding rock and water seepage ensures the stability of the excavation in the surrounding rock. The chosen excavation methods should be studied to ensure the stability of the tunnel excavation after choosing the construction techniques based on engineering expertise during large-span tunnel construction [2]. To reproduce the effect of the tunneling process in the analytical model and to conduct realistic analysis of the tunnel behavior with lining interaction, an extensive knowledge of the process is necessary. Different components of the process, such as ground movements brought by digging, lining installation, and rock-liner behavior, must be idealized in the analytical model [3]. Gao and Davies [4] illustrated how the BEM produces more accurate stress evaluation results when compared to other domain approaches like the Finite Element Method (FEM) at similar levels of discretization [4].

Elsayed [3] studied the rock lining interaction for circular tunnel using finite element analysis using PLAXIS software with various dimension of tunnel such as 3 m, 4.5 m, and 6 m in diameter with surcharge depth of 10 m, 20 m, and 30 m, respectively. The various properties of rock like poor rock, moderate rock, and hard rock were analyzed to study radial displacement in rock mass, average radial displacement in lining system, and final displacement [3].

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Zhu et al. [5] studied the behavior of railway tunnel with large section constructed using different construction methods. The FEA software ANSYS was used to stimulate and analyze the stress and deformation in 2D and 3D. The results indicate that the bench cutting vault give more settlement then the two side walls. The simulation of the construction sequences in ANSYS was done to analyze the stresses in construction stages [5]. Mandal and Singh [1] analyzed the tunnel lining, a support system in the tunnel structure by using Midas GTS NX and USBR software. The results indicated that Midas GTX NX software gives lower values than the USBR software in all cases [1]. Sarkar et al. [6] examined the influence of over load pressure and soil properties on tunnel settlement. It was seen that when the soil layer changed from silty sand to clayey silt, the ground settlement decreased dramatically by 14–25% even though the tunnel depth remained the same [6]. Huo et al. [2] performed the FEM analysis using three step excavations on extra-large cross section of tunnel. Model was generated using FEM software Midas GTX NX with all the support system like rock bolt, middle pipe, steel arch, and shotcrete prescribed as per the geological and geotechnical condition and analyzed using nonlinear construction analysis. The results showed that the maximum vertical deformation of the tunnel vault and the middle of the invert was about 34 mm [2].

2 Project Case Study

2.1 Project Profile

National Highway Authority of India (NHAI) has come up with an up-gradation of the old highway NH17–NH 66 for Karwar-Kundapura highway, to reduce the time of travel by constructing the twin tunnels. The tunnels were constructed in Karwar which are 10.9 m in width and in 300 m long (West tube) and 400 m long (East tube) provided with two lanes. The site investigation was carried out and the rock samples were tested, which indicated the presence of granitic rock which comes under igneous type of rock with surcharge load of lateritic soil of depth 10 m above the granitic rock. The rock samples were tested and rock was classified as per the rock mass rating (RMR) values as good rock mass (61–80) and poor rock mass (21–40). The various support systems required of the stability of that rock in the section are decided based on the rock quality. Figure 1 shows the twin tunnels under construction.

2.2 Components of Tunnel

Portal. The actual doorway or main entrance of tunnel is known as portals. A portal indicates the intersection point between the underground opening and the ground

Fig. 1 Twin tunnel Karwar

surface. The steel rib of ISMB 250 at 500 mm c/c is embedded in 250-mm-thick shotcrete with 300-mm-thick RCC lining on it.

Steel ribsx. Steel members that have been bent into an arch shape are known as H-shaped steel ribs. Despite the availability of parts in a variety of sizes, only a handful is actually used. Traditional H-shaped steel ribs' geometrical and material characteristics for NATM tunneling ISMB 250 and 300 of 8-mm-thick web were used.

Pipe umbrella. The arch construction in the roof and spring line regions, as well as the stability of the face and in front of the face right after the excavation, is to be supplemented by pipe umbrellas. At least 30% of the pipe umbrella should extend past the following excavation's face. The umbrella reinforcement at the site is of perforated steel pipe of 88 mm diameter fully grouted about 12 m long and 300 mm c/c with 25% of overlapping along the excavation direction.

Rock bolts. They take up the load of the surrounding rock mass when rock begin to deform; this specially happens in fractured rock and the rock with multiples of crack formation. The bolt holds the rock in its position avoiding the deformation in the tunnel. The length of the rock bolt depends upon the failure zone of the rock. As the tunnel contains of 4-m-long rock bolt which is yield at 50% of its yield strength the number of rock bolts were decided depending upon the rock mass rating (RMR) values, 20 numbers of rock bolt for poor rock mass section and 8 numbers of rock bolt for good rock mass in staggered position were provided.

Shotcrete. Is a type of concrete that is sprayed on the wall surface after the reinforcing bars and steel mesh is provided. The hose-pipe nozzle with high pressure and velocity is sprayed and the concrete get placed on wall surface without any form work, and it is efficient that needs only a small industry to get manufactured. It creates strong chemical bonds between many materials. The shotcrete ingredients of M20 grade

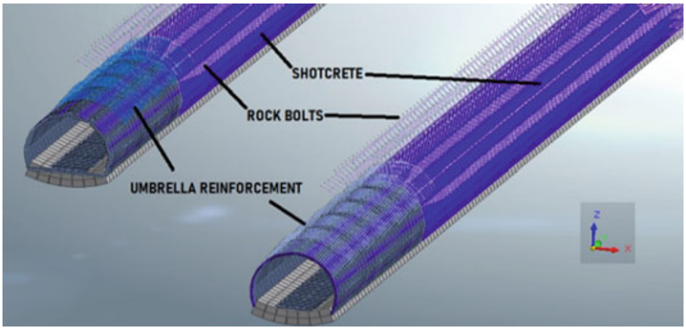


Fig. 2 Components of tunnel

with admixture of Normet and fiber reinforcement conforming to IS: 9012–1978. Figure 2 shows the components of the tunnel.

2.3 Various Model Generated Using Midas GTS NX

Figures 3 and 4 show some of the typical models generated using Midas GTS NX. Figure 3 shows the model generated for Cityringen Copenhagen Metro in Denmark while the model shown in Fig. 4 represents the tunnel system for Trans-Hudson Express in USA.

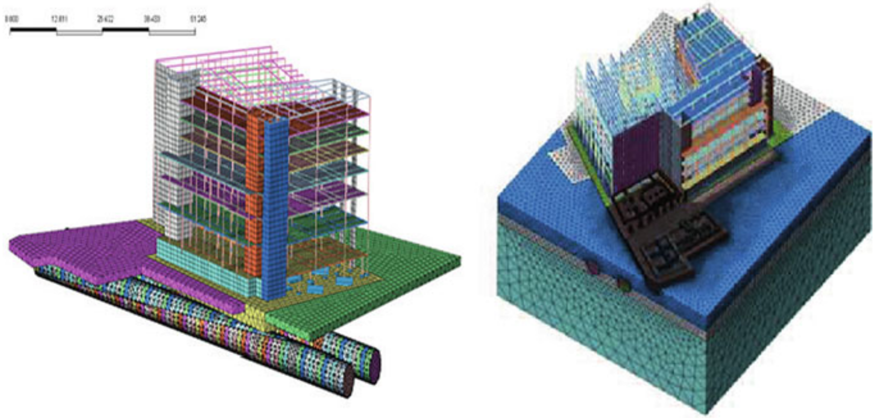


Fig. 3 Cityringen Copenhagen metro, Denmark

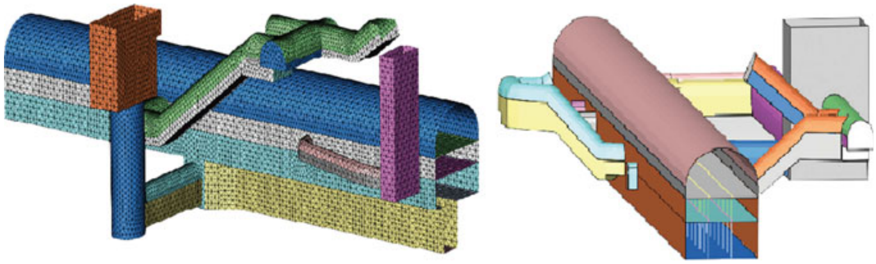


Fig. 4 Trans-Hudson express, USA

2.4 Modeling in Software

The 3D model of twin tunnel was developed using Midas GTS NX software, starting with the profile of the terrain of the tunnel where in the contour map of the site was plotted and exported in to the software. Profile of the tunnel developed is shown in Fig. 5.

Followed by the modeling, the interior components of tunnel like shotcrete, rock bolt, umbrella reinforcement, ISMB section at portal, are modeled as the actual tunnel. Finer meshing was done to increase the accuracy of the result and the boundary conditions, loads were applied, and analysis was performed. Figure 6 shows the interior components of tunnel.

The full tunnel section is classified as per the section such as north portal, south portal, west tunnel, and east tunnel also it classified as per various rock masses like good rock and poor based on then rock mass rating (RMR) value of the each rock which were encountered during the site investigation. Figure 7 shows the classification of various rock masses.

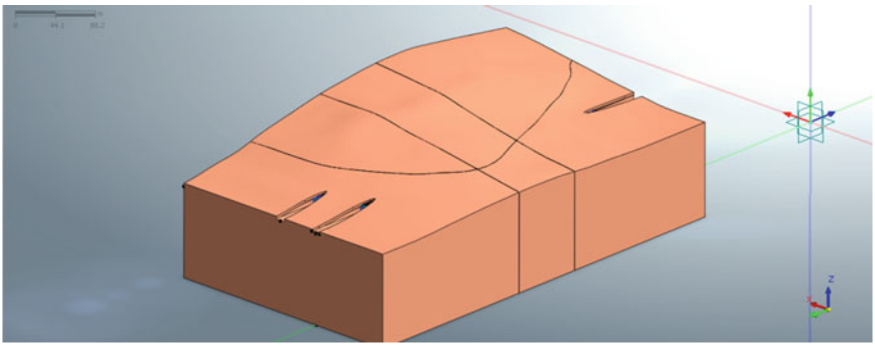


Fig. 5 Profile of the terrain of twin tunnel

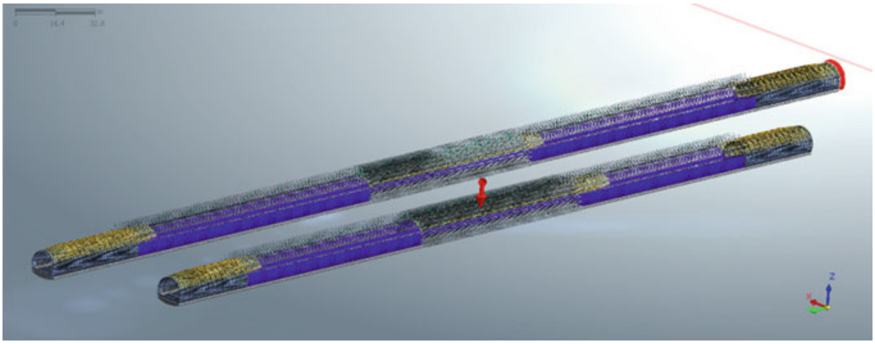


Fig. 6 Interior components of tunnel

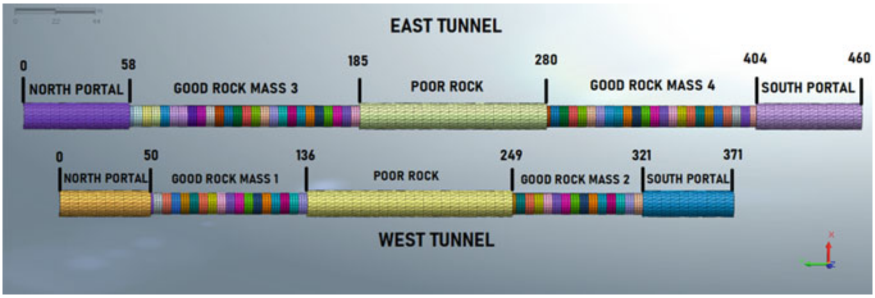


Fig. 7 Classification of various rock masses and sections

2.5 Material Properties of the Tunnel Model Used in Midas GTS NX Software

The properties of the various materials like poor rock, good rock, lateritic soil, structural steel ribs, rock bolt, shotcrete, and the umbrella reinforcement used in the analysis are tabulated in Tables 1, 2, 3, 4, 5, 6, and 7.

Table 1 Properties of the poor rock mass

Sl. no	Properties	Values
1	Elastic modulus (E)	10,000,000 kN/m^2
2	Poisson ratio	0.22
3	Unit weight	20 kN/m^3
4	Damping ratio	0.05

Table 2 Properties of the good rock mass

Sl. no	Properties	Values
1	Elastic modulus (E)	15,000,000 kN/m^2
2	Poisson ratio	0.3
3	Unit weight	28 kN/m^3
4	Damping ratio	0.05

Table 3 Properties of the laterite soil

Sl. no	Properties	Values
1	Elastic modulus (E)	5000 kN/m^2
2	Poisson ratio	0.3
3	Unit weight	16.2 kN/m^3
4	Damping ratio	0.05
5	Cohesion (c)	20 kN/m^2
6	Friction angle ϕ	36^o

Table 4 Properties of the ISMB 300 steel ribs

Sl. no	Properties	Values
1	Elastic modulus (E)	210,000,000 kN/m^2
2	Poisson's ratio	0.2
3	Weight	0.46 kN/m

Table 5 Properties of the rock bolt

Sl. no	Properties	Values
1	Elastic modulus (E)	210,000,000 kN/m^2
2	Poisson ratio	0.3
3	Weight	0.0384 kN/m

Table 6 Properties of the shotcrete

Sl. No	Properties	Values
1	Elastic modulus (E)	5000 kN/m^2
2	Poisson ratio	0.3
3	Unit weight	25 kN/m^3

Table 7 Properties of the umbrella reinforcement

Sl. No	Properties	Values
1	Elastic modulus (E)	210,000,000 kN/m^2
2	Poisson ratio	0.3
3	Unit weight	20 kN/m^2

3 Result and Discussion

The mechanism involving the settlement and shear stress in the tunnel ultimately depends up on the strength of the rock when it is tested in the laboratory and surcharge load coming on the tunnel. The settlement and the shear stresses in the tunnel are measured on the tunnel surface. The rock mass rating (RMR) value gives the idea of the strength of rock containing the features like unconfined compressive strength of rock sample, spacing between the joints in rock sample The rock quality designation (RQD) and the conditions of the discontinuity and the shear stresses depend on the amount of the surcharge load on the cross sectional area of the tunnel per square meter. The results are shown for the analysis carried out for the 3D model of the tunnel shown in Fig. 7, using Midas GTS NX, along the length of the tunnel. Figure 8 exhibits the settlement at the crown for the west tunnel. The maximum settlement is found at the poor rock at chainage 110–210 m at mid-section whose value varies between 34 and 42 mm. The good rock mass 1 and 2 exhibits less settlement as compared to the poor rock mass, which varies between 31 and 37 mm. For the both end sections, also known as portal, the settlement varies between 9 and 12 mm.

Figure 9 shows the shear stress at the crown of the west tunnel due to overburden. It shows the maximum shear stress at the crown (between chainage 110 and 210 m) where poor rock mass exists. This stress value ranges between 110 and 120 kN/m^2. The shear value at the crown dips from 115 to 100 kN/m^2 for the good rock mass 1 (between chainage 50 and 136 m) and good rock mass 2 (between chainage 249 and 321 m). The shear stress values for the both north and south portal ranges between 20 and 70 kN/m^2.

Figure 10 shows the settlement at crown for the east tunnel. The maximum value is observed for poor rock mass at chainage 130–230 m where settlement of 42–39 mm is observed. The settlement for the good rock mass 3 (at chainage 58–185 m) and good rock mass 4 (at chainage 280–404 m) varies between 33 and 36 mm followed by the settlement for the portal at north and south which ranges from 9 to 11 mm, respectively.

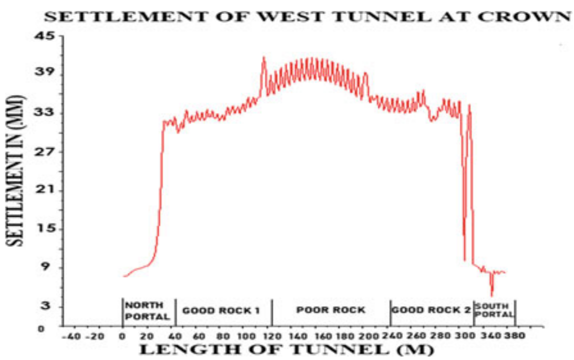


Fig. 8 Settlement of west tunnel at crown

Fig. 9 Shear of west tunnel at crown

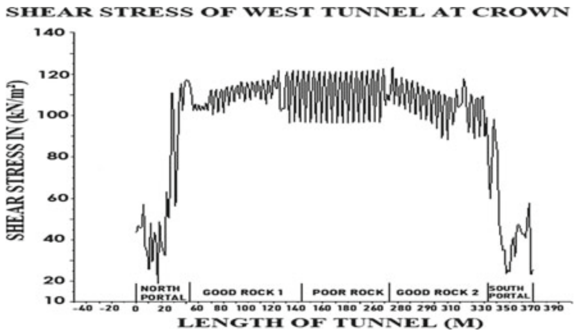


Fig. 10 Settlement of east tunnel at crown

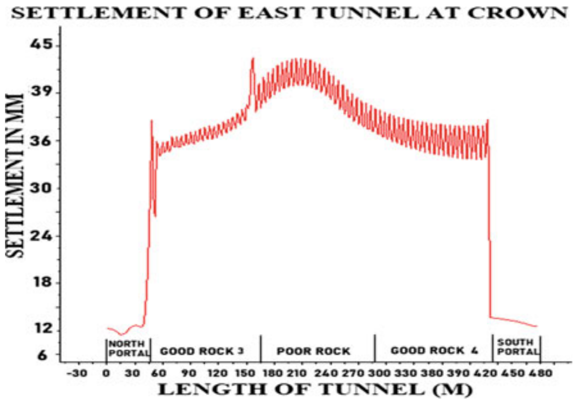
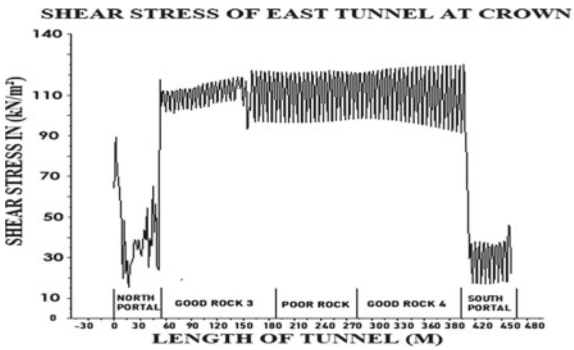


Figure 11 shows the shear stress for the east tunnel at the crown. Shear stress varies between 105 and 120 kN/m^2 for the good rock mass 3 (between chainage 58 and 185 m) and rock mass 4 (between chainage 280 and 404 m) and also for the poor rock mass (between chainage 185 and 280 m).

Fig. 11 Shear of east tunnel at crown



4 Conclusion

Based on the geotechnical investigations conducted and the rock mass rating (RMR) values for good rock mass (RMR value 61–80) and poor rock mass (RMR value 21–40) the tunnel support system can be designed in further stages. The results shown from the analysis carried on the 3D tunnel model exhibit the maximum value of settlement and shear at the crown over the poor rock mass section for both the tunnel whose RMR value ranges between 21 and 40. It is also concluded that the settlement and shear stresses in good rock mass and in portal section are less than those compared to poor rock mass in both the tunnels. The poor rock can be strengthened in further stages by providing steel ribs bent in arch section as provided in portal sections. Also, the number of rock bolts can be increased by reducing the spacing between the each rock bolt, which helps to reduce the amount of settlement and increase the loading carrying capacity of the poor rock.

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