Study on Influence of Fault Dip Angle on Tunnel Lining

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Abstract: The tectonic plate movement causes more Earthquakes of small to medium magnitude in Himalayan regions so it is very essential to study the behavior of underground structures like tunnels under fault movement. The fault dip angle as well as fault thickness on the tunnel lining surrounding rock are the important parameters that control the damage to tunnel lining. The main objective is to study the effect of dip angle on the tunnel lining during fault movement. In the present study, three dip angles 600, 750 and 900 with the fault thickness of 25 m are considered. Three dimensional finite element programming is used for modelling the tunnel-soil interaction. The fault movement is activated by dip slip displacement loads and the results are interpreted. It is observed that increasing the angle of dip increases the stresses in the tunnel lining. With increase in the dip angle, the location of plastic zone slightly shifting towards the footwall side due to the concentration of compressive stresses in the tunnel lining near the hanging wall and fault area..

Keywords: Underground structures; Fault; Tunnel lining, dip angle, Plastic zone.

1 Introduction

In developing countries like India economic growth is very important and as per NITI Aayog june report 2022, the Gross Domestic Product (GDP) growth is expected at 7.0% for the year 2024 – 25 [1]. In this, transportation sector contributes considerable percentage of national GDP. Road and Railway sectors require tunnels that can connect inac- cessible stations/cities separated by mountains or accessed by long route. Tunnels not only reduce the distance between two stations/cities, but also prevent any damage to roads or railway lines, the vehicles and passengers from landslides, heavy snow fall etc., The main example of the above reasons in Indian scenario is construction of Atal Tunnel at Leh – Manali

Highway. This tunnel not only reduces the travelling distance but also reduces the travel time by 5 to 6 hours. It also prevents the National Highway from avalanche slides that leads to many hours of traffic jam for clearing the snow from the road. Thus, it is very important that tun- nels can indirectly increase the GDP and lead to economic growth of thecountry.

The Indian tectonic plate moving at the rate of 4.5 cm/year in the north-east direction towards Eurasian tectonic plate. So it is necessary to study the existing tunnels and also the future planned tunnel design in the Himalayan region. In general, earthquake-related tunnel damage takes one or more of the following processes: (1) damage from surround- ing rock failure brought on by the earthquake, such as liquefaction or landslides at tunnel portals; (2) damage from fault displacement; and (3)damage from ground shaking & Vibration.

Numerous related studies have been conducted to examine the damage process and earthquake resistant approach for tunnels traversing the fault region. Many research works carried out on numerical simulation using numerical method, analytical method(Zhang et al., 2018) [2] and model tests using shake table and centrifuge test (Su et al., 2019; Wang et al., 2019) [3]. Some tunnels crossing active fault zones are subjected to both seismic shaking and fault dislocation when earthquake occurs. However many researchers (Cui et al., 2013; Gao et al., 2009) [4][5] believe that the fault dislocation is the main factor causing damage to tunnels.

The “articulated design” was adopted in the Bolu tunnel in Turkey and the Koohrang-III water transmission tunnel in the region of central Iran (Russo et al., 2002; Shahidi and Vafaeian, 2005) [6]. Liu et al. (2015) analyzed the design of the flexible joints, and demonstrated that the shorter segment plays a better role in resisting failure due to fault rupture[7]. Cui et al. (2015) [8] and Ma et al. (2019) [9] numerically analyzed the distribution characteristics of the stress and strain in lining with dif- ferent length of the lining segments.

The above studies give guidelines for construction of tunnel crossing fault, however, there are some shortcomings. Fault movement may be caused by intense ground motion, and this coupling effect can seriously harm the tunnel's construction and the surrounding rock. This paper aimsto study the effect of fault movement in the tunnel lining for three differ- ent fault dip angle. The failure mechanism of tunnel lining in terms of deformation, axial force and bending moments along the length of thetunnel is studied and discussed.

2. Finite Element Numerical Modelling:

The analyses were performed using finite element programming tool PLAXIS 3D. The minimum transverse section of soil model should be 10 times the diameter of the tunnel, beyond this dimension the bounda- ries has very little effects on the calculation results [12]. In this study 100m x 40 m x 40 m (L x B x H) size of the soil mass was adopted to reduceboundary effects on results. The excavation of tunneling was done in the X direction. The inner diameter of tunnel was adopted as 4 m with thick- ness of lining as 0.25 m. Fully fixed boundary condition was applied in the bottom surface of soil mass. For top surface and sides of soil mass, free and normally fixed boundary conditions was applied respectively.

Rock is an irregular substance made up of entire rock mass and a cer-tain amount of discontinuities, including fractures and stratigraphic divi- sions. For fewer discontinuities of higher quality (that the discontinuities have little effect on the strength and stiffness of the entire rock mass), one can model the soil as e Hoek-Brown model. The rock mass was mod-elled as jointed rock model. On the other hand if the rock mass has morediscontinuities, then it was modelled as Jointed Rock model. In this study the rock masses was modelled as jointed rock model and the grouting was modelled as soil element of linear elastic model. The tunnel lining segments was modelled as plate element with elastic model. In this studyvery fine meshing was used so as to get the exact intervals along the length of the tunnel to obtain the deformation, bending moment and shearforces in the tunnel lining.

The properties of rocks in footwall, hanging wall and fault zone are considered from Longxi tunnel [10]. M45 grade of concrete was consid-ered for tunnel lining. The thickness of tunnel lining is adopted as 0.25 m. The properties of materials used in this study was listed in the Table 1.

Strength reduction factor signifies the ratio of strength of selected soil corresponding to surrounding soil. For sliding to occur strength reduc- tion factor (R_{int}) was used. The rock mass in the fault and hanging wall soil block portion moves downwards by applying the prescribed dis- placement of 0.25 m in the downward direction against footwall. Based on literatures studied, abboodi and Sabbagh [11] conducted numerous studies and found that while using the value of R_{int} = 0.5, they observed the soil mass moved as a single mass without any heaving. In this studyR_{int} = 0.5 was adopted in the interface section of fault block and sur- rounding blocks.

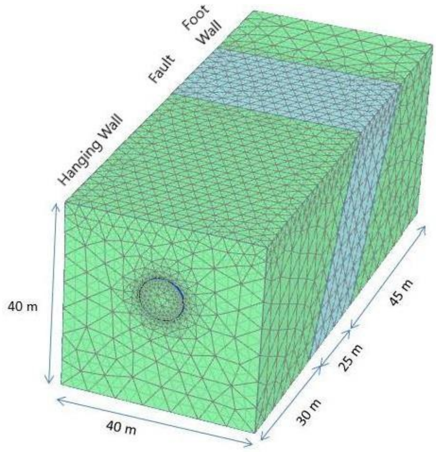
Three Finite Element Models were created with different fault dip an-gles of 60^0, 75^0 and 90^0 with constant vertical downward displacement of 0.25 m in the downward direction. Corresponding effects on the tunnel lining was observed and discussed in detail with a vertical displacementof 0.25 m in hanging wall and fault blocks.

Table 1. Properties of Materials

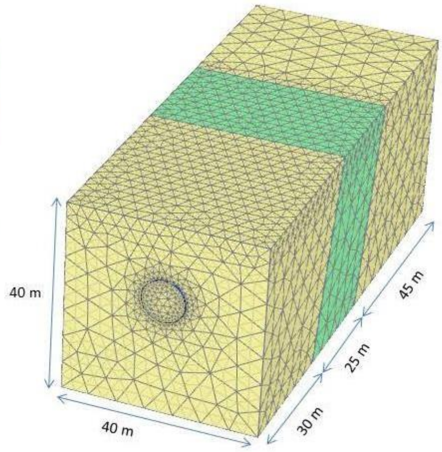
Parameter	**Rock [10]**	**Fault [10]**	**Grouting [13]**	**TBM [13]**
Material Model	Jointed Rock	Jointed Rock	Linear Elastic	Elastic
Drainage type	Non Porous	Non Porous	Non Po- rous	Non Porous
Unit Weight (kN/m^3)	25	18	10	25
Young's Modulus (kN/m^2)	2.7×10^6	0.9×10^6	30×10^6	35×10^6
Poison's Ratio	0.3	0.3	0.2	0.2
Cohesion (kN/m^2)	729	180	-	-
Friction angle	32	25	-	-
Interface Strength	Rigid	Rigid	Rigid	-
R Value	-	0.5	-	-
Thickness (m)	-	-	-	0.25

4. Results and Discussion

The deformations, bending moments and shear forces values were ob- tained along the length of the tunnel in the tunnel lining. The defor- mations, bending moments and shear forces were plotted in y axis by taking the length of the tunnel in x axis



(a)



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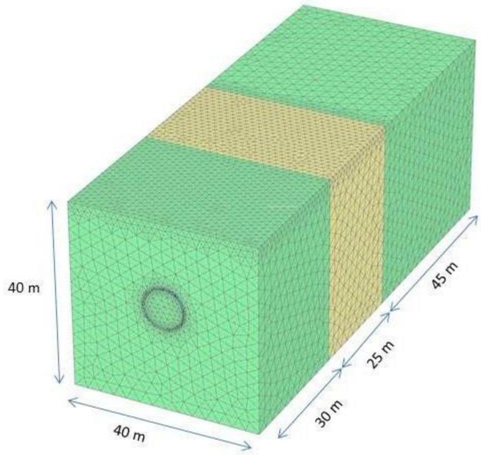

(c)

Fig.1 Meshed models for three different dip angles (a) Meshed modelwith 60^0 dip angle, (b) Meshed model with 75^0 dip angle and (c) Meshed model with 90^0 dip angle

4.1 Analysis of tunnel lining deformation for different dip angles:

The distribution of the tunnel lining deformation curve under variousfault dip angle along the length of the tunnel with vertical downward prescribed displacement of 0.25 m is in the form of a mirrored "S", and the tunnel lining in the hanging wall moves in the same manner and the movement is consistent with the fault's displacement. The curve becomesvery steep if larger footwall length is considered [10]. From the Figure 2, it is clear that the maximum deformation in the tunnel lining occurs in the hanging wall and fault junction irrespective of fault dip angle. The deformation of lining in the hanging wall portion is a straight line and then it inceares small amount when lining crosses in the fault area. Beyond fault area that is, foot wall portion the deformation curve goes on decreasing in a linear manner and reaches zero value.

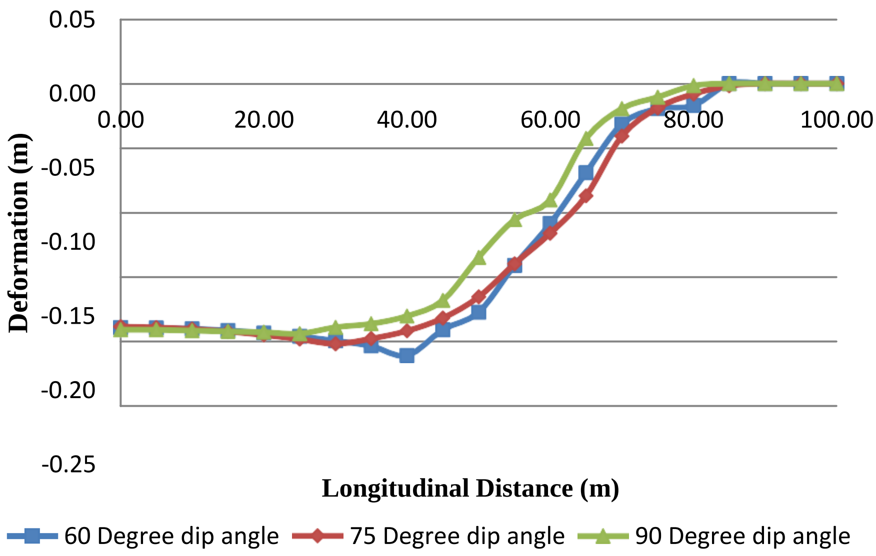

Fig.2. Deformation vs longitudinal distance for three different dip angles

4.2 Analysis of Axial forces in tunnel lining along the length of thetunnel for different dip angles:

The distribution of the axial force in tunnel lining curve under various fault dip angle along the length of the tunnel with vertical downward prescribed displacement of 0.25 m is shown in the Figure 3. The tunnel lining in the hanging wall moves in the same manner and the movement is consistent with the fault's displacement. The curve becomes very steep if larger footwall length is considered. From the Figure 3, it is clear thatfor 60^0 dip angle the maximum axial force in the tunnel lining occurs in the fault area irrespective of fault dip angle. The axial force in lining from the hanging wall area to foot wall area is keeps on increasing and then it nearly reaches zero in the foot wall and fault area junction. Then it increases small amount along the length of tunnel till end. For 75^0 and 90^0 dip angle after reaching the maximum value, the axial force curve becomes nearly flatter.

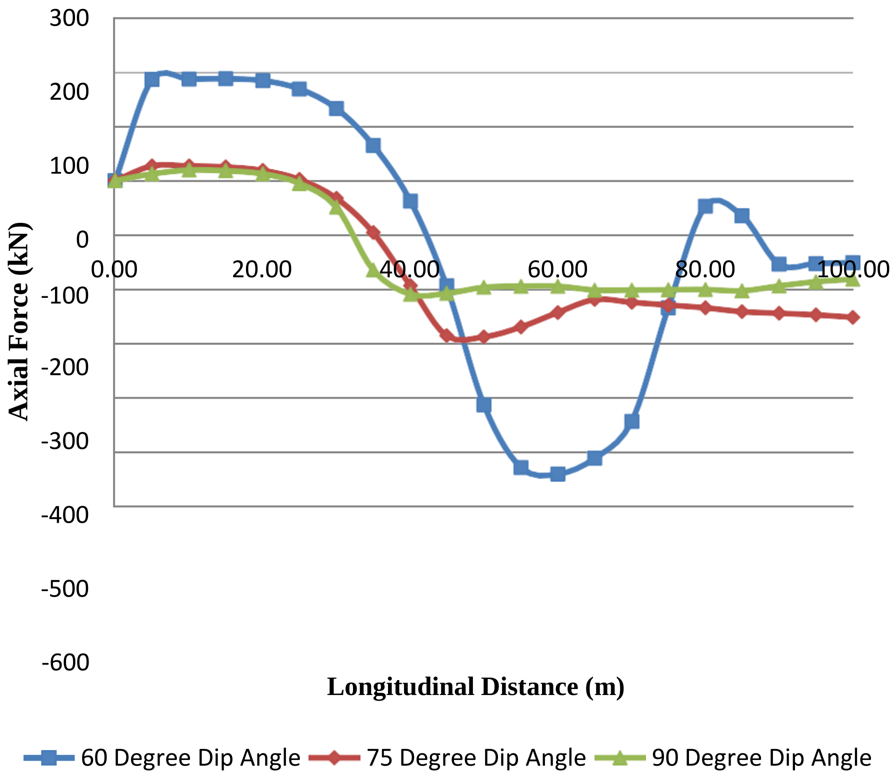

Fig.3. Axial force vs longitudinal distance for three different dip an-gles

4.3 Analysis of bending moments in tunnel lining along the length ofthe tunnel for different dip angles:

The distribution of the bending moment in tunnel lining curve under various fault dip angle along the length of the tunnel with vertical downward prescribed displacement of 0.25 m is shown in the Figure 4. The tunnel lining in the hanging wall moves in the same manner and the movement is consistent with the fault's displacement. The curve becomesvery steep if larger footwall length is considered. From the Figure 4, it isclear that for 60^0 dip angle the maximum bending moment in the tunnellining occurs in the fault area irrespective of fault dip angle. The bending moment in lining from the hanging wall area to foot wall area is keeps on increasing and then it nearly reaches zero in the foot wall and fault area junction. Then it increases small amount along the length of tunnel till end. For 75^0 and 90^0 dip angle after reaching the maximum value, theaxial force curve becomes nearly flatter.

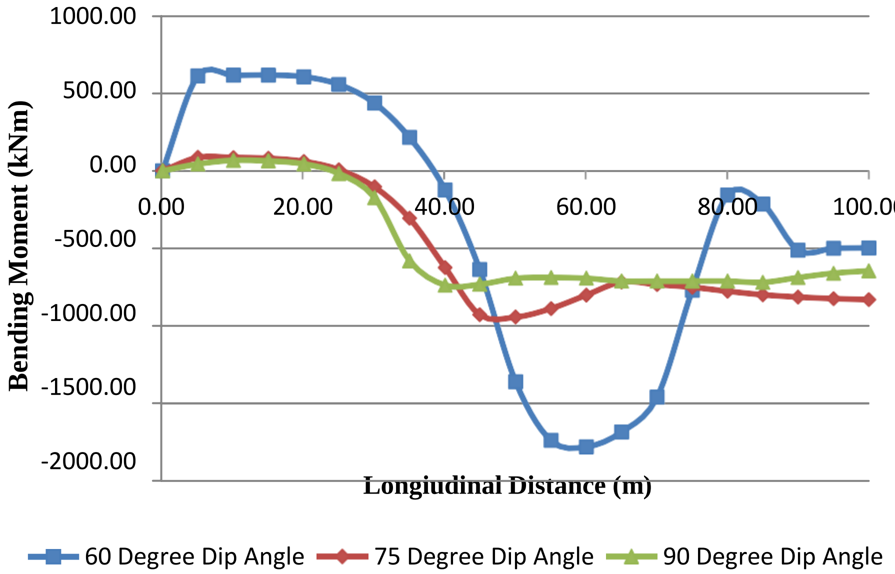

Fig.4. Bending moment vs longitudinal distance for three differentdip angles

Table 2. Comparison of deformation, bending moment and axialforce

	Deformation (m)	**Bending Moment (kNm)**		**Axial Force (kN)**	
	Maximum Downward Deformation (-ve)	**Maximum (+ve)**	**Minimum (-ve)**	**Maximum (+ve)**	**Minimum (-ve)**
60^0 Dip	0.25	620	1780	188	540
75^0 Dip	0.25	87.1	942	25.4	242
90^0 Dip	0.245	67.9	728	18.3	194

5. Conclusion:

From the above results we can interpret the following

(i) The maximum deformation in the tunnel lining is 0.21m, andthis value is equal for three different dip angles.

(ii) The maximum axial force keeps on reducing when we in- crease the dip angle. The axial force versus longitudinalcurve, after axial force reaches the maximum value and it getsreduction becomes flatter for dip angle 75^0 and 90^0.

(iii) The maximum bending moment in the tunnel lining keeps on reducing when we increase the dip angle. The bending mo- ment versus longitudinal curve, after axial force reaches the maximum value and it gets reduction becomes flatter for dipangle 75^0 and 90^0.

So it is recommended to use steel fibre reinforced high performance concrete for tunnel lining. Special care should be taken to predict and find the length of hanging wall and fault thickness from geological data,so that we can use high strength concrete or we can strengthen the sur- rounding rocks using rock bolts or by using grouting the cracked rocks.

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