ANALYSES OF PARAMETERS OF INTERFACE BETWEEN SHOTCRETE AND CONCRETE USED IN TUNNEL CONSTRUCTION

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ABSTRACT
During tunnel construction, shotcrete is used to stabilize the rock mass and to provide a short term support system before installation of the final concrete. The adhesion between these two materials has an important role in rock load transferring during different phases of loading or unloading of a tunnel. Also, the thickness of concrete can be optimized based on the interaction between shotcrete and concrete. The objective of this paper is to provide results of sensitivity analyses on adhesion parameters at the interface between final concrete and shotcrete layers. Impact of different parameters have been studied in order to obtain adhesion parameters of interface in relation to the loading conditions. In addition, the degradation degree of shotcrete has been investigated to evaluate the effect of the most unfavorable degradation state of shotcrete on interface parameters. This paper presents the steps carried out to obtain the interface parameters between shotcrete and concrete and also discusses degradation condition of shotcrete as a function of time.

RÉSUMÉ
Pendant la construction du tunnel, le béton projeté est utilisé pour stabiliser la masse rocheuse et pour fournir un système de soutènement à court terme avant l'installation du béton final. L'adhérence entre ces deux matériaux joue un rôle important dans le transfert de charges rocheuses lors des différentes phases de chargement ou de déchargement d'un tunnel. De plus, l'épaisseur du béton final peut être optimisée en fonction de l'interaction entre le béton projeté et le béton final. L'objectif de cet article est de fournir des résultats d'analyses de sensibilité sur les paramètres d'adhérence à l'interface entre les couches finales de béton et de béton projeté. L'impact de différents paramètres a été étudié afin d'obtenir des paramètres d'adhésion d'interface en fonction des conditions de chargement. De plus, le degré de dégradation du béton projeté a été étudié pour évaluer l'effet de l'état de dégradation le plus défavorable du béton projeté sur les paramètres d'interface. Cet article présente les étapes réalisées pour obtenir les paramètres d'interface entre le béton projeté et le béton finale et traite également de l'état de dégradation du béton projeté en fonction du temps.

1 INTRODUCTION

A large number of transit tunnels and underground stations have been designed using numerical modeling. To design underground structures, an advanced numerical approach has to be used and a comprehensive study on rock-structure interactions should be carried out.

Among the numerical methods, finite element is the one commonly used in tunnel practice. This method facilitates modeling a wide range of rock-structure behavior using different constitutive methods. This method also allows the designer to simulate various sequences of excavation, rock support installation including shotcrete and rock bolts as well as load transferred to the final lining in short and long term.

To evaluate the actual load transferred to the final lining and to obtain the internal forces in the lining, a comprehensive sensibility analysis has been carried out to study the impact of the interface parameters between shotcrete and final lining on the internal forces of the final lining.

2 GEOLOGICAL CONDITION

The geological conditions for the case study consists of relatively horizontal layers of sedimentary rock of interbedded limestone and shale. The intrusive rock can also be encountered locally in some boreholes. The tunnel station is located in the sedimentary rock with an average rock cover of about 10m. There is also 1m of fractured rock and 1m to 2m of soil and backfill material at the surface. Table 1 addresses the soil parameters used in the model.

3 GEOTECHNICAL PARAMETRERS

The properties of the intact rock as well as the structural description of the rock cores are used to assess the rock mass quality and to carry out the rock mass classification. Rock quality is estimated based on the Geological Strength Index, GSI (Hoek 2007).

Rock mass parameters are calculated based on the properties of the intact rock obtained from laboratory tests and the geotechnical investigation data. The rock mass modulus (E_{rm}) is obtained based on the existing empirical equations and then compared with the deformation modulus of rock mass obtained by dilatometer tests.

Table 1 presents the parameters of the rock mass as well as the GSI value representing the rock class. In addition, a disturbance factor "D" of 0.5 and 0.2 are applied in the model to consider the effect of blast damage and long-term behavior of rock mass due to degradation.

Table 2. Soil parameters

Parameters	Soil
Unit weight (kN/m^3)	16.5
Young Modulus E (MPa)	12
Friction Angle φ (^{O})	30
Cohesion (kPa)	0
Poisson ratio	0.30

The Generalized Hoek-Brown criterion (GHB) is taken into account to simulate the rock mass behavior. The in-situ stress ratio (K) is considered equal to 1.5 (Konstantinovskaya et al, 2011) for this study.

Table 1. Characteristics of rock mass

Parameters	D=0	D=0.5	D=0.2
Uniaxial compressive strength of intact rock UCS (MPa)		100	
Intact rock modulus E_i (GPa)		45	
Material constant, mi		9	
Density (kN/m^3)		26.4	
GSI		55	
Rock mass modulus E_{rm} (GPa)	18	9	14

4 STRUCTURAL ELEMENTS PROPERTIES

Table 3 shows the parameters of structural elements including shotcrete, rock bolts and final concrete lining. For modeling the construction and loading sequence, the shotcrete properties are defined as age dependent properties.

To assess the load transfer from the rock to the final lining, an interface element is defined between shotcrete and concrete. The parameters of the interface shown in Table 2 are the basis for the sensibility analysis.

5 MODELING APPROACH

For this study, MIDAS GTS-NX is used for 2D numerical analysis. This software is widely used in the tunneling projects for design purpose as well as to capture the behavior of tunnel structures. To consider the 3D effect of excavation in rock in 2D modeling, the longitudinal displacement profile (LDP) developed by Vlachopoulos and Diederichs is obtained (Vlachopoulos et al. 2009) as a function of tunnel radius.

This approach is used to capture the progressive development of loads and displacements in the rock surrounding the tunnel and, in the support, and final lining elements. The convergence-confinement method (CCM) is also employed to simulate stress relaxation in the rock (Carranza-Torres and Fairhurst, 2000).

In this method, an internal pressure equal to the in-situ stress is applied on the inside of the excavation boundary. This pressure gradually is relaxed until the excavation boundary condition is zero normal stress. The combination of LDP and CCM methods is widely used for assessment of support requirements in underground excavations.

Table 3. Parameters of Structural Elements

Rock bolt			
Nominal capacity (kN)		200	
Young Modulus E (GPa)		200	
Length (m)		4	
Spacing (m)		2	
Shotcrete			
Thickness (m)		0.150	
Young modulus E (GPa)	10 hours → 12	24 hours → 19	28 days → 28
Final Concrete Lining			
Young Modulus E (GPa)		24.6	
Thickness (m)		0.60	
Interface between shotcrete and final lining BP-BF Interface (original Case)			
Cohesion (kPa)		1	
Tension (kPa)		0	
Friction Angle (degree)		25	
Normal Stiffness Kn (kN/m^3)		18E7	
Shear Stiffness Ks (kN/m^3)		16E6	

5.1 Tunnel geometry

Figure 1 presents a cross section of tunnel geometry used in the modeling. As can be seen, the tunnel width is about 15 m while its height is 7,5 m from the tunnel floor.

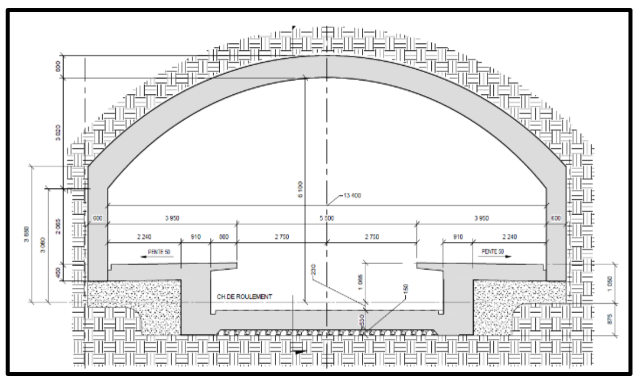

Figure 1. Tunnel Geometry

5.2 Traffic charge

A uniformly distributed static load of 17,6 kPa is applied in the modeling to take into account the equivalent static traffic load on the ground surface.

5.3 Specific Loading Conditions

According to the project criteria, the future urban development should not impose a load of more than 250 kPa 5 m from the tunnel perimeter. To simulate the future development loading, the overburden is excavated up to 5 m from the tunnel crown after installing the rock support and the final lining. Thereafter, a surface load of 250 kPa is applied on the ground surface as shown in Figure 3 to study the impact of this surcharge on the final lining forces.

5.4 Groundwater Condition

The tunnel is drained during construction. The final elevation of water is obtained using the SEEP/W analysis. In this case, the groundwater level is lowered to an elevation of 3 m above the tunnel floor (Figure 2).

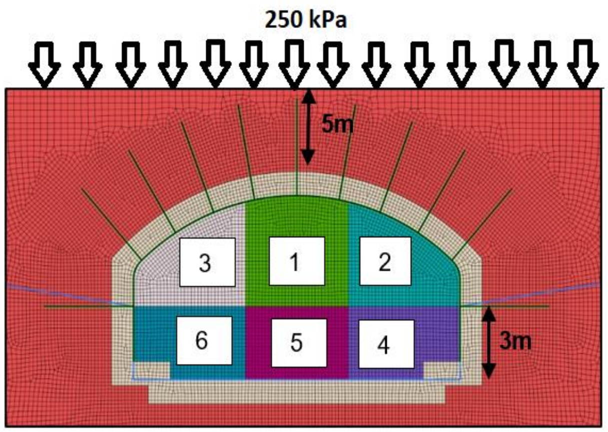

Figure 2. Excavation Sequence and Groundwater Condition

5.5 Excavation Sequences

The tunnel is excavated by top heading and benching method in six (6) sequences as shown in Figure 2. The unsupported length of the excavation in each sequence is about 2.5m. After excavation of each section, the rock support is installed, and the next sequence is followed by excavation and rock support installation as described below. The final lining is then installed when all sequences are completed. The modeling steps can be summarized as follows:

- Application of traffic load of 17.6 kN before tunnel excavation
- Excavation of the central part of the tunnel and rock relaxation
- Installation of shotcrete and rock relaxation, strength gain of shotcrete (from fresh to 10 hours)
- Installation of rock bolts and rock relaxation
- Increasing the shotcrete strength from 10 hours to 24 hours
- Excavation of sections 2 to 6 with the same sequence
- Installation of final lining
- Degradation of rock support
- Excavation of rock cover to 5 m from tunnel perimeter
- Application of 250 kPa on the surface

6 SENSITIVITY ANALYSIS ON INTERFACE PARAMETERS OF SHOTCRETE AND CONCRETE

The sensitivity analysis of shotcrete/concrete interface (BP-BF interface) is done in the following steps to study the effect of each parameters:

➢ Normal (Kn) and Shear stiffness (Ks)

The normal and shear stiffnesses of BP-BF interface are chosen according to the recommendation provided by MIDAS software (10 times greater than the stiffness of the weaker material). Then, the stiffness values are reduced (Kn=180 kN/m3 to 1.8 kN/m3, Ks=16 kN/m3 to 0.16 kN/m3 to study the impact of these values on the forces of the final concrete.

As can be seen in Figure 3, at a certain value of stiffness, the internal forces in concrete no longer change. These stiffness values (Original Case in Table 2) are applied for the BP-BF interface in the model for the next step of sensibility analysis.

➢ Cohesion and Friction Angle

In this step, the interface cohesion is increased from 1 kPa (original value in Table 2) to 1 000 kPa. The friction angle is also increased from 25 degrees to 50 degrees. The results of this analysis are presented in Figure 4. Based on the results of this study, the friction angle is fixed at 25 degrees while the cohesion is considered equal to 1 kPa for the further sensitivity analysis.

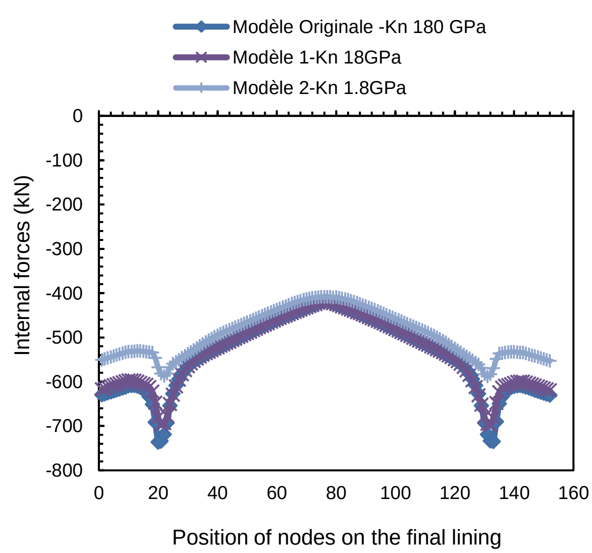

Figure 3. Internal forces in concrete lining as a function of stiffness of BP-BF interface (after application of 250 kPa surcharge load)

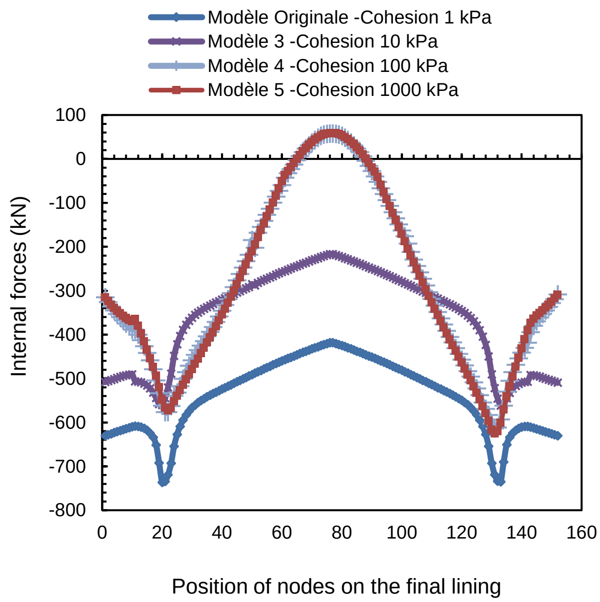

Figure 4. Internal forces in concrete lining as a function of Cohesion of BP-BF interface (after application of 250 kPa surcharge load)

➢ Tension

The impact of the tensile strength of the BP-BF interface is also studied on the forces of the final concrete by increasing the original value (0 kPa) to 10 kPa and then 100 kPa. It should be noted that at this stage, the values of stiffness, cohesion and friction angle of BP-BF interface are equal to the original values in Table 4. The results indicate that an increase in the BP-BF interface tension can reduce the internal forces in the final lining (Figure 5).

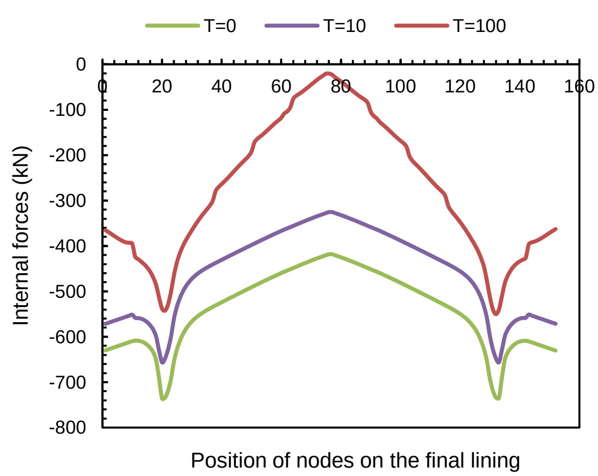

Figure 5. Internal forces in concrete lining as a function of tension of BP-BF interface (after application of 250 kPa surcharge load)

➢ Degradation

Two additional cases are studied with and without degradation of the shotcrete. In the former case, the compressive strength of the shotcrete is reduced to 90% of 28 days compressive strength. Figure 6 depicts the results of this analysis. As shown herein, degradation of shotcrete has not a significant influence on the final lining internal forces.

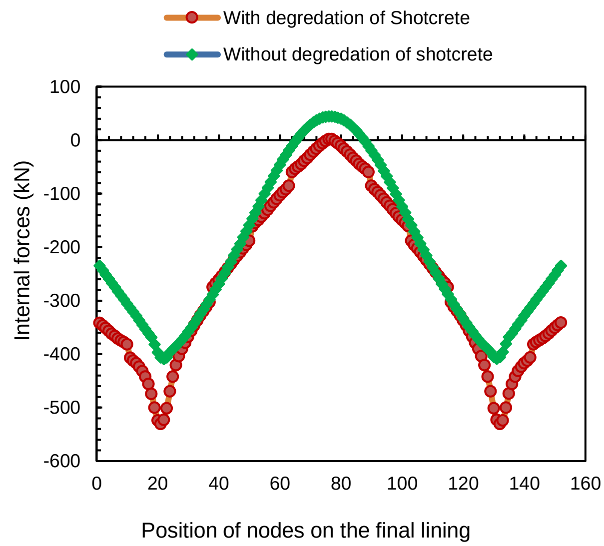

Figure 6. Internal forces in concrete lining as a function of degradation of BP-BF interface (after application of 250 kPa surcharge load)

➢ Bond Strength

To study the impact of the bond strength of interface on the final lining internal forces, i.e., the value of the interface tensile strength is changed as a function of the interface cohesion considering the friction angle of 25º (C=0.5T). Therefore, any change in the cohesion results in a change in the tensile strength. Table 4 presents all cases studied in this step.

As can be seen, the cohesion and the tension of BP-BF interface are considered 500 kPa and 1 000 kPa for the basic case (Case 1).

Then, the BP-BF interface bond strength is reduced from 25% (Case 2) to 97.5% (Case 9) of the OriginalL Case. It should be noted that the degradation of shotcrete in all these cases is considered 90% of 28 days compressive strength.

Two other cases were also considered to study the impact of degradation of 50% (Case 10) and 75% (Case 11) of shotcrete on the internal forces of the final lining. In these cases, the compressive strength of shotcrete is reduced to 50% and 75% of 28 days strength. It should be noted that the bond strength of interface is also reduced with the same percentage.

Figure 7 presents the results of these models. As can be seen, at a certain value of interface bond strength, the internal forces of final lining are constant and are not changed as a function of the interface bond strength.

The results also depict that the ninety percent degradation of shotcrete impose more internal forces in the final lining compared to 50% and 75% degradations.

Table 4. Bond strength parameters of interface as a function of

Model		**Interface parameters**				**Shotcrete Parameters**	
		Short term (after final lining installation)		**Long term (during exploitation)**		**Young Modulus, *E* (GPa)**	**Degradation of shotcrete (%) of 28 days**
Case	**Bond Strength reduction (%)**	**Cohesion (kPa)**	**Tension (kPa)**	**Cohesion (kPa)**	**Tension (kPa)**		
0 (Original)	0	0	0	0	0	0	100
1	0	500	1000	500	1000	9	90
2	25			375	750		
3	50			250	500		
4	**75**			**125**	**250**		
5	82,5			87,5	175		
6	90			50	100		
7	92,5			37,5	75		
8	95			25	50		
9	97,5			12,5	25		
10	50	500	1000	250	500	20	50
11	75			125	250	14,2	75

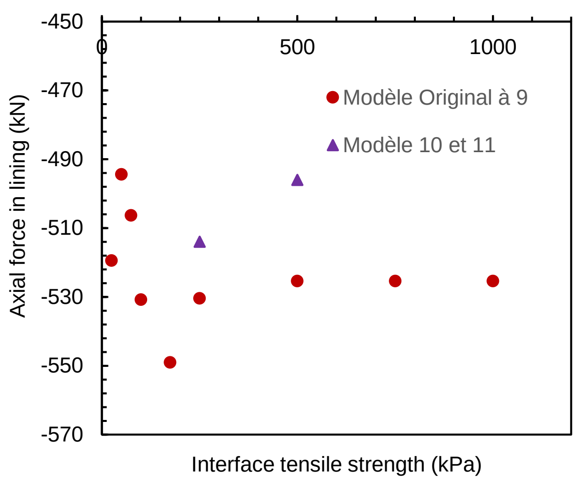

Figure 7. Internal forces in concrete lining as a function of degradation of the BP-BF bond strength and degradation of interface (after application of 250 kPa surcharge load)

7 DISCUSSION

The position of the water table at 3 m above the tunnel floor is valid during the construction period only, the tunnel being considered perfectly drained. In operation, the position of the water table depends on the actual flow conditions. Numerical analyses consider the tunnel to be undrained except at the base. An analysis of groundwater drawdown under these conditions is more conservative. Finally, the distribution of hydrostatic pressures can be done by following the recommendations of the FHWA (Federal Highway Administration - US).

It should be noted that no interface is considered between rock and the shotcrete in this study.

According to the results of the sensitivity analyses, a stiffness equal to the stiffness of the original model can be considered for the interface because the internal forces of the final concrete no longer change with the increase in stiffness. The results of the analyses on the cohesion of interface show that at a certain value of cohesion, the internal forces do not change any more whereas the tensile strength of the shotcrete has a significant influence on the internal forces of the final lining.

The results also illustrate the axial force of the final lining is not changed when the bond strength parameter of the interface is reduced to approximately 75% of those considered for the basic case (Case 4). This means that the most critical (maximum) axial force of the final lining after application of the surcharge of 250 kPa will be obtained when the cohesion and the tensile strength of the BP-BF interface are 125 kPa and 250 kPa, respectively (75% of Case 1).

Moreover, the results of the sensitivity analysis confirm that the degradation of the shotcrete has no impact on the axial force of the final lining when the tensile strength and the cohesion of the interface exceed 250 kPa and 125 kPa, respectively. Small values of tensile strength and cohesion are required to provide a composite behaviour between the shotcrete and the final lining.

Table 5 summarizes the interface parameters obtained in this study.

Table 5. Parameters of BP-BF interface

Parameters	**Value**
Cohesion (kPa)	125
Tension (kPa)	250
Friction angle (deg)	25
Normal Stiffness, Kn (kN/m^3)	18E7
Shear Stiffness, Ks (kN/m^3)	16E6
Young Modulus of shotcrete degraded to 90% (GPa)	9

8 CONCLUSION

The 2D sensitivity analyses were carried out to obtain the axial forces in the final lining as a function of the parameters of the interface between shotcrete and final lining.

The results of these analyses illustrate the impact of shotcrete degradation on the axial forces of the final coating during the application of the 250 kPa load. In addition, the analyses allow to determine the shear strength parameters (Bond strength) of the shotcrete-concrete interface and the percentage of degradation of the shotcrete for which the axial force in the final lining will be the more unfavorable.

The results of these analyses are valid for the rock Class II and III and the geometry of the tunnel presented in this paper.

It is recommended to study some models in weak rock to find interface parameters in this type of rock. It is also worth to carry out more simulations considering different tunnel geometries and different water levels to obtain the interface parameters between shotcrete and concrete.

It is also useful to simulate the same models by considering an interface between rock and shotcrete to study the impact of both interface parameters on the internal forces of final lining and shotcrete.

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