Journal of Rock Mechanics & Tunnelling Technology (JRMTT)
21 (1) 2015 pp 7-20

Available online at www.isrmtt.com

Influence of Support Pressure on Stress Variation in Cracked Concrete Lined Pressure Tunnels

I. S. Parvathi, T. V. Praveen*

Dept. of Civil Engineering, College of Engineering
Andhra University, Visakhapatnam- 530003, India
**Email: isparvathi@gmail.com*

ABSTRACT

In the design of hydro-electric projects, the trend is towards the using of turbines of ever-increasing capacity necessitating larger pressure conduits and penstocks. These pressure conduits and penstocks work in inhomogeneous rock mass condition and under high internal hydrostatic pressure. In tunnel lining design, it is necessary to know the share of the rock load and internal pressure, on the lining which depends on the quality of the rock mass. The rock mass may be self-supporting or may require rock bolting or steel ribs to support the rock while driving the tunnel. When the tunnel is under internal pressure due to water, the resulting stresses get superposed on the stresses for tunnel in empty condition. With large internal water pressure, the construction joints which are generally provided are likely to open up and the number of cracks in the lining may also increase.

In the present work, an attempt has been made to study the influence of support pressure and number of cracks on stress distribution in concrete lining using finite element method. To study the influence of support pressure on stress distribution in the concrete lining, two categories of rocks, viz., hard and intact rock (Category-I) and completely crushed but chemically intact rock (Category-VI) in non-squeezing rock condition are considered. For the study, a predetermined distribution of cracks is assumed in the tunnel lining and the resulting stress distributions in the concrete and rock mass for tunnel under water-pressure and empty condition have been obtained. Cracks are modelled with nodal discontinuity and concrete-rock interface are modelled with two noded interface elements. The results are presented for hoop stress, shear stress and maximum radial displacement.

Keywords: Pressure tunnels; Concrete lining; Cracked concrete; Support pressure; Stress analysis; Rock mass quality; Finite element method

1. INTRODUCTION

Tunnels excavated in rock mass may occasionally be self-supporting; often some form of initial ground support is required for stability. This initial support usually consists of steel ribs, shotcrete, rock reinforcement, or a combination of these. Depending on the quality of rock mass and the type of initial support, installation of the final support in the form of rock reinforcement, pressed concrete lining or shotcrete may be necessary for the permanent stability.

Singh et al. (1988) studied some of the failed lined pressure tunnels, viz., Sydney water supply tunnel, Kotmali power tunnel and Kopli hydel tunnel. They concluded that the failures of these tunnels were primarily due to inadequate rock cover, which failed to counteract the internal pressure developed due to water flow inside the tunnel and the differential pressure led to development of cracks along the construction joints significantly at crown and side walls of the tunnels. Goodman (1989) suggested when the rock mass around the tunnel periphery behaves as a Burger's 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 mass and the time to build 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 primarily 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, it is necessary to consider the differential loading on the lining due to counteraction of support pressure with internal water pressure. Singh et al. (1995) have compared the values of support pressures observed in tunnels and caverns with estimated values by Terzaghi's rock load concept. They found that the support pressure in rock tunnels and caverns does not increase directly with excavation size as assumed by Terzaghi (1946) and others, mainly because of dilatant behaviour of rock masses, joint roughness and prevention of loosening of rock mass by improved and modern tunnelling technology. They have subsequently recommended modified ranges of support pressures in both vertical (p_v) and horizontal (p_h) directions. Singh et al. (1997) have given approaches for prediction of support pressure under squeezing and non-squeezing ground conditions. Non-squeezing ground condition is common in the majority of tunnelling projects. Squeezing ground conditions, on the other hand, have generally been encountered during tunnelling through the lower Himalayas, where the rock masses are weak, highly jointed, faulted, folded, tectonically disturbed and subjected to high in situ stresses. Parvathi et al. (2013) studied the influence of spacing and orientation of rock-joints on lined pressure tunnels considering discrete rock and equivalent continuum approaches. In the approaches, the support pressures in both horizontal and vertical directions are considered depending on the rock mass condition, as suggested by Singh et al. (1995). The results of the both approaches were in the good agreement. However, the values of maximum hoop stresses obtained by continuum rock approach were observed to be marginally larger as compared to the discrete element approach.

A study on effect of rock mass quality and tunnel size on lined pressure tunnels using FEM for two different rock mass conditions has been carried out by Parvathi et al. (2005). It was observed that the size of the tunnel does not affect normalized stresses in the concrete lining under non-squeezing ground conditions. In the present work, to study the effect of rock mass condition, two categories of rocks, viz., hard and intact rock (Category-I of Terzaghi's rock classes) and completely crushed but chemically intact rock (Category-VI of Terzaghi's rock classes) in non-squeezing rock condition have been considered. For both rock mass categories, the value of vertical and horizontal support pressures suggested by Singh et al. (1995) have been considered. Stress analysis has been extended for cracked concrete lining under these two categories of rock mass conditions for tunnel under pressure and empty condition. Discontinuities usually appear in the concrete lining under the action of internal water pressure due to cracking or separation along the construction joints or both as shown in

Fig.1. The effect of the discontinuities on the support pressure, displacement and stress distributions has been analyzed in the present study. A pattern of radial cracks at certain angular intervals in the concrete lining is assumed to understand the effect of number of cracks on the stress distribution.

Analysis considering radial cracks and segments of rock may conveniently be carried out with finite element method; such an analysis has been carried out considering only internal water pressure by Singh et al. (1988).

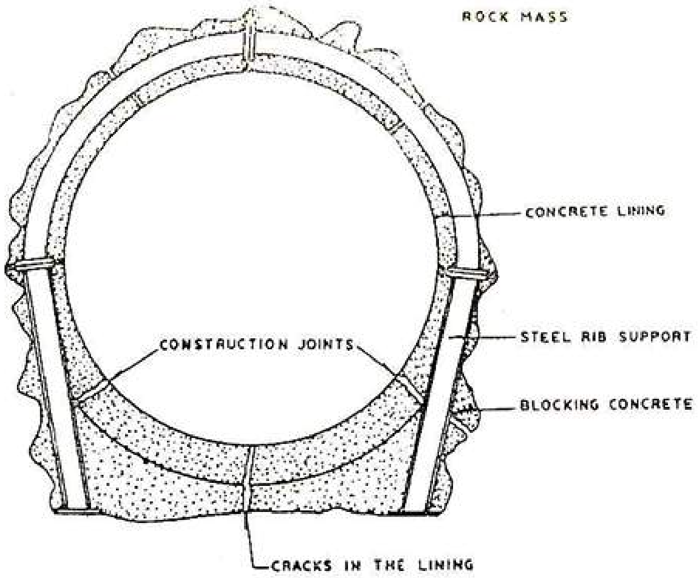

Fig. 1 - Development of cracks and opening of construction joints in a tunnel lining (after Singh et al., 1988)

The present work deals with the study of influence of rock mass condition on tunnel lining with internal water pressure to simulate the field condition. The main objective of the study was to analyse the cracked lined tunnels under water pressure and empty conditions. In addition, an attempt has also been made to understand the effect of number of cracks on stress distribution. As the minimum number of cracks is 8, being equal to the usual construction joints, in the present study, 5 cases i.e. one with un-cracked concrete lining, and with 8, 12, 24 and 36 radial cracks in the concrete lining have been considered for stress analysis. Several methods are available for the analysis of pressure tunnel lining with simple physical and geological features of the rock mass. For typical physical and geological features of the rock mass, the numerical methods are more suitable. The finite element technique can be successfully employed for the analysis of the tunnel lining. The present study uses NISA (Numerically Integrated elements for Systems Analysis) 2007 code based on finite element method for the analysis.

2. ASSUMPTIONS

The following assumptions are made in the present study:

- There is no relative movement between the rock and tunnel lining.
- As the tunnel is very long, a plane strain condition is assumed.
- The water pressure inside the tunnel is uniform in all radial directions.
- Frictional forces due to roughness of lining are neglected.

- The cracks are radial and extend through the lining.
- The rock surrounding the tunnel lining and material of tunnel lining are homogeneous, elastic and isotropic.
- There is no gap between the tunnel lining and excavated rock mass profile.
- Seepage through the tunnel lining and the rock mass is neglected.
- Same amount of internal pressure is taken on cracked surfaces.
- Cracks are symmetrically distributed along the circumference of the tunnel.
- Effect of temperature difference between the concrete lining and the rock mass is not considered.

3. VALIDATION OF THE MODELLING PROCEDURE

Singh et al. (1988) presented details of hoop stress and shear stress variations for different crack patterns, i.e., 8, 12 and 18 number of cracks for the ratio of elastic modulus of rock mass to that of concrete equal to 0.2. The discretization used by them has been shown in Fig. 2. The present modeling procedure has been validated considering the same data and discretization as used by Singh et al. (1988) and the results obtained have been compared and are shown in Fig. 3.

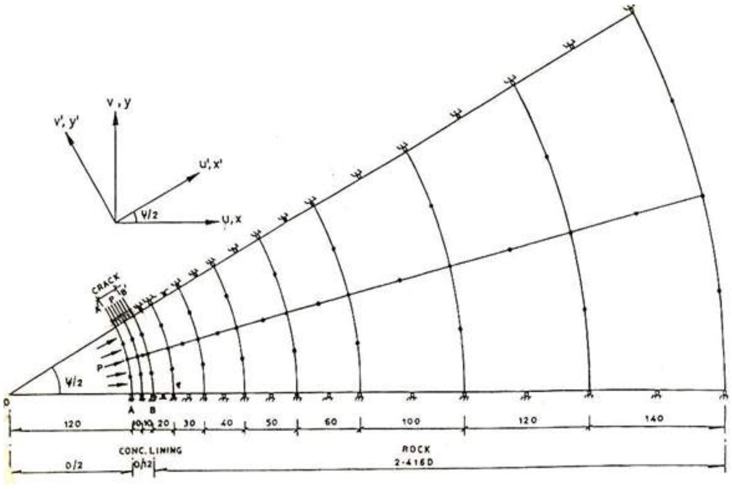

Fig. 2 - Finite element mesh (after Singh et al., 1988)

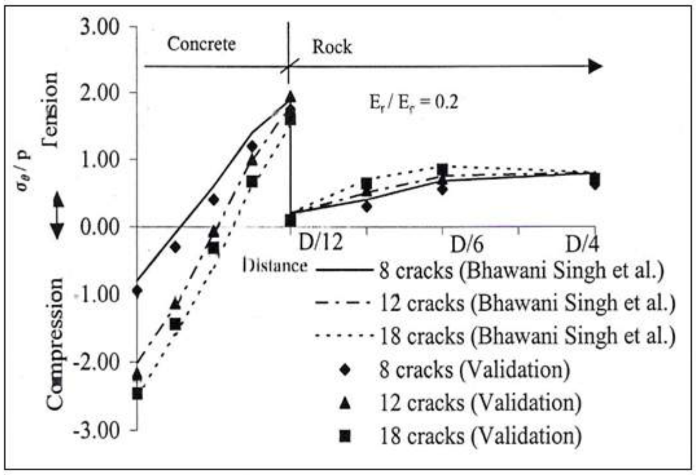

Fig. 3 - Validation of results for hoop stress variation along the radial distance

4. METHODOLOGY

As suggested by Singh et al. (1995), in the analysis, the recommended support pressure is zero in both vertical and horizontal directions for rock mass category-I (hard and intact), whereas for rock mass category-VI (completely crushed but chemically intact), the upper limits of the range of the support pressures have been considered. For the analysis of the concrete lining of hard and intact rock mass case, as the support pressure is zero, only internal water pressure has been considered. In the case of category-VI, the analysis has been carried out for two cases- (i) tunnel under the influence of internal water pressure and support pressures (vertical and horizontal), and (ii) tunnel in empty condition.

The materials of the medium, rock mass and concrete are modelled using 2-D plane strain 8-noded isoperimetric quadrilateral elements to represent long body and are suitable for structures subjected to in-plane loading. A unit thickness of the element is assumed. The concrete-rock interface is modelled 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. Cracks have been analysed with the nodal discontinuity, exposed to the internal water pressure, *p* on cracked surfaces. In cracked concrete lining, the cracks are assumed as radial cracks, which are closed at the outer surface of the concrete lining. The load transfer between concrete and rock would depend upon the normal stiffness and tangential stiffness of the interface elements. The values of stiffness have been taken as 1×10^9 N/m^2 (Kumar and Singh, 1988). The discretization and boundary conditions of the tunnel are presented in Fig. 4.

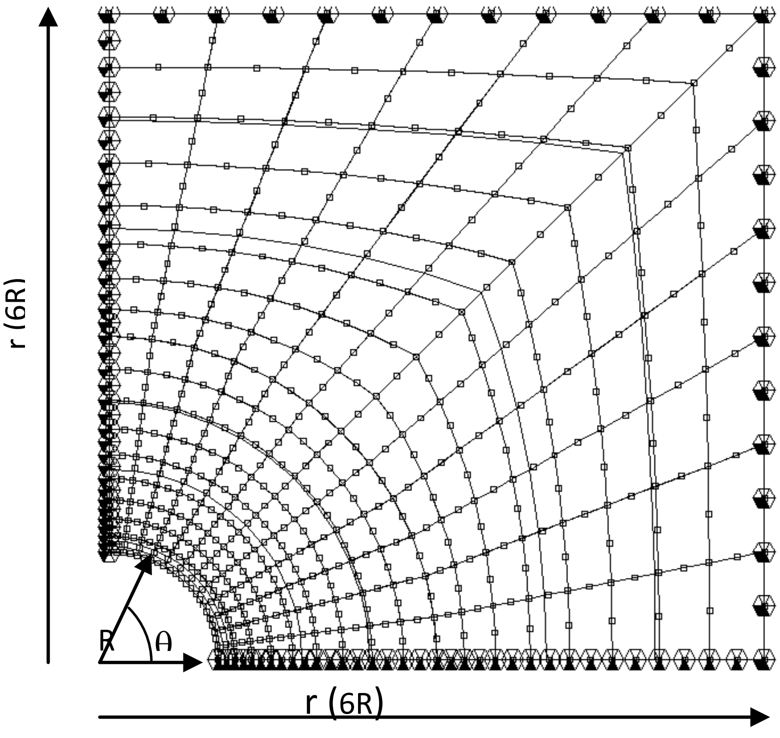

Fig. 4 - Finite element discretization of a lined tunnel

5. DETAILS OF PRESENT STUDY

The present study deals with the stress analysis of the head race tunnel of Tehri dam project located in Uttarakhand state. The tunnel is circular in cross-section with finished diameter of

8 m lined with 0.6 m thick concrete. The tunnel is subjected to an internal pressure *(p)* of 1.2 x 10^6 N/m^2. The material properties and other necessary information of Tehri head race tunnel have been taken from Singh and Goel (2002). The analysis has been carried out for un-cracked, 8 cracks (at intervals of 45^0), 12 cracks (at intervals of 30^0), 24 cracks (at intervals of 15^0), and 36 radials cracks (at intervals of 10^0) in the concrete lining for two different rock mass conditions. The numerical values of various material constants and the details of the various cases considered for the study have been given in Table 1 and Table 2 respectively.

Table 1 – Properties of concrete and rock mass

Materials	Young's Modulus of Elasticity E (N/m^2)	Poisson's ratio ν	Mass Density ρ (kg/m^3)	Safe Tensile strength σ_t (N/m^2)	Safe Compressive strength σ_c (N/m^2)
Concrete	2.0 x10^{10}	0.2	2500	2.0 x 10^6	7.0 x 10^6
Rock mass	8.0 x10^8	0.2	2500	-	-

Table 2 -Details of the studied concrete lined tunnel

Lining Condition with no. of cracks	Category of Rock and Load Condition	Support pressure, MPa (Singh et al., 1995)	Internal water pressure p, MPa
		$p_v = p_h$	
Un-cracked	Category I- without support pressure	0	1.2
Un-cracked	Category VI- with support pressure	0.3	1.2
Cracked (8, 12, 24 and 36)	Category I- without support pressure	0	1.2
Cracked (8, 12, 24 and 36)	Category VI- with support pressure	0.3	1.2
Un-cracked	Category VI- with support pressure	0.3	Empty tunnel
Cracked (8, 12, 24 and 36)	Category VI- with support pressure	0.3	Empty tunnel

6. RESULTS AND DISCUSSIONS

6.1 Stress Distribution in the Concrete Lining without Support Pressure

Hoop stress variations obtained from the stress analysis are presented along radial distance in the crack direction and angular bisecting axis between two successive cracks henceforth called as mid axis of the tunnel. Shear stress distribution is plotted along concrete rock interface and maximum radial displacements are presented in tabular forms.

The normalized hoop stress (σ_θ /p) variation has been presented along *r/R*, in which *r* is the radial distance from inner surface of the lining and *R* is the inner radius of the lining as shown in Figs. 5-12. In these plots, *r/R* zero on the x-axis represents the inner surface of the concrete lining and the positive and negative normalized hoop stresses on y-axis indicate tension and compression respectively. In the first case of un-cracked concrete lining condition, the values of the normalized radial stress, normalized hoop stress and radial deformation observed at the inner surface of the concrete lining are - 0.99, 5.82 and 1.41 mm respectively and these values are - 0.18, 4.97 and 1.31mm respectively at the outer surface of the concrete lining.

The normalized hoop stress variation with radial distance for un-cracked and cracked concrete lining with 8, 12, 24 and 36 radial cracks for rock mass category-I is shown in Fig. 5. It indicates that, the maximum stresses are observed to be concentrated in the concrete lining and are significantly decreasing in the rock due to change in the material properties. In the absence of external support pressure, the stress distribution is axisymmetric and hoop stress is tensile in the concrete lining due to internal water pressure. Due to the presence of the hoop tensile stresses, the construction joints might have opened up leading to symmetric radial cracks. As concrete can withstand only limited tension, the cracking of concrete occurs in several stages by redistribution of the stresses released due to crack propagation. A pattern of radial cracks at certain angular intervals in the concrete lining is assumed to understand the effect of number of cracks on the stress distribution. As shown in Fig. 5, the hoop stress in un-cracked concrete lining is observed to be tensile in nature with marginal variation in the radial direction. However, in cracked concrete lining, the stress variation is significant being compressive at the inner surface and tensile at the outer surface. As the number of cracks increases from 8 to 36, the maximum hoop stresses in the concrete lining are observed to decrease both in tension and compression. As shown in Fig. 6, the stress variation at the mid axis is observed to be similar to that of in crack direction. However, the magnitude of the stresses at mid axis is lesser both in compression and tension when compared to those at the crack direction.

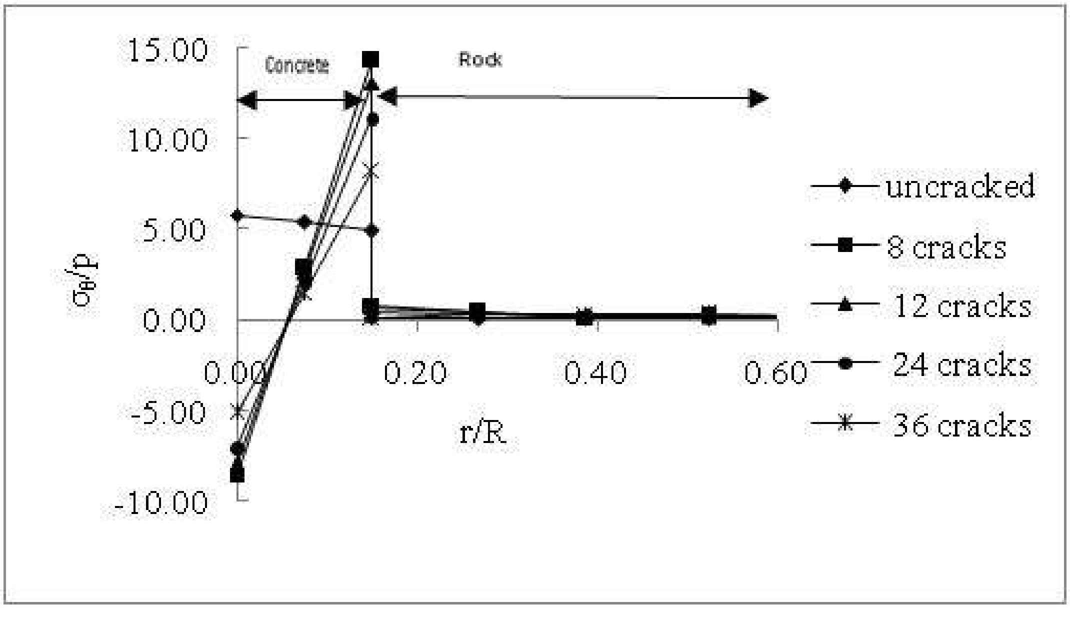

Fig. 5 - Hoop stress variation along radial distance in crack direction without support pressure

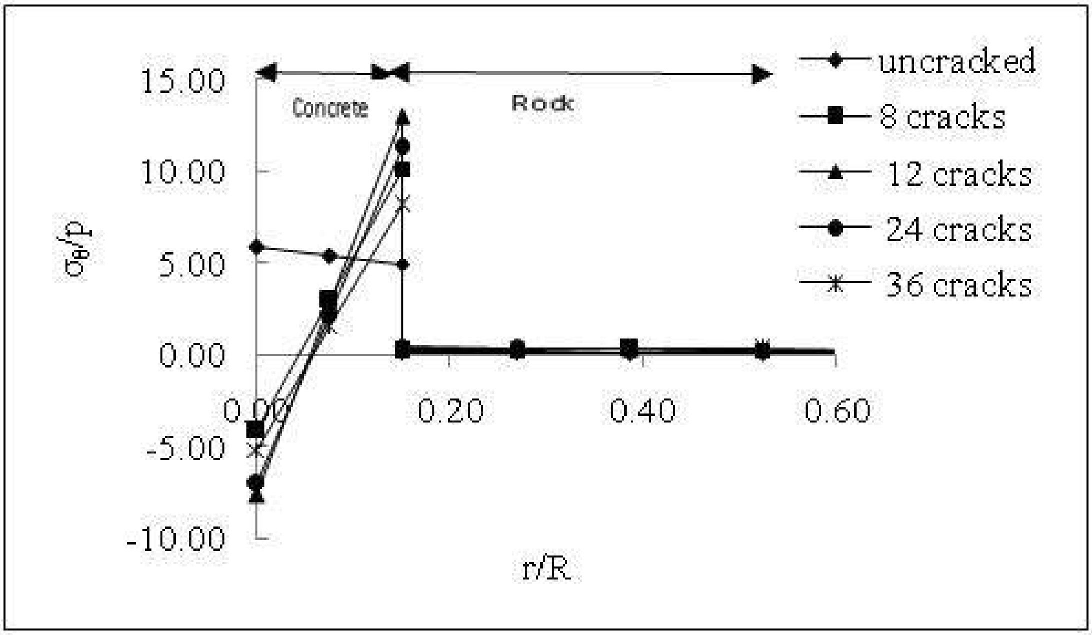

Fig. 6 - Hoop stress variation along radial distance at mid axis without support pressure

Shear stress variation along concrete rock interface for concrete lined tunnel with internal water pressure for un-cracked and cracked cases is shown in Fig. 7. Due to the presence of cracks in the concrete lining, fluctuations are observed along concrete rock interface due to the presence of points of stress singularity. With increase in the number of cracks the maximum shear stresses are observed to decrease in the concrete lining.

Maximum radial displacement at inner surface of the concrete lining is presented in Table 3 for un-cracked and cracked lining conditions.

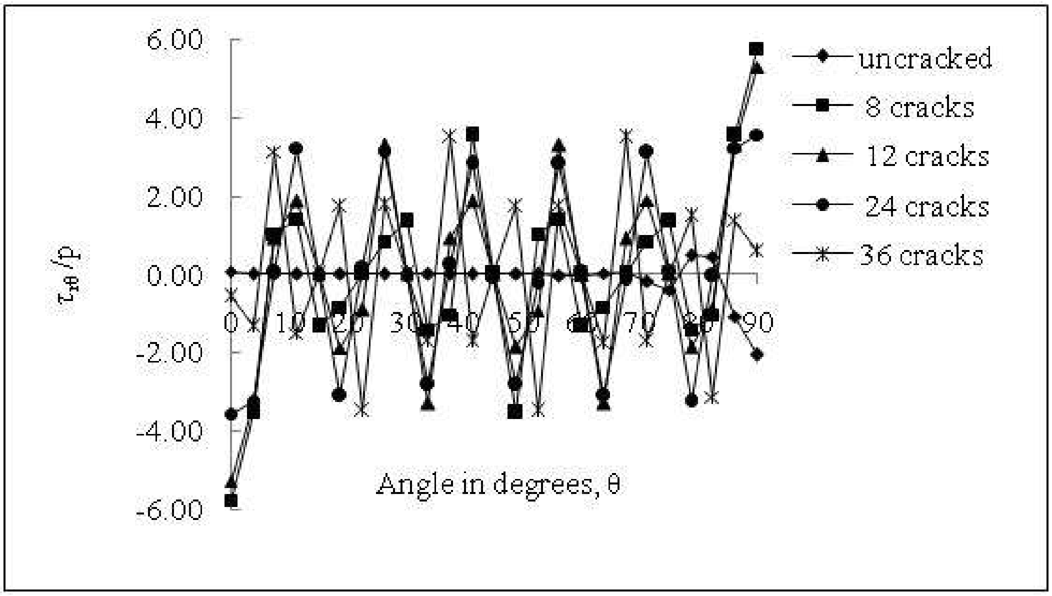

Fig.7 - Shear stress variation along concrete rock interface without support pressure

Table 3 - Maximum radial displacements observed in un-cracked and cracked concrete lined tunnel without support pressure

Concrete lining	Un-cracked	8 cracks	12 cracks	24 cracks	36 cracks
Maximum Radial displacement (mm)	1.40	4.70	4.66	4.6	4.55

6.2 Stress Distribution in Concrete Lining with Support Pressure

The support pressure depends on rock mass quality and in the present study an attempt is made to understand the influence of support pressure on the stress distributions in the concrete lining. Stress analysis has been carried out by considering uniform support pressure along with internal water pressure. The hoop stress variation along crack direction and mid axis along radial direction by considering support pressure along with internal water pressure is shown in Figs. 8 and 9 respectively. For rock mass category-VI, the maximum hoop stress is concentrated in the concrete lining and its variation in concrete lining is also observed to be similar to that in category-I. However, the presence of support pressure led to decrease in tensile and compressive stresses at the outer and inner surface of the concrete lining both in un-cracked and cracked conditions. As the number of cracks increases from 8 to 36, the maximum hoop stresses in the concrete lining are observed to decrease both in tension and compression along crack direction.

The stress variation at the mid axis is observed to be similar to that of crack direction and the magnitude of the stresses at mid axis are lesser both in compression and tension when compared to those at the crack direction.

Shear stress variation along concrete rock interface for concrete lined tunnel with support pressure and internal water pressure for un-cracked and cracked cases is shown in Fig. 10. Due to the presence of external support pressure, the maximum shear stresses are observed to be less than those obtained without considering support pressure as shown in Fig.7.

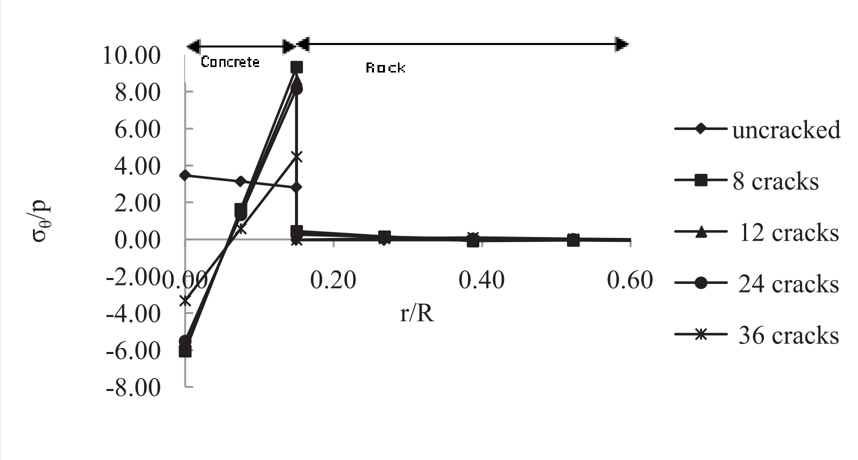

Fig. 8 - Hoop stress variation along radial distance at crack level with support pressure

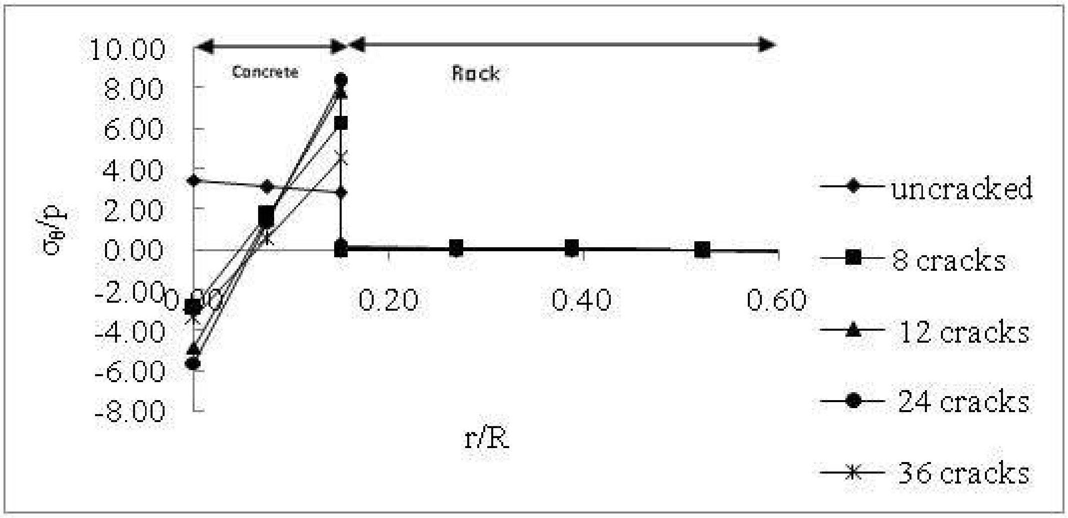

Fig. 9 - Hoop stress variation along radial distance at mid portion with support pressure

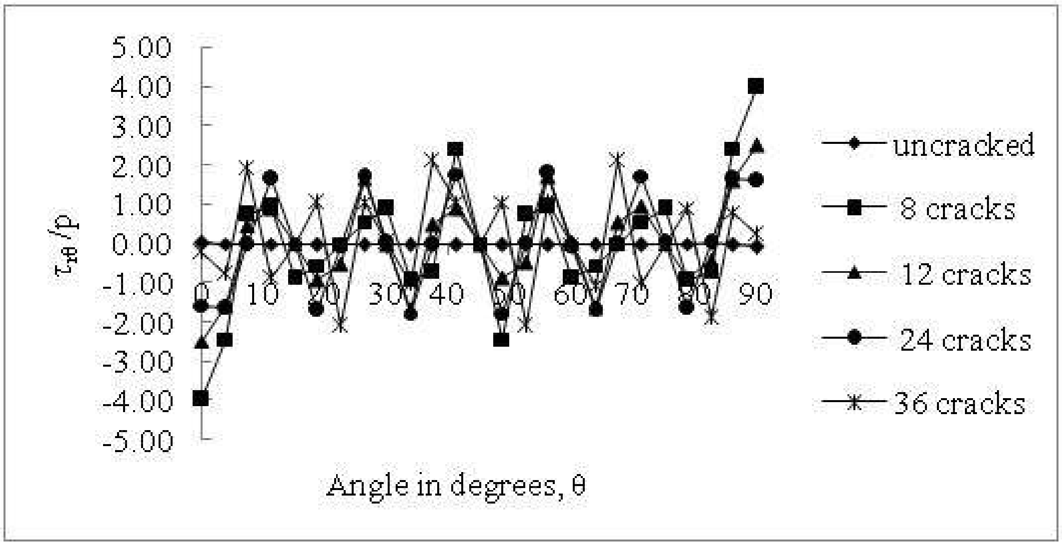

Fig. 10 - Shear stress variation along concrete rock interface with support pressure

The maximum radial displacement at inner surface of the concrete lining is presented in Table 4 for un-cracked and cracked lining conditions with support pressure. Due to the presence of support pressure the maximum displacements are observed to decrease in the concrete lining.

Table 4 - Maximum radial displacements observed in un-cracked and cracked concrete lined tunnel with support pressure

Concrete lining	Un-cracked	8 cracks	12 cracks	24 cracks	36 cracks
Maximum radial displacement (mm)	0.85	3.06	3.06	3.06	2.68

6.3 Stress Distribution in Concrete Lining for Tunnel Empty Condition with Support Pressure

Figure 11 shows the hoop stress variation along radial line in crack direction with support pressure for tunnel empty condition. In un-cracked concrete lining, the stresses are observed to be compressive and decreasing from inner surface to outer surface of the lining. In the presence of cracks, tensile stresses are observed at the inner surface of the concrete lining. As the number of cracks increases, the maximum hoop stresses are observed to decrease both in compression and tension. Hoop stress variation along radial line at mid axis of the concrete lined tunnel with tunnel empty condition for cracked condition is compared with stress variation in un-cracked condition and is shown in Fig. 12. In cracked condition same trend has been observed in concrete lining with increase in tension value at the inner surface. As the number of cracks increases, the maximum compression and tensile stresses are observed to decrease in the concrete lining.

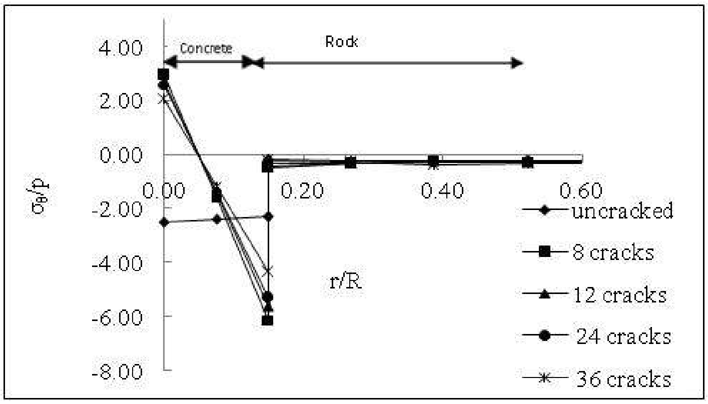

Fig. 11- Hoop stress variation along radial distance at crack level with empty tunnel condition

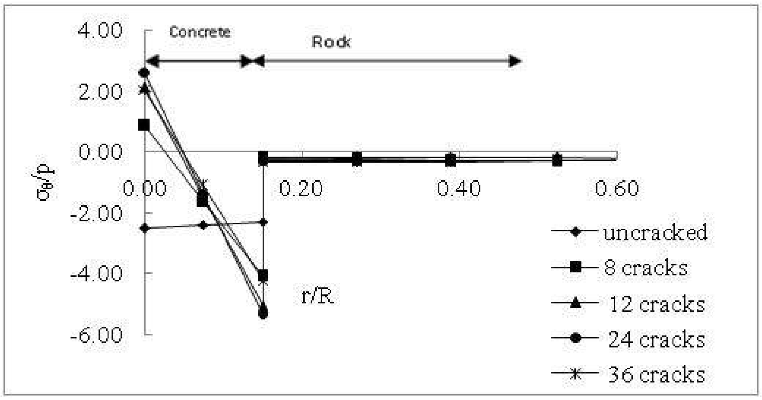

Fig. 12 - Hoop stress variation along radial distance at mid portion with empty tunnel condition

Figure 13 shows the shear stress variation along concrete rock interface for un-cracked and cracked cases. With the increasing number of cracks shear stresses are observed to decrease. The maximum radial displacement observed at inner surface of the concrete lining is presented in Table 5 for un-cracked and cracked lining conditions for tunnel empty condition. Table 6 shows the normalized (σ_θ/p) maximum tensile stresses in the lining at the crack level for different conditions.

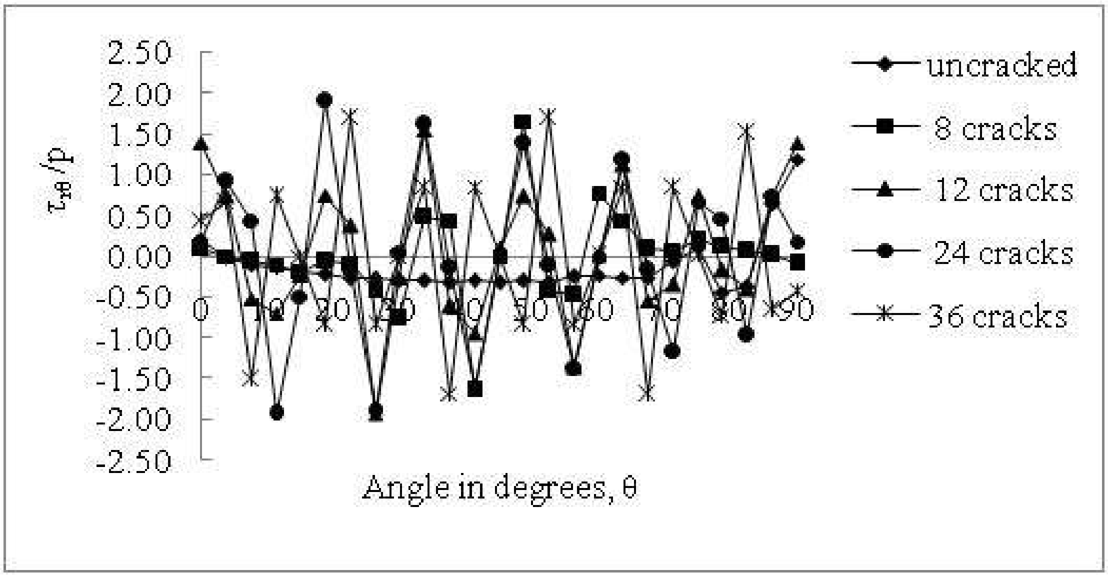

Fig. 13 - Shear stress variation along concrete rock interface with empty tunnel condition

Table 5 - Maximum radial displacements observed in un-cracked and cracked concrete lined tunnel for tunnel empty condition with support pressure

Concrete lining	Un-cracked	8 cracks	12 cracks	24 cracks	36 cracks
Maximum Radial displacement (mm)	0.573	0.778	1.259	1.658	1.97

Table 6 - Normalized maximum tensile stresses (σ_θ/p) observed in the lining at the crack level for different conditions

Lining condition	Without support pressure	With support pressure	Empty tunnel condition
un-cracked	5.82	3.46	---
8	14.33	9.34	---
12	13.11	8.62	4.08
24	11.18	8.16	2.60
36	8.20	4.48	2.04

The maximum tensile and compressive stresses observed in the concrete lining are presented in Figs. 14 and 15, respectively for un-cracked, 8, 12, 24 and 36 radial cracks for tunnel without support pressure, with support pressure and for tunnel empty condition with support pressure.

Thus heavy hoop reinforcement is not really needed in pressure tunnels, except near portals, fault zones, shallow rock cover and crushed rock etc. Analysis must ensure that crack opening does not exceed permissible limit of 3 mm. The rock mass must be grouted well to ensure a good bond between the lining and rock mass.

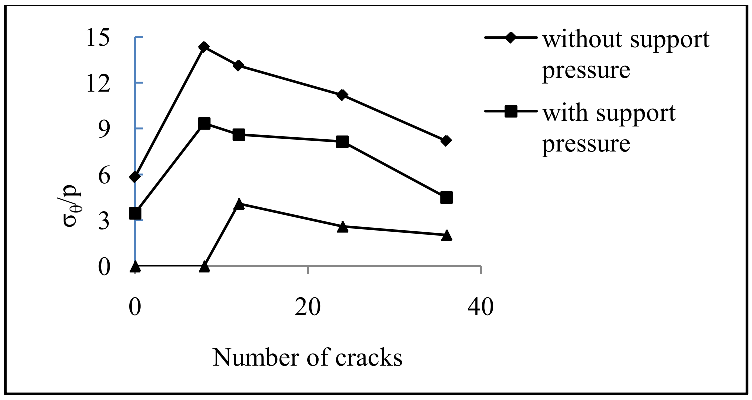

Fig. 14 - Maximum hoop tensile stresses observed in the concrete lining at crack level

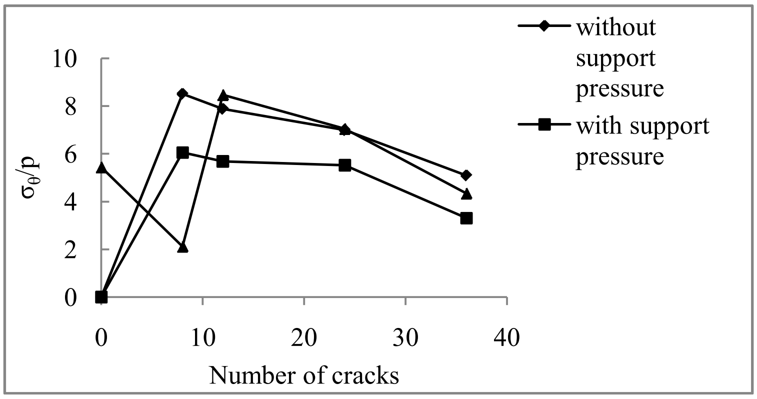

Fig. 15 - Maximum compressive hoop stresses observed in the concrete lining at crack level

7. CONCLUSIONS

- In lined pressure tunnels, maximum hoop stresses are concentrated in the concrete lining, whereas in the rock mass, they abruptly decrease at the concrete-rock interface with the change in the material properties.
- In rock mass category-I, without any support pressure, when the lining is subjected only with internal water pressure, the tensile hoop stresses in un-cracked concrete lining condition have been observed to change to compression with the initiation of cracks in the concrete lining at the inner surface and more tensile at the outer surface.
- After the initiation of cracks, with the increase in the number of cracks the hoop stress variation in the concrete lining along the crack direction is observed to be less compressive and less tensile at the inner and outer surface, respectively. The maximum hoop stresses along the mid axis is observed to be less when those compared along crack direction for similar conditions of cracking.
- It is found that the presence of external load due to support pressure as in category-VI along with internal water pressure leads to decrease in the compressive and tensile stresses at the inner and outer surface of the concrete lining both in cracked and un-cracked condition.
- In rock mass category-VI with empty tunnel condition, i.e. when the lining is subjected only with support pressure, the compressive hoop stresses in un-cracked concrete lining condition has been observed to change to tension with the initiation of cracks in the concrete lining at the inner surface and more compressive at the outer surface.

- The maximum shear stress in the concrete rock interface is observed to decrease with the increase in the number of cracks. Due to the presence of external support pressure, the maximum shear stresses are observed to be less than those obtained without support pressure.
- As the number of segments increase from 8 to 36, the maximum hoop stress in compression as well in tension is observed to decrease. The maximum tensile stress is observed in self-supporting tunnel in full condition when compared to other conditions and no such trend is observed for maximum compressive stress.

References

Kumar, P. and Singh, B. (1988). Pressure on lining due to initial stress field by finite/infinite/interface element method, J. Rock Mechanics and Rock Engineering, 21, 219-228.

Goodman, R.E. (1989). Introduction to Rock Mechanics, 2nd ed., John Willey & Sons, 364pp.

NISA/CIVIL (2007). User's Manual, Cranes Software International Limited v. 14.0, Bangalore.

Singh, B. and Goel, R.K. (2002). Software for Engineering Control of Landslide and Tunneling Hazards, A.A. Balkema, 344p.

Singh, B., Nayak, G.C., Kumar, P. and Chandra, G. (1988). Design criteria for plain concrete lining in water and power tunnels, J. Tunnelling and Underground Space Technology, 3(2), 201-208.

Singh, B., Jethwa, J.L. and Dube, A.K. (1995). Modified Terzaghi's rock load concept for tunnels, Journal of Rock. Mech. Tunlg. Tech., l (1), 13-24.

Singh, B., Goel, R.K., Jethwa, J.L. and Dube, A.K. (1997). Support pressure assessment in arched underground openings through poor rock masses, Engg. Geol., 48, 59-81.

Parvathi, I.S., Praveen, T.V. and Kumar, S. (2013). Effect of spacing and orientation of joints in the rock on stress variation in lined pressure tunnels using finite element method, Journal of Rock Mechanics and Tunnelling Technology, 19(1), 1-17.

Parvathi, I.S., Rao, S.S. and Praveen, T.V. (2005). Effect of rock mass quality and tunnel size on lined pressure tunnels using finite element method, Journal of Rock Mechanics and Tunnelling Technology, 11(1), 35-48.

Terzaghi, K. (1946). Rock defects and load on tunnel supports, Introduction to Rock Tunnelling with Steel Support, R.V. Proctor and T.C. White, Commercial Shearing and Stamping Co., Youngstava, Ohio, USA.