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Article

Engineering geological and geotechnical evaluation of Sathya Sai Prasanthi Nilayam railway tunnel, Andhra Pradesh, India

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Abstract: Detailed engineering geological investigations were carried out for a railway tunnel which was constructed more than two decades ago. 3D engineering geological mapping was carried out using Brunton Compass and Total Station Surveying instruments in 1:100 scale. Coarse-grained pink and grey granite, hornblende-biotite gneiss and dolerite dyke of Archaean age and Lower Proterozoic age were mapped. Rock mass was intersected by sub-horizontal, inclined, and vertical joint sets, which were continuous and persistent, smooth, and planar with thick filling of decomposed and crushed sheared material or with thin coating of clay material. Based on the Q-system, rock mass was classified into different classes. On the basis of large-scale engineering geological mapping and Norwegian Method of Tunnelling, a support system was recommended which includes rock bolt, fibre reinforced shotcrete, grouting and reinforced ribs of sprayed concrete and the same is implemented by the agency. As per the best knowledge of the authors, reinforced ribs of sprayed concrete are first time used for transportation tunnels in India and it will be more effective if it will be compared with ISMB or Lattice Girder.

Keywords: engineering geology; tunnel; Q-system; reinforced ribs of sprayed concrete

1. Introduction

Engineering geological and geotechncial evaluation of a 234.0 m long tunnel which was constructed between Ch. 21,552.50 m and 21,786.50 m for laying of Broad Gauge (BG) railway track near Sathya Sai Prasanthi Nilayam Railway Station (SSPN) of Bangalore-Dharmavaram section of Andhra Pradesh in India during 2001 were carried out. Alignment of the tunnel is partly curved and partly straight, 2.5-degree curve from Ch. 21,552.50 m to 21,733.05 m is provided, and it is straight from Ch. 21,733.05 m to 21,786.50 m (**Table 1**). For the stability of the excavated rock masses, in the roof and walls, ISMB ribs and posts with 600 mm thick concrete lining is provided from both portals ends. At SSPN end, the length of the lined tunnel is 71 m (from 0.0 to 71.0 m) and at Dharmavaram Railway Station (DMM) end, length of lined tunnel is 31 m (from 203.0 to 234.0 m). Between the lined portions, the 132 m length of tunnel is unlined and unsupported. In unlined portions as per design, height and width of excavated tunnel above/at rail formation should be 7.219 m and excavated depth below rail formation should be 1.590 m. Presently the average excavated width of the tunnel at rail formation is 8.280 m and average height above rail formation in center is 7.620 m (**Figure 1**). About 50 cm wide and 70 cm deep drains are constructed along both sides of the walls. In the unlined portion over burden cover varies from 11 to 31 m.

Table 1. Salient features of the SSPN tunnel.

Total length	**234 m including portals**
Curve/straight	Partly curved and partly straight, 2.5° curve from Ch. 21,552.5 to 21,733.05 (180.55 m) straight from Ch. 21,733.05 to 21,786.5 (53.45 m).
Details of the construction	Full face blasting and mucking, in weathered rock location concrete lining of 600 mm thick over ISMB vertical post and arch ribs, no lining and support provided in hard rock area.
Portion lined and thickness of lining	SSPN end lining of tunnel length—71 m, DMM end lining of tunnel length—31 m, thickness of lining 600 mm, unlined tunnel length 132 m.
Ventilation/lighting	Natural ventilation/natural lighting
Drainage	Drainage holes in lined portion and pucca concrete side, drain have been provided throughout the tunnel length
Shape of the tunnel	Arched roof with vertical walls
Minimum height above rail level along centre of tracks excavated/finished	7.219 m/6.469 m
Minimum clear distance from centre line of tracks	5.519/2 = 2.7595 m
Minimum excavated width of the tunnel	7.219 m
Minimum excavated height of the tunnel from invert	8.809 m

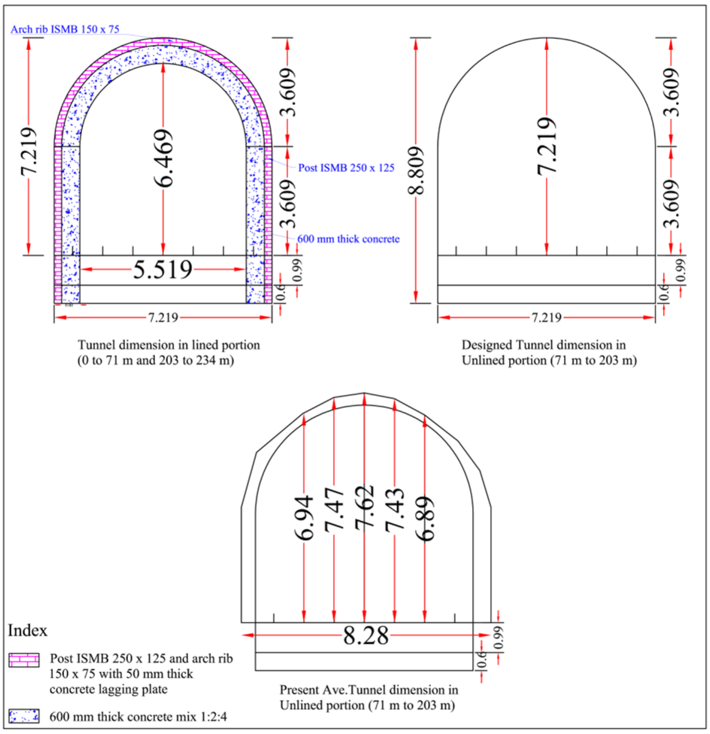

Figure 1. Design cross section of the tunnel in lined and unlined portions and present average excavated dimension.

For an unlined portion of the tunnel, rock mass characterization was done based on 3D geological mapping and engineering geological data which were collected from the exposed walls and crown portions of the tunnel. Based on engineering geological data, Norwegian Method of Tunnelling (NMT) and site geological conditions, a support system was recommended. The climate of this area is characterized by hot summer and generally dry weather except during the southwest monsoon season. The normal mean daily minimum and maximum temperature are 26 °C and 38.3 °C during

May and 17.1 °C and 30.2 °C during January. The normal annual rainfall of this area is 573 mm (Indian Meteorological Department). The southwest monsoon contributes ≈ 56%, northeast monsoon contributes ≈ 29%, and remaining by the winter season.

2. Geology of the project site and area around

This railway tunnel is located around 8 km to the west of the pilgrim town of Puttaparthi of Andhra Pradesh in India. It forms a part of the Peninsular Shield of the Indian Sub-continent and physiographically falls under the north-western plateau and plains forming the Andhra Pradesh region [1]. This area is a part of Eastern Block of Dharwar Craton mainly comprised of Archaean granites and gneiss which are intruded by mafic dykes age ranging from Archaean to Upper Proterozoic [2]. Granites and gneisses are exposed in and around the project sites over a large area. These formations are traversed by several dolerite dyke, quartz-pegmatite-aplite veins trending in different directions. The rocks which are mapped in the unlined tunnel portion are coarse-grained pink and grey jointed granite and hornblende-biotite gneiss of Peninsular Gneissic Complex belongs to Archaean age [3]. The rock mass is intruded by about 51 m wide jointed dolerite dyke of Lower Proterozoic age passing all along the hillock. Strike of the dyke at this location is varying between N050° and N060°. This tunnel is passing through the hillock and topographically the surface area along the tunnel alignment is at lower level and both sides gentle up slope is present. Residual hill and linear ridge are the geomorphological features of the tunnel area.

3. Engineering geological and geotechnical evaluation

3D engineering geological mapping was carried out in 1:100 scale, so that minor geological features can also be mapped. Tunnel crown data was collected using the tower car as shown in **Figure 2**, and for better interpretation, data was also collected from the ground, along the tunnel alignment (**Figure 3**). Brunton Compass, Schmidt Hammer and Total Station Surveying instruments were used for data collection. 3D engineering geological mapping provides a permanent record of all geologic features exposed on the crown and walls of an underground excavation which is very useful in understanding the future failure in case the tunnel is lined. All engineering geological parameters were collected and measured from the rock mass for the characterization of rock mass (**Figure 4**). ISRM [4] classification for weathered rock mass was used to characterize the rock mass into different weathering grades.

Figure 2. Crown data was collected using the tower car.

Figure 3. Bird-eye view of the tunnel.

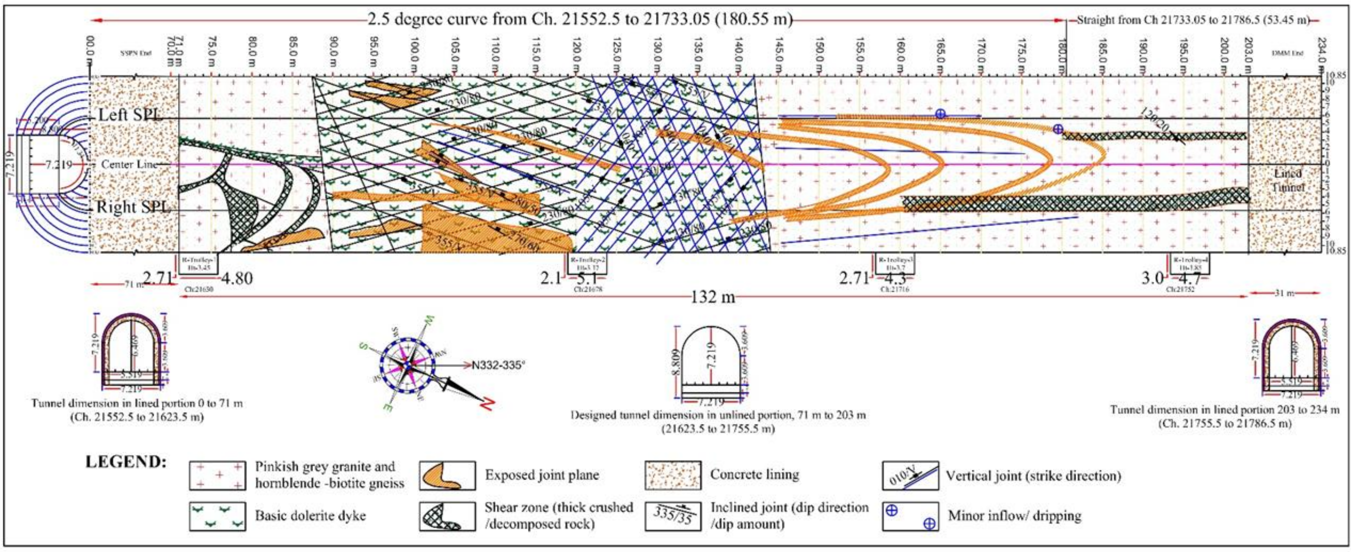

Figure 4. 3D geological map of the tunnel.

For the classification of rock mass, Q-system is used which was developed at Norwegian Geotechnical Institute (NGI) between 1971 and 1974 and updated in 1993 based on 1050 examples and in 2002 with more than 900 new examples from underground excavations in Norway, Switzerland, and India [5–7]. The 2002 update also includes the details of Reinforced Ribs of Sprayed Concrete (RRS) with respect to the load and the rock mass quality. The rock mass quality (*Q*-value) is related to the ultimate support pressure requirement. This system is applicable for the rock mass classification for an underground opening and for filed mapping. Worldwide this system is being used for the design of tunnels, shafts, and caverns in jointed rock mass [8–20]. This classification is being used for the last many decades in India and particularly in the southern, eastern, and western parts of a country for a description of the rock mass stability of an underground opening in jointed rock masses [21–26]. Based on six parameters the *Q*-values were calculated using the Equation (1). All the parameters were determined during geological mapping using tables that give numerical values to be assigned to a described situation as given by Barton et al. [5] and Grimstad and Barton [6]. For the calculation of *Q*-values all the discontinuities per 3 m length and circumference are taken into consideration.

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

where,

RQD is Rock Quality Designation (Degree of jointing), J_n is Number of joint sets, J_r is Joint roughness number, J_a is Joint alteration number, J_w is Joint water reduction factor and SRF is Stress Reduction Factor.

Between Ch. 21,623.5 to 21,641.5 m and 21,692.5 to 21,755.5 m of the tunnel, coarse grained to porphyritic pink and grey granite and hornblende biotite gneiss rocks were mapped. Rock mass was intersected by many prominent sub-horizontal and vertical joint sets, which are continuous and persistent, smooth, and planar with thick filling of decomposed and crushed sheared material (**Table 2**). Rocks are moderately widely to widely spaced and blocky to massive in nature. Joints are very high persistence. All joint surfaces were coated with clay and up to 70 cm thick layer of clay/altered/sheared material as a filling along sheet joints were recorded. The prominent sub-horizontal joints were dipping inside the tunnel from both walls and exposed at the tunnel roof also. In the stretch of about 5 m, 3 joint sets were prominent and between Ch. 21,623.5 to 21,641.5 m joint volume (Jv) varies between 10 to 13 while between 21,692.5 to 21,755.5 m Jv was 8 to 10. Due to sub-horizontal sheet joints with filling of thick sheared material, rock mass in this zone was very unstable.

Table 2. Prominent joint sets recorded in pink and grey coarse/porphyritic granites/gneiss.

Joint No.	Strike/dip direction	Dip amount	Spacing (cm)	Persistence (m)	Roughness	Aperture (mm)	Infilling/alteration	Weathering	Ground water
J1	090–120	20–30	60–80	>20	Smooth planar	-	Clay coated/80 cm filled	W-II to W-III	Dripping
J2	080	50	50–100	>20	Smooth planar	-	Clay coated/30–50 cm filled	W-II to W-III	Dripping
J3	220	70	50–100	>20	Smooth planar	-	Clay coated/50 cm filled	W-II to W-III	Dripping

Table 3. Prominent joint sets recorded in basic dolerite dyke.

Joint No.	Strike/dip direction	Dip amount	Spacing (cm)	Persistence (m)	Roughness	Aperture (mm)	Infilling/alteration	Weathering	Ground Water
J1	105–120	Vertical	15–40	>20	Smooth planar	-	Clay coated	W-II	Dripping
J2	040–055	Vertical	15–40	>20	Smooth planar	-	Clay coated	W-II	Dripping
J3	080	Vertical	15–40	>20	Smooth planar	-	Clay coated	W-II	Dripping
J4	220	50	15–40	>20	Smooth planar	-	Clay coated	W-II	Dripping
J5	280	50	15–40	>20	Smooth planar	-	Clay coated	W-II	Dripping
J6	010	Vertical	15–40	>20	Smooth planar	-	Clay coated	W-II	Dripping

Between Ch. 21,641.5 to 21,692.5 m, rock mass consisted of fine grained intrusive basic dolerite dyke (**Figure 5**). Rock mass was intersected by many prominent inclined and vertical joint sets, which were continuous and persistent, smooth, and planar with thin coating of clay material. Due to intersections of the three joint sets, rock mass was blocky in nature and these blocks were imperfectly interlocked (**Table 3**). Rocks are closely to moderately widely spaced and fractured to blocky in nature. Joints are very high persistence. In the stretch of about 5 m, 3 to 4 joint sets were present and joint volume (Jv) varies between 7 to 14. Due to imperfect interlocking between rock blocks having smooth planar surfaces, failure of rock blocks is likely possible. Since the tunnel surface was excavated for more than two decades and due to jointing nature and continuous flow/dripping of water, the exposed rock mass was deteriorating and slightly weathered (W-II) to moderately weathered (W-III) in nature.

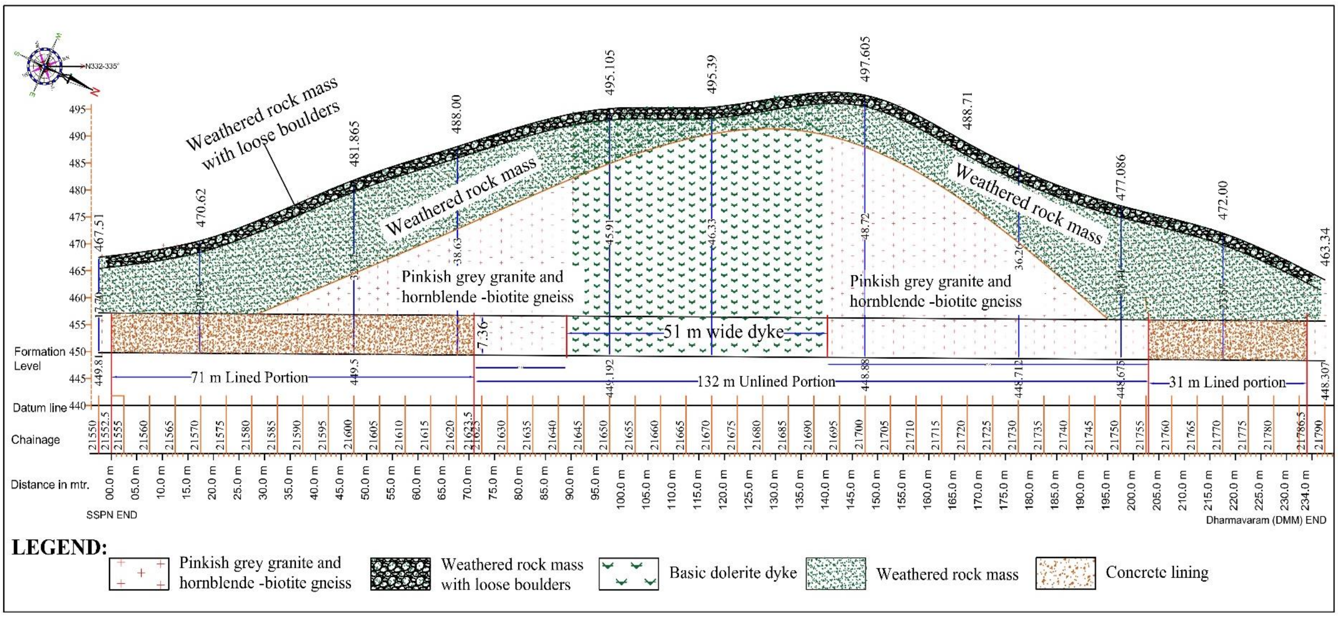

Figure 5. Geological L-section of the tunnel.

Table 4. Rock mass parameters measured for *Q*-values from the tunnel periphery.

Chainage (m)		Distance (m) from SSPN END		Rock mass parameters							*Q*-value	Q-class
From	**To**	**From**	**To**	J_v	**RQD**	J_n	J_r	J_a	J_w	**SRF**		
21,552.5	21,623.5	0	71	Tunnel with lining								
21,623.5	21,635.5	71	83	-	60–65	9	1	6	0.66	7.5	0.1	Very poor
21,635.5	21,641.5	83	89	13	72	9–12	1	6	0.66	7.5	0.1	Very poor
21,641.5	21,647.5	89	95	10	82	12	1	2	0.66	2.5	0.9	Very poor
21,647.5	21,650.5	95	98	10	82	12	1	2	0.66	1	2.3	Poor
21,650.5	21,653.5	98	101	7	92	9	1	2	0.66	1	3.4	Poor
21,653.5	21,656.5	101	104	14	69	12	1	2	0.66	1	1.9	Poor
21,656.5	21,671.5	104	119	12	75	12	1	2	0.66	1	2.1	Poor
21,671.5	21,674.5	119	122	14	69	12	1	2	0.66	1	1.9	Poor
21,674.5	21,677.5	122	125	12	75	12	1	2	0.66	1	2.1	Poor
21,677.5	21,689.5	125	137	7	92	6	1	2	0.66	1	5.1	Fair
21,689.5	21,692.5	137	140	8	89	6	1	2	0.66	1	4.9	Fair
21,692.5	21,695.5	140	143	8	89	6	1	2	0.66	2.5	1.9	Poor
21,695.5	21,701.5	143	149	6	95	6	1	2	0.66	2.5	2.1	Poor
21,701.5	21,707.5	149	155	9	85	6	1	2	0.66	2.5	1.9	Poor
21,707.5	21,755.5	155	203	-	55	9	1	6	0.66	7.5	0.1	Very poor
21,755.5	21,786.5	203	234	Tunnel with lining								

Assessment of the ratings for the parameters of the Q-system at 3 m intervals to classify rock mass is carried out based on 3-D geological mapping and joint wall characteristics (**Table 4**). Engineering geological observations and data reflect that there are wide variations in the geological conditions of the rock masses mapped due to different origin and type of rock formation. Rock mass in this zone is disturbed and shearing occurred all along the sub-horizontal sheet joints which are characterized by the presence of thick decomposed/sheared material may be due to intrusion of dolerite dyke. Overall *Q*-values for mapped tunnel portions vary between 0.1 and 5.1 and average is 1.4 that falls under Poor rock mass category as per NMT Q-system.

4. Recommendations

Based on *Q*-values, site geological conditions and engineering judgement, support for the tunnel was recommended which includes rock bolt, fibre reinforced shotcrete (SFRS/PFRS), grouting and reinforced ribs of sprayed concrete (RRS) (**Table 5**). Proper scaling and cleaning (with water jet and air jet) of the excavated rock faces before execution of support was recommended. A combination of sub-horizontal and sub-vertical joints may create a problem at the crown which may not be seen before failure, and for the same longer rock bolts were recommended. Rock bolts will be equipped with an anchor plate with spherical hexagonal washer and nut. It was suggested that the protruding end of the bolt shall have a minimum of 150 mm threads and the projections of the rock bolt should be fully covered with shotcrete to prevent corrosion. Cement grouting in rock bolting holes before fixing of bolts was suggested. The undulations on the rock face should be chiseled properly before rock bolting to get uniform face slope. There should be a proper contact between the bearing plate and the rock surface. The size of the bearing plate recommended was 200 × 200 × 10 mm. RRS thickness will be 300–400 mm, centre to centre spacing will be 4.0 m, number of 20 mm dia steel bars of in one rib will be 6 which will be equally spaced and welded by 25 mm dia bar or 200 mm (*W*) × 300 mm (*L*) × 15 mm (*T*) steel plate. Welding will be done at 2.0 m interval and anchoring at 2.0 m interval and 1.0 m deep in a rock mass. First two layers of SFRS will smooth out the rock surface, which is very essential for placing RRS. All the recommendations made were implemented by agency and now this track is reopened for the trains (**Figure 6a,b**).

Table 5. Details of rock support arrangements for the unlined portion.

Tunnel chainage (m)	Required support			Grouting	Drainage arrangement
	Grouted rock bolts	Rock bolt spacing	Shotcrete		
Roof Ch. 21,623.50 to 21,647.50 & 21,684.50 to 21,755.50—*Q*-value 0.1 to 5.1	4.0 m long, 25 mm diameter fully cement grouted rock bolts (Fe ≥ 500)	1300 mm c/c (staggered)	200 mm thick SFRS with RRS* and welded wire mesh (50 mm × 50 mm × 3.15 mm dia.)	Consolidation grouting up to 4.5 m deep at 3.0 c/c spacing	-
Walls Ch. 21,623.50 to 21,647.50 & 21,684.50 to 21,755.50—*Q*-value 0.1 to 5.1	3.0 m long, 25 mm diameter fully cement grouted rock bolts (Fe ≥ 500)	1300 mm c/c (staggered)	200 mm thick SFRS with RRS* and welded wire mesh (50 mm × 50 mm × 3.15 mm dia.)	Consolidation grouting up to 3.5 m deep at 3.0 c/c spacing	4.0 m long 45 mm diameter drain hole @4.0 m c/c (longitudinal distance) @2.5 m c/c (vertical distance) from spring level up to invert level (staggered)
Roof & Walls Ch. 21,647.50 to 21684.50—*Q*-value 1.9 to 5.1	3.0 m long, 25 mm diameter fully cement grouted rock bolts (Fe ≥ 500)	1750 mm c/c (staggered)	150 mm thick SFRS in three layers with welded wire mesh ((50 mm × 50 mm × 3.15 mm dia.)	Consolidation grouting up to 3.5 m deep at 3.0 c/c spacing	4.0 m long 45 mm diameter drain hole @4.0 m c/c (longitudinal distance) @2.5 m c/c (vertical distance) from spring level up to invert level (staggered)

(a) **(b)**

Figure 6. (a) installation of reinforced ribs of sprayed concrete; **(b)** view of tunnel after installation of RRS.

5. Conclusion

After the critical examination of the rock types, a support system which includes rock bolt, SFRS, grouting and RRS was recommended and the same is implemented by the agency. The track was closed for two months and now it is reopened for the trains.

This is a critical example where engineering geological investigations were started after the rock block started falling from the crown on the railway track (**Figure 7**). This may be hazardous and some time may be a huge economic loss to the Corporation who is looking after the maintenance part of the railway track if the track is closed for long time.

Figure 7. Falling of rock block from the crown of tunnel.

Almost all the Indian Railway tunnels are either lined or unsupported and engineering geological records are also not available regarding the selection of a support system. Emphasis is given for the lining where the geological condition of rock mass is not good and one should understand it is passive support and the life of the tunnel will be less if only passive support is being provided.

Over the period, natural deterioration of rock mass will be there which is a very natural process. In those tunnels where ingress of water is there, deterioration of the lined portion of the tunnel will be more because corrosion in ribs or iron rods will be very fast.

Urgent need is that all the tunnels should be assessed properly regarding their stability because it is concerned with the safety of the passengers.

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