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A Finite Element Model for Optimum Design of Plain Concrete Pressure Tunnels under High Internal Pressure

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ABSTRACT

Plain concrete lining of pressure tunnels are not absolutely tight and water can seep out of the tunnel. Seeped water is lost of energy in hydropower system, but can also cause serious stability problems in the surrounding rock mass. If the rock mass around the tunnel is tight (originally or tighten by grouting) seeped water, however, stays in the vicinity of the tunnel and increases the external (ground) water pressure. Such increased external water pressure decreases the gradients between internal and external pressure and reduce the seepage and losses. For simulation of hydraulic mechanical interaction in the process of cracking, a coupled seepage-stress method based on the 2D elasto-plastic finite element method (FEM) is proposed. The coupling has been carried out by superimposing results of consolidation and water flow analyses. The coupling principle produces the change of stress field and leads to change of permeability coefficient and the redistribution of the seepage field. The calculation results are compared with results of existing tunnel and with the analytical solutions. A design criterion based on this study can be suggested for pressure tunnel design procedure in stable rock conditions.

Keywords: *Plain concrete, Pressure tunnel, permeable lining, stress-seepage analysis, numerical simulation*

1. INTRODUCTION

The study is based on plain concrete lined pressure tunnels where the internal water pressure is restricted by low tensile strength of concrete. The internal water pressure generates tensile stresses in the concrete lining and if the lining stress exceeds tensile strength cracks in the concrete occurs, resulting in reduced lining functionality.

Bearing of internal water pressure by plain concrete lined pressure tunnels is limited by the low tensile strength of concrete. Shrinkage of concrete and cooling of the lining by first filling causes a gap between the concrete linings and surrounding rock mass and therefore the surrounding rock mass cannot be included in the bearing of the internal pressure.

According to Seeber, (1984) and Schleiss, (1987) the cooling and shrinkage after concreting often result into stresses and deformation which produce contraction in concrete lining. The contraction, hence, detaches the lining from the rock mass and form a gap. A grout is required to fill on one hand the gap between the lining and surrounding rock and on the other hand fills fractures and large pores in the rock masses (Schleiss, 1986; Marence and Oberladstatter, 2005 and Kocbay et al, 2009). The low pressure grouting reconstitutes the contact with the surrounding rock mass and increases the bearing capacity, but still the bearing capacity of plain concrete lining stays limited.

Generally, unlined, shotcrete or simple concrete lined tunnels are not tight and water can leak in and out. In case of the rock mass that is not resistant on loading by pressurized water because of washing out of joint filling, slaking effect or erosion, the contact of rock mass with pressurized water and rock mass has to be omitted (Marence, 2008). The concrete lining represents a suitable solution. The plain concrete lining has limited tensile strength and therefore the bearing of the internal water pressure is limited (Seeber, 1984; Schleiss, 1997; and Kang et al, 2009). The bearing capacity of the plain concrete lining can be increased if the lining is before filling with water artificially pre-stressed. Pre-stressing of the concrete lining can be done by different methods; by cables - very expensive for long structures like tunnels and is used mostly in case of repair of short sections, or by high pressure grouting between the lining and the surrounding rock mass. Such grouting method is then limited by the compressive bearing capacity of the lining and is usually used up to the internal water pressures of 10-20 bars.

Today, plain concrete lined pressure tunnels are mostly pre-stressed by grouting. Different grouting methods are used (Seeber, 1984, Benson, 1989, and Marence, 2005). Grouting through radially set grout holes additionally increase the rock mass strength and stiffness, but also reduce the rock mass permeability. Reduced permeability of the rock mass gives possibility for additional effect that was up to now not used in the design of the lining. Relatively tight rock mass around the concrete lined tunnel reduces water losses and produces external water pressure that, as a contra-pressure, reduces the tensile stresses in the concrete lining. Including of the increased external water pressure (contra-pressure) caused by water seepage through the concrete lining in the design gives possibility to extend the applicability of the plain concrete lining and will allow estimation of the water losses through the concrete lining.

The numerical analysis is matched with analytical solutions resulting in a rational methodology for the design of plain concrete lining under high internal water pressure of up to 35 bars. In all the analyses the following assumptions have been made: (1) the rock mass behaviour is assumed to be in drained conditions; (2) lining material is elastic; (3) plane strain conditions apply at any cross-section of the tunnel; (4) deep tunnel, where the ground is considered weightless; the errors introduced are small for tunnels located at a depth of at least five times the tunnel radius (Nam and Bobet, 2006); (5) The stresses existing in the rock mass are related to the weight of the overlying strata and geological history. No geotechnical stresses are expected and the vertical stress is assumed as a weight of overburden. Ambient stresses are applied far from the tunnel and no displacement constraints at the boundaries.
This developed method can be used for design of plain concrete lining in case where standard plain concrete with high pressure grouting theory reaches its limits. In case of the good rock mass conditions and relatively tight rock mass the suggested method would extend the applicability of the plain concrete lining with pre-stressing and could reduce the length of much more expensive steel lined sections. Additionally, the method gives possibility to estimate the amount of lost - leaked out - water.

2. ANALYTICAL METHOD

2.1 Seepage in pressure tunnels

Fragmenting rocks surrounding the tunnel and concrete lining are assumed to be pervious material (Figure.1). There are a number of empirical, analytical, numerical solutions that can be used to estimate seepage loss in the support, but with restrictions (Seeber, 1985; Schleiss, 1997 ; and Nam and Bobet, 2006).

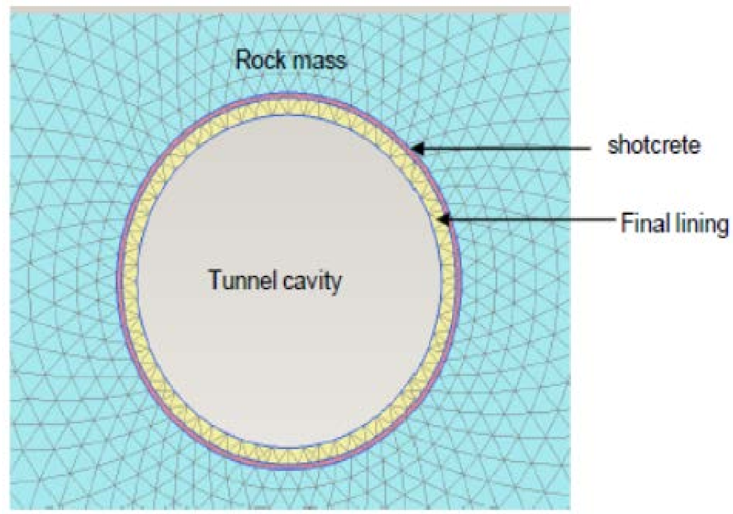

Figure.1. Schematic diagram for tunnel and ground

The seepage potential field formed by water in pervious material is

$$H = \frac{p}{\gamma} + y \tag{1}$$

Where p is the water pressure, γ is the specific gravity of water, and y is the vertical coordinate of the studied point.

The seepage volumetric forces, formed by the gradient of water pressure, are:

$$P_x = \frac{\partial p}{\partial x} = -\gamma \frac{\partial H}{\partial x} \tag{2a}$$

$$P_y = \frac{\partial p}{\partial y} = -\gamma \frac{\partial H}{\partial y} + \gamma \tag{2b}$$

The increments of seepage volumetric forces in time interval Δt are:

$$\Delta P_x = -\gamma \frac{\partial(\Delta H)}{\partial x} \tag{3a}$$

$$\Delta P_y = -\gamma \frac{\partial(\Delta H)}{\partial y} \tag{3b}$$

$where\ \Delta H = H_{i+1} - H_i$ i.e. the head difference between the water head at time $(i+1)\Delta t$ and that at time $i\Delta t$.
Seepage becomes more significant if cracks exist in the lining and water leak-out to the surrounding rock mass resulting in loss of energy (Seeber, 1984, Hendron et al, 1987, Fernandez, 1994, Bobet and Nam, 2007, and Kang et al., 2009).

The respective equations for estimating the water pressure at any point in a cracked liner and the pressure gradient has given by (Kai Su and He-gao Wo, 2010) are:

$$p = \frac{p_1(R-r_p)+p_2(r_p-r)}{R-r} \tag{4a}$$

$$\frac{d_p}{d_r} = \frac{p_2-p_1}{R-r} \tag{4b}$$

Where p_1 and p_2 are inner and outer liner pressures respectively while r and R are the corresponding radii.

Water losses through concrete liner, grouted zone and rock mass zone are computed iteratively from equation 5 (Schleiss, 1987).

$$\frac{p_i}{\rho_w g} - \left(\frac{3}{4} r_g\right) = \frac{q}{2\pi K_r} ln \frac{q}{\pi K_r r_g} + \frac{q}{2\pi}\left[\frac{1}{K_c} ln\left(\frac{r_a}{r_i}\right) + \frac{1}{K_g} ln\left(\frac{r_g}{r_a}\right)\right] \tag{5}$$

where p_i is the internal water pressure

q is the seepage loss.

$K_r, K_c\ and\ K_g$ are permeability coefficients for rock mass, concrete and grouted rock zone respectively.

$r_i, r_a\ and\ r_g$ are internal, external and grouted zone radii with reference to the centre of the tunnel.

The calculated internal water pressure (absorbed by the lining) during operation of the tunnel by applying a safety factor is given by (Seeber, 1984)

$$p_i^{out} = f.s \times p_i \frac{r}{R} \tag{6}$$

where r and R are the tunnel internal and external radii.

3. METHODOLOGY

3.1 Numerical simulation

Finite Element computer program for two dimensional coupled stress-seepage analyses is used in this paper. A tunnel section of Ermenek pressure tunnel in Sothern Turkey has been used for computational method. In the first project stage the simulation of different phenomena and loading condition were carried. Seepage through the cracked concrete is studied on small models. Finally, the partial results are summarized in the numerical simulation of stresses in the lining due to internal water pressure and operation of the pressure tunnel.

Calculation results is compared with the values collected from the tunnel projects and validated using analytical design methods in case of seepage through cracked concrete lining.

The modeled tunnel was excavated in rock mass with overburden depth of 200m above the ground surface. The excavation was done using tunnel boring machine (TBM) and with installing the primary lining behind it. The flow chart of numerical design of pressure tunnel in this study is shown in Figure 2.

3.2 Simulation algorithm

(1) Simulating the process of excavation, the initial stress field of the surrounding rock of the tunnel subjected to gravity by using load relieving method. The Mohr-Coulomb failure criterion is used in elasto-plastic analysis of the surrounding rock of the tunnel during this step.
(2) 2D simulations of 3D arching effect of the excavation around the tunnel face and the description of the influence on the deformation in the tunnel.
(3) Installation of shotcrete lining.
(4) Modelling of final lining as triangular element.
(5) Grout modelling.
(6) Operational loading of varying internal water pressure with concrete permeability.
(7) Parametric/sensitivity analysis.

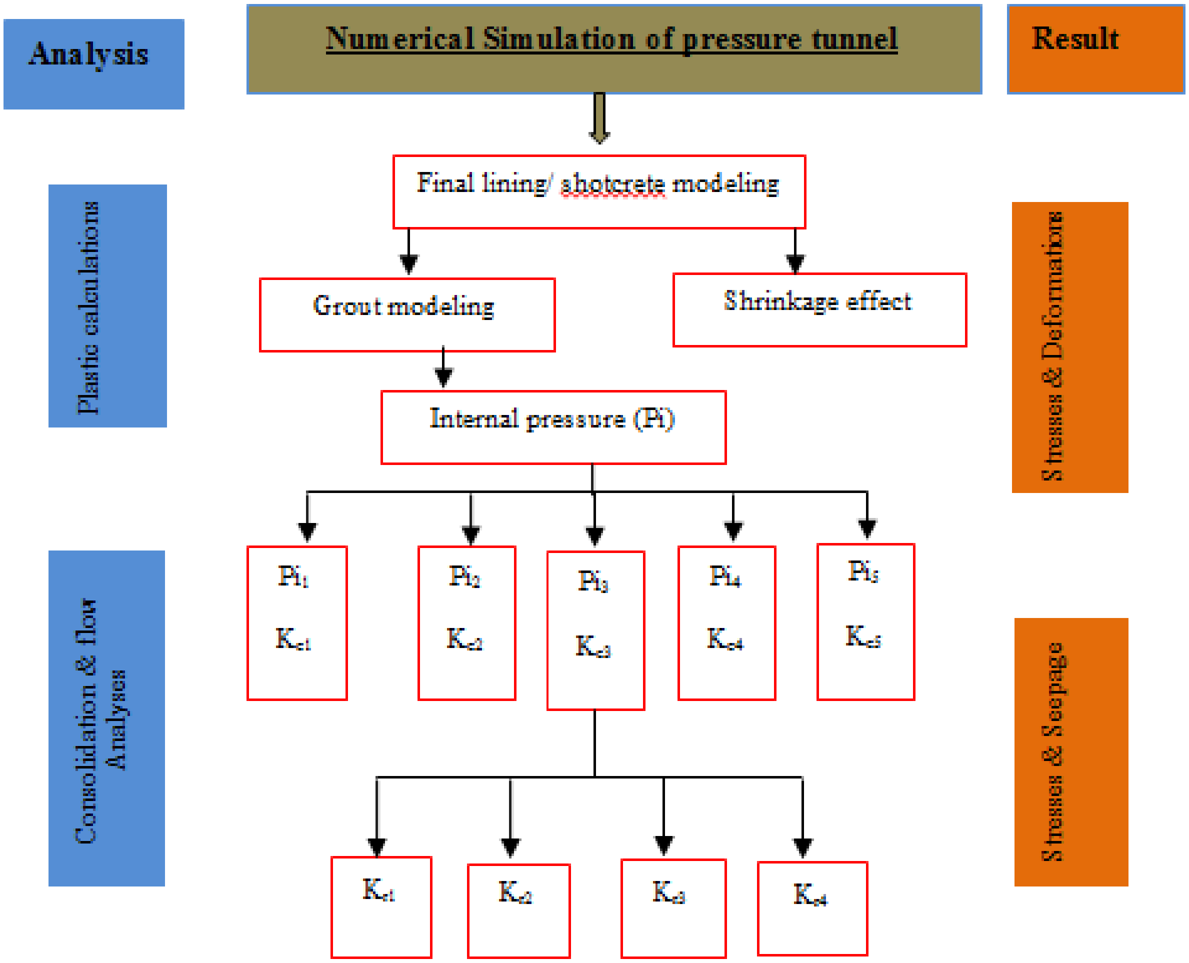

Figure 2: Flow chart for numerical analysis of pressure tunnels

3.3 Tunnel geometry/Material properties:

The tunnel is excavated by the tunnel boring machine (TBM) with following main geometry data: overburden height of 200m; internal radius of 3m and groundwater level is below the tunnel.

In this study, the rock mass is defined as elastoplastic material, with yield function defined by Mohr - Coulomb model. Since long term deformation is of interest, the material behaviour is set to *drained condition*. The rock input parameters are presented in Table 1.

Table 1: Material Parameters

Parameters	Symbol	Rock mass	Shotcrete	Final lining	Unit
Modulus of elasticity	E	10	20	30	GPa
Poisson's ratio	υ	0.20	0.22	0.22	-
Unit weight	γ	26	24	24	kN/m^3
Frictional angle	ϕ	40	40	40	°
Cohesion	c	1000	1000	1500	kN/m^2
Thickness of lining	d	-	0.1	0.3	m
Weight	w	-	2.4	7.2	kN/m/m
Thermal coefficient	α		1.2×10^{-5}		$/\,^\circ C$

3.2 Mesh generation

Mesh consists of 15-nodes as the basic element type. The global mesh is set to fine and, clusters and lines refined (Figure. 3).

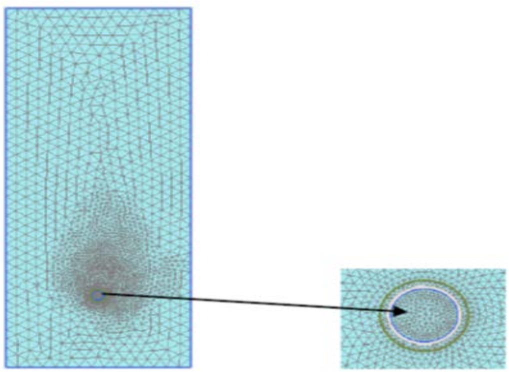

Figure 3: Meshing of FEM model and boundary conditions

3.4 Parametric/sensitivity analysis

Case 1: Simulation of the effect of water pressures on stresses in the liner (consolidation analysis)

$p_{i1} < p_{i2} < p_{i3} < p_{i4} < p_{i5}$ and
$K_{c1} = K_{c2} < K_{c3} < K_{c4} < K_{c5}$

Case 2: Simulation of seepage flow in final lining due to high internal water pressure (seepage flow analysis)

$p_{i1} = constant$ and $K_{r1} < K_{r2} < K_{r3} < K_{r4}$

4. RESULTS AND DISCUSSION OF RESULTS

4.1 Modeling result

Figure 4 shows that prestressing of the rock mass produced about 85% increase the bearing resistance in the lining. The prestressing effect provides external pressure acting upon lining increases the stiffness of the rock mass and reduces rock permeability.

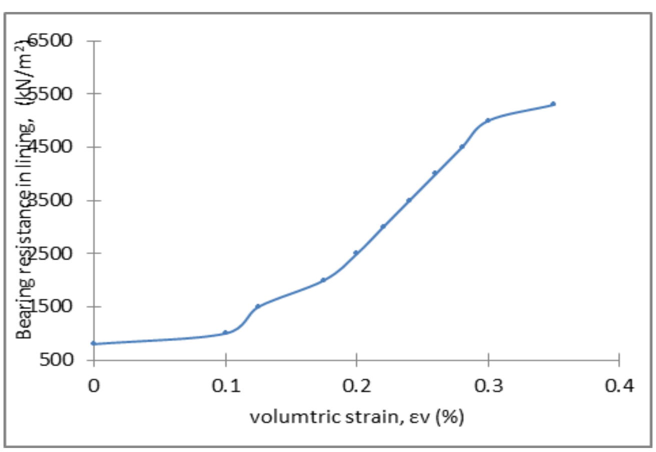

Figure 4: Prestressing Effect on Final Lining

The result change of internal water pressure on stresses in the lining, grouted zone and rock mass zone is presented in Table 2.

Table 2: Stresses σ_3 (kN/m^2) in the Elements (crown)

Pressure (bars)	Stress in Lining (Element 2715)		Grouted zone (Element 1650)		Rock zone (Element 120)	
	σ_1	σ_3	σ_1	σ_3	σ_1	σ_3
10	1678	605	9042	1572	6283	2324
20	1758	21*	9022	2160	6367	2230
25	2194	4*	9024	2548	6424	2172
30	2577	1.5*	9024	2927	6484	2112
35	2980	0.3*	9026	3310	6545	2053

*cracks in concrete (tensile strength of concrete is exceeded)

The lining is found to be compression with 10 bars internal water pressure and (no crack is visible). Further increase of water pressure in the tunnel results in tension crack (Appendix A). This implies that 18 bars of internal water pressure have been found to initiate the cracks, i.e. the tensile strength of the lining is exceeded. As the inner pressure in the tunnel is increased, the stiffness matrix of the element will change as soon as concrete cracks. In order to understand the transition of concrete stresses from compression to tension and obtain the point of initiation of cracks, the internal water pressure is gradually increased from (10, 12, 16, 18,20,25,30 and 35 bars). Increase in pressure increase the number of cracks as well as sizes thereby changing stress field (Figure.7). Thereby resulting in change in permeability.

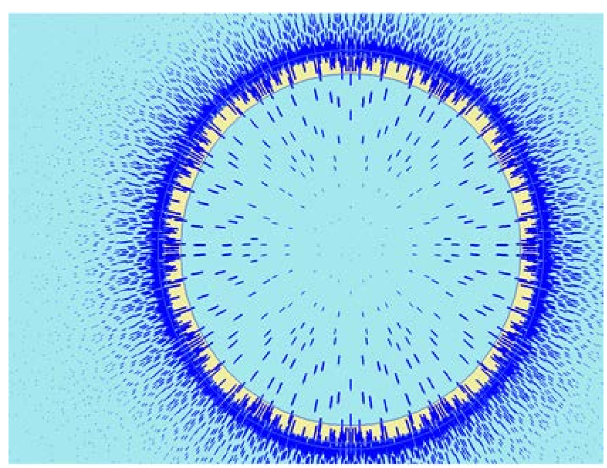

Figure 5: Flow pattern of seepage out of tunnel

The prestressing effect increases the bearing capacity of the rock mass which reduces the tensile stresses in the lining (Figure. 4). Increase in tensile stresses by water pressure lead to decrease in compressive stresses in the lining. Sensitivity analysis of variation of rock mass permeability on seepage flow through lining, grouted zone and rock mass zone is presented in Table 3 and the flow pattern in Figure.5.

Table 3: Seepage through the Lining and Ground

S/N	K_c/K_r	Seepage, $q \times 10^{-6} m/s$		
		Lining (Element 1137)	*Grouted zone* (Element 893)	*Rock zone* (Element 1089)
1	1.000	6.162	2.96	5.735
2	0.100	9.474	8.261	10.077
3	0.020	9.329	10.318	12.140
4	0.002	8.821	56.280	66.977

The extent of the reach of the seepage outside the grouted zone for rock of higher permeability is as shown in (Figure.6).

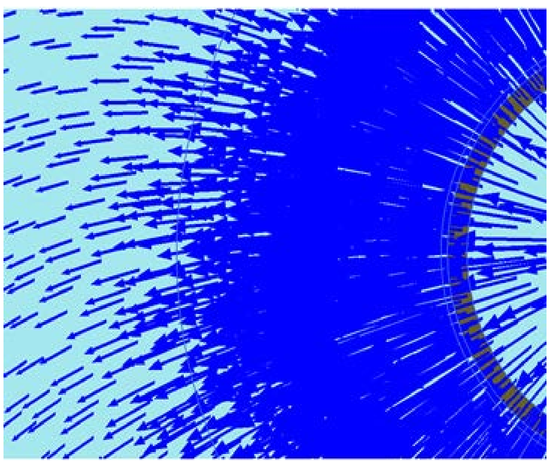

Figure 6: Reach of Seepage Out of Grouted Zone of Tunnel

The porewater pressure in the grouted zone increase with increase in inner pressure and attain its peak value at 20 bars pressure correspondence (Figure.7). The different between the internal water pressure and pore pressure at the contact of the lining - surrounding rock mass decrease leading to decrease in tensile stress in the lining while the suction pressure is constant. Based on continuity of flow, increase in the magnitude of hydraulic pressure at the liner - rock boundary will tend to attain equilibrium. This is because the rate at which water is leaking through the cracked lining is more than the rate at which it seeps into the surrounding rock mass due to prestressing effect. The prestressed rock provides the lining good resistance to the inner water pressure by reducing the rock permeability and increasing the compressive strength of the concrete (Table 3). This explains why there is no significant difference in tensile stress in the lining under such high internal water pressures of 30 and 35bars.

Even though, it has been established that the lining is fully in compression for ($p_i = 10\ bars$), seepage of water is seen through the liner which confirms concrete liner as permeable (Appendix B).

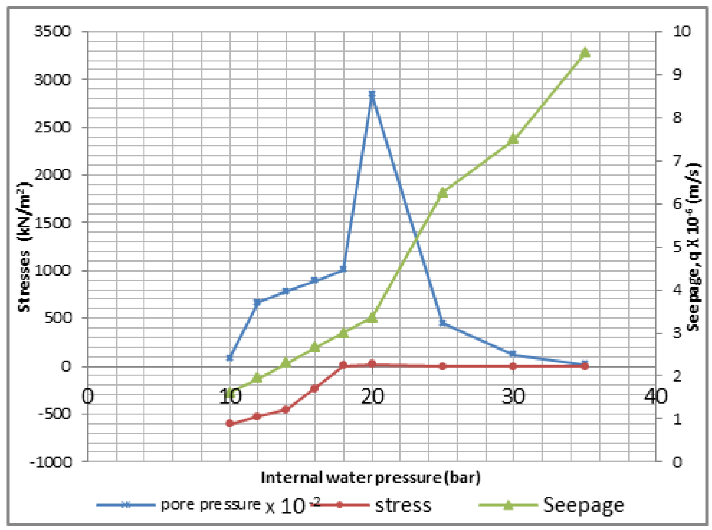

Figure 7: Pore pressure, Stress -seepage transformation in lining and internal water pressure

The water force (Figure. 8) support the body force theory of Schleiss, (1986, 1987), Kang et al, (2009) and Kai Su and He-gao Wu, (2010).The increase in internal water pressure ($p_i = 18\ bars$) cracked the concrete (this is comparable maximum allowable pressure of 20 bars from analytical solution of Seeber (Figure. 9). This results to increased seepage flow through the liner to the grouted zone. The change in permeability is introduced for each simulation to reflect reality because change in seepage flow corresponds to change in permeability of the liner due cracking. It can be observed that at such high inner pressure of 25, 30 and 35 bars, the seepage losses are not significantly different (Figure. 10).

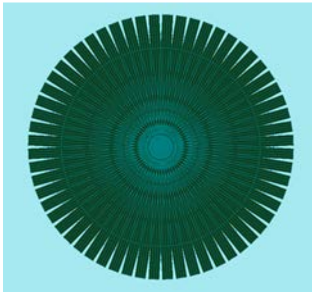

Figure 8: Water Force on the Liner Transmitting along Seepage Line as Body Force

This is an indication of steady state of flow because all leaked out water are confined within the grouted zone with concentration at the liner - rock boundary (Appendix B).

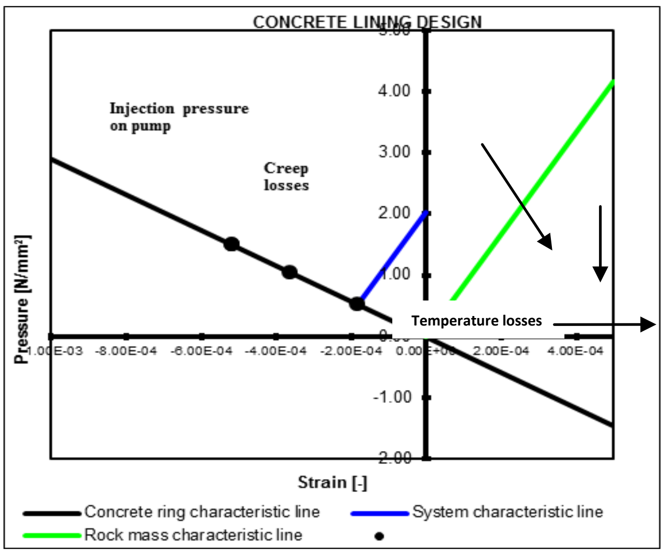

Figure 9: Seeber Analytical Solution

The result showed less difference in seepage losses through the lining at high inner pressure. This is because the prestressed rock around the concrete tunnel reduced water losses and produced external pressure that, acts as a contra-pressure. Thereby, result in reduction of tensile stresses in the concrete lining (Table 2).

By superimposing the consolidation and groundwater flow analyses showed that change in internal water pressure (of cracked lining) result to change in stress field, which, in turn, result to change in permeability of the lining and seepage flow. The performance and accuracy of the model results tested by carrying out seepage analysis using Schleiss analytical solution confirm the validity of the numerical results (Figure. 10). The water losses or leakage in the tunnel were found to be in range of values ($1\ to\ 2\ l/s/km/bar$) specified by Schleiss irrespective of the internal pressure (Figure. 11).

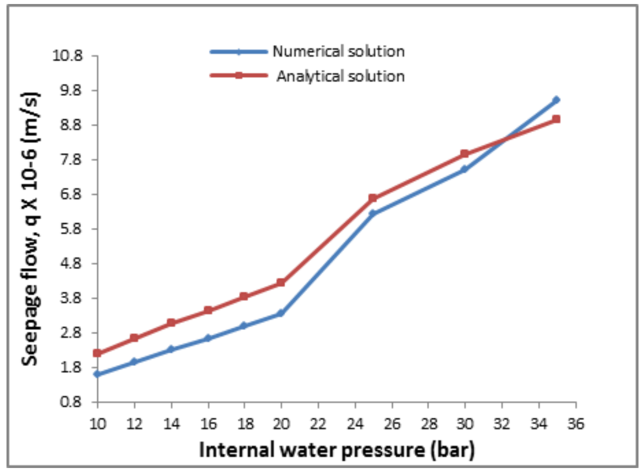

Figure 10: Inner Water Pressure and Seepage in Pressure Tunnel

4.1.1 Seepage flow analysis

The result showed that the efficiency of grouting is dependent on the permeability coefficient of the rock mass. The seepage through the lining has been reduced by prestressing of the lining even with the rock permeability is increased (Table 3). Since the prestressing reduced the rock permeability by increasing its strength, hydraulic pressure is built up behind the concrete lining. Hence, seepage through the rock tends to reduce gradually, this account for drop in seepage flow (Table 3). The reduction in seepage flow through rock increases the hydraulic pressure and result into strain relief in the lining. However, the reach of seepage flow extends beyond the grouted zone into the un-grouted rock mass (Appendix C). This is associated to high permeability assigned to the rock mass during simulation.

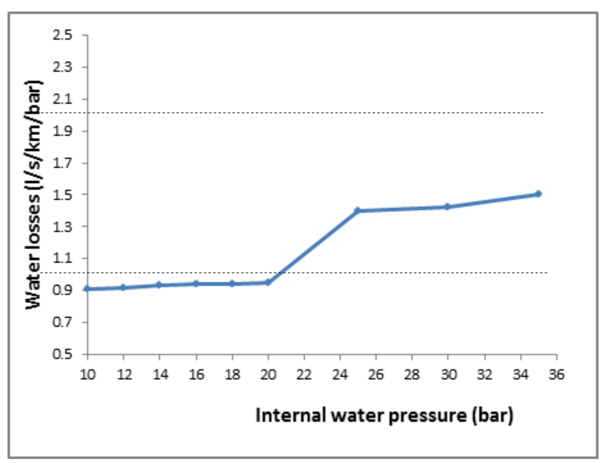

Figure 11: Water losses in the pressure tunnel

5. CONCLUSIONS

The main goal of this research was to optimize the use of plain concrete lining in the construction of pressure tunnel in a stable rock formation site. In this research, loading operation in pressure tunnel is simulated. Based on the 2D elasto plastic finite element method, a coupled stress - seepage numerical design of pressure tunnel is studied to simulate the cracking process in the lining of plain concrete pressure tunnel.The coupling of stress - seepage in pressure tunnel is complex because of the changes in behaviour of material. The effect of internal water pressure on the lining has been studied. The cracks encountered from high internal water pressure are simulated.

The hydraulic-mechanical interaction due to change in stress in cracked liner change permeability which results to change seepage flow in the rock zone. The stress field and seepage field affect each other while trying to attain a state of equilibrium. The water flowing out of cracked concrete changed the material behaviour of concrete, the leaked out water were found to be in the usual and accepted range in practice even though with higher internal water pressure. The proposed method apart from optimizing the use of plan concrete is capable of assessing the performance of lining, predicting the effect of internal pressure on the lining, reach of seepage through lining to the surrounding rock mass as well as estimating the leakage in pressure tunnels.

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