Effect of Spacing and Orientation of Joints in the Rock on Stress Variation in Lined Pressure Tunnels using Finite Element Method

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ABSTRACT

The majority of tunnels for hydroelectric purpose are located in mountainous region and the rock medium in which these openings are made is usually non-homogeneous and anisotropic. Major geological structural features such as joints, major shear zones or faults intersecting the excavation area cause discontinuous behavior of rock mass, which may lead to complex rock mechanics problems. In tunnel lining design, it is necessary to know the share of the rock load and internal pressure on the lining. The share of the rock load or the support pressure on the lining depends on the quality of the rock mass.

In the present study, the stress analysis has been carried for lined pressure tunnel considering rock mass with horizontal joints, vertical joints and orthogonal joints for joint spacings of ¼, ½, 1 and 2 times the diameter of the tunnel using FEM. The analysis is carried out by considering discrete rock approach and equivalent continuum approach. The results are presented for hoop stress, shear stress and radial displacement. The maximum non dimensional hoop stress in the concrete lining is presented for discrete rock approach and equivalent continuum rock approach.

Keywords: Pressure tunnel; Concrete lining; Jointed rock; Equivalent continuum approach; Stress analysis; Rock mass quality; Finite element method.

1. INTRODUCTION

Rock is distinguished from other engineering materials by the presence of inherent discontinuities such as joints, bedding planes and faults that control its behavior. The number of joints in a rock mass is many and it is difficult to obtain information about all of them, and deal with each joint individually. It is necessary to replace the jointed rock mass with an equivalent continuum body for analysis with an appropriate associated constitutive model. A numerical approach, treating the rock mass with equivalent continuum material properties to obtain the overall response has been advocated in recent years.

Duncan and Goodman (1968) have described a jointed rock mass as an equivalent anisotropic continuum. Singh (1973) has presented continuum characterization methods for jointed rock masses and expressions were presented to estimate the elastic moduli of the equivalent continuum anisotropic rock mass. Kumar (1999) has used the equivalent continuum approach for nonlinear analysis of jointed rock. Sridevi (2000) has carried out experimental and numerical modelling and obtained statistical relationships leading to a fair estimate of jointed rock behavior for modelling highly discontinuous systems.

However, the constitutive models which are discussed above are complicated and need much input data from experimental or field-testing in order to carry out the analysis. So, there is a need for a simpler technique where the equivalent continuum method can capture sufficiently well the behavior of a jointed rock mass using minimal input from the field or from tests and experiments.

For highly jointed rock material Singh (1973) suggested a constitutive law which is governed by five parameters E_1, E_2, ν_1, ν_2 and G_{12} where E_1 and E_2 are modulus of elasticity in the direction of joint and perpendicular to the joint respectively, ν_1 and ν_2 are Poisson's ratio in the direction of joint and perpendicular to the joint respectively and G_{12} is shear modulus and the shear modulus is independent of E and ν due to anisotropy. The anisotropic continuum approach is applicable where size of the structure is far more than the spacing of joints obviously.

Some of the past failures of lined pressure tunnels are given by Singh et al. (1988). As suggested by Goodman (1989) when the rock behaves as a burgers body, the final pressure on the lining can be approximated by assuming it to be loaded as a thick walled cylinder having a uniform pressure equal to the initial stress in the rock and the time to built up the pressure on the lining may require years or tens of years. If the tunnel is not completely stabilized before the concrete lining is laid, some portion of the loosened rock mass may be supported by the concrete lining. The share of the rock load or the support pressure on the lining depends on the rock mass quality. The prime reason for these failures may be attributed to not giving due consideration of support pressure while designing the lining. In the design of concrete lining of the tunnel, it is necessary to consider the share of the rock load and internal pressure to be taken by the lining. Singh et al. (1995a) have suggested ranges of support pressures in both vertical (p_v) and horizontal (p_h) directions. A study on effect of rock mass quality and tunnel size on lined pressure tunnels using FEM has been carried out by Siva Parvathi et al. (2005).

The present study deals with the stress analysis of lined pressure tunnels in jointed rock mass with horizontal, vertical and orthogonal joints for joint spacings, viz., ¼, ½, 1 and 2 times the diameter of the tunnel, to understand the stress variations in the concrete lining under the above said conditions. A comparative study of explicit modelling of joints with equivalent continuum approach for jointed rock has been carried out. To have a better representation of the mechanical behavior of discontinuities of the jointed rock, nonlinear finite element analysis has been carried out.

2. CONTINUUM MODEL OF JOINTED ROCK MASS

Singh (1973) suggested that continuum theories can be used to solve problems of rock mechanics with sufficient accuracy, provided that an average influence of bedding planes and joints can be accounted for instead of considering each discontinuity individually. An anisotropic continuum model based on the average influence of the joints has been derived by Singh (1973) and some of the details are as follows.

Let 1 and 2 denote axes of anisotropy, which are orthogonal to the joint sets 1 and 2 as shown in Fig. 1.

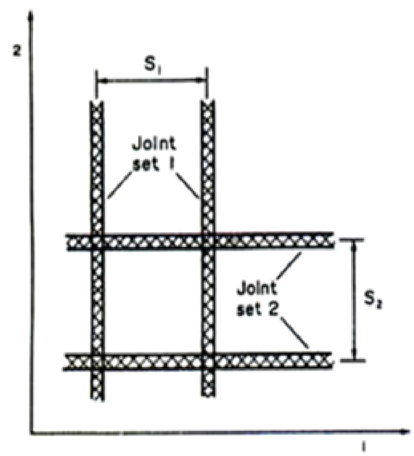

Fig. 1: Geometry of orthogonal joint sets after Singh (1973)

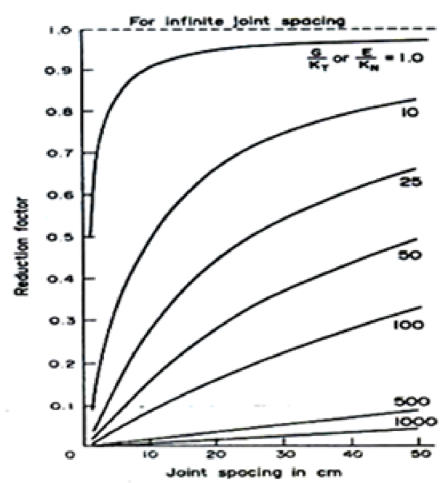

Fig. 2: Modulus reduction factor due to single joint set after Singh (1973)

The modulus reduction factors for simple joint set can be obtained from Fig. 2. The average properties so obtained have been used in the numerical model of this study. From Table 1 it can be observed that rock mass anisotropy affects both the modulus of elasticity and shear modulus. The reductions depend upon the relative magnitudes of normal and shear stiffness of joints.

According to Singh (1985), elastic constants may also be obtained from following correlations for anisotropic rock masses.

$$E_1 = E_r.\ MRF_1;\quad MRF_1 = \frac{1}{1+n_1A_1}; \nu_1 = \nu_r.MRF_1$$

$$E_2 = Er.\ MRF_2;\quad MRF_2 = \frac{1}{1+n_2A_2}; \nu_2 = \nu_r.MRF_2$$

$$G_{12} = \frac{E_2}{10}\ to\ \frac{E_2}{20}(E_2 < E_1)$$

Where n, E, ν and A are joint frequency per meter along axes of anisotropy, Modulus of elasticity, Poisson’s ratio of rock material and Equivalent joint opening perpendicular to the axis. Where the subscripts r refers to rock material and 1 and 2 refers to the joint sets. K_N and K_T are normal and tangential stiffness of joints; MRF_1 and MRF_2 are modulus reduction factors. In unweathered rock mass the value of A for loose bedding planes and continuous joints, discontinuous joints and open cleavage planes are given as 0.60, 0.25 and 0.05 metre respectively.

Table 1: Anisotropic continuum model of jointed rock after Singh (1973)

Discontinuity Description	Reduction factor for Young's Modulus.		Shear Modulus
	$\frac{1}{MRF_1}$	$\frac{1}{MRF_2}$	$\frac{1}{G_{12}}$
Single joint set normal to axis 2.	1	$1+\frac{E_r}{S_2 K_{N_2}}$	$\frac{1}{G_r}+\frac{1}{S_2 K_{T_2}}$
Orthogonal joint sets normal to axes 1 & 2.	$1+\frac{E_r}{S_1 K_{N_1}}$	$1+\frac{E_r}{S_2 K_{N_2}}$	$\frac{1}{G_r}+\frac{1}{S_1 K_{T_1}}+\frac{1}{S_2 K_{T_2}}$
Orthogonal joint sets with staggered cross joints normal to axis 1.	$1+\frac{BN_1 E_r}{S_1 K_{N_1}}$	$1+\frac{E_r}{S_2 K_{N_2}}$	$\frac{1}{G_r}+\frac{BT_1}{S_1 K_{T_1}}+\frac{1}{S_2 K_{T_2}}$

3. MODELLING DETAILS

In the present approach the jointed rock has been analyzed by finite element method using both discrete jointed rock and equivalent continuum approach. The concrete lining and rock mass are modelled using 2-D plane strain isoparametric quadrilateral elements to represent long body and are suitable for structures subjected to plane loading. Concrete–rock interface and joints are modeled with interface elements. The non-linearity introduced due to change in boundary at the joint, is modelled explicitly using 2-D gap and friction element is as shown in Fig. 3 (a). At the joint we have two surfaces, which can have open or closed status. This boundary non-linearity arising at the joint due to the presence of two surfaces is represented using interface elements. In the boundary non-linearity, the material strain behavior remains linear. The nonlinear behavior is from changing of boundary at the joint, i.e., contact between two or more bodies as in this case. In this approach the contact forces are updated incrementally until the system is balanced at the contact. This approach is numerically stable but requires more number of iterations and computation time to obtain the solution. Boundary non-linearity is considered in the present analysis.

The 2D gap and friction element is a 2-node interface element used to model node-to-node contact between two bodies. The element has two degrees of freedom, displacements in X and Y directions at each node consists of a pair of coupled orthogonal springs as represented in Figs. 3 (b) and 3 (c) in the normal and tangential directions. The load transfer between concrete and rock would depend upon the normal stiffness and tangential stiffness of the interface elements. The values of stiffness assumed are 1×10^9 N/m^3 as suggested by Kumar (1988). In the present work NISA

(Numerically Integrated Elements for Systems Analysis) software package has been used to carry out the finite element analysis.

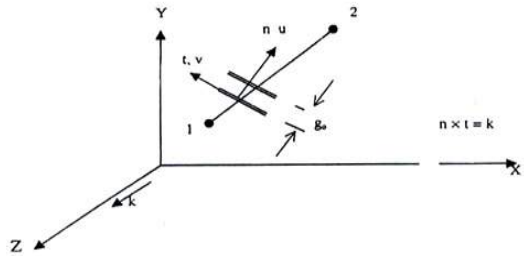

Fig. 3(a): Joint element – 2D Gap/Friction element

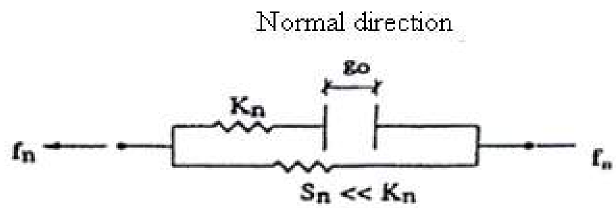

Fig. 3(b): Stiff and soft springs in the normal direction

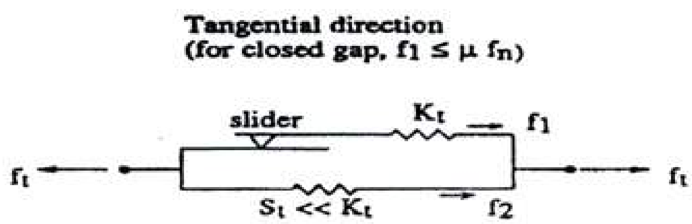

Fig. 3(c): Stiff and soft springs in the tangential direction

The validity of the anisotropic continuum model has been examined by comparing the displacement field and the stress field predicted for the following problem, using both the continuum and the discrete-joint models. Finite element analysis has been carried out for strip load acting on a semi-infinite rock mass containing joint set no.2 (i.e. horizontal joints) only. The details of the material properties used for continuum model and the joint properties for discrete-joint model are taken from Singh (1973) which are given below,

3.1 Properties of Joint Set

Normal stiffness (K_n) = 1.505×10^6 N/m^3, Shear stiffness (K_t) = 1.505×10^6 N/m^3, Spacing of joints (S_2) = 0.254m, Elastic modulus of rock (E) = 34.45×10^9 N/m^2, Poisson's ratio ν = 0.2

3.2 Continuum Rock Properties

$E_1 = 34.45\times10^9$ N/m^2, $E_2 = 3.445\times10^9$ N/m^2, $\nu_1 = 0.2$, $\nu_2 = 0.02$,

$G_{12} = 34.45\times10^9$ N/m^2

The schematic representation of horizontal jointed rock mass with equal joint spacing is shown in Fig. 4, which is considered to validate the numerical model. Similar mesh was adopted in both joint and the continuum models to minimize the error due to the finite element idealization. However, in the continuum model, the influence of joints was eliminated by assigning them a very high stiffness (2.71×10^{15} N/m^3). The boundary conditions at sides of the rock mass are shear free, whereas the bottom was assumed to be clamped.

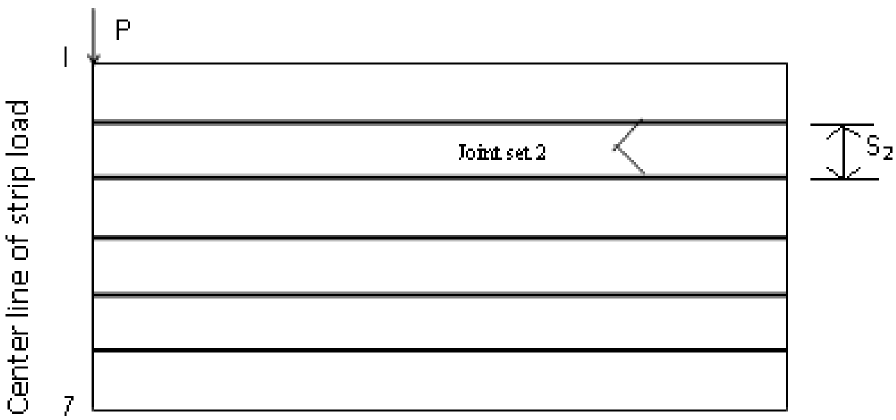

Fig. 4: Horizontal jointed rock after Singh (1973)

Figs. 5 and 6 compare the vertical displacement and hoop stress variation for both the continuum model and the discrete joint models respectively. It is observed that, the results are in satisfactory agreement and provide a critical test for the validity of the continuum model.

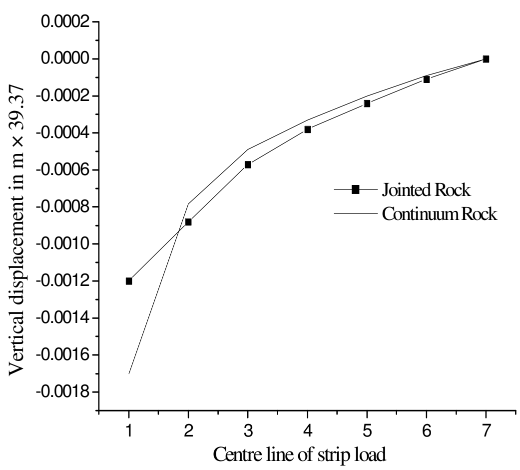

Fig. 5: Comparison of vertical displacement for jointed rock and equivalent continuum rock

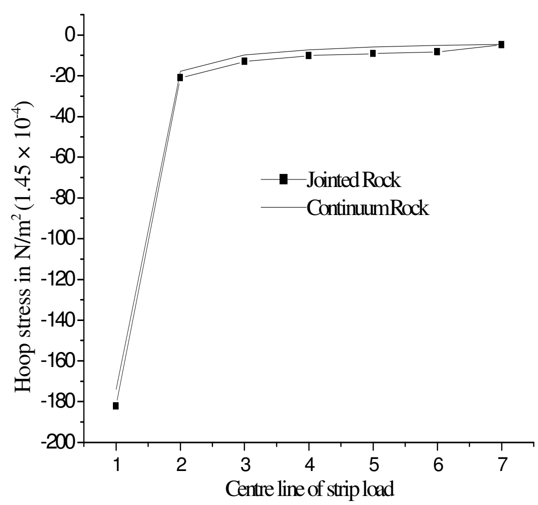

Fig. 6: Comparison of hoop stress variation for jointed rock and equivalent continuum rock

4. DETAILS OF PRESENT STUDY

The present study has been carried out considering the plain concrete tunnel lining for the head race tunnel of Tehri Dam project. The tunnel of this project is circular in cross section with an opening of 8 m diameter, concrete lining of 0.6 m thicknesses and is subjected to an internal pressure (p) of 1.2×10^6 N/m^2. To study the effect of joint spacing on the stresses in the concrete lining, rock mass and the interaction between the two, some typical cases of horizontal jointed rock, vertical jointed rock and orthogonal jointed rock with different joint spacing are considered. The domain of the problem is as shown in Figs. 7 (a), (b) and (c). Same domain and mesh have been considered for equivalent continuum model. Since the problem is doubly symmetric, only one quadrant of the system is discretized. Singh et al. (1995) have suggested ranges of support pressures in both vertical (p_v) and horizontal (p_h) directions. To study the effect of jointed rock on the stress distribution in the concrete lining, category 4 (moderately blocky, seamy and very jointed case in non-squeezing rock condition) from modified Terzaghi`s rock mass classification is considered. Which recommends vertical support pressure as 0.1 MPa and the horizontal support pressure as 0.2 p_v.

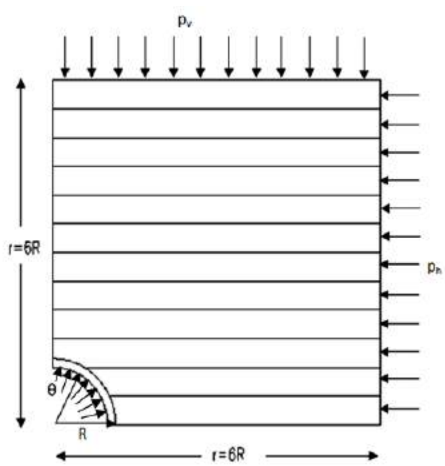

Fig. 7(a): Details of the lined tunnel for horizontal jointed rock with 2 m spacing

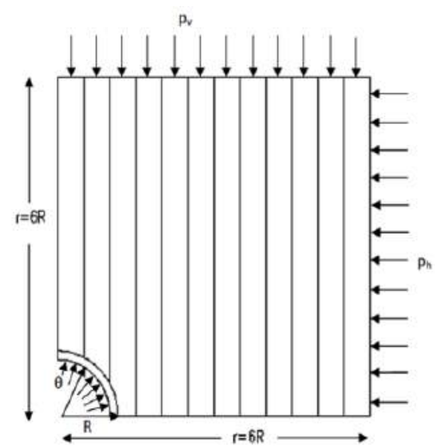

Fig. 7(b): Details of the lined tunnel for vertical jointed rock with 2 m spacing

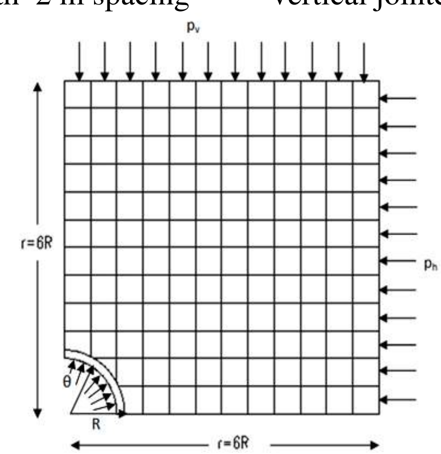

Fig. 7(c): Details of the lined tunnel for orthogonal jointed rock with 2 m spacing

4.1 Details of Material Properties

The details of the material properties for jointed rock are given below,

Intact Rock: $E_r = 8\times10^8$ N/m^{2,} $\nu_r = 0.2$, $G_r = 3333.33\times10^5$ N/m^2
Concrete: $E_c = 2\times10^{10}$ N/m^{2,} $\nu_c = 0.2$, $G_c = 833.33\times10^7$ N/m^2

4.1.1 Joint Properties

$K_{N1} = K_{N2} = 0.1\ E_r$, $K_{T1} = K_{T2} = 0.01\ G_r$, (as suggested by Singh, 1973)

Joint spacings: $S_1 = S_2 = ¼, ½, 1$ and 2D i.e. 2, 4, 8 and 16m

(i) Equivalent continuum rock properties for horizontal jointed rock (Table 1)

For Joint Spacing 2m; $E_1 = 8\times10^8$ N/m^2, $E_2 = 1.33\times10^8$ N/m^2, $\nu_1 = 0.2$, $\nu_2 = 0.033$, $G_{12} = 6.534\times10^6$ N/m^2
For Joint Spacing 4m; $E_1 = 8\times10^8$ N/m^2, $E_2 = 2.286\times10^8$ N/m^2, $\nu_1 = 0.2$, $\nu_2 = 0.057$, $G_{12} = 12.82\times10^5$ N/m^2
For Joint Spacing 8m; $E_1 = 8\times10^8$ N/m^2, $E_2 = 3.55\times10^8$ N/m^2, $\nu_1 = 0.2$, $\nu_2 = 0.089$, $G_{12} = 24.69\times10^5$ N/m^2
For Joint Spacing 16m; $E_1 = 8\times10^8$ N/m^2, $E_2 = 4.923\times10^8$ N/m^2, $\nu_1 = 0.2$, $\nu_2 = 0.123$, $G_{12} = 45.98\times10^6$ N/m^2

(ii) Equivalent continuum rock properties for vertical jointed rock (Table 1)

For Joint Spacing 2m; $E_1 = 1.33\times10^8$ N/m^2, $E_2 = 8\times10^8$ N/m^2, $\nu_1 = 0.033$, $\nu_2 = 0.2$, $G_{12} = 6.534\times10^6$ N/m^2
For Joint Spacing 4m; $E_1 = 2.286\times10^8$ N/m^2, $E_2 = 8\times10^8$ N/m^2, $\nu_1 = 0.057$, $\nu_2 = 0.2$, $G_{12} = 12.82\times10^5$ N/m^2
For Joint Spacing 8m; $E_1 = 3.55\times10^8$ N/m^2, $E_2 = 8\times10^8$ N/m^2, $\nu_1 = 0.089$, $\nu_2 = 0.2$, $G_{12} = 24.69\times10^5$ N/m^2
For Joint Spacing 16m; $E_1 = 4.923\times10^8$ N/m^2, $E_2 = 8\times10^8$ N/m^2, $\nu_1 = 0.123$, $\nu_2 = 0.2$, $G_{12} = 45.98\times10^6$ N/m^2

(iii) Equivalent continuum rock properties for orthogonal jointed rock (Table 1)

For Joint Spacing 2m; $E_1 = 1.33\times10^8$ N/m^2, $E_2 = 1.33\times10^8$ N/m^2, $\nu_1 = 0.033$, $\nu_2 = 0.033$, $G_{12} = 3.297\times10^6$ N/m^2
For Joint Spacing 4m; $E_1 = 2.286\times10^8$ N/m^2, $E_2 = 2.286\times10^8$ N/m^2, $\nu_1 = 0.057$, $\nu_2 = 0.057$, $G_{12} = 65.36\times10^5$ N/m^2
For Joint Spacing 8m; $E_1 = 3.55\times10^8$ N/m^2, $E_2 = 3.55\times10^8$ N/m^2, $\nu_1 = 0.089$, $\nu_2 = 0.089$, $G_{12} = 128.2\times10^5$ N/m^2
For Joint Spacing 16m; $E_1 = 4.923\times10^8$ N/m^2, $E_2 = 4.923\times10^8$ N/m^2, $\nu_1 = 0.123$, $\nu_2 = 0.123$, $G_{12} = 0.246\times10^8$ N/m^2

4.2 Discretization of the Domain of Orthogonal Jointed Rock

In the present work, the materials of the medium rock mass and concrete are modeled using 2-D plane strain 8 noded isoparametric quadrilateral elements to represent long body and are suitable for structures subjected to in-plane loading. The concrete-rock interface and joints of the medium are modeled using 2 noded interface elements with unit thickness. The region of the domain is considered up to 6 times the radius of the opening in both horizontal and vertical directions. Same domain and mesh are considered for equivalent continuum model. Since the problem is doubly symmetric, only one quadrant of the system is discretized and analyzed. The discretization and boundary conditions of the tunnel are presented in Fig. 8. The horizontal axis corresponds to $\theta = 0^0$ represents side wall of the tunnel while the vertical axis $\theta = 90^0$ represents crown.

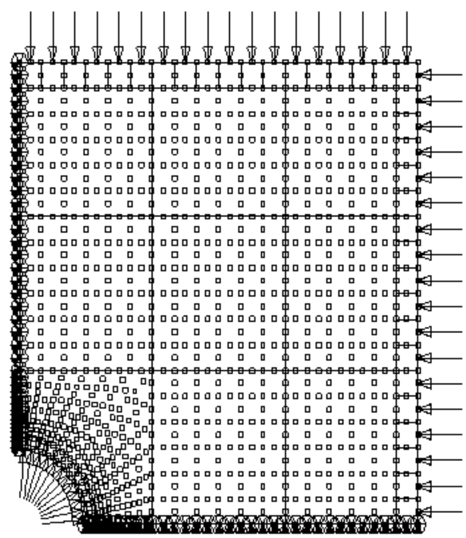

Fig. 8: Discretization for lined tunnel in orthogonal jointed rock mass with 8 m joint spacing

5. RESULTS AND DISCUSSIONS

Hoop stress variations obtained from the stress analysis are presented along two important radial lines, i.e., sidewall and crown which are subjected to maximum compressive and tensile stresses respectively around an opening. Shear stress distribution is plotted along concrete rock interface. Maximum radial displacements along the side wall and crown are presented in tabular forms.

5.1 Effect of Joint Spacing on Stress Variation in Concrete Lining for Rock with Horizontal Joints

The non-dimensional hoop stress (σ_θ/p) variation along r/R, in which r the radial distance from inner surface of the lining and R is the inner radius of the lining along two important radial lines i.e. along side wall and crown are presented in Fig. 9 and Fig.10, respectively. The figures represent the hoop stress variation with radial distance for different joint spacings of horizontal jointed rock and also for an equivalent continuum rock. It is observed that maximum stresses are concentrated in the concrete lining and they are tensile. The maximum hoop stresses in the concrete lining both at the side wall and the crown decrease with the increase in the joint spacing. The equivalent continuum approach predicted increased non uniform variation of hoop stress in concrete lining at both the side wall and the crown when compared to that with discrete jointed rock approach. However, the hoop stress in the concrete lining is observed to increase in the radial direction at the side wall and decrease in radial direction at the crown. The continuum approach resulted in larger maximum hoop stresses in the concrete than those obtained from the discrete joints approach. A good agreement of hoop stress variation is observed in rock for discrete joint model and equivalent continuum model.

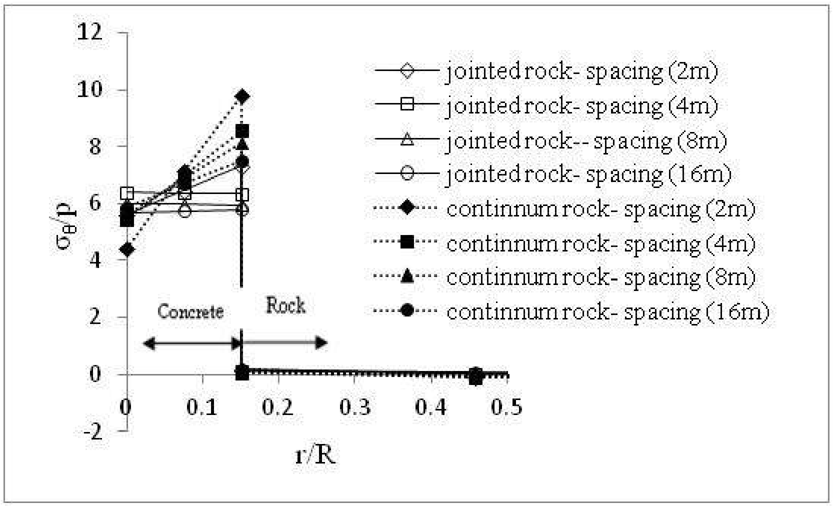

Fig. 9: σ_θ/p variation along sidewall for different joint spacings for horizontal jointed rock

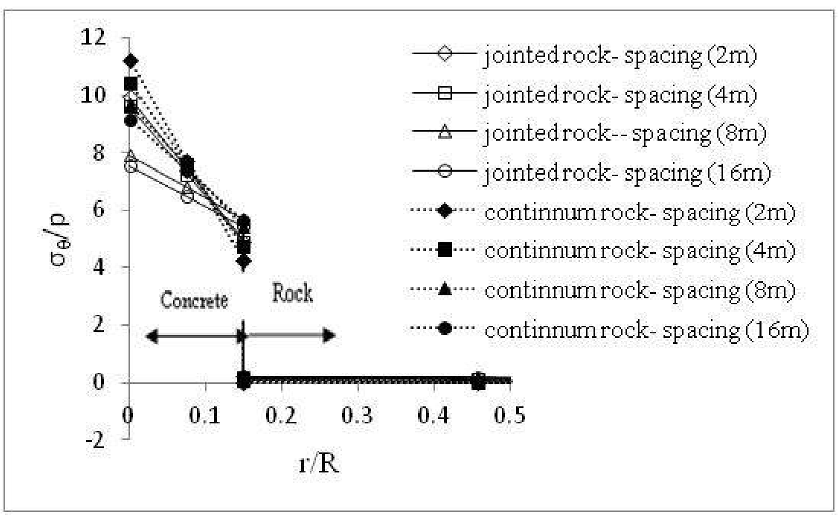

Fig. 10: σ_θ/p variation along crown for different joint spacings for horizontal jointed rock

The variation of non-dimensional shear stress ($\tau_{r\theta}/p$) along concrete rock interface is plotted for jointed rock and to an equivalent continuum rock and is as shown in Fig. 11.

In the case of heavily jointed rock more discontinuities are observed whereas the equivalent continuum approach predicted smoother variation of shear stress. The maximum shear stress is observed to decrease with increased joint spacing in both the approaches and the continuum approach predicted higher values of maximum shear stress when compared to those with jointed rock approach.

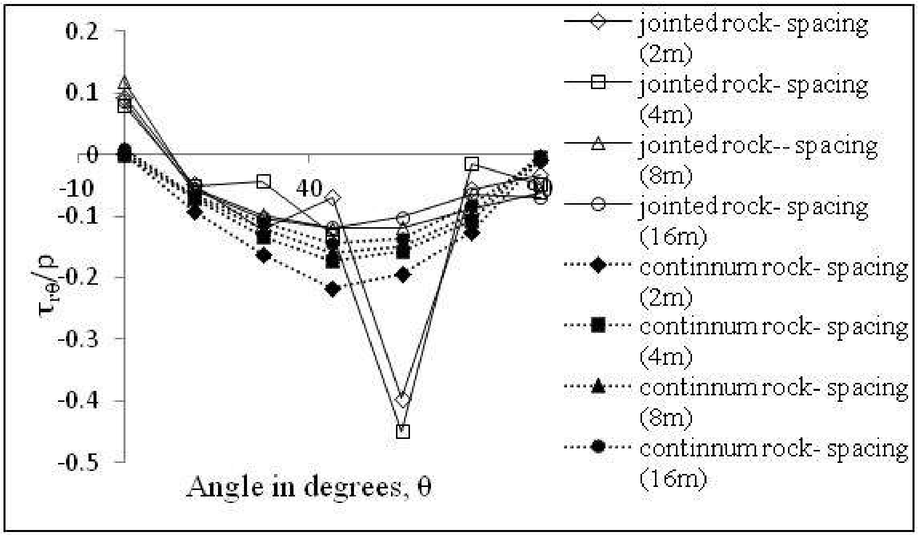

Fig. 11: $\tau_{r\theta}$ /p variation along concrete rock interface for different joint spacings for rock with horizontal joints

Maximum radial displacements at side wall and crown are presented in Table 2 for different joint spacing's of horizontal jointed rock and equivalent continuum rock.

Table 2: Maximum radial displacements in concrete lining for different joint spacing's of rock with horizontal joints

Joint spacing →	2m		4m		8m		16m	
Radial displacement (mm) ↓	Jointed Rock	Continuum Rock	Jointed Rock	Continuum Rock	Jointed Rock	Continuum Rock	Jointed Rock	Continuum Rock
Side wall	-0.170	-0.161	0.436	-0.784	0.573	-0.148	0.667	0.238
Crown	3.130	4.840	2.480	4.010	2.220	3.310	1.980	2.830

5.2 Effect of Joint Spacing on Stress Variation in the Concrete Lining for Rock with Vertical Joints

The Figs. 12 and 13 represent the hoop stress variation with radial distance for different joint spacings of vertical jointed rock and also for an equivalent continuum rock along sidewall and crown respectively. Similar to that observed in horizontal jointed rock case, the maximum stresses are concentrated in the concrete lining and they are tensile. As the joint spacing is increased, the hoop stresses in the concrete lining are observed to decrease at the side wall and also at the crown. The equivalent continuum approach predicted increased non uniform variation of hoop stress in concrete lining at both the side wall and the crown when compared to that with discrete jointed rock approach. However, the hoop stress in the concrete lining is observed to increase in the radial direction at the side wall and decrease in radial direction at the crown. The maximum hoop stress which is an important design parameter is predicted to be more in the continuum rock approach when compared to that in jointed rock approach in concrete lining.

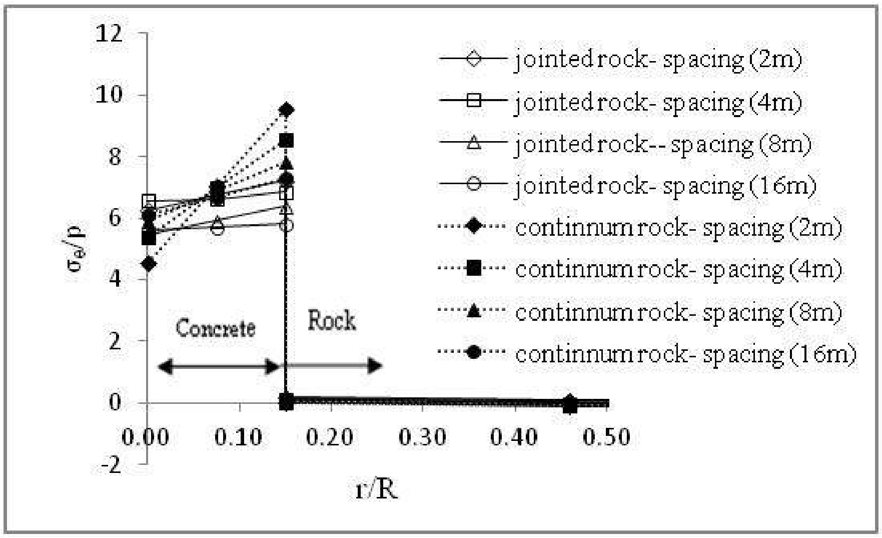

Fig. 12: σ_θ/p variation along sidewall for different joint spacings for rock with vertical joints

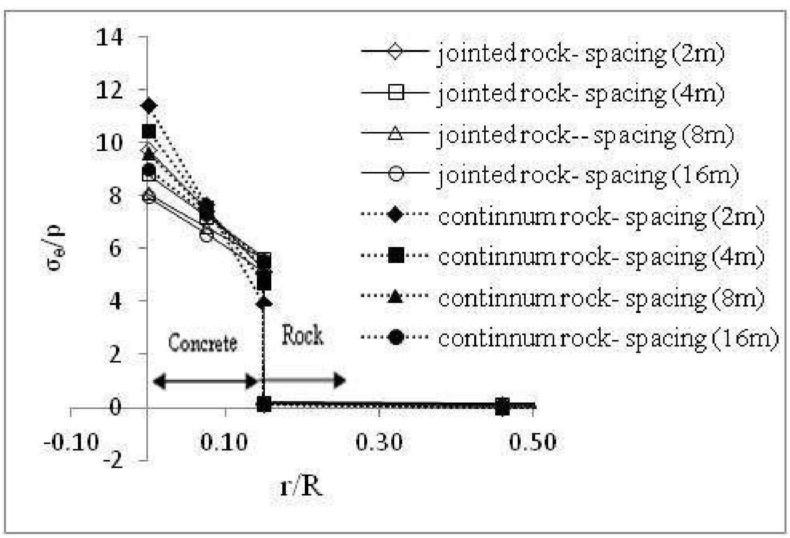

Fig. 13: σ_θ/p variation along crown for different joint spacings for rock with vertical joints

The variation of non-dimensional shear stress ($\tau_{r\theta}/p$) along concrete rock interface has been plotted for jointed rock and for an equivalent continuum rock and is as shown in Fig. 14. In the case of heavily jointed rock more discontinuities are observed whereas the equivalent continuum approach predicted smoother variation of shear stress. The maximum shear stress is observed to decrease with increased joint spacing and the continuum approach predicted higher values of maximum shear stress when compared to jointed rock approach.

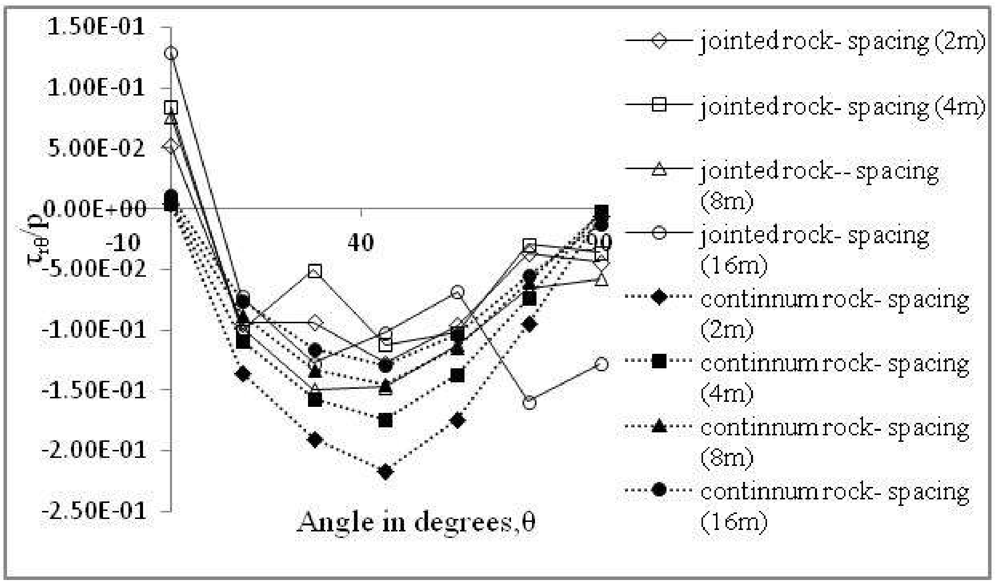

Fig. 14: $\tau_{r\theta}/p$ variation along concrete rock interface for different joint spacing's for rock with vertical joints

Non-dimensional shear stress, $\tau_{r\theta}/p$ variation along concrete rock interface has been plotted for jointed rock and to an equivalent continuum rock and is as shown in Fig. 14. In the case of heavily jointed rock, more fluctuations are observed. As the joint spacing is increases the shear stress is observed to decrease as in the case of horizontal joints.

Maximum radial displacement observed at side wall and crown is presented in Table 3 for vertical jointed rock and equivalent continuum rock with different joint spacing. The maximum displacement is observed at sidewall for jointed rock whereas for continuum rock it is observed at crown.

5.3 Effect of Joint Spacing on Stress Variation in Concrete Lining for Rock with Orthogonal Joints

The stresses are concentrated in the concrete lining and are found to be tensile both at the sidewall and crown are as shown in Figs. 15 and 16. As the joint spacing is increased, the maximum hoop stresses in the concrete lining are observed to decrease both at sidewall and crown. The hoop stress in the concrete lining is observed to increase in the radial direction at the sidewall whereas at the crown it is observed to decrease. The maximum stresses in concrete lining obtained by equivalent continuum rock approach are observed to be more than those obtained by discrete jointed rock approach for all the joint spacing's which are considered in the present study.

Table 3: Maximum radial displacements in the concrete lining for different joint spacing's of rock with vertical joints

Joint spacing →	2m		4m		8m		16m	
Radial displacement (mm) ↓	Jointed Rock	Continuum Rock	Jointed Rock	Continuum Rock	Jointed Rock	Continuum Rock	Jointed Rock	Continuum Rock
Side wall	3.00	-0.1.56	2.47	-0.676	2.26	-0.04	1.94	-0.33
Crown	-0.044	4.68	0.438	3.77	0.55	3.10	0.684	2.66

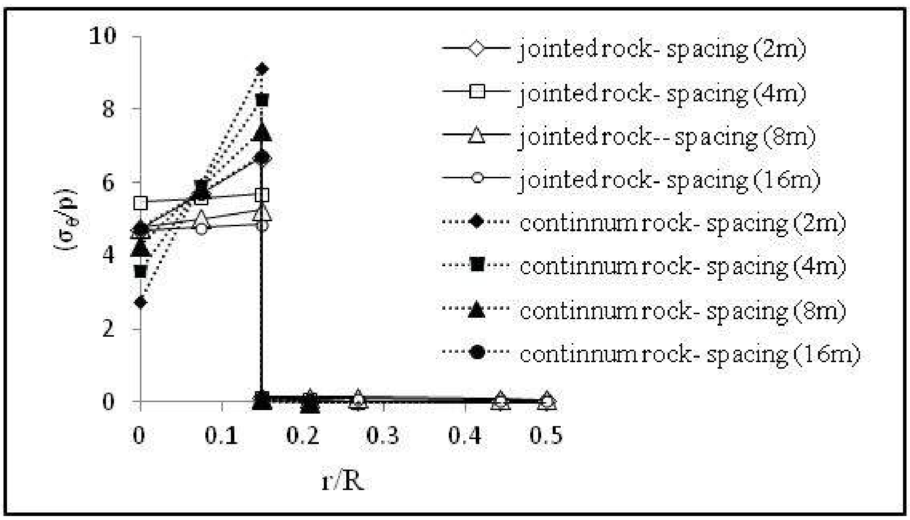

Fig. 15: σ_θ/p variation along sidewall for different joint spacing for rock with orthogonal joints

Non-dimensional $\tau_{r\theta}/p$ variation along concrete rock interface has been plotted for jointed rock and to an equivalent continuum rock and is as shown in Fig. 17. In the case of heavily jointed rock more fluctuations are observed. As the joint spacing is increased the shear stresses are observed to decrease and smooth variation is observed.

Radial displacement observed at side wall and crown is presented in Table 4 for orthogonal jointed rock and equivalent continuum rock with different joint spacing's. In all the cases maximum displacement is observed at crown.

The maximum non dimensional hoop stresses for different joint spacing's i.e., 2m, 4m, 8m and 16m for horizontal, vertical and orthogonal joints obtained by both discrete rock approach and continuum approach are given in Table 5. The maximum hoop stress is observed to decrease with increasing the spacing in both the approaches for all the joint orientations considered in the study. However, the continuum approach is observed to predict larger values of maximum hoop stress in concrete lining than the discrete joint approach, whereas the difference in the stress variation in the rock obtained by both approaches is found to be insignificant.

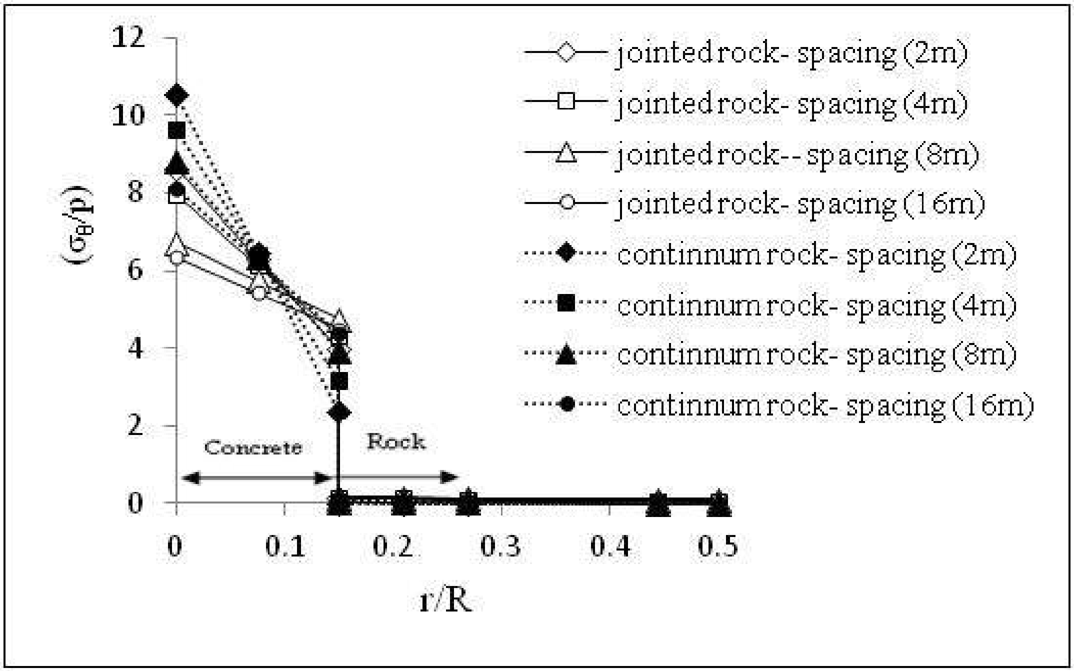

Fig. 16: σ_θ/p variation along crown for different joint spacings for rock with orthogonal joints

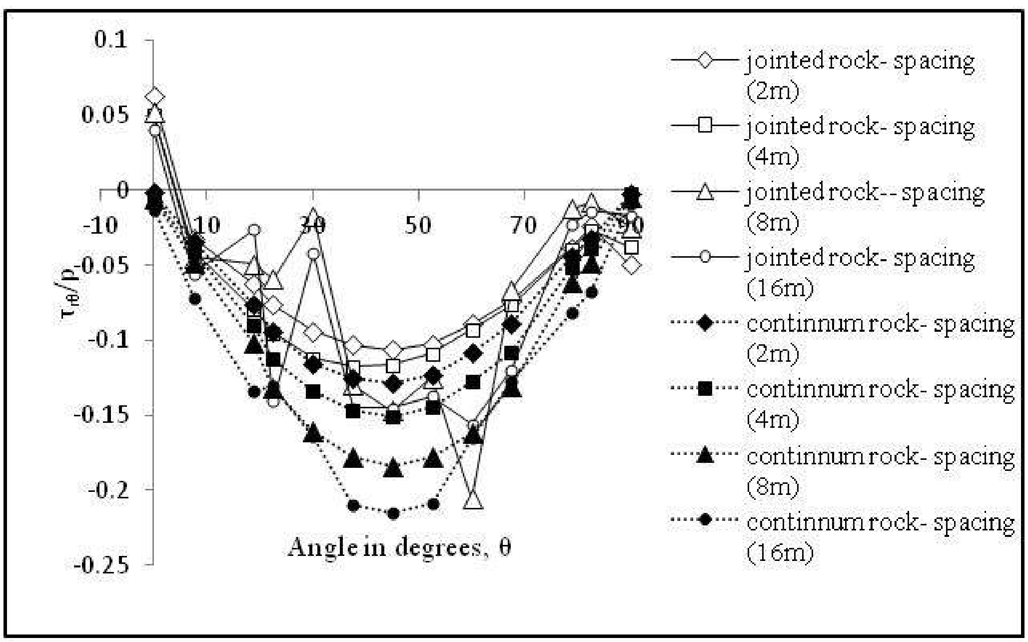

Fig. 17: $\tau_{r\theta}$/p variation along concrete rock interface for different joint spacings for rock with orthogonal joints

Table 4: Maximum radial displacements in the concrete lining for different joint spacing's of rock with orthogonal joints

Joint spacing →	2m		4m		8m		16m	
Radial displacement (mm) ↓	Jointed Rock	Continuum Rock	Jointed Rock	Continuum Rock	Jointed Rock	Continuum Rock	Jointed Rock	Continuum Rock
Side wall	0.708	-0.273	0.669	-0.175	-0.205	-0.830	-0.757	-0.156
Crown	3.780	5.900	3.070	4.940	2.150	3.990	1.940	3.260

Table 5: Maximum hoop stress/p ($\sigma_{\theta\ max}/p$) in concrete lining for various jointed rock condition

Joint Spacing	Location	Horizontal jointed rock		Vertical jointed rock		Orthogonal jointed rock	
		Discrete rock approach	Continuum approach	Discrete rock approach	Continuum approach	Discrete rock approach	Continuum approach
2m	Side wall	7.30	9.78	7.21	9.54	6.69	9.17
	Crown	9.93	11.20	9.77	11.46	8.67	10.58
4m	Side wall	6.41	8.54	6.85	8.57	5.69	8.24
	Crown	9.61	10.42	8.81	10.46	7.96	9.67
6m	Side wall	6.00	8.16	6.37	7.84	5.24	7.41
	Crown	7.90	9.69	8.10	9.65	6.73	8.83
8m	Side wall	5.70	7.51	5.81	7.29	4.86	6.73
	Crown	7.53	9.13	7.97	9.04	6.36	8.13

6. SUMMARY AND CONCLUSIONS

In the present study the analysis has been carried out for lined pressure tunnels, for various jointed rock mass conditions, via; horizontal jointed rock, vertical jointed rock and orthogonal jointed rock for different joint spacings. The results are presented along two significant radial lines, viz., sidewall and crown, which are subjected to maximum stresses around an opening. The present study attempts to understand the effect of joint spacing and its orientation on the stress variation in the concrete lining. Further, an attempt is also made to compare the stress variations obtained by using discrete jointed rock approach and continuum approach in concrete lining and rock. Based on the results the following conclusions are drawn.

- The maximum hoop stress in the concrete lining is observed to decrease with the increase in the joint spacing for horizontal, vertical and orthogonal joint orientations.
- The continuum rock approach resulted in slightly larger values of maximum hoop stresses in the concrete lining when compared to the discrete element approach.
- In rock mass a good agreement is observed between jointed rock approach and equivalent continuum rock approach.

- The shear stresses along the concrete rock interface is observed to decrease with increased joint spacing and the shear stress variation obtained using continuum approach is observed not to have any discontinuities.

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