Effect of Rock Mass Quality and Tunnel Size on Lined Pressure Tunnels using FEM

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ABSTRACT

Lined tunnels form an important component of the water conductor system for hydroelectric projects located in mountainous regions. The condition of the rock is quite varied. The rock may be integral rock mass or in a jointed condition. The rock may be self-supporting or may require rock bolting or use of steel ribs to support the rock while driving the tunnel. Depending on the condition of the rock, the lining may be plain concrete lining or reinforced concrete lining or plain concrete lining together with steel lining.

In tunnel lining design, it is necessary to know the share of the rock load and internal pressure, which is to be taken by the lining. The share of the rock load or the support pressure on the lining depends on the rock mass quality. In disintegrated rock mass, stress concentrations will develop around an opening under the action of rock load. When the tunnel is under internal pressure, the stresses resulting from internal water pressure get superposed on the stresses for the empty tunnel condition. Due to the action of internal pressure the concrete lining as well as rock up to certain radius gets cracked. A pattern of radial cracks at certain angular intervals in the concrete lining is assumed to account for the effect of radial cracks on the stress distribution.

In the present work, the stress analysis of concrete lined pressure tunnels has been carried out for uncracked and cracked concrete lining for two different rock mass conditions using finite element analysis. An attempt is made to study the effect of size of the tunnel on the stress distributions in the concrete lining for two different rock mass conditions. The variations of hoop stress with radial distance and shear stress along concrete rock interface have been obtained. Based on the results obtained, the total amount of tension and compression in the lining required for its design are presented.

Keywords: Concrete lining, Pressure tunnels, Stress analysis, Rock mass quality, Tunnel size effect, Finite element method, and Rock mechanics

1. INTRODUCTION

The analysis and design of tunnels should be rationalised, as the cost of tunnels in hydroelectric projects and urban mass transport projects is very high. In power tunnels, the lining acts as a tunnel support system and it performs two important functions, viz., supports the rock mass and internal water pressure. Such lining is generally unreinforced for tunnels with low internal pressures. Discontinuities usually occur in the concrete lining under the action of internal water pressure due to cracking or separation along construction joints. Stress analysis of cracked liner- rock mass system is required to ensure that the assembly will remain stable. Finite element analysis can handle such problems effectively.

In the design of tunnel lining, it is necessary to know the share of the rock load and internal pressure, which is to be taken by the lining. "When a stiff lining is cast against the rock so that it remains in contact with the rock surface as the tunnel rock deforms. If the rock behaves as a burgers body, in time the pressure will build up on the lining while the stress difference in the rock declines. The final pressure on the lining can be approximated by assuming it to be loaded as a thick walled cylinder by a uniform pressure equal to the initial stress in the rock. This may require years or tens of years" [Goodman (1989)]. 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. Prediction of support pressures in tunnels and the effect of tunnel size on support pressure are two important problems in tunnel design. Various empirical approaches for predicting support pressures have been suggested in the recent past.

The present work attempts to study the effect of rock mass condition and tunnel size effect on stress distribution in the concrete lining. Further, an attempt is also made to understand the effect of cracked concrete lining on stress distribution considering minimum number of radial cracks, i.e., 8 being equal to the usual number of construction joints.

2. MODIFIED ROCK LOAD THEORY OF TERZAGHI

The rock load theory of Terzaghi (1946) and wedge theory suggest that support pressures are proportional to the tunnel size. Terzaghi's theory of arching for tunneling through soils is not applicable for rock masses because rocks have preexisting planes of weakness unlike soils. Theory of rigid rock wedges does not give realistic predictions, as the in-situ stress along the axis of tunnels and caverns pre-stress rock wedges. Recently Singh et al. (1995a) have compared support pressures measured from tunnels and caverns with estimates from Terzaghi's rock load concept. They found that support pressure in rock tunnels and caverns does not directly increase with excavation size as assumed by Terzaghi (1946) and others mainly due to dilatant behavior of rock masses, joint roughness and prevention of loosening of rock mass by improved and modern tunneling technology. They have subsequently recommended modified ranges of support pressures for different categories of non-squeezing, squeezing and swelling rocks as given in Table 1.

2.1 Effect of Tunnel Size on support pressure

Some researchers [Daemen, 1975; Barton et al., 1974; Jethwa, 1981; Singh et al., 1992] have concluded that, because the stresses induced in the rock mass around an excavation are independent of the size of the excavation, the stability of excavation is also independent of its size. Goel et al. (1996) have suggested that if the rock mass is perfectly elastic and completely free of defects this conclusion would be reasonably correct, but it is not valid for rock masses which are already fractured. The support pressure under non-squeezing ground conditions is practically independent of tunnel size in arch shaped roof tunnels.

3. METHODOLOGY

The stress analysis has been carried out by the finite element method. To study the effect of rock mass condition 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 from Table 1. For each category Singh et al. (1995a) have suggested ranges of support pressures in both vertical (p_v) and horizontal (p_h) directions. For category-I, i.e. hard and intact rock the recommended support pressure is zero in both vertical and horizontal directions. For category-VI, i.e. completely crushed but chemically intact rock the lower limits of the range of the support pressures have been considered in the present study. For the analysis of the concrete lining of hard and intact rock mass case, as the external pressure is zero only internal water pressure has been considered. In the case of concrete lining of completely crushed but chemically intact rock, the analysis has been carried out with internal water pressure and vertical & horizontal support pressures. The region of the domain and boundary conditions of the concrete lined tunnel are as shown in Fig.1.

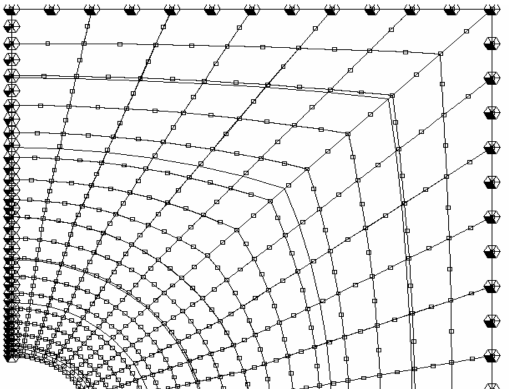


Fig. 1 – Finite element discretization of a lined tunnel

Table 1 - Recommendations of Singh et al. (1995a) on support pressure for rock tunnels and caverns

Terzaghi's Classification			Classification of Singh et al. , 1995				Remarks
Cate-gory	Rock Condition	Rock Load Factor Hp	Cate-gory	Rock Condition	Recommended Support Pressure MPa		
					pv	ph	
I	Hard & intact	0	I	Hard & intact	0	0	--
II	Hard stratified or schistose	0 to 0.25B	II	Hard stratified or schistose	0.0-0.04	0	--
III	Massive, moderately jointed	0 to 0.5B	III	Massive, moderately jointed	0.04-0.07	0	--
IV	Moderately blocky seamy & jointed	0.25B to 0.35 (B+Ht)	IV	Moderately blocky seamy very jointed	0.07-0.1	0-0.2 pv	Inverts may be required
V	Very blocky & seamy, shattered arched	0.35 to 1.1 (B+Ht)	V	Very blocky & seamy, shattered highly jointed, thin shear zone or fault	0.1-0.2	0-0.5 pv	Inverts may be required, arched roof preferred
VI	Completely crushed but chemically intact	1.1 (B+Ht)	VI	Completely crushed but chemically unaltered, thick shear and fault zone	0.2-0.3	0.3-1.0 pv	Inverts essential, arched roof essential
VII	Squeezing rock at moderate depth	1.1 to 2.1 (B+Ht)	VII	Squeezing rock condition			
VII Contd.	Squeezing rock at moderate depth	1.1 to 2.1 (B+Ht)	VII	A. mild squeezing (u_a/a upto 3 %)	0.3-0.4	Depends on primary stress values ph may exceed pv	Inverts essential. In excavation flexible support preferred. Circular section recommended
				B..moderate squeezing (u_a/a = 3 to 5 %)	0.4-0.6	-do-	-do-
VIII	Squeezing rock at great depth	2.1 to 4.5 (B+Ht)	VII	C. high squeezing (u_a/a >5%)	6.0-1.4	-do-	-do-
IX	Swelling rock	upto 80m	VIII	Swelling rock			
				A. mild swelling	0.3-0.8	Depends on type & content of swelling clays, ph may exceed pv	Inverts essential in excavation, arched roof essential
				B. moderate swelling	0.8-1.4	-do-	-do-
				C. high swelling	1.4-2.0	-do-	-do-

Notations: p_v = vertical support pressure; p_h = horizontal support pressure; B = width or span of opening; Ht = height of opening; u_a= radial tunnel closure; a = B/2; thin shear zone = upto 2m thick

4. FINITE ELEMENT ANALYSIS

The rock mass and concrete is modeled using 2D plane strain isoparametric quadrilateral elements. A unit thickness of the element is assumed. The finite element discretization is as shown in Fig. 1.The concrete rock interface and radial cracks in the concrete lining are modeled explicitly using 2D gap and friction element which are shown in Fig. 2a. This 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 consisting of a pair of coupled orthogonal springs (Figs. 2b and 2c) in the normal and tangential directions. The element may assume open or closed status and may be sticking or sliding depending on whether the friction limit $\mu| f_n|$ is reached, where μ is the coefficient of friction and f_n is the normal compressive force in the gap. 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 will be 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 stiffnesses assumed are 1×10^9 N/m^2. In the present work NISA (Numerically Integrated Elements for Systems Analysis) software package has been used to carry out the finite element analysis.

For validation purpose, finite element analysis has been carried out for concrete lined pressure tunnel in isotropic medium using the following data.

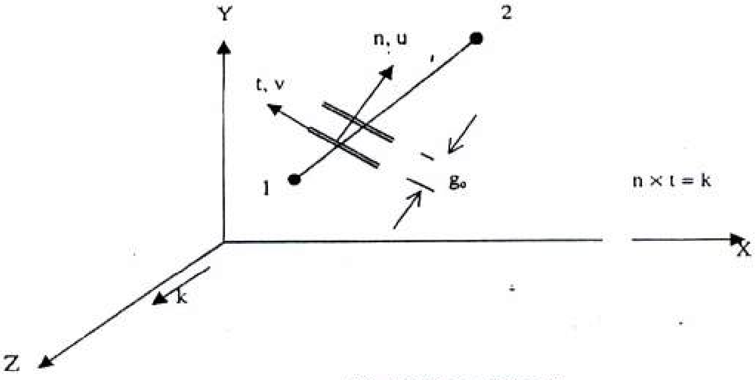
$b = 4.5$ m; $c = 5.0$ m; $E_c = 2\times10^{10}$ N/m^2; $E_r = 2\times10^9$ N/m^2; $\nu_c = 0.15$;
$\nu_r = 0.2$; $K_n = K_t = 1\times10^9$ N/m^2; $p = 1\times10^5$ N/m^2.

Where b and c are inner and outer radii of the concrete lining, E_c and E_r are modulus of elasticity of concrete and rock, ν_c and ν_r are poisson's ratio of concrete and rock, K_n & K_t are normal and tangential stiffness of interface element and p is internal water pressure.

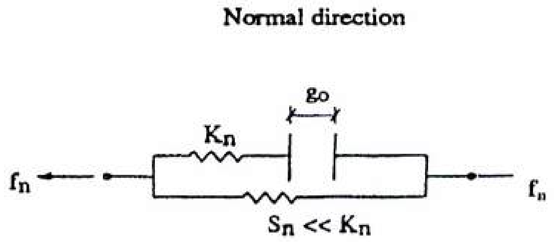
The results have been compared with the theoretical solution for lined pressure tunnel given by Jaeger (1972) and are shown in Table 2 and Fig. 3. It is found that the results obtained from the numerical analysis are in satisfactory agreement with the results obtained from the analytical solution.

Table 2 - Comparison of FEM result with analytical solution for stress concentrations in concrete lining

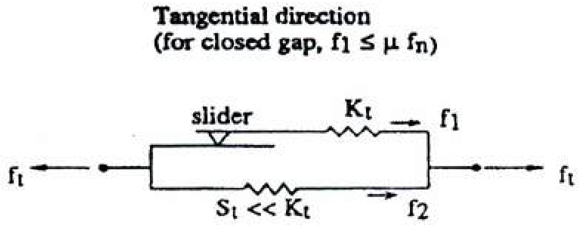
Location	Analytical value (MPa)	Numerical value (MPa)
σ_r (inner)	0.1	0.0989
σ_t (inner)	-0.5325	-0.5356
σ_r (outer)	0.0399	0.0412
σ_t(outer)	-0.4724	-0.4738



(a) Interface element



(b) Stiff and soft springs in the normal direction



(c) Stiff and soft springs in the tangential direction

Fig. 2 – Details of the interface element

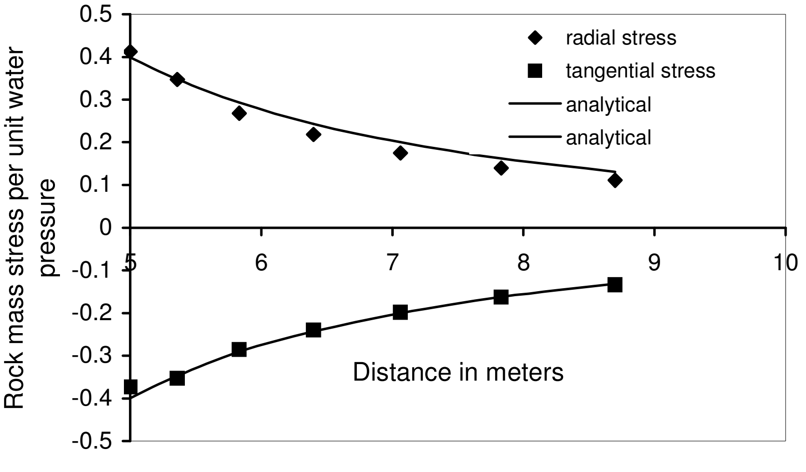


Fig. 3 – Stresses on rock mass

5. DETAILS OF THE PRESENT WORK

The present study has been carried out on the feasibility of plain concrete tunnel lining for diversion tunnel of Tehri dam project. The tunnel of this project is circular in cross section with an opening of 8 m diameter and concrete lining of 0.6 m thickness. The cross section of the tunnel is shown in Fig. 1. To study the effect of rock mass condition the stress analysis has been carried out for uncracked and cracked concrete lining for two different rock mass conditions, viz., hard and intact rock and crushed rock. To study the effect of tunnel size, the stress analysis has been carried out for 4m diameter of the tunnel with a lining thickness of 0.3 m for two different rock mass conditions, viz., hard and intact rock and crushed rock. The details of the various cases are presented in Table 3 .The numerical values of various material constants are given in Table 4.

Table 3 - Details of the cases studied

Case	Tunnel diameter and lining thickness, m	Lining Condition	Rock mass quality	Support pressure, MPa		Internal water pressure p, MPa
				p_v	p_h	
1	8, 0.6	Uncracked	Hard and intact	0	0	1.2
2	8, 0.6	Uncracked	Completely crushed but chemically intact	0.2	0.3 p_v	1.2
3	8, 0.6	Cracked	Hard and intact	0	0	1.2
4	8, 0.6	Cracked	Completely crushed but chemically intact	0.2	0.3 p_v	1.2
5	4, 0.3	Uncracked	Hard and intact	0	0	1.2
6	4, 0.3	Uncracked	Completely crushed but chemically intact	0.2	0.3 p_v	1.2
7	4, 0.3	Cracked	Hard and intact	0	0	1.2
8	4, 0.3	Cracked	Completely crushed but chemically intact	0.2	0.3 p_v	1.2

Table 4 - List of material properties

Material Properties					
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	2.0×10^{10}	0.2	2500	2.0×10^6	7.0×10^6
Rock	8.0×10^8	0.2	2500		

6. RESULTS AND DISCUSSIONS

In intact rock mass condition external support pressure is zero and is subjected to only uniform internal water pressure, p. The hoop stress, σ_θ obtained for the case of hard and intact rock is presented only along a single radial line, as the stress distribution is axi-symmetric. The hoop stress distribution is asymmetric in the case of crushed rock since it is subjected to external support pressure along with internal water pressure. Hence, the hoop stress variation obtained from the stress analysis is presented along two significant radial lines, i.e., sidewall ($\theta = 0°$) and crown ($\theta = 90°$) that are subjected to maximum compressive and tensile stresses around an opening. The non-dimensional hoop stress σ_θ/p variation 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 is presented. Non-dimensional shear stress τ/p distributions are presented along concrete rock interface.

6.1 Effect of Rock Mass Quality on Stress Distribution in Concrete Lining

Figure 4 shows the non-dimensional hoop stress variations with r/R for intact rock mass condition and crushed rock mass condition in uncracked concrete lining. The stresses are observed to be concentrated in the concrete lining and significantly decreasing in the rock due to changes in the material properties. The maximum hoop stress in the case of concrete lining of intact rock mass is observed to be at the inner surface of the lining. In the absence of support pressure the stress distribution is axisymmetric and tensile in the concrete lining due to internal water pressure. Hence the stress distribution in hard and intact rock is tensile and axisymmetric. In the case of concrete lining of crushed rock mass maximum hoop stress is also observed to be at the inner surface along crown and at the interface of concrete and rock along side wall. In crushed rock mass the presence of support pressure due to rock load leads to increase in tensile stresses at the inner surface of the concrete lining along crown whereas at sidewall it decreases. The total amount of tension and compression in the lining are calculated and presented in Table 5. From Table 5 it is observed that the hoop tension in uncracked concrete lining of the intact rock mass is more than that of crushed rock mass.

Due to the presence of tensile stresses in the concrete lining it is expected to be cracked. 8 radial cracks at an interval of 45° are assumed in the concrete lining. The cracks are assumed to be along two significant radial lines viz., sidewall and crown and in between those lines. In the case of concrete lining of intact rock the hoop stresses are drawn along cracked surface of single radial crack due to axisymmetric stress distribution. Due to asymmetric stress distribution in the case of concrete lining of crushed rock hoop stresses are drawn along two radial cracks viz., sidewall and crown, which are subjected to maximum stresses. Non-dimensional hoop stress variation along cracked surface of the concrete lining for two different rock mass conditions is as shown in Fig. 5. The stress distribution on cracked concrete lining is observed to be compressive at the inner surface of the lining and tensile at the interface of the concrete and rock in both the cases of rock mass conditions. The maximum stresses obtained in the cracked concrete lining are observed to be more than those of uncracked concrete lining. From Table 5 the hoop forces in the cracked concrete lining are observed to be more in the case of hard and intact rock than those of crushed rock. In the case of cracked concrete lining compressive forces are also observed in addition to the tensile forces.

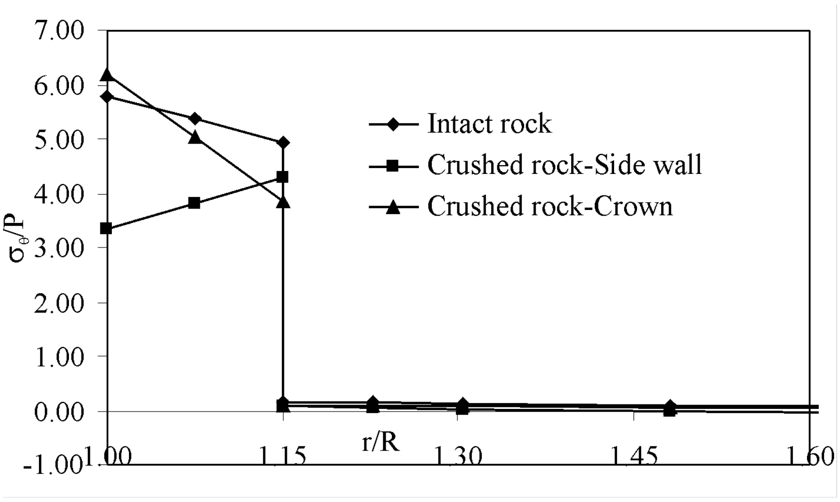


Fig. 4 – Variation of hoop stress in uncracked concrete lining of intact rock and crushed rock

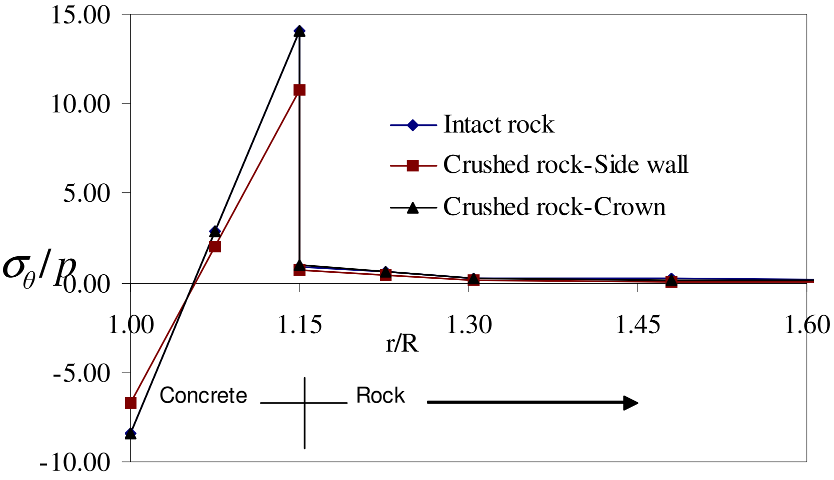


Fig. 5 – Variation of hoop stress in cracked concrete lining of intact rock and crushed rock

Table 5 - Hoop force values in the concrete lining

Rock Mass Condition	Tunnel Dia & Lining Thickness in m	Concrete lining	Location	Hoop force, KN per meter length of the tunnel	
				Tension	Compression
Hard and intact	8, 0.6	Uncracked	Sidewall (θ = 0°)	3858	-
			Crown (θ = 90°)	3858	-
		Cracked	Sidewall (θ = 0°)	2957	1262.5
			Crown (θ = 90°)	2957	1262.5
Completely crushed but chemically intact	8, 0.6	Uncracked	Sidewall (θ = 0°)	2742	-
			Crown (θ = 90°)	3612	-
		Cracked	Sidewall (θ = 0°)	2257	1011.25
			Crown (θ = 90°)	2957	1262.5
Hard and intact	4,0.3	Uncracked	Sidewall (θ = 0°)	1929	-
			Crown (θ = 90°)	1929	-
		Cracked	Sidewall (θ = 0°)	1478	631
			Crown (θ = 90°)	1478	631
Completely crushed but chemically intact	4,0.3	Uncracked	Sidewall (θ = 0°)	1371	-
			Crown (θ = 90°)	1806	-
		Cracked	Sidewall (θ = 0°)	1128	505
			Crown (θ = 90°)	1478	631

The non-dimensional shear stress distribution along concrete rock interface of the uncracked and cracked concrete lining is shown in Fig. 6 for two different rock mass conditions. In the case of intact rock mass, the shear stress along uncracked concrete-rock interface is observed to be zero due to axisymmetric hoop stress variation. In the cracked concrete-rock interface, on the other hand, fluctuations are observed due to the presence of cracks. The maximum shear stress in the cracked concrete lining of the crushed rock mass and intact rock mass are observed to be same.

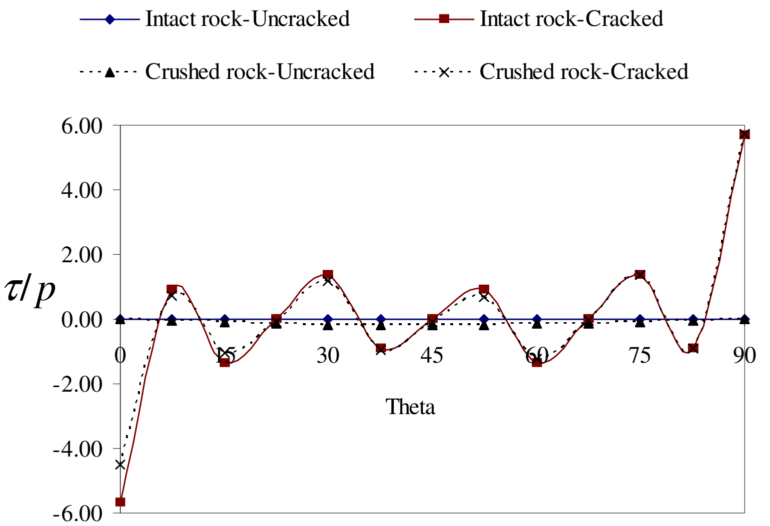


Fig. 6 – Variation of hoop stress in uncracked concrete lining of intact rock and crushed rock

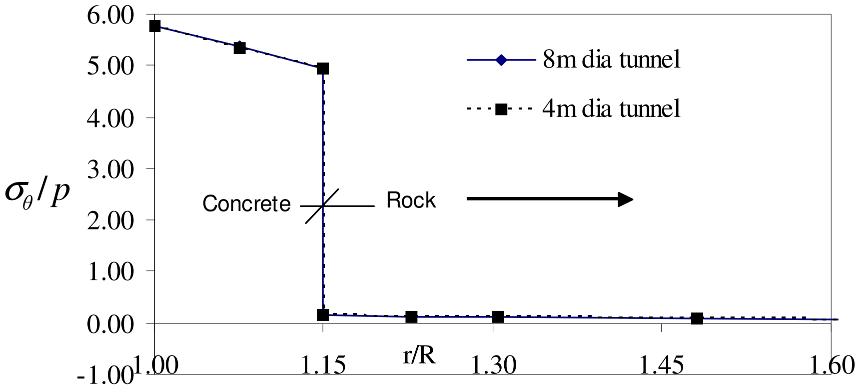


Fig. 7 – Variation of hoop stress with radial distance in uncracked concrete lining of 8m and 4m diameter tunnels in intact rock

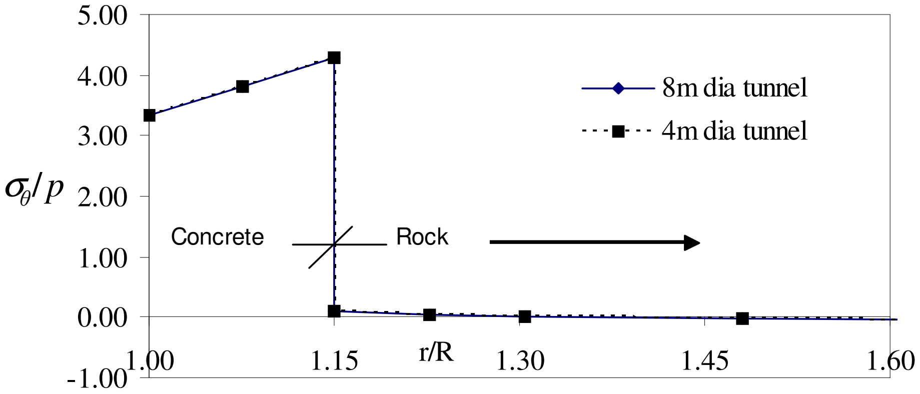


Fig. 8 – Variation of hoop stress at side wall in uncracked concrete lining of 8m and 4m diameter tunnels in crushed rock

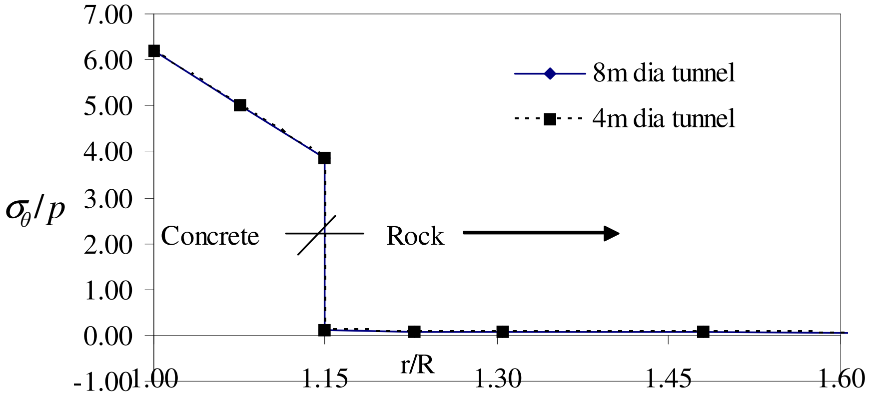


Fig. 9 – Variation of hoop stress at crown in uncracked concrete lining of 8m and 4m diameter tunnels in crushed rock

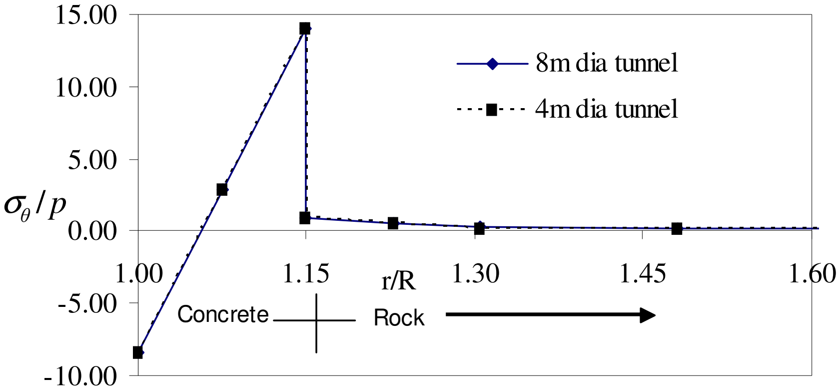


Fig. 10 – Variation of hoop stress at radial distance in cracked concrete lining of 8m and 4m diameter tunnels in intact rock

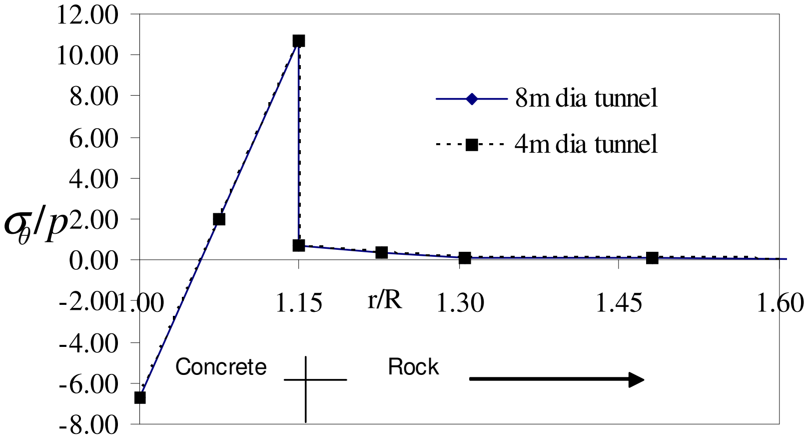


Fig. 11 – Variation of hoop stress at side wall in cracked concrete lining of 8m and 4m diameter tunnels in crushed rock

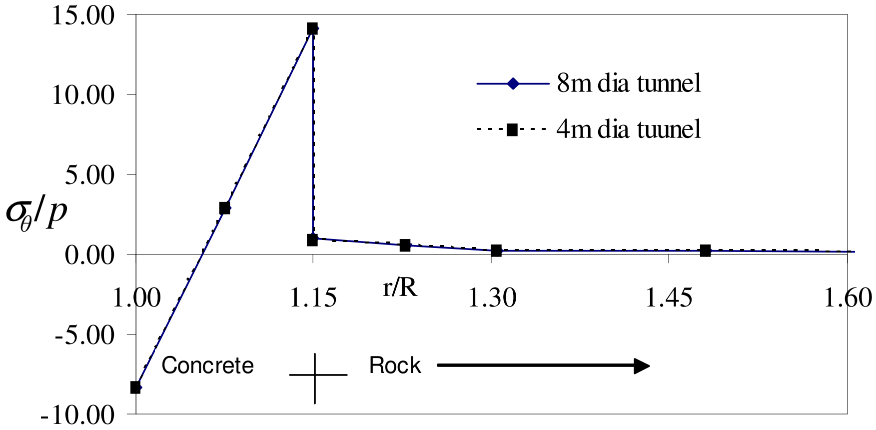


Fig. 12 – Variation of hoop stress at crown in cracked concrete lining of 8m and 4m diameter tunnels in crushed rock

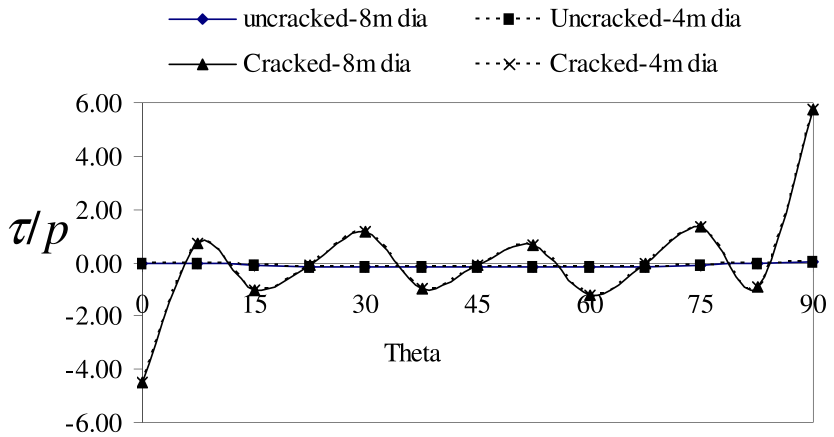


Fig. 13 – Variation of shear stress along concrete-rock interface of 8m and 4m diameter tunnels in crushed rock

6.2 Effect of tunnel size on stress distribution in concrete lining

For comparison the variations of non-dimensional hoop stress are plotted with radial distance proportional to the diameter of the tunnel lining of 8m and 4m diameter tunnels. Figure 7 shows the non-dimensional hoop stress variation in uncracked concrete lining of the intact rock for two different diameters of the tunnels viz., 8 m and 4 m. In intact rock mass hoop stress variation is observed to be unaffected by the size of the tunnel. The hoop stress variation in uncracked concrete lining of the crushed rock along side wall and crown are shown in Figs. 8 and 9 respectively for two different diameters of the tunnel. As the size of the tunnel changes, the stress variation in the concrete and rock appears to be same along sidewall and crown respectively from Figs. 8 and 9. Figs. 10, 11 and 12 shows the hoop stress variation in cracked concrete lining of 8m and 4m diameter tunnels for intact and crushed rocks. Fig. 10 shows that the effect of tunnel size is insignificant in intact rock mass and same have been observed for crushed rock mass from Figs. 11 and 12. The hoop forces for 4m and 8m diameters of the tunnel are presented in Table 5.The non-dimensional shear stress distribution along concrete rock interface of the crushed rock mass is as shown in Fig. 13. With the change in the size of the tunnel, shear stresses are also observed to be unaffected along the interface of concrete and rock.

7. CONCLUSIONS

The following conclusions are drawn from the present study:

- The maximum hoop stresses are observed to be in concrete lining of both intact and crushed rock mass whether the lining is uncracked or in cracked condition.
- Hoop forces obtained in the concrete lining of the intact rock mass are found to be more than those of crushed rock mass. The presence of support pressure over lined tunnels of non-squeezing rocks leads to reduction in tensile stresses, which will be developed due to the internal water pressure.

- Compressive and tensile hoop stresses concentrated at the inner and outer surface of the cracked concrete lining are observed to be more than those of uncracked concrete lining, at the corresponding points.
- The maximum shear stresses in the case of cracked concrete-rock interface are observed to be more than those of uncracked concrete-rock interface.
- The stress distribution in the uncracked and cracked concrete lining of hard & intact rock and for crushed rocks are found to be independent of the size of the tunnel. The size of the tunnel under non-squeezing ground conditions does not affect stresses in the concrete lining.
- Hoop forces are axisymmetric in the case of intact rock mass for tunnel with internal pressure only whereas in the case of crushed rock for tunnel with internal pressure and support pressure, crown is the governing radial line for compression as well as tension. The effect of the rock mass condition and concrete lining condition on the hoop forces in the concrete lining are presented in Table 5.

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