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Impact of construction phase on the interaction between lining and rock mass in pressure tunnel and shafts

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ABSTRACT: Designing the lining of pressure tunnels is a complex engineering task, requiring careful consideration of both hydraulic and mechanical factors and the complex reaction between the lining and the surrounding rock mass. The design must minimise head losses, prevent excessive leakage, eliminate the risk of hydraulic fracturing or displacement of the rock, and ensure long-term structural integrity during filling, commissioning, operation, and de-watering phases. In reinforced concrete-lined pressure tunnels or shafts, when the internal water pressure exceeds the external groundwater pressure, the differential pressure in distributed between the lining and the surrounding rock mass. The load distribution depends on the stiffness and hydraulic conductivity of both the undisturbed and disturbed rock mass zones, as well as the properties and behaviour of the lining. Commonly used analytical methods, such those proposed by Fernandez (1994) and Schleiss (1986, 1997), assume that the water pressure on the extrados of the lining just before first filling is equal to the height of the existing groundwater level. However, this assumption does not accurately reflect the actual changes in groundwater pressure caused by tunnel excavation. In reality, the water pressure on the extrados of the lining can be significantly lower than the initial groundwater pressure. This discrepancy between the real groundwater pressure and the assumed value in these analytical methods can lead to unsafe lining design for pressure tunnels.

1 INTRODUCTION

Hydropower and pumped hydro projects are a highly relevant sources of renewable energy and play a crucial role in the provision of sustainable energy supply and storage. The design of pressure tunnels is one of the most critical technical challenges of this type of projects.
If the intrados of a pressure tunnel has higher water pressure compared to the extrados, the support of the differential water pressure will be split between the lining and the surrounding rock mass. The distribution of the load between the lining and the rock mass depends on the stiffness and hydraulic conductivity of both. Structural cracking of the lining occurs when the stresses in the concrete exceed its tensile strength. In general, stiffer rock masses will absorb a larger portion of the differential water pressure, reducing the likelihood of lining cracks. When designing a reinforced lining, the primary objective is to determine the most economic thickness of the lining and the density of reinforcement, while also ensuring that the width of cracks caused by differential water pressure remains within a specified limit.

Commonly used analytical methods, such those proposed by Fernandez (1994) and Schleiss (1986, 1997), assume that the water pressure on the extrados of the lining just before first filling is equal to the height of the existing groundwater level. However, this assumption does not accurately reflect the actual changes in groundwater pressure caused by tunnel excavation. In reality, the water pressure on the extrados of the lining can be significantly lower than the initial groundwater pressure due to active drainage during the construction. Therefore, the differential pressure between intrados and extrados of the lining can be higher than the assumption made in the analytical methods. This paper examines this issue in greater detail using a numerical model of a typical pressure tunnel. The findings offer additional insights into the safe design of reinforced concrete linings for pressure tunnels and shafts.

2 ANALYTICAL FORMULATIONS

Jaeger (1979) used thick elastic cylinder theory to calculate the magnitude of the stress transmitted from the concrete lining to the rock surface (P_{fa}) due to the water pressure (p_i) acting to the intrados of a pressure tunnel/shaft (Figure 1).

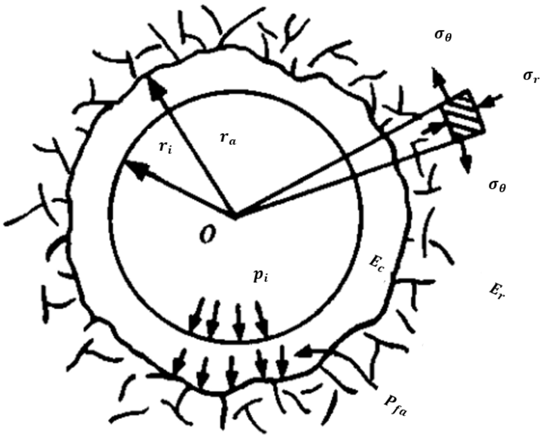

Figure 1. Schematic of boundary conditions considered in Jaeger's (1979) formulation.

Legend:
- r_i…internal tunnel radius
- r_a…external tunnel radius
- E_c and E_r …elastic modulus of the concrete lining and the rock
- m_c and m_r…the inverse of Poisson ratio for the concrete lining (ν_c) and rock (ν_r)
- λ …ratio of the transmitted stress to the internal water pressure.
- p_i…internal pressure inside the tunnel

The formula to calculate the stress transmitted from the concrete lining to the rock surface, applicable for a pressure tunnel/shaft below the groundwater (wet rock) with no consideration of a disturbed zone around the tunnel is presented in Equation (1).

$$P_{fa} = \lambda p_i = \frac{\frac{2r_i^2}{E_c(r_a^2-r_i^2)}}{\frac{m_r+1}{m_r E_r}+\frac{(m_c-1)r_a^2+(m_c+1)r_i^2}{m_c E_c(r_a^2-r_i^2)}}(p_i - P_a) \qquad (1)$$

where p_a is the groundwater pressure acting on the extrados of lining which is assumed to be equal with the original groundwater pressure. Jaeger (1979) also proposed the following equation to calculate the tensile stress developed in the lining:

$$\sigma_t = -\frac{r_a^2+r_i^2-2\lambda r_a^2}{r_a^2-r_i^2}(p_i - P_a) \qquad (2)$$

Fernandez (1994) developed his method by establishing analytical formulations to determine the pore pressure changes in the rock mass due to the water pressure difference ($\Delta p_w = p_i - p_a$) between intrados and extrados (caused initially by the existing groundwater head) of the concrete lining as follows:

$$P_{fa} = \lambda \Delta P_w = \frac{\Delta P_w}{1+\frac{E_c\, t_c}{E_r\,(r_i+{}^{t_c}/_2)}(1+\nu_r)} \qquad (3)$$

The design method proposed by Fernandez (1994) relies on the tensile strain developed in the lining. Following formulation can be developed to calculate the induced tensile stress by combining the formulation presented in Fernandez (1994) and stress-strain relationships in cylindrical coordinate.

$$\sigma_t = E_C * \left[\frac{\Delta P_w}{\left(1+\frac{E_c}{E_r}*\frac{t_c}{\left(r_i+{}^{t_c}/_2\right)}(1+\vartheta_c)\right)}\frac{(1+\vartheta_r)}{E_r}\right] + \vartheta_c \Delta P_w \qquad (4)$$

Schleiss (1986, 1997) used the porous thick elastic cylinder theory to formulate the magnitude of stress transmitted to the rock surface. Schleiss assumed that the internal hydrostatic pressure (p_i) generates an excessive pore pressure at the lining extrados and in the rock mass and proposed the following equation to calculate the transmitted stress to the rock surface.

$$P_{fa} = \frac{\{(p_i - p_a)[\frac{2(2-\vartheta_c)}{({r_a}/{r_i})^2 - 1} + \frac{1-2\vartheta_c}{1-{r_i}/{r_a}}] - 3\left(\frac{E_c(1+\vartheta_c)}{E_r(1+\vartheta_c)}\right)p_a\}}{3[\frac{2(1-\vartheta_c)}{({r_a}/{r_i})^2 - 1} + \frac{E_c(1+\vartheta_r)}{E_r(1+\vartheta_c)} + 1 - 2\vartheta_c]} \quad (5)$$

Schleiss (1997) also proposed the following formulation to calculate the magnitude of tensile stress developed in the lining:

$$\sigma_t = \frac{(p_a - p_i)(2-\upsilon_c)}{3(1-\upsilon_c)}\left[\frac{1+\frac{r_a^2}{r_i^2}}{\frac{r_a^2}{r_i^2}-1} + \frac{1-\frac{r_i(1+\upsilon_c)}{r_a(2-\upsilon_c)}}{1-\frac{r_i}{r_a}}\right] + \frac{2P_{fa}}{1-\frac{r_i^2}{r_a^2}} \quad (6)$$

It should be noted that in Equation (6), the term (p_i) denotes the differential water pressure between the intrados and extrados of the lining, which is equal to $(p_i - p_a)$.

All the analytical methods mentioned above assume that, just prior to the first filling, the groundwater pressure (p_a) acting on the extrados of the lining remains equal to the pre-excavation groundwater pressure and is unaffected by the construction process.

3 DEPRESSURISATION OF GROUNDWATER DURING CONSTRUCTION

In the most cases, the pressure tunnels and shafts are constructed by drained excavation techniques. In drained tunnelling, the groundwater pressure at the excavation boundary drops to atmospheric pressure, creating a hydraulic gradient toward the tunnel and extending groundwater depressurisation beyond the excavation boundary.

The following equation is derived by rearranging the formulation proposed by Fernandez (1994) to calculate the groundwater pressure distribution (depressurisation) along the springline of a circular tunnel lined with concrete, assuming a lining hydraulic conductivity of K_c ($K_c = 1e-9\ m/s$ was used in this paper based on Fernandez, 1994) and atmospheric pressure at the intrados:

$$P_w(r) = h_0 - [(h_0 - h_l) * \frac{Ln\left(1+\frac{L^2}{r^2}\right)}{Ln\left(1+\frac{L^2}{r_a^2}\right)}] \quad (7)$$

where r is the radial distance from the tunnel center, h_0 is the initial groundwater pressure at the tunnel boundary prior to excavation, and h_l represents the groundwater pressure immediately behind the lining, resulting from head loss through the lining. This pressure is a function of the hydraulic conductivities of both the lining and the surrounding rock mass (K_r), as expressed below:

$$h_l = \frac{h_0}{1+\left(\frac{Ln\left(\frac{2*h_0}{r_i}\right)}{Ln\left(\frac{r_a}{r_i}\right)}\right)*\left(\frac{K_c}{K_r}\right)} \quad (8)$$

Equations (7) and (8) were used to calculate the groundwater pressure gradient behind the lining just prior to the first filling (Figure 2) for a tunnel with an intrados radius of 4.93 m and a lining thickness of 0.42 m (resulting in an excavation radius of 5.35 m). It is important to note that the analysis assumes all drainage holes are closed, allowing groundwater pressure to build up behind the lining prior to the filling. In addition to the results from the analytical equations, the plot (Figure 2) also presents results from a simplified numerical model using RS2 (Rocscience©). In this analysis and modelling, the hydraulic conductivity of the rock mass is assumed to be 1e-8 m/s, with an initial groundwater head of 584 m at tunnel level prior to excavation.

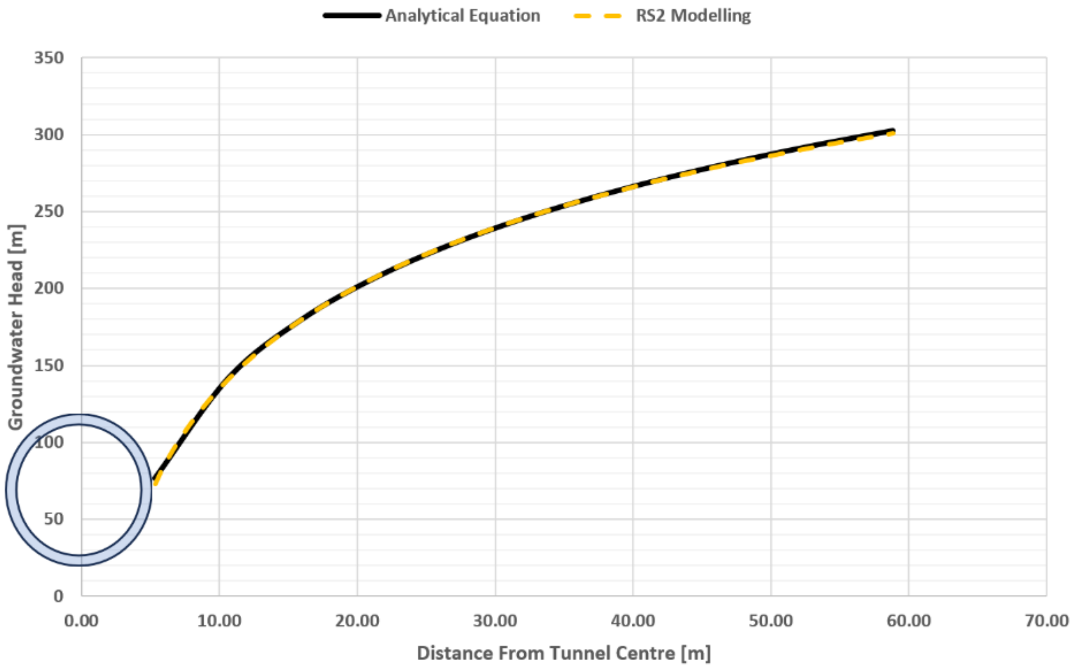

Figure 2. Groundwater pressure distribution behind the lining before first filling

As shown in Figure 2, there is excellent agreement between the results of the analytical equation and the numerical modelling. The results indicate that, when the drainage holes are closed prior to the first filling, groundwater pressure behind the lining reaches approximately 76 m and gradually increases with distance from the tunnel boundary into the surrounding rock mass.

4 INDUCED TENSILE STRESS IN LINING

As previously mentioned, when the internal water pressure in the pressure tunnel or shaft increases during filling and exceeds the external pressure acting on the lining extrados, the resulting differential pressure is distributed between the rock mass and the lining, depending on their relative stiffness and hydraulic conductivity. The commonly used analytical framework for designing linings in pressure tunnels and shafts (Equations 1 to 6) does not account for groundwater depressurisation caused by excavation. To evaluate the impact of this depressurisation on the induced resulting tensile stresses in the lining, numerical modelling was employed. The model considered both the rock mass and the lining as a continuum elastic material with uniform and isotropic properties. Figure 3 illustrates the geometry of the numerical models employed in the comparative investigation presented in this paper. It is important to notice that the consideration of an elastic constitutive model for the rock mass is a conservative approach for the assessment of cracking pressure of linings in pressure tunnels. For the purposes of this study, the rock mass is assumed to have a deformability modulus of 13 GPa ($E_r = 13\ GPa$) and a relatively low hydraulic conductivity of 1×10−8 m/s ($K_r = 1e - 8\ m/s$). The initial groundwater head is 584 m, while the hydrostatic water head inside the tunnel at the end of filling is assumed to be 668 m.

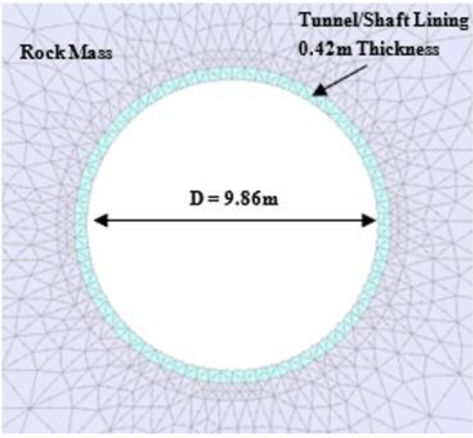

Figure 3. RS2 model used for a typical pressure tunnel.

It should be noted that the filling rate for each pressure tunnel or shaft is determined based on the critical requirement of avoiding significant differential water pressure acting on the lining. This consideration is especially important in lower-quality rock masses, where lower stiffness and higher hydraulic conductivity increase the risk of significant cracking. Consequently, monitoring groundwater pressure in the rock mass behind the lining is essential for designing a safe first-filling strategy, including appropriate filling rates and pauses. Assessing the impact of the filling rate requires more advanced numerical modelling, including an elastic-plastic constitutive model and simulation of the evolution of the lining's hydraulic conductivity. As such, the effect of filling rate is not evaluated in this study. A filling rate of 2 m/h which is common in commissioning of most pressure tunnels was used in this study to avoid unreasonable boundary conditions.

Table 1 presents the results from analytical methods assuming groundwater depressurisation prior to filling. Numerical modelling was used to evaluate both boundary conditions: with and without groundwater depressurisation.

Table 1. Comparison between analytical formulation and RS2 model for full groundwater head acting to the extrados of lining.

Parameter	Without depressurisation				With de-pressurisation
	Method				
	Jaeger (1979)	Fernandez (1994)	Schleiss (1997)	RS2 Model	RS2 Model
Tensile stress in lining [MPa]	-2.13	-2.18	-2.74	-2.3	-6.2

As shown in Table 1, there is a relatively close agreement between the results from the RS2 model and all analytical formulations when the full initial groundwater pressure is assumed to act on the extrados of the lining. Similar consistency between analytical and numerical results was also reported by Zoorabadi et al. (2023).

The induced tensile stress obtained from the numerical model that accounts for groundwater depressurisation prior to filling is approximately three times greater than that from the model which neglects the depressurisation effect. In real cases, when the induced tensile stress exceeds the tensile strength of the lining, cracks may form, leading to an increase in the lining's hydraulic conductivity and allowing greater water leakage. This leakage raises the groundwater pressure at the interface between the rock and the lining. If the pore pressure at this interface exceeds the mechanical pressure transferred to the rock, separation can occur, creating a void that allows pressure equalisation between the intrados and extrados of the lining. This mechanism helps to limit the development of further excessive tensile stress in the lining. Therefore, the induced tensile stress value presented in the last column of Table 1 should be viewed as illustrative only and are unlikely to develop in the lining under real-world conditions.

5 DISCUSSIONS AND CONCLUSIONS

The primary design philosophy for linings in pressure tunnels and shafts is not to prevent cracking altogether, but to control crack width through appropriate reinforcement design. Therefore, it is important to assess the initial cracking stress with adequate accuracy. Tensile stress develops when the internal water pressure exceeds the groundwater pressure acting on the extrados of the lining. Depressurisation caused by water inflow during excavation lowers the groundwater pressure near the tunnel boundary and, in highly permeable rock masses, can even reduce the regional groundwater level. Despite the dynamic nature of groundwater pressure around pressure tunnels, existing analytical design methods for tunnel and shaft linings do not account for the effects of depressurisation. This oversight effectively assumes that the lining acts as an impermeable barrier, which is not accurate. This paper presents an illustrative numerical model to highlight this limitation in existing analytical formulations, aiming to prevent unsafe design of linings for pressure tunnels.

An analytical formulation based on the method proposed by Fernandez (1994) was first developed to calculate the depressurisation profile resulting from drained excavation. The results from this formulation showed excellent agreement with those obtained from seepage analysis using RS2.

Subsequently, the numerical model was extended to evaluate the induced tensile stress in the lining for an illustrative case. While there was strong agreement between the numerical model and the analytical methods proposed by Jaeger (1997), Fernandez (1994), and Schleiss (1997) under conditions without groundwater depressurisation, a significant difference in tensile stress was observed when the effect of groundwater depressurisation was included. These results underscore that neglecting excavation-induced groundwater depressurisation can lead to unsafe designs of concrete linings for pressure tunnels and shafts.

Further investigation into the effects of filling rate, the evolution of the lining’s hydraulic conductivity, and potential gap formation during filling requires more advanced coupled hydro-mechanical numerical modelling. This will be the focus of the author's ongoing research and will be presented in future publications.

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