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Hydro-mechanical interaction analysis of reinforced concrete lining in pressure tunnels

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ABSTRACT

Concrete-lined pressure tunnels under high internal water pressures require to be reinforced to withstand failure. Since these tunnels exert the sources of water flow to the rock formations, a suitable arrangement of lining reinforcement is required to minimize water losses from the tunnel. A simulation of this hydro-mechanical interaction can be implemented based on a direct-coupled method using the ABAQUS finite element program. In addition, a subroutine code has been developed to evaluate the influence of internal water pressure on the permeability coefficient variation of porous media. In the present study, the reinforcement distribution in the lining is investigated to limit water losses from the tunnel. To verify the proposed model, the numerical and analytical solutions are compared based on the elastic behavior of the media and a reasonable agreement is obtained. The results of the structural nonlinear analysis indicate that water losses from the tunnel remain at a lower amount with small diameters and spacing in the concrete lining for at the same percentage of reinforcement.

1. Introduction

Pressure tunnels are constructed to convey water to hydroelectric powerhouses and to supply water for downstream purposes. Ensuring the stability of the tunnel structure and limiting water losses are the two main concerns in the design of pressure tunnels. The conventional design criterion, as recommended by Brekke and Ripley (1987), suggests that the minimum principal stress around the pressure tunnel should be 1.3 times greater than the internal water pressure in order to prevent the occurrence of hydraulic jacking. If this criterion is not satisfied, steel lining is thus the only applicable method to prevent hydraulic jacking. However, using steel linings in these structures increase the cost and the time of construction (Zhou et al., 2015). Therefore, minimizing the tunnel length with steel lining is an important element in the design of pressure tunnel. Further, the need for a more economical design has marked a shift from steel linings to other alternatives, such as concrete linings (Simanjuntak et al., 2014).

Cracks most often occur in tunnels either during or shortly after the first filling of pressure tunnels, because the tensile stress exceeds the tensile strength of the concrete lining. With the development of crack in the concrete lining, inner water leaks through the rock mass. Thus, we should consider the hydro-mechanical interaction of the fluid with porous media, because high water pressure with changes of stress distribution leads to changes in the permeability coefficient, which in turn leads to seepage redistribution in the lining and the surrounding rock mass (Schleiss, 1986, 1997; Olumide, 2013).

In stable rock conditions, plain concrete lining should be prestressed using consolidation grouting in order to limit water losses. On the other hand, in unstable rock conditions, the concrete lining should be reinforced to resist to external loads leading to failure and to prevent water losses from the tunnel. Ahmadi et al. (2007) presented a model using Schleiss technique (1986) within the FEM framework for the stability analysis and the optimum design of pressure tunnels. The researchers explained that to enhance the safety, an increase in the reinforcing percentages is more effective than the increase in the lining thickness.

Zhang et al. (2008) presented analysis of pressure tunnels based on elasto-plastic behavior of surrounding rock mass considering nonlinear softening liner. These researchers have taken the influence of intermediate principal stress in their models and presented their results for the ideal plastic and brittle model. Simanjuntak et al. (2012) studied a coupled stress-seepage numerical design of the concrete lining of the pressure tunnel using the thick-walled porous cylinder theory. Olumide and Marence (2012, 2013) proposed a coupled seepage-stress based on

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a 2D finite element analysis (FEA) for simulating the hydro-mechanical interaction. They solved the problem by superimposing results of consolidation and water flow analyses. Parvathi et al. (2013) investigated the effect of rock mass quality and tunnel size on the lining of the pressure tunnels using finite element method (FEM). In their research, they presented the total amount of tension and compression required in lining design. The researchers found that in order to prevent cracking propagation and deformation, the reinforcement should be designed carefully based on the behavior of the rock mass and the in situ stress. Moreover, Zhou et al. (2015) developed a water-filled joint element to simulate the conditional interaction between the reinforced concrete lining of the high-pressure hydraulic tunnel and the surrounding rock mass. These researchers applied an equivalent coupling method to calculate the hydro-mechanical interaction in a hydraulic tunnel.

In this paper, a three-dimensional finite element method (3D-FEM) is proposed to simulate the hydro-mechanical interaction of the reinforced pressure tunnels. The model takes into account the effect of the stress-dependent permeability of reinforced concrete lining and surrounding rock mass using a coupled pore fluid/stress analysis. Since hydro-mechanical interaction is based on the indirect-coupled method in the majority of the previous works, the direct hydro-mechanical coupling is adopted in the present research as a change in internal water pressure leads to a corresponding change in the volume of the media.

2. Hydro-mechanical interaction

Hydro-mechanical interaction is a complex process in which the inner water seepages through the cracked lining and the porous rock mass (Bian et al., 2009). This interaction aligns itself with the concepts of compatibility and continuity conditions. The full contact between the concrete lining and the surrounding rock mass after the contact grouting is a concept of the compatibility condition. In addition, there are no tensile strains or tensile stresses in the lining-rock mass interface (Simanjuntak et al., 2012).

On the other hand, continuity conditions help to define unknown water pressure (Schleiss, 1997). The mechanism of the internal water pressure acting on the concrete lining and the rock mass is based on the body force theory. When analyzing the lining of pressure tunnels, the analytical solutions presented by Schleiss (1986, 1997) and Fernandez (1994) seem to be more appropriate comparing to real behavior. Through these approaches, the computations are performed by assuming concrete lining and the surrounding rock as an elastic, homogeneous, and isotropic material. The main difference between these approaches is in simulating the seepage flow from the tunnel.

Before lining cracking, the permeability coefficient of reinforced concrete lining is very small and the pore water pressure in the lining has a logarithmic distribution (Schleiss, 1986). The pore water pressure at any point of the concrete lining is computed by the following equation:

$$p = \frac{p_1(lnr_2 - lnr) + p_2(lnr - lnr_1)}{lnr_2 - lnr_1} \tag{1}$$

where p_1 and p_2 are the water pressure on the inner side and the outer side of the concrete lining, r_1 and r_2 are the internal and the external radius of the lining, respectively; and r is the distance from the center of the tunnel to the point where the pore water pressure is to be estimated (Zhou et al., 2015).

When the internal water pressure increases, the concrete lining will crack as soon as the tensile stress in the concrete lining exceeds its tensile strength (Zhou et al., 2015). There is an approximate linear water pressure distribution through the lining, which is obtained at any point in a cracked lining (Schleiss, 1986):

$$p = \frac{p_1(r_2 - r) + p_2(r - r_1)}{r_2 - r_1} \tag{2}$$

The water losses through rock mass in a tunnel above groundwater level are obtained (Schleiss, 1997):

$$\frac{P_a}{\rho_w.\ g} - \left(\frac{3}{4}r_a\right) = \frac{q}{2\pi.\ k_r}.\ ln\frac{q}{\pi.\ k_r.\ r_a} \tag{3}$$

in which q is the water loss through rock mass (m^3/s), g is the gravitational acceleration (m^2/s), r_a is external radius of lining (m), k_r and k_c are permeability coefficients for the rock mass and concrete lining (m/s) respectively, and P_a is the water pressure on the outer side of the concrete lining (bar), which is obtained as:

$$P_a = \frac{P_i}{1 + (k_r.\ (ln\frac{r_a}{r_i}))/(k_c.\ (ln\frac{R}{r_a}))} \tag{4}$$

where P_i is internal water pressure (bar) and R is external radius of the rock zone affected by the seepage (Olumide, 2013).

Fernandez (1994) estimated the pore pressure distribution caused by the internal water pressure at an arbitrary point around the concrete lining using the image-well method. In this method, the magnitude of the seepage flow into the lining is obtained as:

$$q = \frac{2\pi k_c(h_i - h_{w1})}{ln\frac{b}{a_1}} \tag{5}$$

in which q is the water losses into the rock mass per unit length of the tunnel (m^3/s), h_i is the pressure loss across the rock mass (m), h_{w1} is the hydraulic head at the rock-liner boundary (m), and k_c is the permeability of the lining (m/s).

2.1. Modification of permeability coefficient after cracking

Neglecting the change of permeability coefficient, the problem will be simplified to the case that was solved by Schleiss (1986) and Fernandez (1994). When cracks occur in the concrete lining at high water pressure, the properties of the concrete lining will change and as a result, the permeability characteristic and the constitutive model of the concrete lining should be reconstituted (Bian et al., 2009). Therefore, the stress dependent permeability of the lining and surrounding rock mass in pressure tunnels should be considered.

The permeability controls the rate of seepage flow in porous and fractured media. Although permeability represents an original geometric property of the porous medium, it can be changed when subjected to the stress variations. For homogeneous porous media, the permeability variations can be associated with the stress changes. Instead of change in aperture, changes in either void space or grain volume are the typical consequence that leads in permeability changes (Bai et al., 1997). This permeability coefficient change can be expressed as:

$$k = k_0\left[\left(\frac{1}{\varnothing_0}\right)(1 + \varepsilon_v)^3 - (\frac{1-\varnothing_0}{\varnothing_0})(1 + \varepsilon_v)^{-(1/3)}\right]^3 \tag{6}$$

where k_0 is the initial permeability coefficient (m/s), ε_v is the volumetric strain corresponding to the evolution of plasticity, and $\varnothing_0$ is the initial void ratio (Jun et al., 2013; Ying et al., 2014). Also, an increase in permeability coefficient of concrete lining based on continuum damage evolution is given (Cabot et al., 2009):

$$k = k_0.\ exp[(\alpha.\ D)^{\beta}] \tag{7}$$

where k and k_0 are respectively the current and the initial material permeability, α and β are the parameters fitted by the author to 11.3 and 1.64 respectively, and D is the damage variable of the concrete lining.

To represent mechanical responses of the concrete lining in tension and compression, the damage variable is divided into two parts: $D = \alpha_t D_t + \alpha_c D_c$, in which D_t and D_c are the damage variables in tension and compression, respectively. These variables are combined with