South African National Committee on Tunnelling

SANCOT SYMPOSIUM 2026

13-14 APRIL 2026
SOUTHERN SUN ROSEBANK, JOHANNESBURG

Unlocking Africa's Potential: Advances in Tunnelling in Civil Engineering and Mining

Preliminary Programme

Conference Day 2 – Tuesday 14 April 2026

Session 4
Session Chair:

09:45-10:05	**Lining design for pressure tunnels and shafts focusing on more reliable crack spacing and crack width calculations** M. Zoorabadi, *SMEC, Australia*
10:05-10:25	**Pressure tunnel/shafts – risk of oversimplifications or overdesigning** M. Zoorabadi, *SMEC, Australia*
10:25-10:45	**Mid-Morning Refreshments**

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Lining Design for Pressure Tunnels and Shafts: Focusing on more reliable crack spacing and crack width calculation

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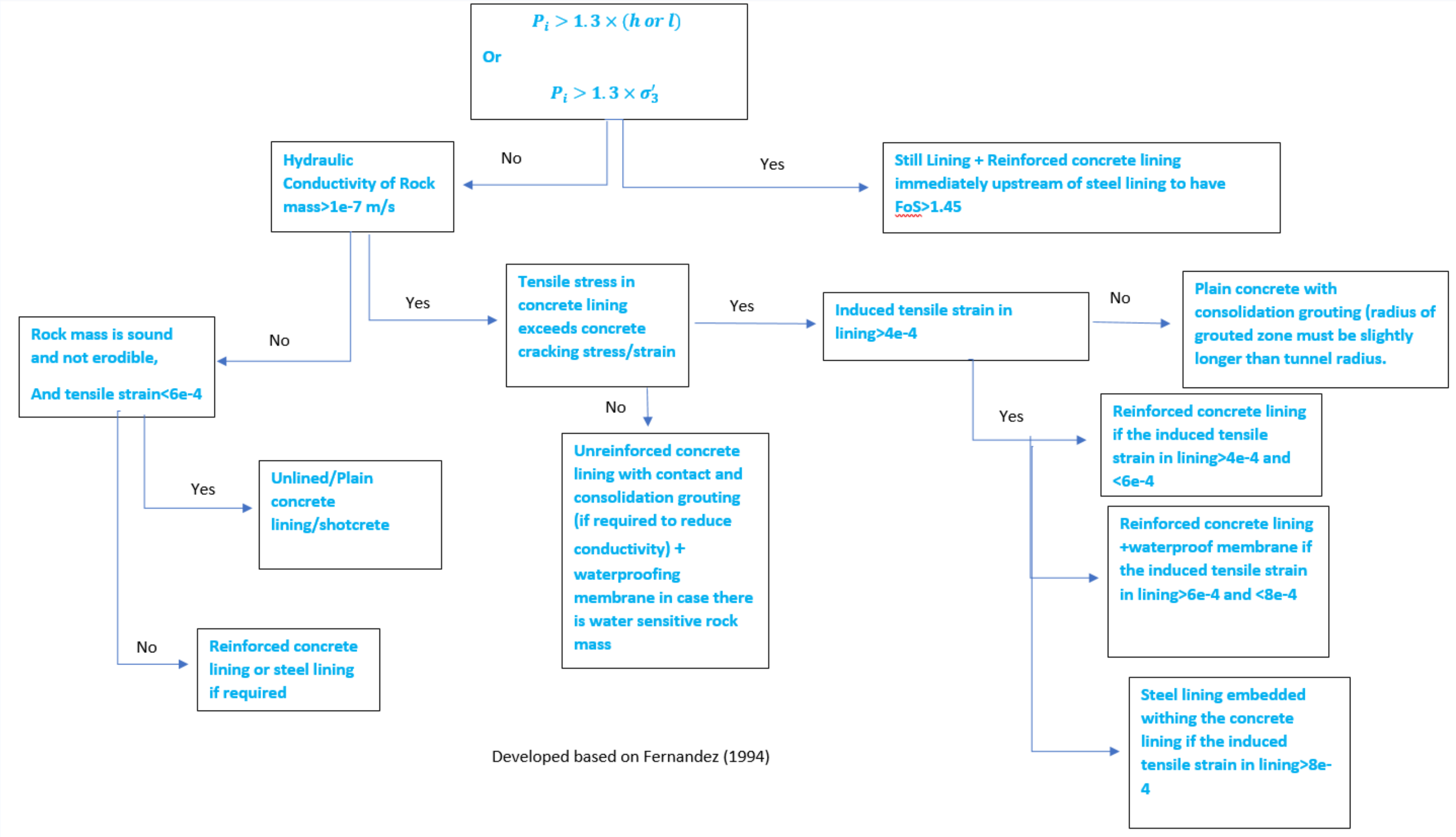
Chief Technical Principal – Underground Space and Rock Engineering

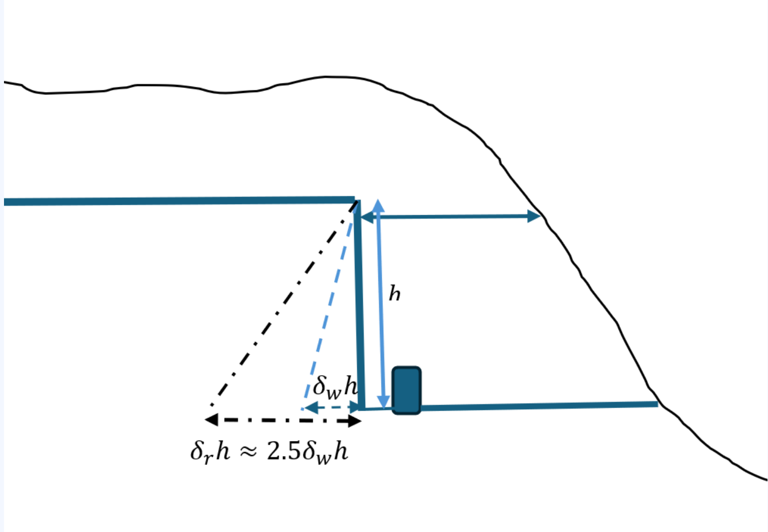
Lining – Type? When?



(Zoorabadi, 2023, developed based on Fernadez,1994)

Lining – Type? When?

- Reinforced concrete lining is generally the most optimised solution for pressure shafts. Exceptions apply at the upper and lower bends of vertical shafts, where highly turbulent water flow occurs and steel lining would be preferred.
- Steel lining is only required in vertical shafts when either:
    - Horizontal rock cover is inadequate due to varying topography (low confinement), or
    - Rock mass hydraulic conductivity is sufficiently high that leakage exceeds acceptable criteria.



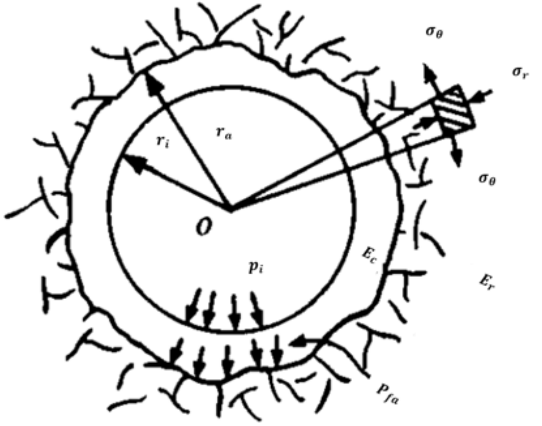
Overburden stress gradient is approximately 2.5 time of internal water pressure gradient minimizing the likelihood of hydraulic jacking at sub-horizontal rock defects

Based Schleiss (2013), vertical shaft is an optimised design (particularly when raise boring is being used to excavate the shaft) for hydropower and pumped storage project to avoid excessive use of steel lining in the high-pressure zones.

Lining Design Requirements

Basis of Lining Design:

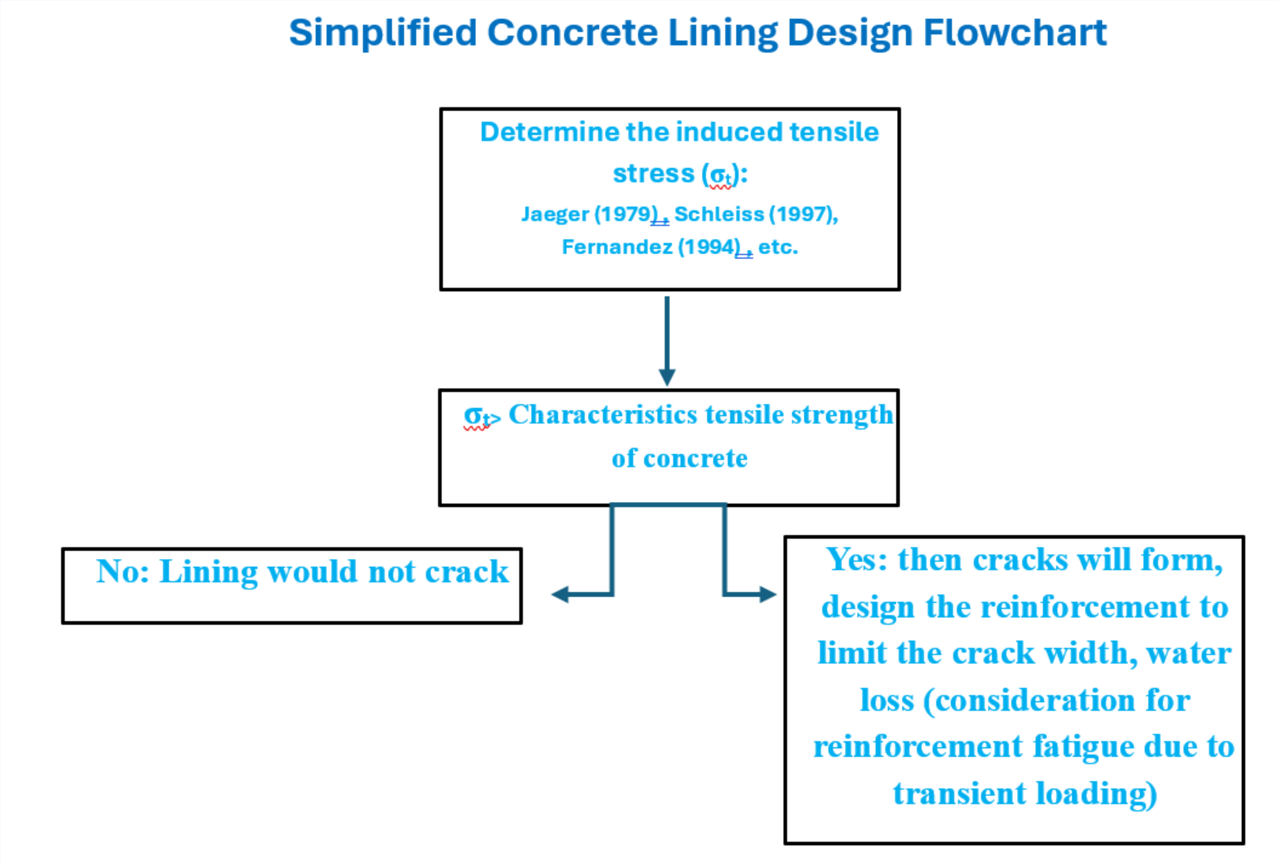
1. **The differential water pressure is shared between rock mass and lining.**
2. **Load sharing between rock mass and lining is mainly controlled by the stiffness of rock mass and lining (with some influence from hydraulic conductivity of lining and rock mass).**
3. **The primary objective is to determine the most economic thickness of the lining and the density of reinforcement, while also 1) ensuring that the width of cracks caused by differential water pressure remains within a specified limit, 2) water loss is minimal, 3) reinforcements stress way below yield.**



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

Lining Design Requirements



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

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

Jaeger (1979)

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

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

Schleiss (1997)

Lining Design Requirements

Main Issues with using tensile stress/tensile Strength as crack initiation criterion:

Tensile strength of concrete is highly variable depending on compressive strength of concrete at time of loading.

$f'_{ct} = 0.36\ (f'_{c})^{0.5}$

fc: characteristic compressive strength of concrete at 28 days.

AS 5100.5: 2017

$$f_{ct} = k(f_c)^n$$

Table 1. Values of the constant coefficients (k) and (n)

Sources	k	n
ACI 318 [4]	0.56	0.5
ACI 363R [5]	0.59	0.5
Gardner [6]	0.47	0.59
Nihal [7]	0.387	0.63
JCI [8]	0.13	0.85
JSCE [9]	0.23	0.67
CEB-FIB [10]	0.3	0.67
Raphael [11]	0.313	0.667
Ahmad and Shah [12]	0.462	0.55
Oluokun et al. [13]	0.294	0.69

Jaber et al. (2018)

Concrete fails as soon as induced tensile strain exceeds 0.01 to 0.15 percent (100 to 150 μs) irrelevant of tensile strength of concrete (Leonhardt, 1987).

Lining Design Requirements

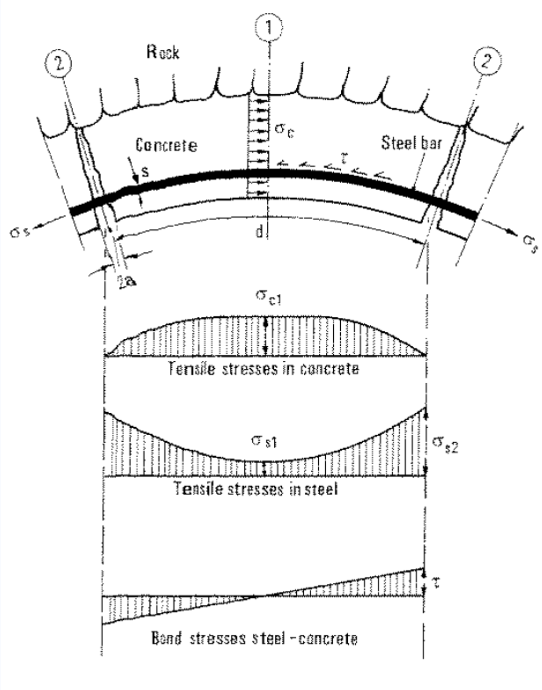
Main Issues with using tensile stress/tensile Strength as crack initiation criterion:

- **Concrete fails as soon as induced tensile strain exceeds 0.01 to 0.15 percent irrelevant of tensile strength of concrete (Leonhardt, 1987).**
- **Tensile strength of concrete is much less sensitive to the compressive strength of concrete.**

Lining Design Requirements

Crack Spacing and its impact on crack width:

- **Crack width depends on the calculated crack spacing: In Schleiss (1997) method, crack spacing is calculated by try and error which is function of bond strength between reinforcement and concrete, crack width and the induced tensile stress in the reinforcement at cracked section. However, the tensile stress in the reinforcement at cracked section depends on the tensile stress of reinforcement at uncracked section.**



Lining Design Requirements

Crack Spacing and its impact on crack width:

- **Crack width depends on the calculated crack spacing: In Fernandez (1994) method, the crack spacing is calculated using an empirical equation as follows:**

sion simplified by Hendron et al. (1987) as follows:

$$S = \frac{d}{10\rho} \quad (15)$$

where d = diameter of the reinforcing bar; and ρ = ratio of the area of steel to the area of concrete.

When crack spacing is calculated then the crack width is calculated as multiplication of induced circumferential strain and crack spacing.

$$w = \varepsilon_{\theta L} S$$

Based on this method, crack width is independent of induced stress in the reinforcement which is a critical factor for design of reinforced concrete lining. This assumption is arguable.

Lining Design Requirements

New Method:

Step 1: Calculate the reduced groundwater pressure behind the lining prior to filling (leakage through uncracked lining and drainage if exist any).

$$h_a = h_0 - [h_0 - \frac{h_0}{1+\left(\frac{Ln\left(\frac{2*h_0}{r_i}\right)}{Ln\left(\frac{r_a}{r_i}\right)}\right)*\left(\frac{K_c}{K_r}\right)}]$$ (zoorabadi, 2025)

$$K_c = 1e-8\ to\ 1e-9\ \frac{m}{s}\quad (Schleiss, 1997, Fernanadez, 1994)$$

Step 2: $t_s = \frac{A_s}{A_L} T_L = (\frac{\left(\frac{\pi}{4} n_{sr} d_s^2\right)\left(\frac{2\pi r_c}{s_s}\right)}{2\pi r_a T_l}) T_l$

Step 3: $M = 1 + \left({}^{E_s}/_{E_r}\right)\left(\frac{t_s}{r_i + {}^{T_l}/_2}\right) * (1 + \vartheta_r)$

Step 4: $\varepsilon_{\theta l}[\mu s] = \left(\frac{(P_i - P_a) * \gamma_w g}{r_c}\right) * \frac{1+\vartheta_r}{E_r}$

Step 5: if $\varepsilon_{\theta l}[\mu s] \geq 100$ then concrete cracks then go Step 5, otherwise lining would not crack and practically plain concrete is adequate.

Step 6: Calculated crack spacing and crack width using EN 1992-1-1 2004:

Step 6-1: $\rho_{eff} = \left[\frac{\pi d_s^2}{4} * \frac{n_{sr}}{s_s}\right] / (\frac{T_l}{2})$

Step 6-2: Crack Spacing= $Cr_s = k_3 C_{nom} + k_1 k_2 k_4 d_s / \rho_{eff}$

$$k_1 = 0.8, k_2 = 1, k_3 = 3.4, k_4 = 0.425$$

Step 6-3: Crack Width= $Cr_w = \varepsilon_{\theta l} Cr_s$

Lining Design Requirements

New Method:

Step 7: Calculate the hydraulic conductivity of lining after cracking using cubic law

$$K_l = \frac{gCr_w^3}{12Cr_s\vartheta}$$

Step 8: Check to see there would be contact between rock and lining after cracking due to induced pore pressure at the contact

Step 8-1: $A = Ln(\frac{2h_w}{r_a})/Ln(\frac{r_a}{r_i})$

Step 8-2: Hydraulic Head outside the lining: $h_{w1} = h_i - [\frac{h_i - h_w}{1+A\left(\frac{K_l}{K_r}\right)}]$

Step 8-3: Ratio of pressure difference formed in the contact to the initial differential pressure between introduce and extrados of lining = $\frac{\Delta P_{w1}}{\Delta P_w} = 1 - [\frac{1}{1+A\left(\frac{K_l}{K_r}\right)}]$

Step 8-4: Ratio of mechanical stress transferred to the rock mass to the initial differential pressure between introduce and extrados of lining= $\frac{P_r}{\Delta P_w} = \frac{1}{M}$

Step 8-5: If the induced differential pressure in the contact is less than the mechanical stress transferred to the rock the lining remains in full contact with rock. Otherwise lining gets separated from the rock= $\begin{cases} if\,(\frac{P_r}{\Delta P_w} > \frac{\Delta P_{w1}}{\Delta P_w} & Lining\ remain\ in\ contact \\ if\,(\frac{P_r}{\Delta P_w} > \frac{\Delta P_{w1}}{\Delta P_w} & Lining\ seperates\ from\ the\ rock \end{cases}$

Lining Design Requirements

New Method:

Note 1: If the lining remains in contact with the rock after cracking, stress transfer through the bond between the concrete and reinforcement may cause additional cracking in the uncracked sections of the lining.

Note 2: Although theory indicates that separation of the lining from the surrounding rock due to water pressure at the interface leads to a negligible pressure difference between the intrados and extrados, thereby reducing lining strain and hydraulic conductivity, design assumptions should remain conservative. Consequently, reinforcement demands, crack widths, and lining hydraulic conductivity should be assessed without relying on the potentially beneficial effects of gap formation, to ensure a safe-side design. Nevertheless, it is noted that the likelihood of new crack formation is expected to be significantly reduced, as induced strains in the lining decrease following separation from the surrounding rock.

Step 9: Leakage through cracked lining in full contact with rock =

$$\frac{q}{\Delta P_w} = \frac{2\pi}{\gamma_w Ln\left(\frac{r_a}{r_i}\right)} \frac{K_r}{A} \left(\frac{\Delta P_{w1}}{\Delta P_w}\right)$$

Step 10: Induced stress in the reinforcements

Step 10-1 Stress in reinforcement at cracking stress of lining =

$$St_{r-Cr} = \left(\frac{f_{ct}}{\rho_{eff}}\right)\left[\left(1 + \frac{E_s}{E_l}\right)\rho_{eff}\right]$$

Step 10-2: $St_r = \left(\frac{Cr_w}{Cr_s}\right) E_s + 0.6\, St_{r-Cr}$

Lining Design Requirements

New Method: Example

Inputs	
Pre-existing Groundwater head [m]	52
Excavation Radius [m]	2.7
Lining Radius [m]	2.4
Rock Mass Modulus [GPa]	2.07
Poisson Ratio -Rock Mass	0.3
Hydraulic Conductivity-Rock Mass [m/s]	1.60E-06
Lining	
Elastic Modulus of Lining [GPa]	33
Poisson Ratio -Lining	0.2
Uniaxial Strenght of Lining [MPa]	30
Pre-cracking Hydraulic Conductivty of Lining [m/s]	1.00E-08
Thickness of Lining [m]	0.3
Tensile strength of Concrete [MPa]	2.9
Reinforcement	
Number of Ring	2
Diameter of Rebars [mm]	30
Rebars Spacing [m]	0.1
Elastic Modulus of Rebars [GPa]	200
Radius to Centre of Lining [m]	2.55
Concrete Cover [m]	0.15
Water	
Kinematic Viscosity of Water [m2/s]	1.00E-06
Unit Weight of Water [kg/m3]	1000
Internal Water Pressure [m]	142

Water Pressure Behind the Lining Prior Filling [m]	**Crack Initiation Assessment**								
	ts	M	εθL [μS]						
43.3	0.00641	1.31552	462						
	Assessment of Contact between Lining and Rock After Cracking								
	ρeff	Crack Spacing [m]	Crack width [mm]	KL	A	hw1	ΔPw1/ΔPw	Pr/ΔPw	Contact Remains
	0.045	0.78	0.36	4.92E-05	30.998854	141.9	1.00	0.76	No
	Leakage Through Cracked Lining When Lining - Reinforcement Stress								
			q [L/s/m]	St_r_cr [MP]	St_r [MPa]				
			2.66	81.7	141.4				

By increasing the reinforcement rings to 2

↓

Water Pressure Behind the Lining Prior Filling [m]	**Crack Initiation Assessment**								
	ts	M	εθL [μS]						
43.3	0.01281	1.63103	373						
	Assessment of Contact between Lining and Rock After Cracking								
	ρeff	Crack Spacing [m]	Crack width [mm]	KL	A	hw1	ΔPw1/ΔPw	Pr/ΔPw	Contact Remains
	0.090	0.65	0.24	1.76E-05	30.998854	141.7	1.00	0.61	No
	Leakage Through Cracked Lining When Lining - Reinforcement Stress								
			q [L/s/m]	St_r_cr [MP]	St_r [MPa]				
			2.66	49.7	104.3				

THANK YOU

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