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Seismic Analysis of Tunnels in Jointed Rock Mass in Himalaya

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Abstract. Tunnels are constructed in mountainous region to provide straight and comfortable routes. Often, mountains consist of rock mass, which are of highly vulnerable in nature because of the presence of random discontinuities. In Himalayan region of India, many tunnels are proposed to be constructed due to their high strategic importance because these tunnels help to provide the troops quick access to the border areas in all weather conditions. Himalayan region is seismically very active and falls in seismic zones IV and V. Seismic analysis of tunnels situated in Himalayan region considering jointed rock mass is hardly reported in the literature and the same has been studied in the present research work. In this research work, the dynamic response in terms of acceleration and vertical deformations in static as well as in dynamic conditions are evaluated at the crown and invert of the tunnel. The discontinuity in the rock mass is considered by jointed rock model with different orientation of joints. In the present study, FE analysis using 15-noded triangular elements has been carried out using PLAXIS 2D software to examine the harmonic response of tun- nel in jointed rock mass and then effect of frequency of excitation is also examined.

Keywords: Tunnel, Jointed Rock Mass, Seismic Analysis.

1 INTRODUCTION

When the shear waves travel from the fault toward the surface, the amplitude of acceleration gets amplified due to attenuation of wave velocity and resonance conditions (Yoshida, 2015) [1]. When the wave velocity is less, the amplification is more and vice-versa. In rock mass, due to its high modulus of elasticity, the shear wave velocity is large compared to the soil; hence amplification in the rock mass is less compared to soil. Most of the research for seismic analysis is found when the tunnel is present in the soil because of its considerable damage [2-9]. Some studies reveal that tunnels in the rock mass are also vulnerable to damage and have faced damage in past earthquakes [10-12]. Some researchers [13-14] studied the behavior of tunnels in rock mass during the earthquake and assumed the rock mass as continuous. Srivastav and Satyam (2020) [15] studied the behavior of tunnel in a single jointed rock mass, Roy and Sarkar (2015) [16] considered three discontinuities in the rock mass having the tunnel, Mei et.al.

(2018) [17] assumed rock mass with parallel joints with 45^0 dip angle and varied the joint spacing. In the present study, the jointed rock mass is considered without and with a tunnel, and amplification at different depths of rock mass is observed for different joint angles. Deformations due to harmonic excitation on tunnel crown and invert are also reported.

2 FINITE ELEMENT MODELING

Two Dimensional Finite Element Analysis (2D FEA) is carried out to simulate the seismic response of the tunnel in the jointed rock mass. A Schematic diagram of rock mass block geometry (Length, L=100m and Height =100m) is shown in figure 1. The tunnel is placed at different depths *D* meters from the top surface. The crown of the tunnel is named as point A and invert as point B.

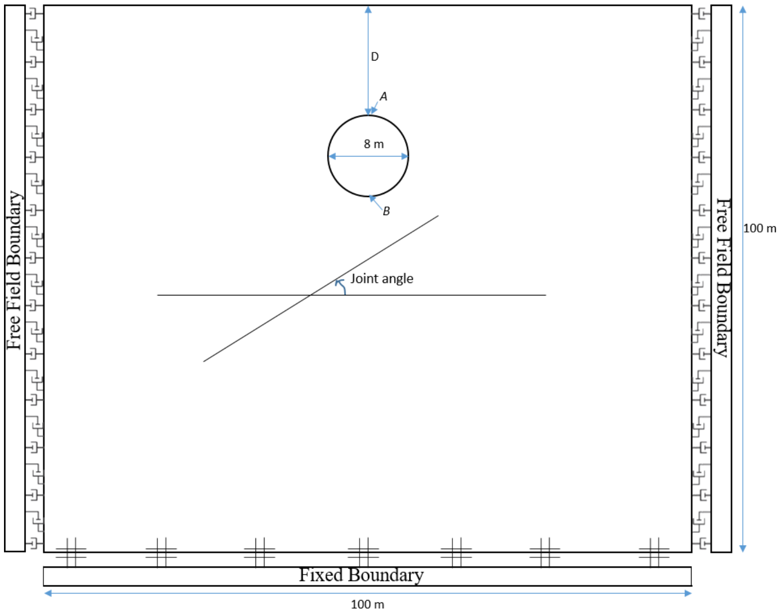


Fig. 1. Geometry of rock mass and tunnel with boundaries

In this study, limestone is used, whose properties are obtained from a study by Rao (2009) [18] as given in Table 1. The inbuilt jointed rock mass model, which considers the rock mass having parallel joints with a very small spacing between them as compared to the domain dimensions in PLAXIS 2D [19] for one set of joints, is used with varying joint angle orientations from 0^0 to 90^0. This model considers the rock mass as linear elastic material with the joint material as the Mohr-coulomb model. In this present study, the joints have cohesion 2000kPa and a friction angle 30^0. The circular cross-section of the tunnel in the rock mass is taken for the present study having a diameter of 8m. The depth of the crown (D) from the top surface is varied to 10m, 20m, 30m, and 46m, which means that the tunnel is reaching near to the bottom boundary. The lining is simulated by a plate element having a thickness 300mm, properties of which material are given in table 1. For static analysis, the vertical boundaries are made fixed in the horizontal direction and free in vertical direction so the rock mass can move freely due to self-weight under gravity. For dynamic analysis, these vertical boundaries are converted to free field boundaries so that the waves strike to that should be absorbed and not reflected back into the domain. The bottom boundary is made fixed because of assuming that the rock below it is hard strata. The top of the domain remains free for both conditions.

Table 1. Rock mass properties (after Rao, 2009) [18]

Properties	Rock mass	Lining
Unit Weight, γ (kN/m^3)	26	24
Friction Angle, ϕ (^{0})	34	-
Cohesion, c (kN/m^2)	3900	-
Poisson's Ratio, ν	0.3	0.2
Modulus of Elasticity, E (kN/m^2)	1.19×10^7	2.5×10^7

The jointed rock model is used to define the properties of the rock mass, which is an anisotropic elastic perfectly-plastic model. However, in this study, the isotropic medium is considered by assuming the same elastic modulus in all directions. In this model, joint sets are parallel, not filled with the gouge, and spacing is very small compared to the rock domain dimensions. 15 noded triangular elements are used for meshing such that the maximum size of the element is less than $\frac{Vs}{8f}$; where V_s, is the maximum shear wave velocity and *f*, is the frequency of excitation.

Response curves are generated at each point of interest, and then the maximum value of amplitude after a steady state, generally after 5 seconds, is considered as the response value to plot the curves.

In the first case, the response is recorded at various locations inside the rock mass at various points along the height for different joint angles, and then the tunnel is created at different depths without lining and after that with lining to find the deformation due to the overburden load. Finally, a seismic effect is observed in the tunnel's lining.

2.1 Input Motions

In this study, it is assumed that the fault is present at the bottom boundary, so harmonic excitation is applied at the bottom boundary of the domain by providing prescribed unit displacement and harmonic acceleration wave as a multiplier to it.

The fundamental natural frequency of this system can be calculated by $\frac{Vs}{4H}$ (where V_s is the shear wave velocity (m/s) in the rock mass, and H is the total height (m) from the fault), which is equal to 3.5Hz. So three types of harmonic excitations are used here, one having a frequency of 3.5Hz, to create resonance conditions as shown in figure 2. The Second frequency is chosen on the lower side of the fundamental natural frequency, so it should also be away from the other modes of natural frequencies as 2Hz, which is far away from resonance conditions; And the other frequency chosen is 5Hz, which is on upper side of the fundamental natural frequency but lower than second natural frequency; all three have the amplitude of 3m/s^2.

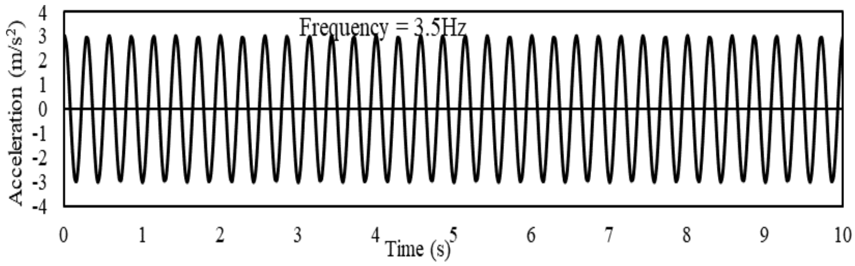


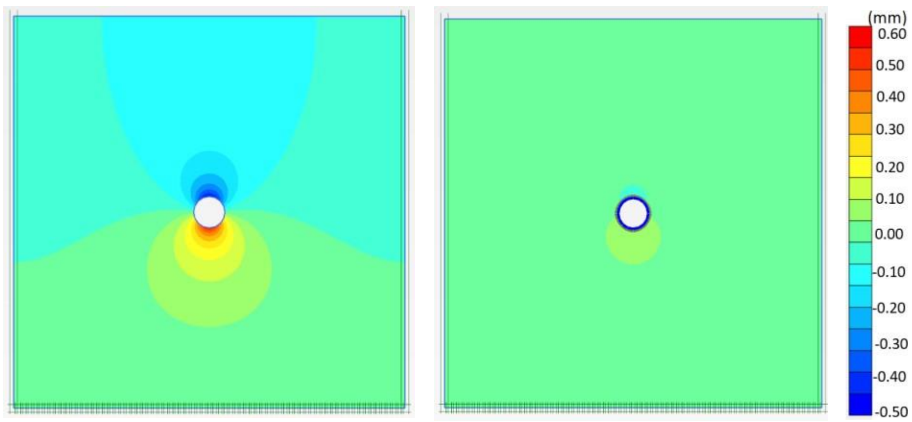
Fig. 2. Harmonic Excitation time histories of frequency, f = 3.5Hz with amplitude 3m/s^2

3 RESULTS AND DISCUSSION

Deformations and seismic response (in terms of acceleration) of jointed rock mass with different joint angles are recorded at various points with and without the tunnel. Following are the result in static and dynamic conditions.

3.1 Static condition

Due to the self-weight of the rock, the tunnel crown and invert shows some deflection. These deflections are observed for two conditions one by creating tunnel space without providing any lining as shown in figure 3 (a) and other by providing lining as shown in figure 3 (b). Values of the deformations are presented in table 2 and compared graphically in figure 4. The analysis is done for each joint angle orientation, but it is observed that, there is no effect on the vertical deformation at the crown and invert. Results of this analysis shows that without providing lining, the crown settles in the downward direction but invert moves upward. When the lining is provided, deformations are reduced drastically.



(a) (b)

Fig. 3. Deformations in the rock mass when tunnel is at the center i.e. at depth 46m (a) without lining and (b) with lining

Table 2. Vertical Deflection at crown (*A*) and invert (*B*) under static condition

Depth of crown, *D* (m)	*A*		*B*	
	Without lining	With lining	Without lining	With lining
10	-0.029	0.057	0.260	0.100
20	-0.150	0.025	0.339	0.104
30	-0.270	-0.002	0.410	0.117
46	-0.464	-0.045	0.546	0.132

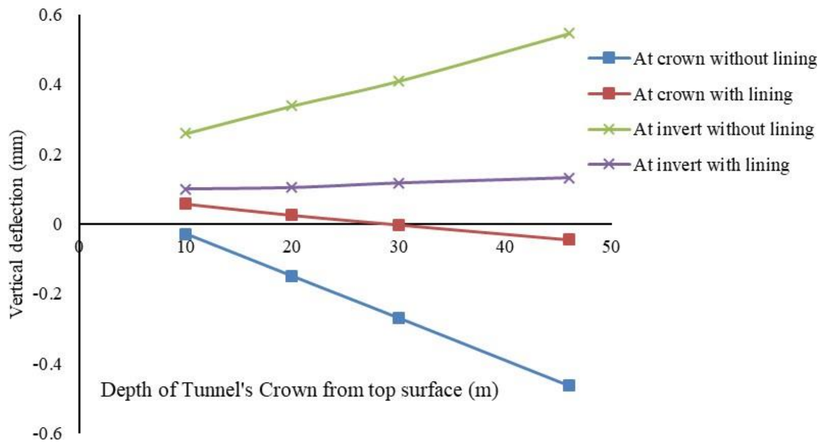


Fig.4. Comparison of vertical deflections at the crown and invert under static conditions

3.2 Seismic Condition

Seismic condition is simulated by applying input motion as discussed in previous section at the bottom boundary. Effect of joint angle orientation and frequency of excitation without tunnel is observed and the deformations in the tunnel at various depths is obtained.

3.2.1 Effect of Joint Angle on Free Field Condition

When the rock domain is subjected to harmonic loading so that the resonance condition is reached, the amplification is observed, as shown in figure 5. It can be observed that the maximum amplification occurs at the surface as expected. It is found that the amplification is highly affected by joint angle orientation. For 30^0 joint angles the amplification is maximum, and for the joint angles of 0^0 and 60^0 the amplification is quite small compared to 30^0.

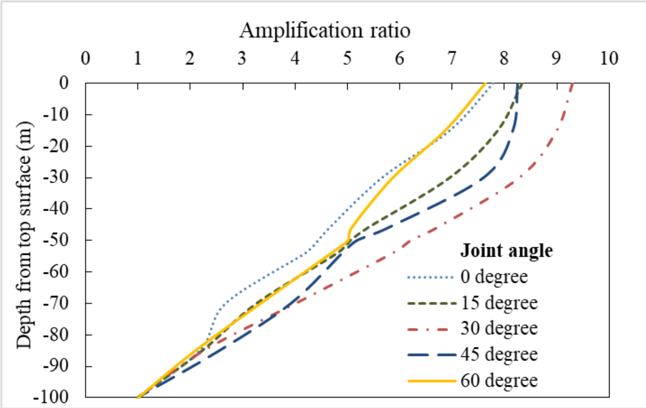


Fig. 5. Amplification of amplitude in the rock mass for different joint angles at frequency f = 3.5Hz

3.2.2 Effect of frequency

Figure 6 shows the effect of frequency of excitation on the amplification ratio with the depth, without tunnel. Considering the dimensions of the domain and rock properties, the natural frequency of the system can be found using equation 1

$$f_0 = V_s/4H \qquad \text{.......(1)}$$

Here $$V_s = \sqrt{\frac{E}{2(1+\nu)\rho}} \qquad \text{........(2)}$$

$$\approx 1330\text{m/s}$$

Therefore for H=100m f_0 =3.3Hz

As the frequency of excitation is 3.5Hz, the amplification in the rock mass is maximum i.e. 9.3 at the top of the surface. However, when the frequencies are 2Hz and 5Hz, which are far away from the fundamental natural frequency, the amplification reaches only to 1.6 and 1.36 respectively as shown in figure 6 for the angle of joint orientation of 30^0.

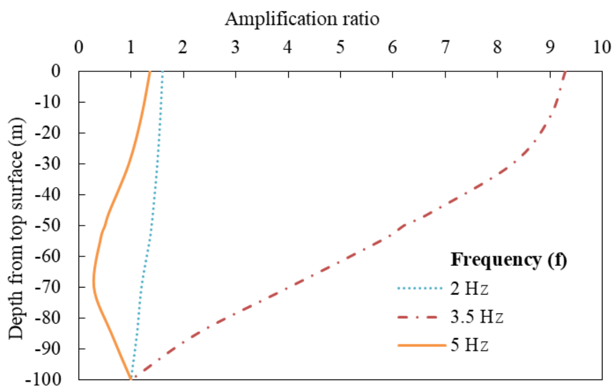


Fig. 6. Effect of frequency of excitation on amplification without tunnel for joint angle 30^0

To examine the effect of tunnel at different depths the increment in the amplitude has been calculated for all 3 frequencies for joint angle 30^0 as shown in figure 7. It can be observed that effect of tunnel is maximum for frequency 3.5 Hz due to resonance condition.

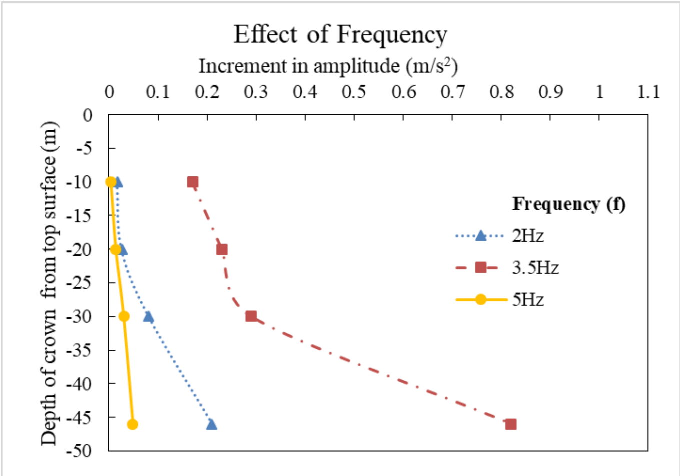


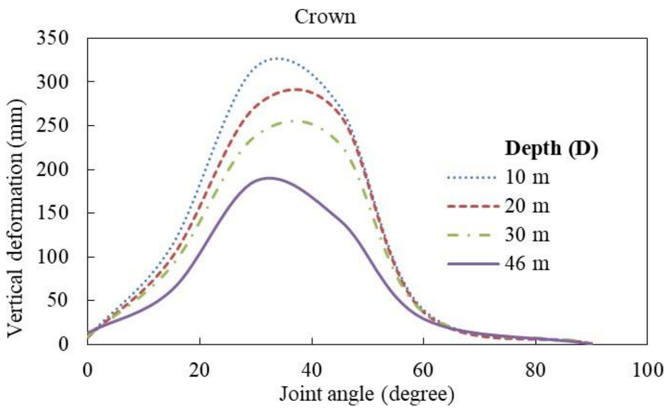
Fig. 7. Increment in the response due to presence of tunnel for joint angle 30^0

3.2.3 Deformation of Tunnels

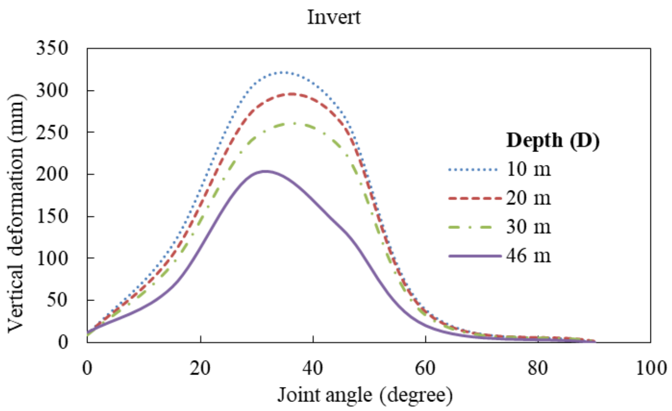
Deflection of tunnel crown and invert is obtained for 3.5Hz frequency. From Table 3 and figure 9, it can be observed that the deformations are maximum at joint angle 30^0. Further, deformations decreases as the depth of the tunnel increases from 10m to 46m. In general the deformations at invert is greater than at the crown. As compared to 30^0 joint, deformations at the crown and invert in 0^0 jointed rock is quite small.

Table 3. Deformation at tunnel crown (A) and invert (B) (in mm) due to 3.5Hz frequency

Joint angle →	0^0		15^0		30^0		45^0		60^0	
Depth of crown (m) ↓	A	B	A	B	A	B	A	B	A	B
10	8.3	10	112	115	317	310	272	275	39	39
20	8.2	9.7	99	103	272	280	263	262	37	36
30	8.5	8.7	89	92	238	245	229	231	36	32
46	13.3	12.2	62	66	187	202	142	136	29	20



(a)



(b)

Fig. 8. Comparison of vertical deformation at tunnel (a) crown and (b) invert due to harmonic excitation of 3.5Hz frequency

4 CONCLUSION

Based on the 2D Finite Element Analysis of tunnel situated in jointed rock mass for static and dynamic conditions, the following outcomes can be coined

- For static condition, as the depth of tunnel increases, the magnitude of vertical deflection also increases in both cases, without lining and with lining. However the effects of lining is significant to reduce the deflections.
- Free field response was obtained maximum at joint angle 30^0 and it is highest at ground surface.
- Effect of frequency is significant. Maximum response is obtained at 3.5Hz frequency.
- As the depth of tunnel increases, the vertical deformation decreases both at the crown and invert.

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