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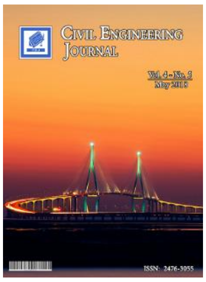
Civil Engineering Journal

Vol. 4, No. 5, May, 2018



Numerical Analysis of TBM Tunnel Lining Behavior using Shotcrete Constitutive Model

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Received 19 March 2018; Accepted 27 May 2018

Abstract

Shotcrete is a fundamental support element for tunnels and underground constructions. Shortly after application, shotcrete linings undergo a high load while the ordinary concrete is not fully hardened yet. Therefore, the time-dependent behaviour of the shotcrete material must consider. Traditional approaches assume a linear elastic behaviour using a hypothetical young modulus to model this time-dependency and creep effects. In this paper, a new constitutive model of shotcrete is applied to evaluate the time-dependent behaviour of TBM tunnel lining under high in-situ stress state. The Shotcrete model is based on the framework of Elasto-plasticity and designed to account for non-linear and time-dependent behaviour for concrete material more realistically. A parametric study of the time-dependent behaviour of the shotcrete lining, using the shotcrete model, is performed. To achieve this, the influence of the lining thickness, tunnel diameter and tunnel depth on the development of the stresses and displacement of the shotcrete lining with time is investigated. The results showed that the development of the lining tensile stress with time at tunnel crown increases by increasing the lining thickness and tunnel depth, whereas it decreases by increasing of the tunnel diameter. At the tunnel sidewall, the lining compression stress with time increases with the increase of the tunnel depth and diameter, while higher lining thickness decreases the lining compressive stresses. However, the results showed the ability of the shotcrete model to simulate the structural behaviour of the shotcrete lining with time.

Keywords: Shotcrete Model; Shotcrete Lining Stress; Lining Thickness; Tunnel Depth; Numerical Modelling.

1. Introduction

The usage of the underground structures has become more important over the past few decades. Construction of underground openings necessitates a safe and economic design. Therefore, the evaluation of the accurate calculation of stresses and movements that occur in the support and the ground surrounding these structures is very significant. The underground openings need to be supported to stabilize the rock mass, this can be accomplished by many types of rock support elements. One of the most important support elements of tunnel constructions is sprayed concrete, often known as shotcrete. It is a special type of concrete conveyed through a hose at high pressure onto a surface to form different structural elements. Shotcrete lining is often fiber reinforced or unreinforced. Generally, fibers are strong in tension, adding fibers could improve many significant properties of shotcrete such as the ductility, energy absorption, impact resistance as well as time and cost saving. There are several types of fibers used in concrete mixes such as; steel, plastic, wood, carbon, glass, and cellulose. Steel reinforcing enhances the shotcrete performance and increase the tunnel stability [1]. In addition to the Steel reinforced ability to improve the ductile behavior of shotcrete lining under ultimate loadings, it could increase the load capacity of a composite arch before fully development of the shotcrete hardening [2]. Reinforced Shotcrete became the fundamental element used in hard rock tunnelling. It is used widely in all types of

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http://dx.doi.org/10.28991/cej-0309155

engineering projects which require limited access space, minimum formwork and difficult-to-reach areas, including overhead, underground and flat or curved surfaces. After tunnel excavation, shotcrete is applied immediately to the tunnel walls to achieve a temporary support. Generally, the shotcrete material shows a time-dependent behavior after few hours of application leading to possible stress levels within the lining which are comparatively high or approaching the failure. It is important to evaluate the time-dependent behavior of shotcrete material to investigate the ultimate and serviceability limit states during tunnel construction [3]. The shotcrete lining behavior develops with time, during the cement hydration process, leading to a sophisticated stress-strain curve history [4]. The shotcrete primary supports are loaded early thus, the effect of time-dependent material properties on the deformation and load-bearing capacity is more significant than the ordinary concrete. After application, shotcrete material displays plastic and ductile behavior with low stiffness and strength. As the stiffness and strength increase with time, the shotcrete material becomes more brittle [5]. The development of shotcrete stiffness and strength with time, due to shotcrete hydration process, has been investigated by many studies. Moreover, the increase of these shotcrete parameters with time considered as the most effective factor on the axial forces and bending moments for the shotcrete lining design [6]. This time dependency is affected by the shotcrete mix design used for the tunnel construction and the used of additives that accelerate the hydration process.

The prediction of the time-dependent behaviour of the shotcrete material requires realistic constitutive model of shotcrete. In the numerical simulation, the constitutive behaviour of the shotcrete is modelled using a simple linear-elastic model. There are many models simulate the highly non-linear and time-dependent material behaviour of shotcrete and performed in numerical modelling, more details about these models are available in Thomas [7]. These methods include the rheological models, models with simple power laws for creep, Hypothetical Modulus of Elasticity methods and Rate of Flow method. The creep effect, which has a major influence on the stresses of the shotcrete lining, has been considered in those models. One of these models is the shotcrete model, presented by Schaedlich and Schweiger [8]. It is a non-linear model represents the mechanical behaviour of shotcrete based on multi-surface plasticity theory with a non-associated flow rule. This viscoelastic-plastic shotcrete model is developed and implemented in 2D finite element software by Brinkgreve et al. [9]. Shotcrete model can account for non-linear and time-dependent behaviour for concrete. As the non-linearity of the concrete is considered, the shotcrete model can obtain the stress distribution of the shotcrete lining more realistically consequently, the tunnel stability could be checked at all construction phases without any further capacity checks of the support cross-section [10]. The influence of the shotcrete models on the lining behavior and the difference between these models have been evaluated by many studies. The shotcrete model predications have been compared with the uniaxial compressive test and creep test at different ages. The results indicated the efficiency of the shotcrete model to reproduce the lining behavior in numerical modeling [8]. Schweiger et al. [11] applied a constitutive model of shotcrete to the numerical analyses for near surface tunnels to evaluate the deformation behavior. The shotcrete model has a noteworthy influence on the lining stresses while the overall lining deformation was not affected. The shotcrete model has been used by Saurer et al. [3] to simulate the tunnel lining behavior during the excavation process numerically. The results indicated the ability of the model to get realistic boundary conditions and design of the tunnel lining. Paternesi et al. [12] investigated the differences in terms of shotcrete lining displacements and forces using shotcrete constitutive Model and Rate of flow method. The shotcrete model considers the plasticity while the Rate of flow is not. The results showed that the influence of the shotcrete model on the lining displacement is not pertinent, whilst the lining forces are noticeably affected. Maatkamp [13] showed the possibility of modelling and designing a reinforced concrete diaphragm wall more accurately using of the shotcrete constitutive model. The time-dependent behaviour of the steel fibre reinforced shotcrete lining (SFRS) has been estimated using the constitutive model of shotcrete. This investigation was carried out though the development of the shotcrete lining properties, such as the elastic stiffness, compressive strength, and the major stresses with time. The results showed the ability the shotcrete model to simulate the lining behaviour with time Shaalan et al. [14]. Neuner et al. [15] illustrated capabilities the shotcrete model to represent the time-dependent material behavior of shotcrete very well. Neuner et al. [16] evaluated the effect of different shotcrete models on the predicted displacements and stresses in shotcrete shells of tunnels under high overburden depth.

The shotcrete model is used for the current study to evaluate the development of the steel fibre reinforced shotcrete lining (SFRS) stress with time. The basic data of the TBM tunnel of Pahang-Selangor Raw Water Transfer Project under high overburden stress is analysed. The effect of different parameters on the time-dependent behaviour of the tunnel lining is to investigate. For this purpose, a parametric study is carried out to investigate the development of the lining stress and displacement with time at a different location along the tunnel lining. These parameters include; lining thickness, tunnel diameter and tunnel depth.

1.1. Shotcrete Constitutive Model

In this work, the steel fiber reinforced shotcrete lining is simulated using a constitutive model of shotcrete which has been developed and implemented in Plaxis 2D software by Brinkgreve et al. [9]. It is based on the framework of Elasto-plastic strain hardening/softening plasticity and can be used for any cement-based materials such as shotcrete, cast concrete, jet grout etc. To simulate the tunnel lining behavior in numerical modelling, traditional engineering approaches assume a linear elastic method with a gradual increase of shotcrete stiffness. This approach cannot predict the time-dependent ductility of shotcrete and leads to high internal forces [8, 10, 11]. In the shotcrete model, continuum elements are used to model the shotcrete lining in which the user can investigate the time-dependency of stiffness, strength, creep and shrinkage effects, as well as the plastic deformation before and after achieving the maximum strength. Determining the hardening and post-peak softening behaviour in tension and in compression is one of the functions of this model. The model formulation is explained in detail by Schaedlich and Schweiger [8] and Schaedlich et al. [11] and a brief description is provided in this work. The input parameters of this model are listed in Table 1.

Shotcrete model uses both of Mohr-Coulomb yield surface for deviatoric loading and Rankine yield surface in the tensile regime. Plastic strains are calculated according to strain hardening/softening Elasto-plasticity. The total strain includes the sum of elastic strain ε^{e}, plastic strain ε^{p}, and creep strain ε^{cr} and shrinkage strain ε^{shr}, as in Equation (1).

$$\varepsilon = \varepsilon^{e} + \varepsilon^{p} + \varepsilon^{cr} + \varepsilon^{shr} \tag{1}$$

The shotcrete stiffness and strength increase immediately with time due to the hydration process of the cement paste. The development of shotcrete stiffness with time follows the recommendation of CEB-FIP model code [17]:

$$E(t) = E_{28}\, e^{s_{stiff}\ (1-\sqrt{28/t})} \tag{2}$$

Where E_{28} represents Young's modulus at 28 days and E_1 indicates Young's modulus at 1 day. S_{stiff} is related to the stiffness ratio at 1 day and t_{hyd}, $\frac{E_1}{E_{28}}$ as in Equation (3). Furthermore, the S_{stiff} parameter controls the variation of stiffness with time.

$$s_{stiff} = -\frac{\ln(E_1 / E_{28})}{\sqrt{28} - 1} \tag{3}$$

The evolution of shotcrete strength up to 24h can be achieved according to the early strength classes J1, J2 and J3 provided by EN 14487-1[18] and shown in Figure 1. The shotcrete model considers the mean values of the classes defined in the standard. The purpose of each class is summarized as:

Class J1: It is appropriate to use for the thin layers of shotcrete or in dry surfaces. No structural requirements are to be expected shortly after installation.

Class J2: Shotcrete of this class is used when thicker layers are required to achieve within a brief time. In addition, it can use for vertical, overhear and difficult surfaces.

Class J3: Due to its fast setting, high dust and rebound occur within the application, this class is used only in particular cases, e.g. high groundwater pressures, very rapid tunnel advance, etc.

However, Oluokun [19] suggested an approach to calculate the shotcrete strength between 24h and t_{hyd}:

$$1.\ f_{c(t)} = f_{c,28}\,(\frac{f_{c1}}{f_{c,28}})\,[(t_{hyd} - t)/(t_{hyd} - 1\ day).\,t] \tag{4}$$

Where $f_{c,\,1}$ and $f_{c,\,28}$ are the compressive strength of shotcrete after 1and 28 days respectively. t_{hyd} is the time for full curing (usually 28 days) and t is a time in days. Creep is modelled according to a viscoelastic approach. Creep strains ε^{cr} show linearly increase with stress σ as:

$$\varepsilon^{cr}(t) = \frac{\varphi^{cr}\sigma}{D}\frac{(t - t_{\circ})}{(t + t_{50}^{cr})} \tag{5}$$

Where φ^{cr} and D are the creep factor and the linear elastic stiffness matrix respectively, t0 is the loading time and t_{50}^{cr} is the required time to develop 50% of creep strain. In case of shotcrete utilization, more than 45% of f_c, non-linear creep effects can be calculated by an equation provided by EC2 [20]. According to the recommendation of ACI 209-R92 [21], the Shrinkage strain ε^{shr} can be found at:

$$\varepsilon^{shr}(t) = \varepsilon_{\infty}^{shr}(\frac{t}{t + t_{50}^{shr}}) \tag{6}$$

Here is the final shrinkage strain and the t_{50}^{shr} related to the time of %50 of shrinkage strain.

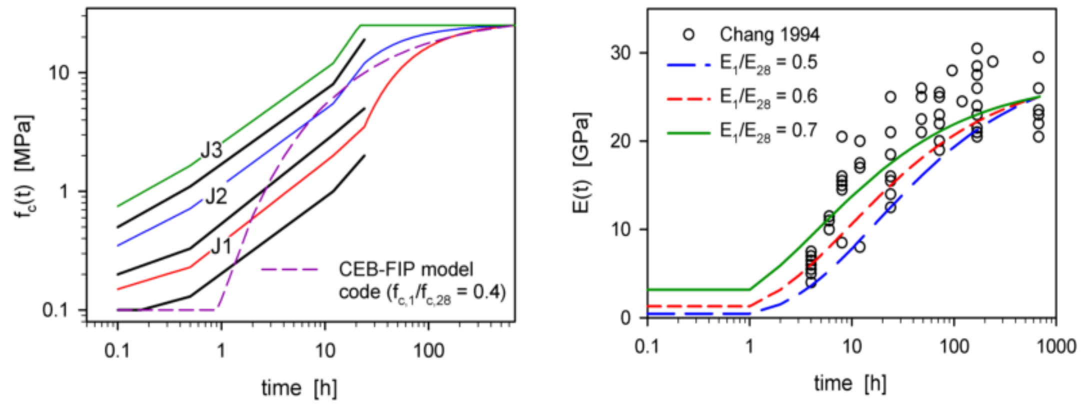


Figure 1. Evaluation of shotcrete strength and stiffness with time [22]

Table 1. Shotcrete model input parameters

Parameter	Explanation	Unit
E_{28}	Young's modulus	GPa
ν	Poisson's ratio	-
$f_{c,28}$	Uniaxial compressive strength at t_{hyd}	MPa
$f_{t,28}$	Uniaxial Tensile strength at t_{hyd}	MPa
ψ	Dilatancy Angle	Deg
$\emptyset_{max}$	Maximum friction angle	Deg
E_1/E_{28}	Time dependency of elastic stiffness	--
$f_{c,1}/f_{c,28}$	Time dependency of strength	--
f_{con}	Normalized initially mobilised strength	--
f_{cfn}	Normalized failure strength	--
f_{cun}	Normalized residual strength	--
$G_{c,28}$	Compressive fracture energy shotcrete	KN/m
t_{tun}	Ratio of residual vs. Peak tensile strength	--
$G_{t,28}$	Tensile fracture energy of shotcrete	KN/m
ε_{cp}^{p}	Uniaxial plastic failure strain at 1h, 8h, and 24h	--
$\emptyset^{cr}$	The ratio between creep & elastic strain	%
t_{50}^{cr}	Time for 50% of creep strain	d
$\varepsilon_{\infty}^{shr}$	Final shrinkage strain	%
t_{50}^{shr}	Time for 50% of shrinkage strain	d
t_{hyd}	Time for full hydration	d

2. Research Methodology

2.1. Case Study

The time-dependent behaviour of the steel fibre reinforced shotcrete lining of Pahang-Selangor raw water tunnel is investigated. The project is in the central zone of Peninsular Malaysia and connects the states of Pahang and Selangor through a long water transfer tunnel (see Figure 2). It is one of the largest infrastructure projects in Asia. The tunnel length is 44.6 km with 5.2 m diameter. It was excavated using three TBMs (TBM 1, TBM 2, and TBM 3) for about 35 km of the whole tunnel length by 1,200 m deep. The conventional tunnel excavation method (NATM) has been used to excavate 4 sections of the total 9.1 km long while the Cut and Cover Method used to excavate one section of 0.9 km long. The deepest section is 1,246 m and about 5,000 m of the tunnel has over 1,000 m deep [23]. Along the entire tunnel length, the type of the rock mass is granite. In this work, the shotcrete lining of TBM-2 section at Ch. 23048 m, as shown in Figure 3, is selected for the numerical analysis. The tunnel overburden depth is about 1002m.

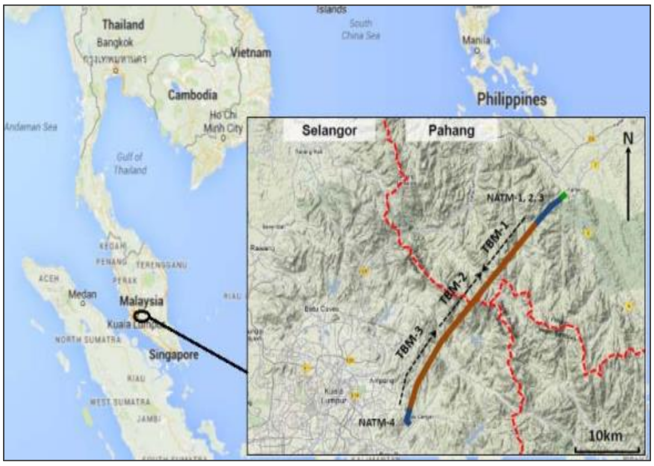


Figure 2. Tunnel structure of Pahang-Selangor Raw Water Transfer tunnel [23]

In-situ stress conditions at three locations along the Pahang–Selangor Raw Water Transfer tunnel were estimated through a series of stress measurements as shown in Figure 3. Both hydraulic fracturing and compact conical-ended borehole overcoring methods were utilized to determine the in-situ stress magnitude and direction [24]. The results indicated that high stresses were at the center of the tunnel, especially at TBM 2 section. The maximum, medium and minimum principal stresses are 28.76, 10.29 and 5.17 MPa, respectively, as shown in Figure 4. The maximum principal stress (σ_1) was observed along the vertical direction and the horizontal stress is comparatively small. In addition, the maximum principal stress is inclined by 80.22° with respect to the horizontal stress.

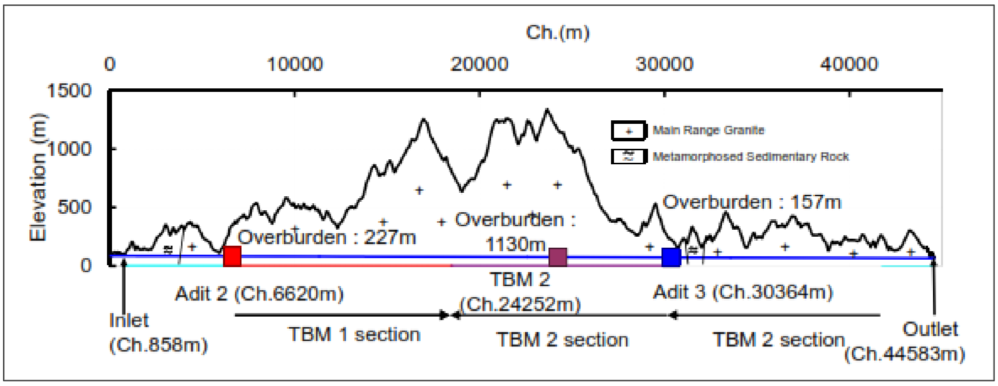


Figure 3. In-situ stress test locations in Pahang-Selangor Water Transfer Tunnel

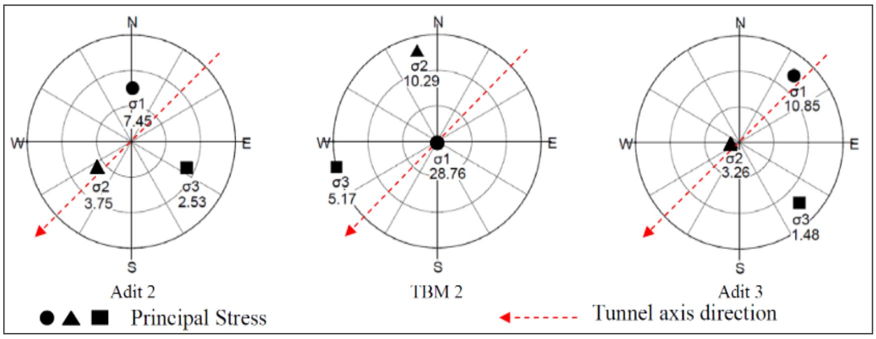
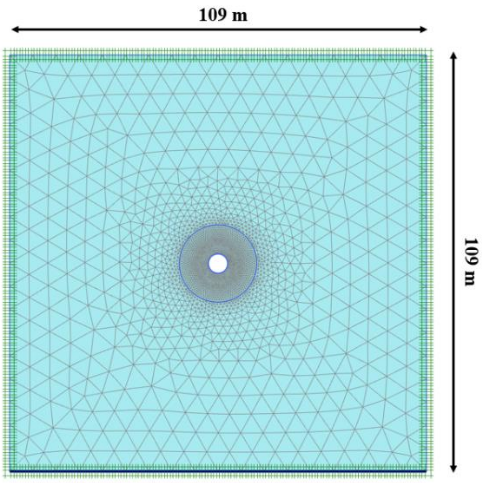


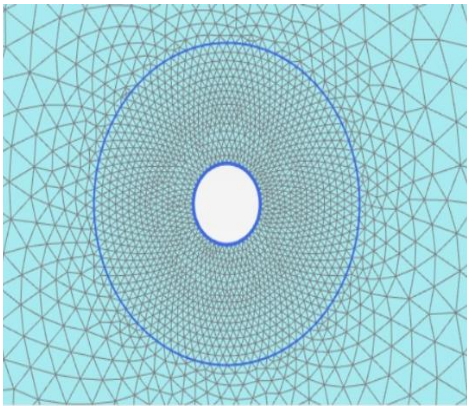
Figure 4. Schmidt Net Projection of principal stress [24]

2.2. Numerical Modeling

In order to evaluate the effect of some parameters on the time-dependent behaviour of the SFRS lining a new constitutive model of shotcrete is used. This model has been developed and implemented in numerical software. A parametric analysis of TBM tunnel lining is presented using a plane-strain finite element program Plaxis 2D. The analysed tunnel section is described by a circular excavation profile with a diameter of 5.2 m and a depth of 1002m. The geometric model and finite element mesh are presented in Figure 5. The model boundary is adapted to 10 times of the tunnel diameter to make sure that the model is not affected by the restraining impact [25]. A circular geometry of 20 m is introduced around the tunnel to refine the mesh locally. A 15-noded triangular element mesh is set up with the Plaxis code (2017) [26]. A fine mesh is used around the tunnel to enhance the accuracy of the stress analysis. Granite is the type of the rock mass along Pahang-Selangor water transfer tunnel project. The average unit weight and Poisson's ratio of the rock are 27 KN/m^3 and 0.2, respectively. The input parameters of the rock mass are determined using RockLab software by fitting the Mohr–Coulomb failure envelope with the Hoek–Brown failure envelope, as listed in Table 2. The rock mass around the tunnel is simulated assuming an elastic perfectly plastic behaviour using the equivalent Mohr-Coulomb model. The input parameters for the equivalent Mohr-Coulomb model used in this analysis are listed in Table3.



(a) Geometric model



(b) Meshing around the tunnel

Figure 5. (a) Geometric model, (b) Mesh around the tunnel

Table 2. Input parameters of the numerical modeling

Term	Unit	Case 1	Case 2	Case 3
Input parameters for RockLab				
Intact Compressive Strength σ_{ci}	MPa	124	94	118
Material constant for intact rock m_i	--	32	32	32
Disturbance Factor D	--	0	0	0
Geological Strength Index GSI	--	67	60	67
Modulus ratio MR	--	425	425	425
Unit weigh γ_d	KN/m^3	27	27	27
Tunnel depth	m	1002	1241	1239
Output parameters for RockLab				
Young modulus E	MPa	35516	20774	33798
Rock mass compressive strength σ_{cm}	MPa	19.7	10.06	18.74
Rock mass tensile strength σ_t	MPa	0.322	0.144	0.306
Friction angle $\emptyset_m$	°	52.34	46.85	50.46
Cohesive strength C_m	MPa	6.239	5.75	6.96
m_b	--	9.84	7.66	9.84
s	--	0.026	0.011	0.025

Table 3. Input parameters for the equivalent Mohr-Coulomb model

Item	Unit	Value
Young Modulus E	MPa	35516
Poisson ratio ν	-	0.2
Friction angle $\emptyset_m$	°	52.34
Cohesive strength C_m	MPa	6.239
Unit weight γ_d	KN/m^3	27

2.2.1. Field Stress

The high in-situ stresses of the project are modelled using the Field stress option. In Plaxis 2D 2017, in addition to the K_0 -procedure and Gravity loading, it is possible to introduce the initial stress field in the model using Field stress. This option allows for setting up a homogeneous initial stress state, taking in to account the rotation of the principal stresses. This important for application in deep soil or rock layers where the generation of these layers in the geotechnical history has caused a rotational of the principal stresses [26]. In the model, this option is selected as Calculation type for the initial phase. In addition, the magnitude of the three principal stresses $\sigma_1, \sigma_2, \sigma_3$, as well as the orientation of the first principal stress direction are defined based on the in-situ stress values provide in Section 2.

2.2.2. Tunnel Excavation Process

In numerical modelling it is possible to simulate the construction process of tunnel supported using sprayed concrete lining. The major point in such analysis is to account for 3D arching effect that occurred in the rock around the unsupported tunnel face. This can be achieved using converge confinement method or β-method. The principal of this method is that the initial stresses P_k acting around the location where the tunnel is to be constructed are divided into a part $(1-\beta)$ P_k that is applied to the unsupported tunnel and a part β P_k that is applied to the supported tunnel. The β coefficient $(0 < \beta < 1)$ is an experience value depending on the tunnel round length and equivalent diameter. In the initial phase the Field stress option is selected for the stage construction calculation in which the force fully applied to the activated mesh. In the second phase, 60% of the in-situ stress will applied with deactivating the tunnel cluster. The last phase involves activation of the shotcrete lining with part of the in-situ stress, as shown in Figure 6.

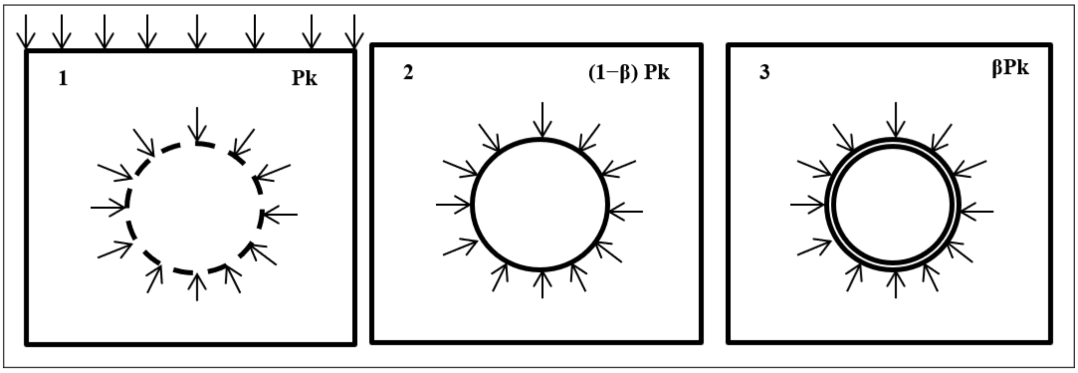


Figure 6. Schematic representation of β-method for the analysis of TBM tunnel

2.2.3. Material Parameters for the Shotcrete Model

The tunnel was supported using a steel fiber reinforced shotcrete lining of 0.1m thick. The time-dependent behavior of the shotcrete lining is analyzed using a shotcrete constitutive model which has been developed and implemented in a numerical software. The SFRS lining is simulated in the model using continuum elements as shown in Figure 7. Input parameters for SFRS lining based on the shotcrete constitutive model are listed in Table 4. Some of these parameters could be investigated from standard compression tests such as; $f_{c, 28}$, f_{con}, f_{cfn} and fcun. The 4-point bend beam test could be used to determine the uniaxial tensile strength $f_{t, 28}$ and the tensile fracture energy $G_{t, 28}$ of shotcrete. The compressive fracture energy $G_{c, 28}$ of shotcrete could be obtained by the plate test, and the creep and shrinkage strains are estimated from the creep and shrinkage tests, respectively. For the current analysis of tunnel lining, some of the material parameters for the shotcrete model are calibrated based on the shotcrete samples that tested during the tunnel construction as shown in Table 3. Tensile strength parameters $f_{t, 28}$, $G_{t, 28}$ and ftun represent the steel fiber content of 35 Kg/m^3. Other parameters have been assumed base on the recommended values, provided by Schädlich and Schweiger [22], which are obtained based on previously published experimental data of shotcrete and concrete.

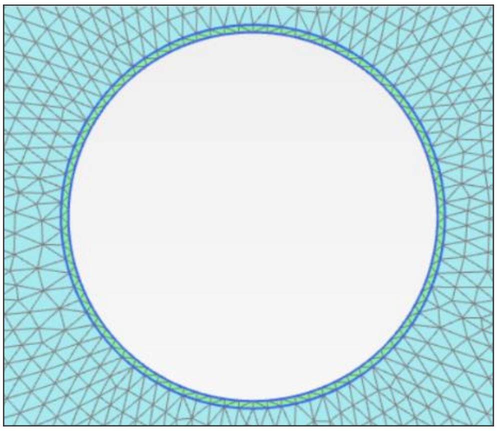


Figure 7. SFRS shotcrete tunnel lining

Table 3. Site results of the SFRS compressive strength

Age	Compressive strength (MPa)
1 h	1.5
8 h	7.8
1 d	15
3 d	30.7
7 d	3.24
28 d	35

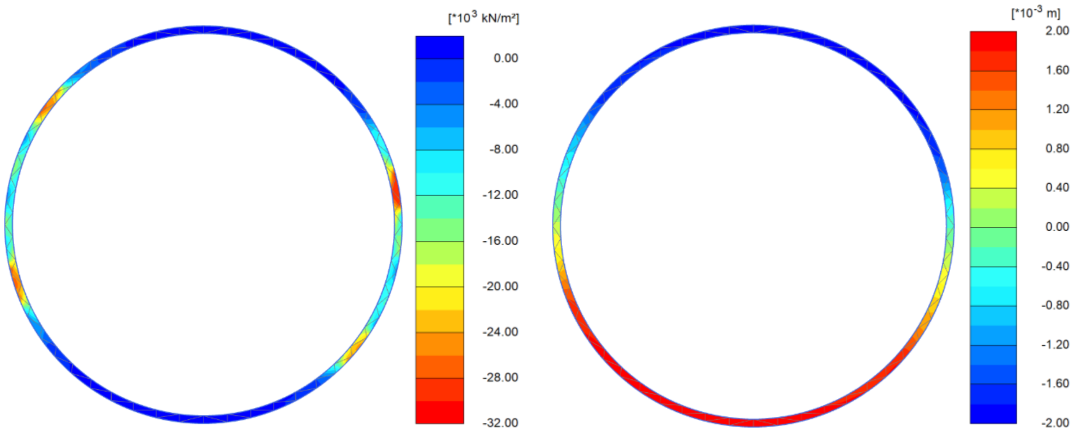
Table 4. Shotcrete model input parameters

Parameter	Value	Unit
E_{28}	28	GPa
ν	0.2	-
$f_{c,28}$	35 (UCS test)	MPa
$f_{t,28}$	2.5 (4-point bend beam test)	MPa
ψ	0	Deg
$\emptyset_{max}$	37	Deg
E_1/E_{28}	0.65	--
$f_{c,1}/f_{c,28}$	-2 (class J2) [20]	--
f_{con}	0.15	--
f_{cfn}	0.1	--
f_{cun}	0.1	--
$G_{c,28}$	70	KN/m
t_{tun}	0.1	--
$G_{t,28}$	2.72 (Acc. to Barros and Figueiras) [27]	KN/m
ε_{cp}^{p}	1h= -0.03, 8h= -0.001, after 24h= -0.0007 [22]	--
$\emptyset^{cr}$	2.6	%
t_{50}^{cr}	1.5	d
$\varepsilon_{\infty}^{shr}$	-0.0005	%
t_{50}^{shr}	45	d
t_{hyd}	28	d

3. Results and Discussion

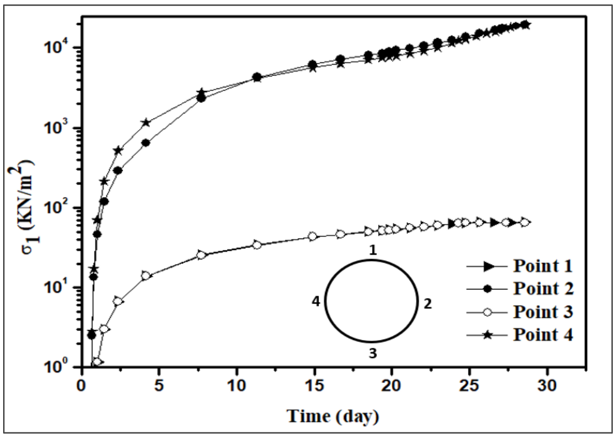
3.1. Parametric Study

To study the relative importance of different parameters on the time-dependent behaviour of the shotcrete lining, a parametric study is performed. These parameters include; lining thickness, tunnel depth and tunnel diameter. In each step, one of these parameters is changed while keeping the others constant to evaluate its effect on the development of the shotcrete lining stress and displacement with time. The stresses and vertical displacement along the tunnel lining are investigated as shown in Figure 8. The results indicated that the stresses at the crown and toe of the tunnel lining are compression stresses while the sidewalls are undergoing tensile stresses. The development of the major stresses and vertical displacement in four different points along the tunnel lining with time is evaluated (see Figures 9). It's obvious that the lining stresses increase with the time of application and the compression stresses at the sidewalls of the tunnel are higher than the tensile stresses at the crown and toe. The vertical displacement at the tunnel crown and toe is higher than that at the sidewalls. In another word, the vertical displacement of the shotcrete lining is more in tension than in compression. In addition, the stresses and displacement in the tunnel lining are approximately symmetric around the y-axis so that the analysis of one half of the tunnel lining is considered for the parametric study.

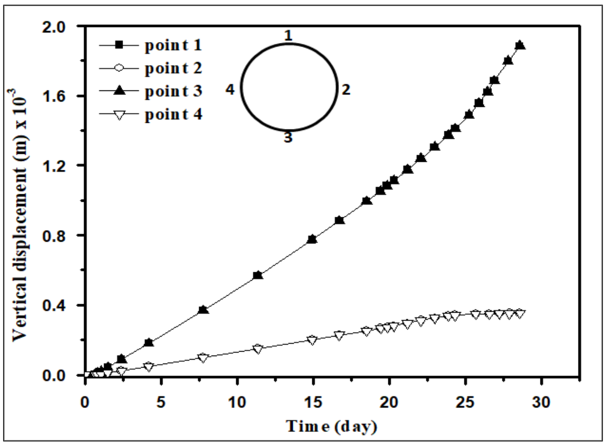


a) Major stress **b) Vertical displacement**

Figure 8. Distribution of the principal stresses and vertical displacement along the tunnel



a) Major stress



b) Vertical displacement

Figure 9. Development of the stress and vertical displacement around the tunnel lining with time

3.1.1. Effect of Lining Thickness

The influence of the SFRS lining thickness on the development of the SFRS lining stress and displacement with time, at tunnel crown and sidewall, is investigated. Different values for the lining thickness are used including 0.1, 0.15, 0.2 and 0.25 m [28]. The thickness of 0.1 m is the actual lining thickness so that it considered as a reference thickness to compare with the others. The tunnel depth and diameter of 1002 and 5.2 m, respectively, were kept constants. Stress distribution along the tunnel lining using different lining thicknesses is shown in Figure 10. Figure 11a shows the effect of the shotcrete lining thickness on the tensile stresses of the SFRS lining, at tunnel crown. In the first day of application, the lining thickness of 0.15, 0.2 and 0.25 m increases the lining tensile stress by 50%, 100% and 150%, respectively. At 14 days, the lining tensile stress increases by 50%, 900% and 150% in case of lining thickness of 0.15, 0.2 and 0.25 m, respectively. Whereas, at 28 days, increasing the lining thickness with time to 0.15, 0.2 and 0.25 m increases the lining tensile stress by 50%, 95% and 140%, respectively. It is evident that the development of the tensile stresses with time is increased by increasing the lining thickness. In addition, the increase in the lining tensile stresses with time is visible from the early days of application.

The effect of the shotcrete lining thickness on the development of the compressive stresses of the SFRS lining with time, at tunnel sidewall, is shown in Figure 11b. The lining thickness of 0.15, 0.2 and 0.25 m decreases the lining compression stress with time, in the first day of application, by 25%, 36% and 38%, respectively. At 14 days, the lining compression stress decreased with time by 15%, 20% and 28% when the lining thickness is 0.15, 0.2 and 0.25 m, respectively. At 28 days, the lining compression stress decreases with time by 23%, 30% and 45% when the lining thickness increases to 0.15, 0.2 and 0.25 m, respectively. The lining compression stress at the tunnel sidewall decreases with time by increasing the lining thickness. Furthermore, the increment in the lining tensile stresses with time, due to the increase in the lining thickness, is higher than the decrease in the lining compression stresses with time.

The effect of shotcrete lining thickness variation on the vertical displacement along the tunnel lining is shown in Figure 12. The development of the lining vertical displacement with time using different thicknesses is evaluated as in Figure 13. At tunnel crown, it is observed that increasing the lining thickness did not show very much change on the development of the lining vertical displacement with time, particularly for the range of $0 \leq t \leq 24$ days (see Figure 13a). For Figure 13b, increasing the SFRS lining thickness, in the first day of application, causes a decrease in the lining vertical displacement with time by 11%, 13% and 16% for the lining thickness of 0.15, 0.2 and 0.25 m, respectively. At 14 days, increasing the lining thickness to 0.15, 0.2 and 0.25 m lead to decrease the lining vertical displacement with time by 16%, 20% and 25% and by 10%, 14% and 20% in 28 days, respectively. In general, increasing the lining thickness can decrease the lining vertical displacement with time along the tunnel lining.

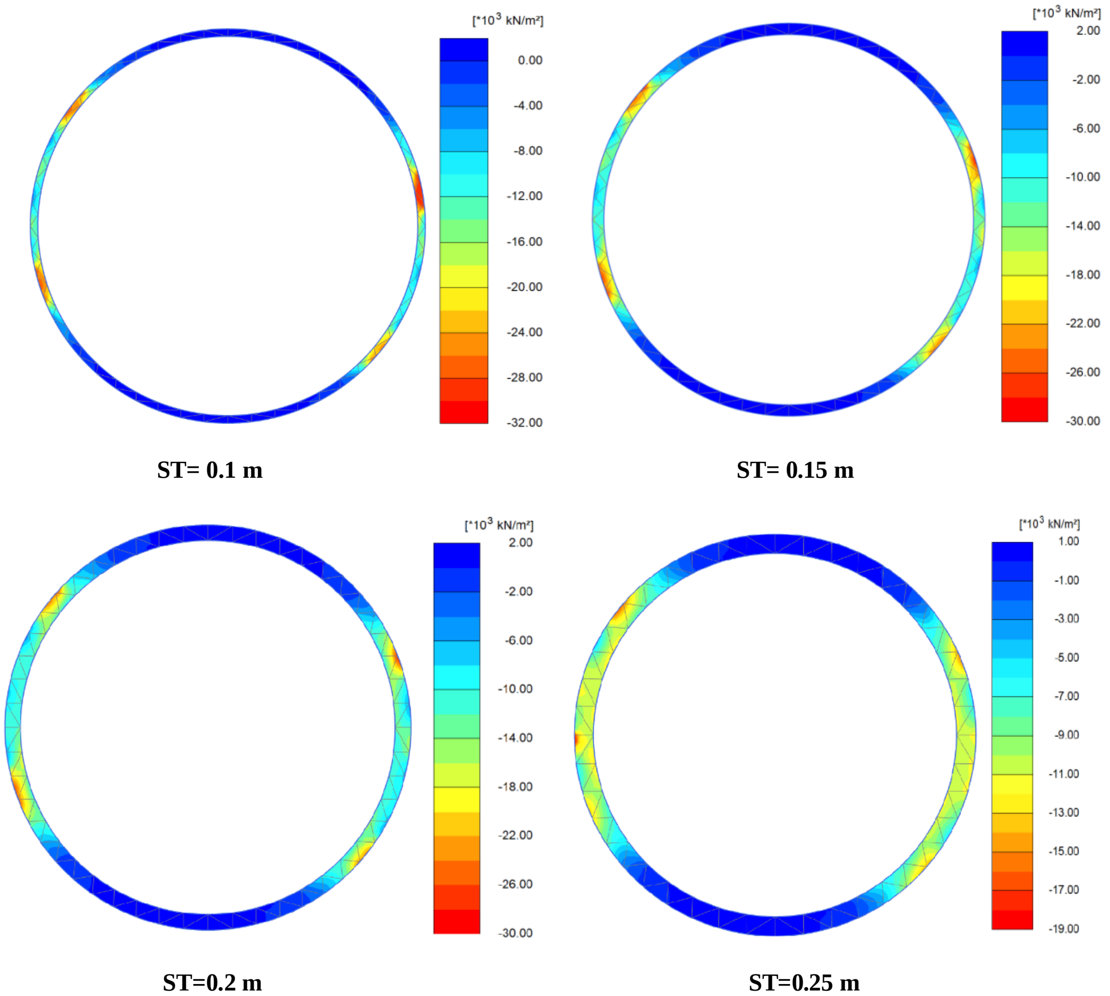
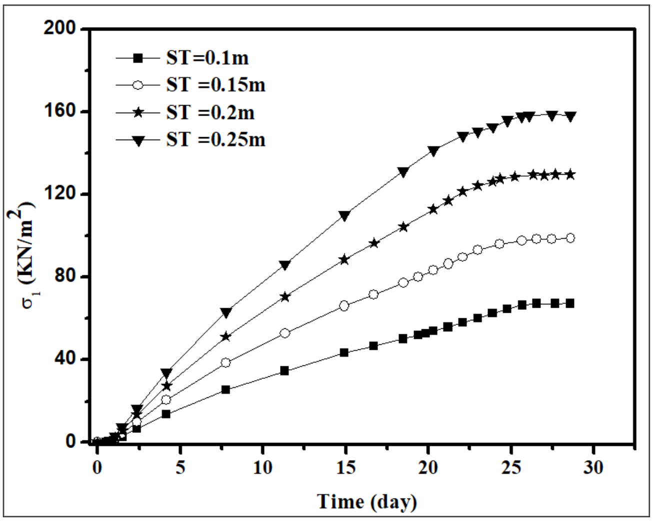
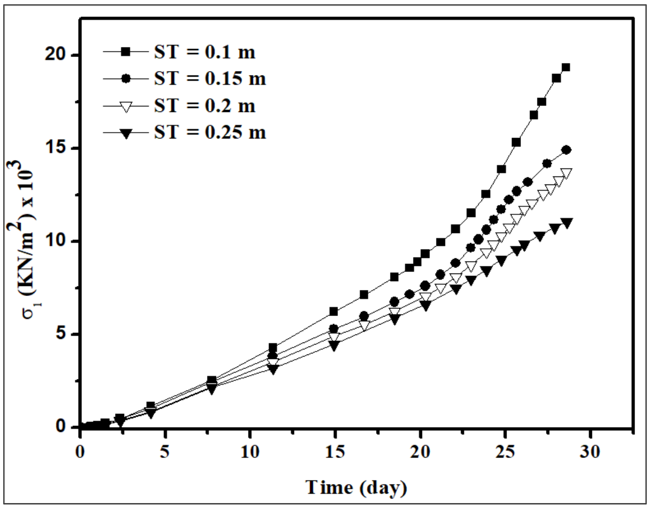


Figure 10. Stress distribution along the tunnel lining with different lining thicknesses

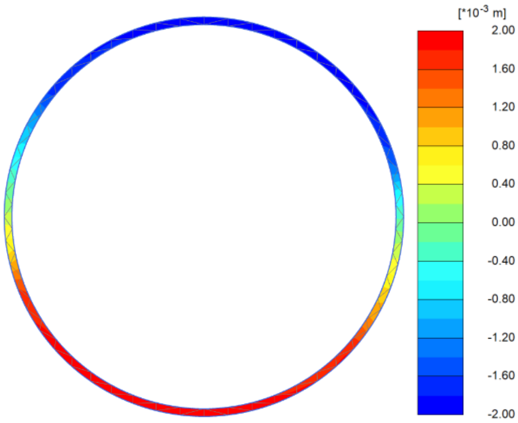


a) Tunnel crown

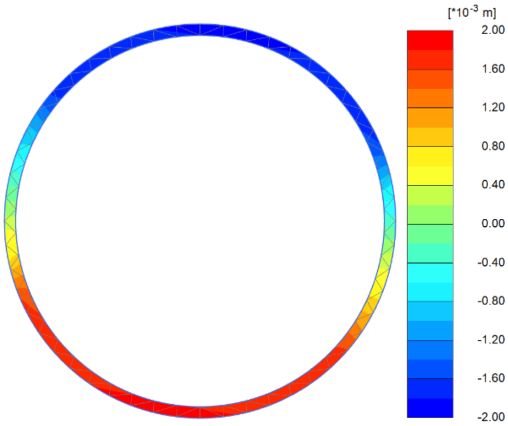


b) Tunnel sidewall

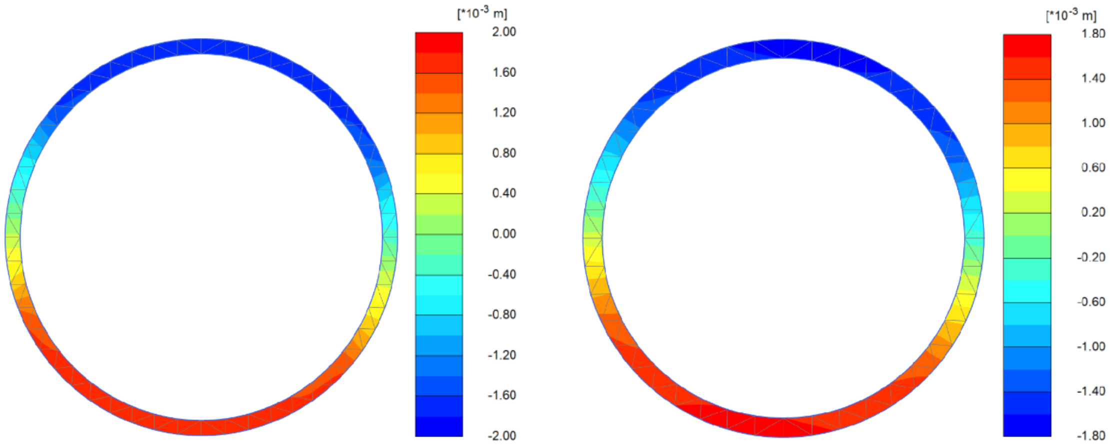
Figure 11. Effect of lining thicknesses on the SRFS lining stresses with time



ST= 0.1m

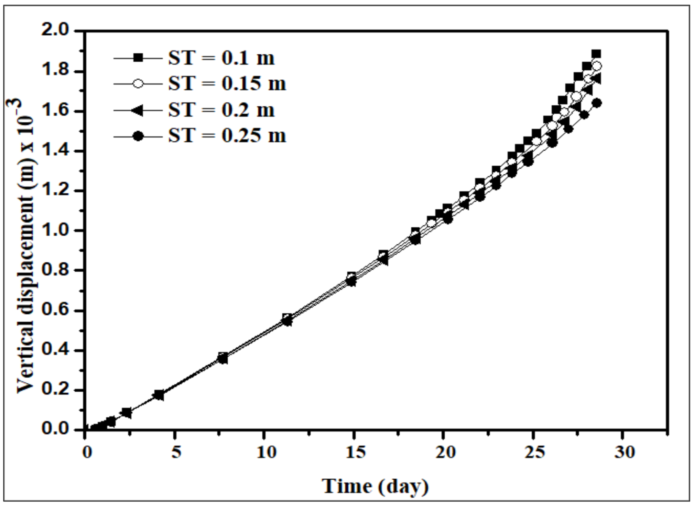


ST= 0.15m

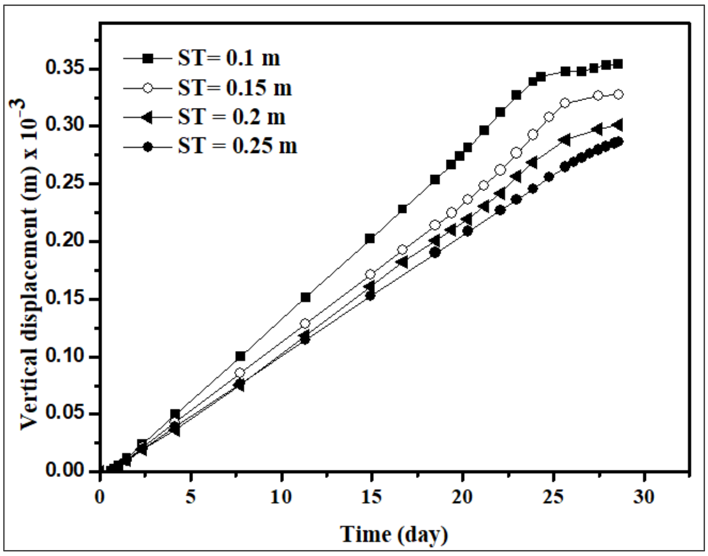


ST= 0.2 m **ST= 0.25 m**

Figure 12. Vertical displacement along the tunnel lining with different lining thicknesses



a) Tunnel crown



b) Tunnel sidewall

Figure 13. Effect of lining thicknesses on the SRFS lining vertical displacement with time

3.1.2. Effect of the Tunnel Depth

To investigate the influence of tunnel depth on the shotcrete lining stresses and displacement with time, different tunnel depths of 700, 800, 900 and 1002 m are used. The lining thickness and the tunnel diameter of 0.1 and 5.2 m, respectively, are kept constants. The tunnel depth of 1002 m is the reference depth used to compare with other cases.

Stress distribution along the tunnel lining under different tunnel overburden depths is presented in Figure 14. Figure 15a shows the effect of the tunnel overburden on the development of SFRS lining tensile stresses with time, at tunnel crown. The impact of the tunnel depth on the lining tensile stress is not very significant. However, the influence of the tunnel overburden depth on the development of the lining compression stresses with time at tunnel sidewall is illustrated in Figure 15b. Decreasing the tunnel depth to 900, 800 and 700 m, in the first day, leads to decrease the lining compression stress with time by 42%, 44% and 66%, respectively. At 14 days, the lining compression stress decreases with time by 35%, 45% and 53% due to decrease the tunnel depth to 900, 800 and 700 m, respectively. Whereas, at 28 days, the lining compression stress decreases with time by 26%, 35% and 45%. It is obvious that lower tunnel depth decreases significantly the lining compression stresses with time. Increasing the tunnel overburden depth could result in highest principal stresses of the surrounding rock mass at the tunnel sidewalls. Thus, the lining stress increases by increasing the tunnel depth.

The development of the vertical displacement of the tunnel lining with time under different depths is also investigated as presented in Figure 16. Figure 17a shows the effect of the tunnel depth on the vertical displacement of the shotcrete lining with time at tunnel crown. In the first day, decreasing the tunnel depth to 900, 800 and 700 m causes a reduction in the lining vertical displacement with time by 26%, 30% and 70%, respectively. At 14 days, the lining vertical displacement with time decreases by 20%, 28% and 37% due to decreasing the tunnel depth to 900, 800 and 700 m, respectively. In addition, at 28 days, the lining vertical displacement decreases with time by 22%, 30% and 40%, respectively. The tunnel depth has a considerable effect on the development of the lining vertical displacement with time, at the tunnel crown. Figure 17b shows the influence of the tunnel depth on the lining vertical displacement with time, at tunnel sidewall. In the first day, the lining vertical displacement with time decreases by 27%, 37% and 40% due to decreasing the tunnel depth to 900, 800 and 700 m, respectively. At 14 days, decreasing the tunnel depth to 900m, 800 and 700 m show a decrease the lining vertical displacement with time by 25%, 35% and 40%, respectively. In addition, at 28 days, the lining vertical displacement decreases with time by 23%, 30%and 37%, respectively. Generally, decreasing the tunnel overburden depth causes a reduction in the development of the lining vertical displacement with time. Reducing the tunnel overburden depth leads to lower displacement in the rock mass around the tunnel opening. Consequently, lower lining displacement could obtain.

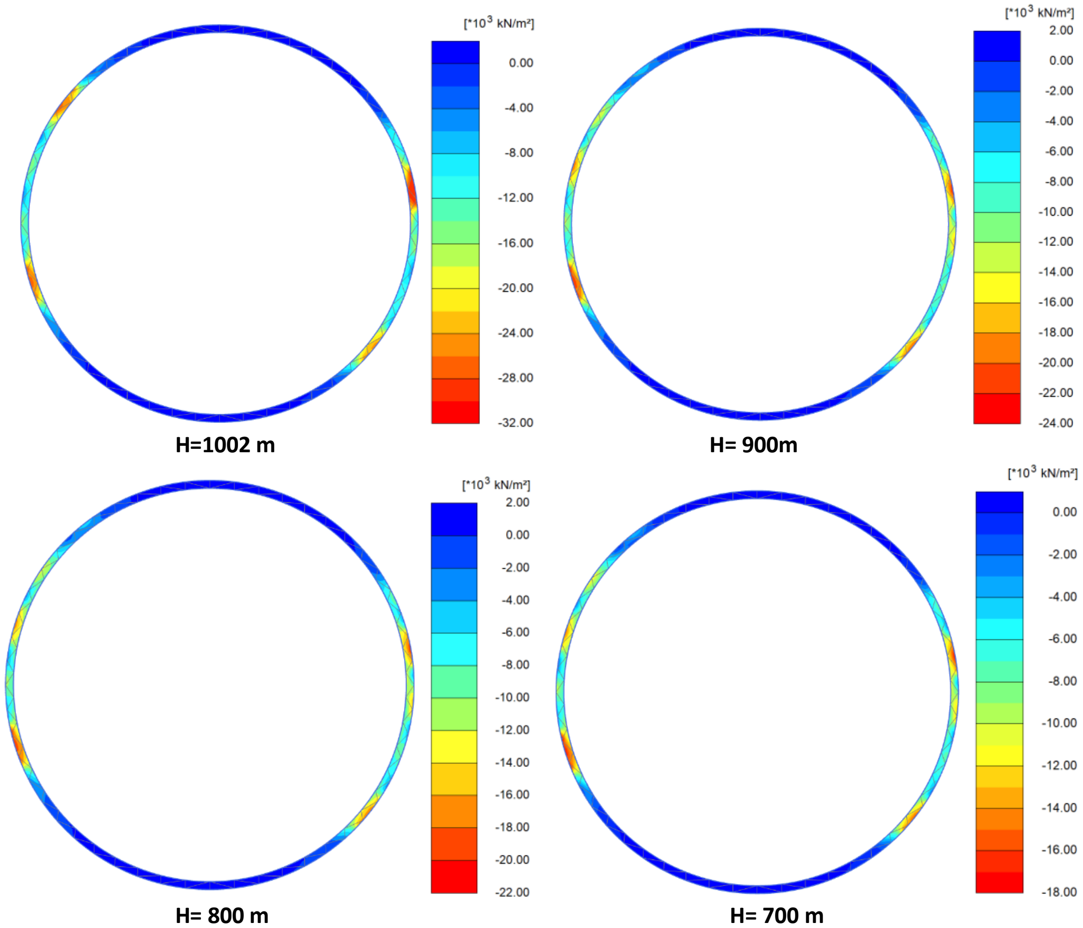
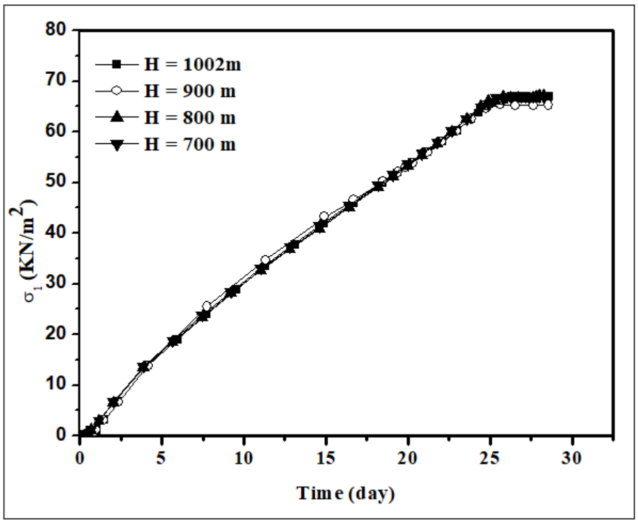
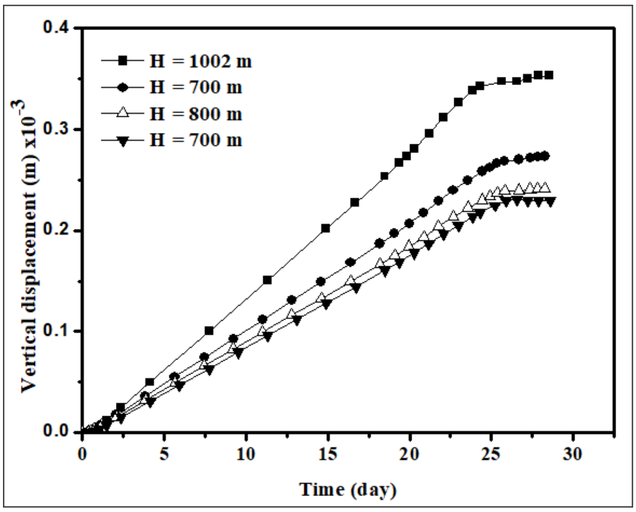


Figure 14. Stress distribution along the tunnel lining under different tunnel overburden depths

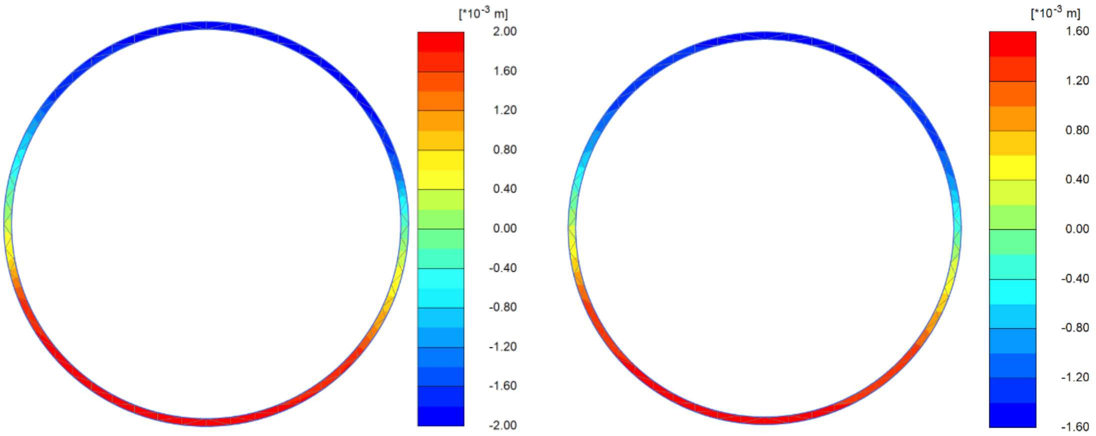


a) Tunnel crown



b) Tunnel sidewall

Figure 15. Effect of tunnel depth on the SRFS lining stresses with time



H= 1002m **H= 900m**

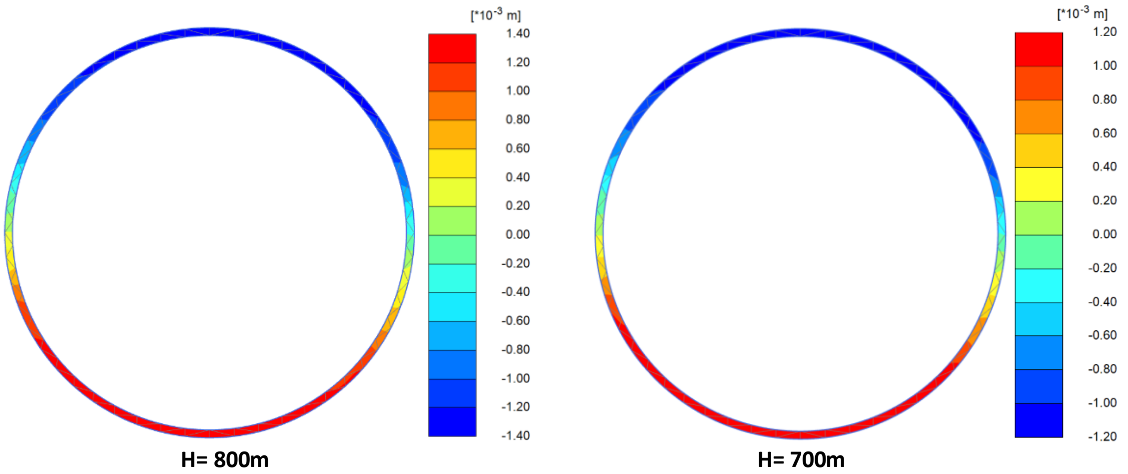
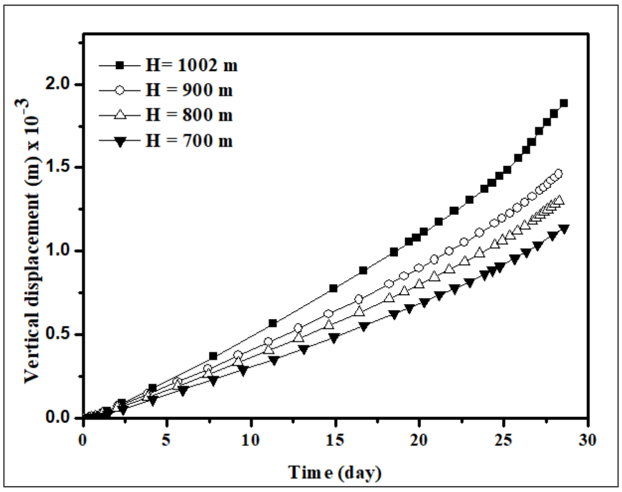
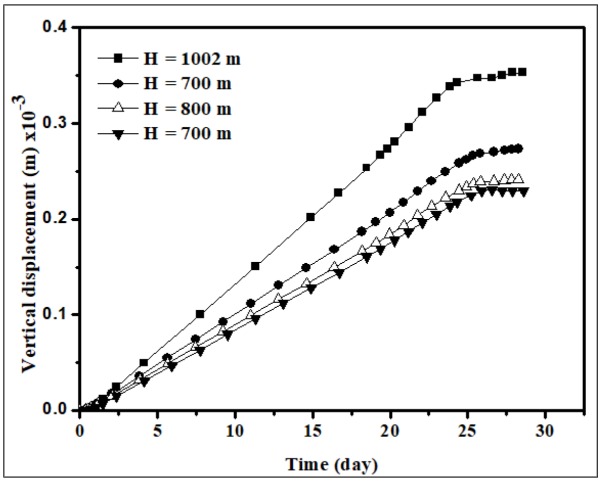


Figure 16. Vertical displacement along the tunnel lining under different tunnel overburden depths



a) Tunnel crown



b) Tunnel sidewall

Figure 17. Effect of tunnel depth on the SRFS lining vertical displacement with time

3.1.3. Effect of the Tunnel Diameter

The influence of tunnel diameter on the development of the SFRS lining stress and displacement with time is performed. Different tunnel diameters of 4, 4.5 and 5.2 m, based on the trails carried out by Shaalan et al. [28], are used. The lining thickness and tunnel depth of 0.1 and 1002 m, respectively, are kept constants. The actual tunnel diameter is 5.2 m which used as a reference to compare with other diameters. The stress distribution along the tunnel lining using different tunnel diameters is presented in Figure 18.

Figure 19a shows the effect of the tunnel diameter on the development of the lining tensile stress with time, at tunnel crown. In the first day, the tunnel diameters of 4.5 and 4 m display an increase the lining tensile stresses with time up to 33% and 17%, respectively. At 14 days, the development of the lining tensile stress with time increase by 32% and 17% due to increasing the tunnel diameter to 4.5m and 4m. At 28 days, the lining tensile stress with time increases by 34% and 20%. It is evident that lower tunnel diameter results in a higher increase in the lining tensile stress with time. Whereas, at the tunnel sidewall, the effect of the tunnel diameter on the lining compression stress with time shows the inverse behaviour, in which decreasing the tunnel diameter leads to decrease the lining compression stress with time. Figure 19b presents the impact of the tunnel diameter on the development of the lining compression stress with time, at tunnel sidewall. In the first day, the lining compression stress with time decreases by 20% and 37% in case of decreasing the tunnel diameter to 4.5 and 4 m, respectively. At 14 days, decreasing the tunnel diameter to 4.5 and 4 m causes a reduction in the lining compression stress with time by 14% and 32% while at 28 days, the lining compression stress with time decreases by 30% and 42%, respectively.

The vertical displacement along the tunnel lining using different tunnel diameters is illustrated in Figure 20. Figure 21a presents the influence of different tunnel diameters on the development of the lining vertical displacement with time, at the tunnel crown. Decreasing the tunnel diameter to 4.5 and 4 m, in the first day of application, show a decrease in the lining vertical displacement with time by 14% and 24%, respectively. At 14 days, the lining vertical displacement with time decreases by 13% and 23% due to decrease the tunnel diameter to 4.5m and 4m, respectively. Whiles, at 28 days, the lining vertical displacement with time decreases by 18% and 28%. Similar to the lining vertical displacement with time at tunnel crown, decreasing the tunnel diameter, at the tunnel sidewall, results in lower lining vertical displacement with time, as shown in Figure 21b. However, in the first day, the lining vertical displacement with time decreases by 25% and 70% in case of tunnel diameter of 4.5 and 4 m, respectively. Lower tunnel diameters of 4.5m and 4m lead to decrease the lining vertical displacement with time by 23% and 70% at 14 days and by 17% and 60% at 28 days, respectively. Generally, increasing the tunnel diameter can increase the vertical displacement of the tunnel lining with time. This increase in the vertical displacement with time is visible from the first days of application for both tunnel crown and sidewall. However, the decrease in the lining vertical displacement in tunnel sidewall, due to decreasing the tunnel diameter, is higher than that of the tunnel crown.

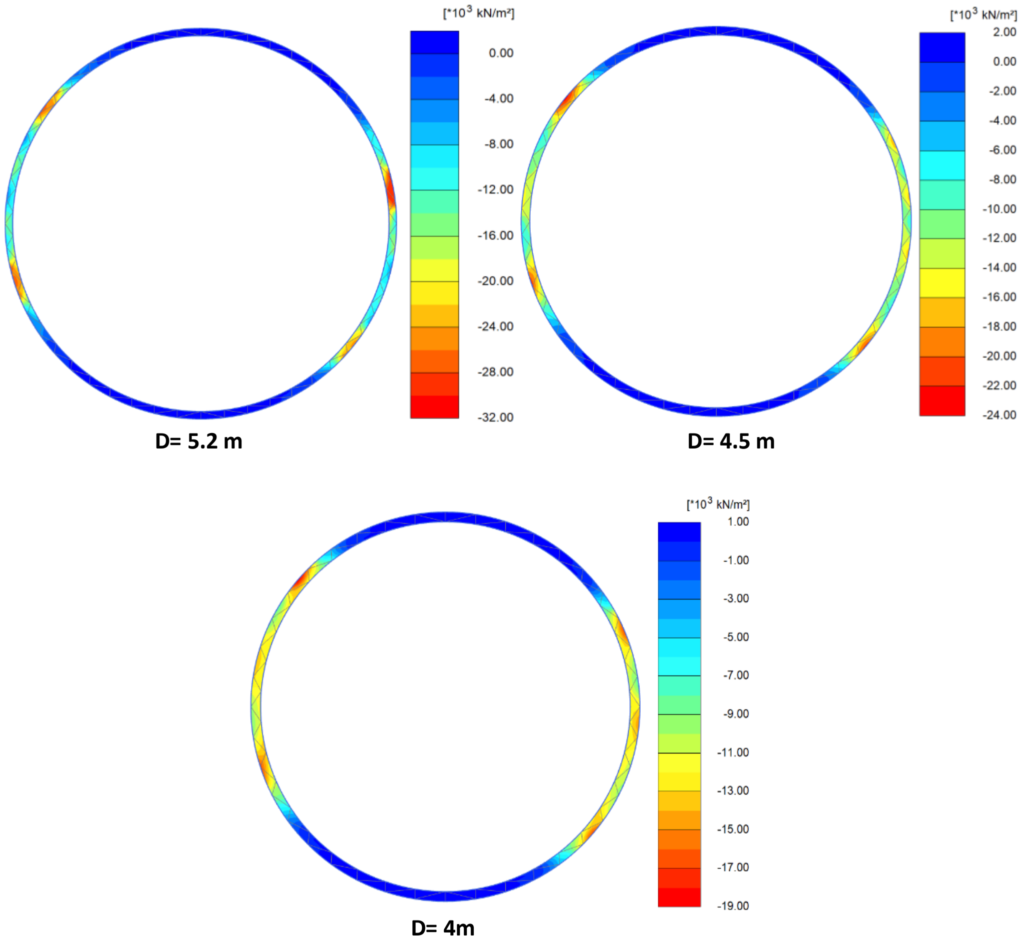
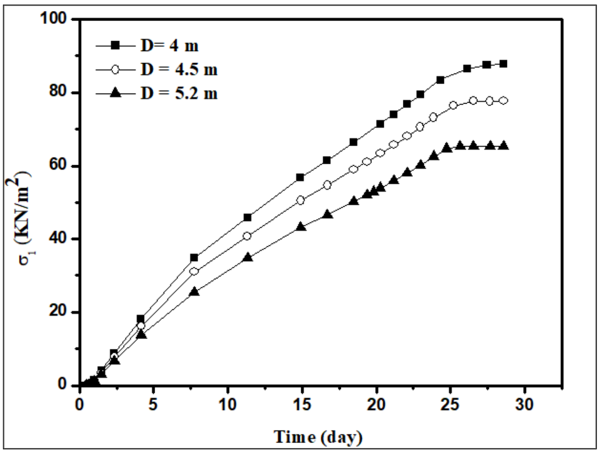
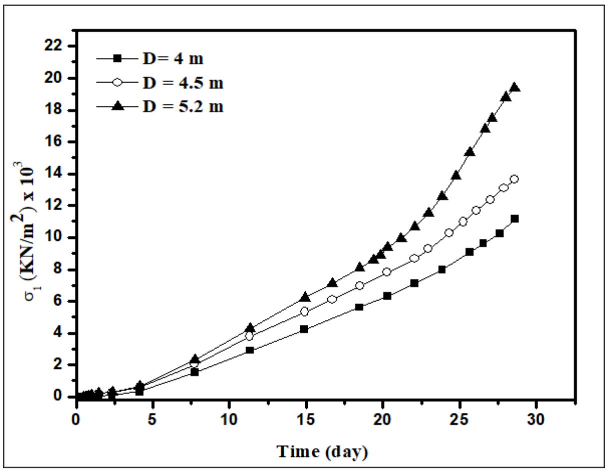


Figure 18. Stress distribution along the tunnel lining using different tunnel diameters

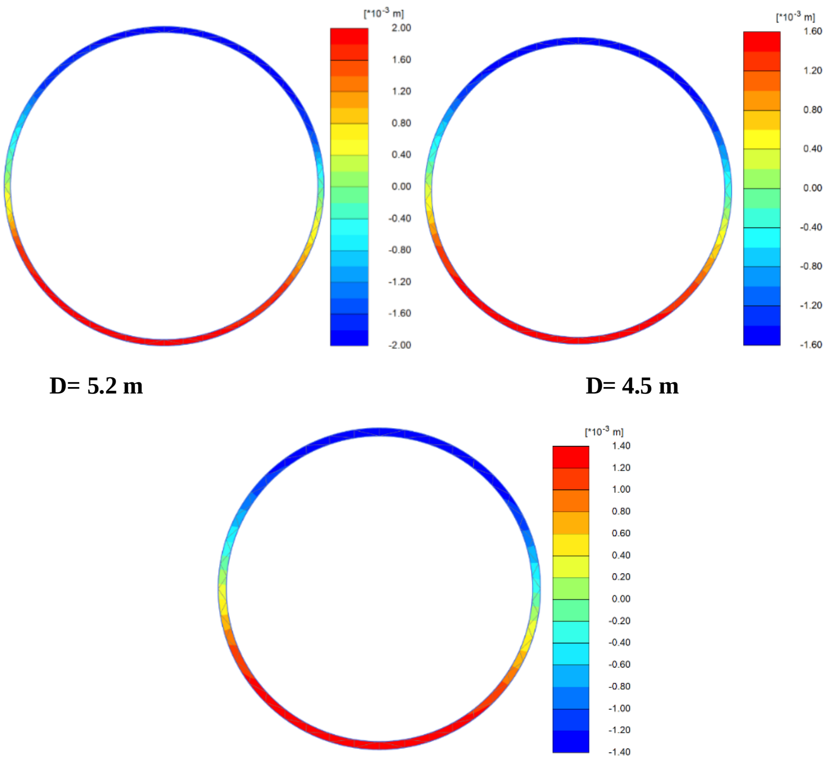


a) Tunnel crown



b) Tunnel sidewall

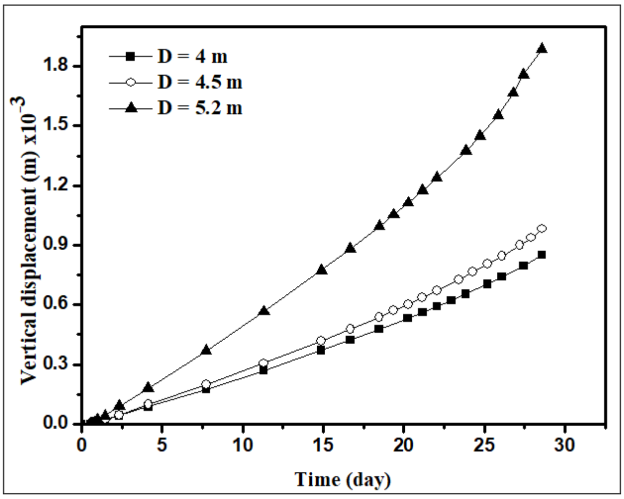
Figure 19. Effect of tunnel diameter on the SRFS lining stresses with time



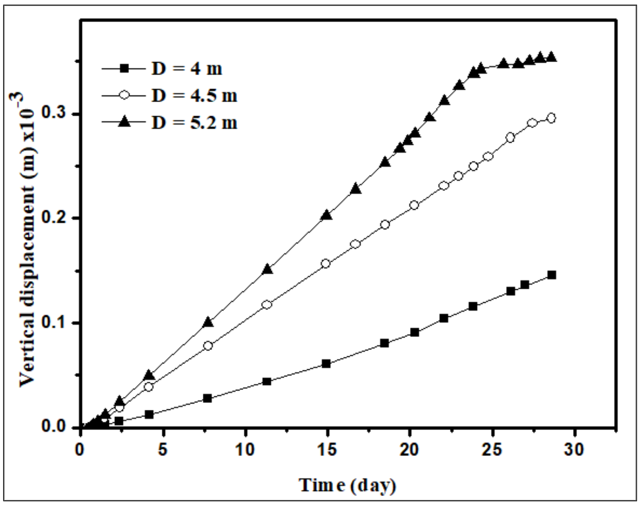
D= 5.2 m **D= 4.5 m**

D= 4 m

Figure 20. Vertical displacement along the tunnel lining using different tunnel diameters



a) Tunnel crown



b) Tunnel sidewall

Figure 21. Effect of tunnel diameter on the SRFS lining vertical displacement with time

4. Conclusion

The steel fibre reinforced shotcrete lining of a deep tunnel with a circular cross-section, driven in granite rock mass by the Tunnel Boring Machine TBM, is considered. The development of the lining stress and displacement with time is evaluated using a constitutive model of shotcrete. This model is based on the framework of Elasto-plastic strain hardening/softening plasticity and can account for non-linearity and time-dependent behaviour for any cement-based material. Thus, a realistic stress distribution of the shotcrete lining can be obtained. In this paper, a parametric study is carried out, using the shotcrete model, to investigate the effect of some parameters on the development of the shotcrete lining stress and displacement with time. These parameters include the lining thickness, tunnel depth and tunnel diameter. The stress and displacement along the tunnel lining are evaluated. The lining stresses at the crown and toe of the tunnel are compression stress while the sidewalls are undergoing tensile stresses. The lining compression stresses at the sidewalls of the tunnel are higher than the tensile stresses at the crown and toe. Whereas, the lining vertical displacement at tension is high that that at compression. The result of the parametric study showed that:

- Increasing the lining thickness leads to increase the lining tensile stress with time, at tunnel crown, and decreases the lining compressive stress with time, at tunnel sidewall.
- At tunnel crown, the development of the lining vertical displacement with time is less affected by the variation in the lining thickness.
- A considerable reduction in the development of the lining vertical displacement with time, at tunnel sidewall, is observed with higher lining thickness.
- The effect of the tunnel depth showed that higher tunnel depth increases the development of lining compression stress at the tunnel sidewall with time, whereas the development of lining tensile stress at the tunnel crown with

time is not affected.

- The development of the lining vertical displacement with time at tunnel crown and sidewall increases by increasing the tunnel depth.
- At the tunnel crown, increasing the tunnel diameter decreases the development of the lining tensile stress with time and increases the lining compressive stress with time.
- Increasing the tunnel diameter leads to higher lining displacement with time.
- In addition, these results indicate the ability of the shotcrete model to simulate the structural behaviour of the shotcrete lining with time.

5. Acknowledgements

The authors gratefully acknowledge the assistance and cooperation given by KeTHHA (Ministry of Energy, Green Technology and Water Malaysia) and Tokyo Electric Power Services Co., Ltd. (TEPSCO) to carry out this study successfully.

6. Funding

The work in this paper was partially supported by funding from the Fundamental Research Grant Scheme of the Ministry of Education Malaysia: Analysis of Rock Burst Behavior under Overstressed Rock in Deep Tunnel Excavation across the Titiwangsa Range, Malaysia. Grant No.: 203/PAWAM/6071259.

7. References

[1] Yu, J., Kim, J., Kim, M., and Kim, M. K. "Numerical Study on Structural Behavior of Arched Shotcrete Liner Reinforced with Steel Supports." International Journal of Latest Engineering Research and Applications (October 2016): 48-54.

[2] Kim, J., Kim, M. and Yoo, H. "Nonlinear Finite Element Analysis of Shotcrete Lining Reinforced with Steel Fibre and Steel Sets." IACSIT International Journal of Engineering and Technology (December 2013) doi: 10.7763/IJET.2013.V5.638.

[3] Saurer, E., Marcher, T., Schaedlich, B., and Schweiger, H. F. "Validation of a novel constitutive model for shotcrete using data from an executed tunnel." Geomechanics and Tunnelling (August 2014): 353–361. doi: 10.1002/geot.201400023.

[4] Schütz, R., Potts D, and Zdravkovic, L. "Advanced Constitutive Modelling of Shotcrete: Model Formulation and Calibration." Computers and Geotechnics (September 2011): 834–845. doi: 10.1016/j.compgeo.2011.05.006.

[5] Schütz, R "Numerical Modelling of Shotcrete for Tunnelling." Ph.D thesis, Imperial College London, London. (February 2010)

[6] Thomas, A., "Numerical modelling of sprayed concrete lined (SCL) tunnels." PhD thesis, University of Southampton, UK. (2003)

[7] Thomas, "Sprayed concrete lined tunnels." (October 8, 2008).

[8] Schädlich B., and Schweiger H.F. "A new constitutive model for shotcrete." Proceedings of the 8th European Conference on Numerical Methods in Geotechnical Engineering. doi: 10.1201/b17017-20.

[9] Brinkgreve, R B J., Engin, E., and Swolfs W M "Finite element code for soil and rock analyses." Plaxis 2D Manual (2012) http://www.academia.edu/8233451/PLAXIS_-Finite_Element_Code_for_Soil_and_Rock_Analyses.

[10] Schweiger H, Marcher, T., and Schädlich B. "Application of a new shotcrete constitutive model to numerical analysis of tunnel excavation." Proceedings of the Geo-Shanghai 2014 International Conference.

[11] Schaedlich, B., Schweiger, H. F., Marcher, T., and Saurer, E. "Application of a novel constitutive shotcrete model to tunnelling." Rock Engineering and Rock Mechanics: Structures in and on Rock Masses. doi: 10.1201/b16955-137.

[12] Paternesi, A., Schweiger, H. and Schubert, R. "Verification of a rheological constitutive model for shotcrete through back-analysis." Geomechanics and Tunnelling, (August 2016) doi: 10.1002/geot.201500053.

[13] Maatkamp, T. "The capabilities of the Plaxis Shotcrete material model for designing laterally loaded reinforced concrete structures in the subsurface." MSc thesis, Delft University of Technology (October 2016).

[14] Shaalan, H., Ismail, M.A.M., and Azit, R. "Time-dependent behavior of steel fiber reinforced shotcrete lining under rock overstressing using shotcrete model." Electronic journal of geotechnical engineering EJGE, 2016.

[15] Neuner, M., Gamnitzer, P and Hofstetter, G. "An Extended Damage Plasticity Model for Shotcrete: Formulation and Comparison with Other Shotcrete Models." Materials, (January 2017) doi:10.3390/ma10010082.

[16] Neuner, M., Schreter, M., Unteregger D. and Hofstetter, G. "Influence of the Constitutive Model for Shotcrete on the Predicted Structural Behavior of the Shotcrete Shell of a Deep Tunnel." Materials, (May 2017) doi:10.3390/ma10060577.

[17] "CEB-FIP MODEL CODE 1990" (January 1993). doi:10.1680/ceb-fipmc1990.35430.

[18] EN 14487 2006. Sprayed concrete. European Committee for Standardization.

[19] Oluokun, F.A., Burdette, E. G., and Deatherage J H. "Splitting tensile strength and compressive strength relationship at early

ages." Aci material journal (March 1991): 115-121.

[20] EN 1992-1-1 2004. Eurocode 2: Design of concrete structures. European Committee for Standardization.

[21] ACI 209R-92 1992. Prediction of creep, shrinkage and temperature effects in concrete structures. American Concrete Institute, Committee 209.

[22] Schädlich B, & Schweiger H. Internal report shotcrete model: Implementation validation and application of the shotcrete model. Delft: Plaxis. (2014).

[23] Kawata, T., Nakano, Y., Matsumoto, T., Mito, A., Pittard, F., and Azman, A. A. S. "The Relationship between TBM Data and Rockburst in Long-Distance Tunnel, Pahang-Selangor Raw Water Transfer Tunnel, Malaysia." 8th Asian Rock Mechanics Symposium, Sapporo, Japan.

[24] Azit, R., Ismail, M. A. M., Syed Zainal, S. F., Mahmood, N. "Rock overstressing in deep tunnel excavation of Pahang-Selangor raw water transfer project." Applied Mechanics and Materials (October 2015): 16-21. doi: 10.4028/www.scientific.net/AMM.802.16.

[25] Lee, S., Ismail, M., and Ng, S. M. "The Evaluation of Tunnel Behaviours under High Rock Stress Using Numerical Analysis Method". EJGE: (January 2012) 3605-3626.

[26] Plaxis 2D (2017). Reference Manual. https://www.plaxis.com/support/manuals/plaxis-2d-manuals/.

[27] Barros, J. A. O, and Figueiras, J. A. "Flexural behaviour of SFRC: testing and modelling." J. Mat. Civ. Eng. ASCE (November 1999): 331-339. doi: 10.1061/(ASCE)0899-1561(1999)11:4(331).

[28] Shaalan, H., Ismail, M.A.M., and Azit, R. "Evaluation of TBM tunnels with respect to stability against spalling". AIP Conference Proceedings 1892, 030010.