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Numerical Evaluation of Segmental Lining System with Compressible Layer in Deep Soft Rock

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ABSTRACT

Tunnel boring machines (TBMs) are increasingly preferred over conventional tunneling methods because noise and vibration are minimized, and continuous and repetitive construction is possible. The development of TBM technology enables tunnel excavation with minimal ground deformation, a capability that is currently being utilized in challenging conditions. Despite this, geo-risk issues such as rock burst, squeezing, and spalling during tunneling in deep soft rocks induce excessive stress in the segmental linings, which results in stress concentrations, cracks, and fractures. Increasing the thickness of segmental lining, utilizing high or ultra-high performance concretes, and using double shell lining are structural solutions to this issue; however, there are drawbacks such as manufacturing and transportation difficulties, increased construction costs, and a reduction in effective cross-sectional area. On the basis of the yielding principle, studies are currently being conducted to reduce the support pressure for tunneling in the overstressed rock by allowing some deformation of the ground. Although many studies on yielding support in the form of a compressible layer preferred for shield tunnels have been conducted, the design is not well-established. In addition, there are insufficient studies on the stiffness and interaction of backfill material and ground during the excavation process. In this study, a three-dimensional numerical analysis based on the finite element method was performed to investigate the effect of the compressible layer on the segmental lining and surrounding ground during shield TBM tunneling. The parametric study was conducted by controlling the thickness ratio of the compressible layer and the backfill material, the strength of the rock, and the stiffness of the backfill material.

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1. INTRODUCTION

Tunnel boring machines (TBMs) are being favored over conventional tunneling methods due to the reason that noise and vibration are reduced and continuous and repetitive construction is possible (Tarkoy and Byram, 1991, An *et al.*, 2022). With the advancement of TBM technology, the earth pressure balanced shield TBM (EPB shield TBM) enables tunnel excavation with minimal ground deformation, and the number of shield TBM tunneling cases under challenging conditions is increasing (Shahriar *et al.*, 2008, Galli and Thewes, 2014). Nevertheless, overstressing of the segmental lining is induced during tunneling in deep soft rock, resulting in issues such as stress concentration, cracking, fracture of segmental lining, or jamming of the shield TBM equipment (Ramoni and Anagnostou, 2010). Three major structural solutions are being considered in a rigid support system based on the “resistance principle” like segmental lining (Kovári *et al.*, 1988). There is an increase in the thickness of the segmental lining, an increase in the strength of the segmental lining through the use of high or ultra-high performance concretes, and a double shell lining by installing an additional inner lining to the existing lining (Mezger *et al.*, 2017). However, these solutions result in issues such as manufacturing and transportation problems due to the increased weight of the segment lining, difficulty in maintaining uniform quality, an increase in construction costs, and a decrease in the effective cross-sectional area. The cost of segment lining already accounts for 25 to 40 percent of the direct construction cost and is expected to increase as the depth of the tunnel and the diameter of the tunnel cross-section increase (Jang *et al.*, 2017), requiring a new concept support system that combines stability and economy.

Geo-risks such as rock burst (Kaiser and Cai, 2012), squeezing (Aydan *et al.*, 1993, Hoek and Marinos, 2000), and spalling (Cai and Kaiser, 2014) failure exist when tunneling in an overstressed rock mass if deformation is not properly restrained by supports. Particularly, it is known that the probability of squeezing, in which pressure and internal displacement raise with time, increases significantly during tunneling in deep soft rock. Therefore, on the basis of the "yielding principle", yielding supports that allow some displacement of the surrounding rock during the yielding deformation phase have been investigated (Anagnostou and Cantieni, 2007). An ideal yielding support should have three elements: opportune support; yielding deformation; high stiffness; and the support characteristic curve (SCC) is shown in Fig. 1 (Wu *et al.*, 2021). The yielding support design can effectively reduce the support pressure applied to the segmental lining from the perspective of the convergence-confinement method (CCM). In the tunnel supported by linings, yielding support has been divided into instances in which deformable elements are used as tangentially between the divided shotcrete linings and as a radially compressible layer between the primary support and secondary linings (Cantieni and Anagnostou, 2009). Various materials for deformable elements have been studied or constructed, including Meypo, Wabe, hiDCon, LSC, DeCo-Grout, and Compex (Brunar and Powondra, 1985, Billig *et al.*, 2007, Schneider *et al.*, 2005). Key parameters in the design of yielding support include initial stiffness, yielding pressure, deformation capacity, installation procedure, serviceability, and costs (Mezger *et al.*, 2018). Recent numerical and experimental studies have been performed on polyurethane (PU), polyethylene (PE), PU foam, PE foam, compressible concrete, and expanded clay as the material of the compressible layer (Hu *et al.*, 2020, Tian *et al.*, 2021, Tian *et al.*, 2022). In addition, theoretical research has been conducted on tunnel performance according to the compressible layer application (Chu *et al.*, 2021, Wu and Shao, 2019, Wu *et al.*, 2022, Do *et al.*, 2021). Nonetheless, there are insufficient studies on the shield tunnel employing segmental lining as the primary support, the consideration of three-dimensional spatial stress change during excavation, and the effect on the surrounding ground.

In this study, a simplified finite element method (FEM)-based model was used to analyze numerically the impact of the support system, in which the compressible layer is coupled to the outer surface of the segmental lining (Fig. 2), on the segmental lining and surrounding ground during shield TBM tunneling in deep soft rocks. A parametric study was performed with thickness ratio of the compressible layer and the backfilling, the strength of the rock, and the stiffness of the backfill material as the major factors, and a three-dimensional numerical analysis was conducted to consider the effect of spatial stress changes that result from longitudinal excavation. For finite element analysis (FEA), FE code based on ABAQUS/CAE 2022 was used. The ground was modeled assuming the linearly elastic and perfectly plastic material that satisfies the Mohr-Coulomb failure criterion with the typical physical properties of soft rock (Ramoni *et al.*, 2011). As structural elements for shield TBM tunneling, segmental lining, shield TBM, and backfilling were considered, and they were all modeled assuming linear elastic materials (Comodromos *et al.*, 2014, Moeinossadat and Ahangari, 2019). The compressible layer was modeled under the assumption that it follows the radial stress-strain behavior proposed by laboratory-scale research on polyurethane (PU) as an highly compressible material (Tian *et al.*, 2021). The Shield TBM tunneling sequence was modeled so that each element was activated and deactivated according to the excavation process, and the "hard contact" algorithm of ABAQUS/CAE 2022 was used to consider the interaction properties between the elements (Liu *et al.*, 2008).

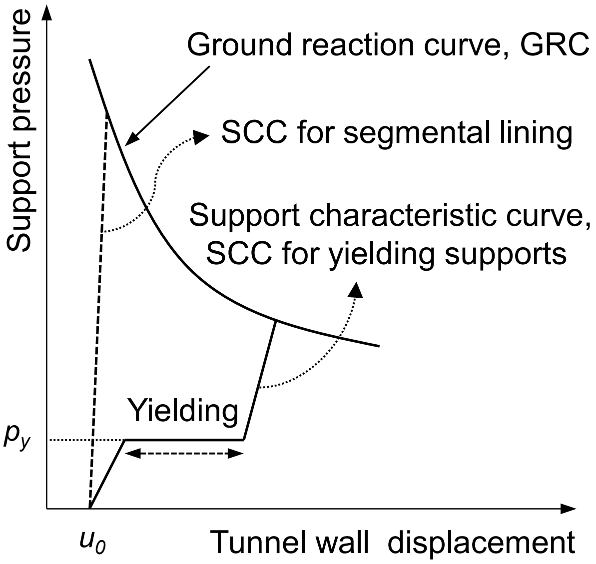


Fig. 1 Support characteristic curve (SCC) for yielding supports

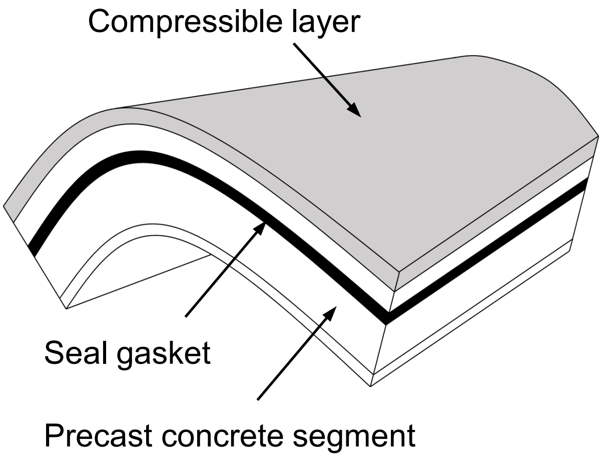


Fig. 2 Conceptual diagram of segment with compressible layer

2. NUMERICAL METHODOLOGY

Numerical analysis based on the FEM was performed for various cases representing the effect of compressible layers on the segmental lining and surrounding ground under various conditions. ABAQUS/CAE 2022, developed by Dassault Systems, was used for three-dimensional finite element analysis. In this study, a simplified model was employed to investigate numerically the effect of the compressible layer on shield TBM tunneling in deep soft rocks. The model consisted of the ground, structural elements, and the compressible layer. And geometric parameters were assumed for numerical analysis (Table 1).

Table 1 Assumed geometric parameters for reference case

Parameter	Value [m]
Boring diameter	10
Depth of cover	100
Length of shield	9
Thickness of backfill mateiral	0.15
Thickness of compressible layer	0.05
Thickness of segmental lining	0.35

2.1 Ground modeling

The ground was assumed to be a linearly elastic and perfectly plastic material that satisfies the Mohr-Coulomb failure criterion, and it was modeled as a three-dimensional solid element that disregards the flow rule. To simplify the analysis, it was assumed that the cross section of tunnel was circular and that the ground was homogeneous and isotropic. For the analysis of short-term stability, time-dependent behaviors such as creep and consolidation were neglected. On the side of the ground model, the roller supports boundary condition was applied, while the pinned supports boundary condition was implemented to the base. The length of the ground model was set to (H+3D), the width to 2 (H+4D), and the height to (H+4D) in order to ignore errors resulting from boundary condition assignment (Lambrughi *et al.*, 2012). In this instance, H is the depth of cover and D is the desired boring diameter. In order to minimize the analysis time, the mesh size was configured to increase gradually as the distance from the tunnel's center increased. Table 2 displays physical properties of soft rock. And The ground geometry and finite element mesh are depicted in Fig 3.

Table 2 Mechanical properties of typical soft rock

Cohesion [MPa]	2.0
Density [kg/m^3]	2,500
Dilatancy angle [°]	10
Young’s modulus [GPa]	6
Internal friction angle [°]	30
Poisson’s ratio	0.3

Source: Data from Barla (2005)

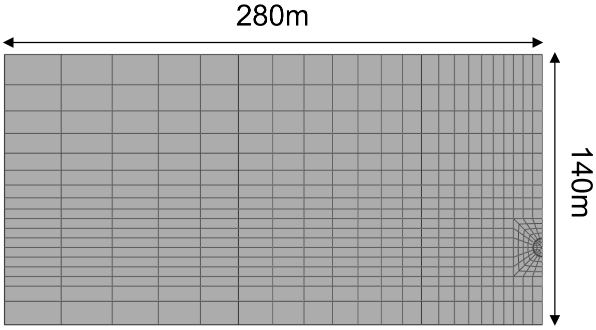


Fig. 3 Schematic diagrams for ground finite element mesh

2.2 Structural elements modeling

The structural elements consisted of segmental lining, shield TBM, and backfill material (Fig. 4). All three structural elements were assumed to be constituted of linear elastic materials and were modeled as three-dimensional solids without flow rules. The shield was simplified to a cylindrical shape without a taper, and in the case of segmental lining, an elastic continuum element was assumed without considering the joint. Table 3 displays the physical properties of structural elements. For efficient analysis, it was assumed that the stiffness change due to backfill material hardening was not considered and a constant value was assumed.

Table 3 Mechanical properties of structural elements

	Density [kg/m^3]	Young's modulus [GPa]	Poisson's ratio
Shield	7840	200	0.25
Segment	2400	27	0.20
Backfill material	1200	1	0.25

Source: Data from Moeinossadat and Ahangari (2019)

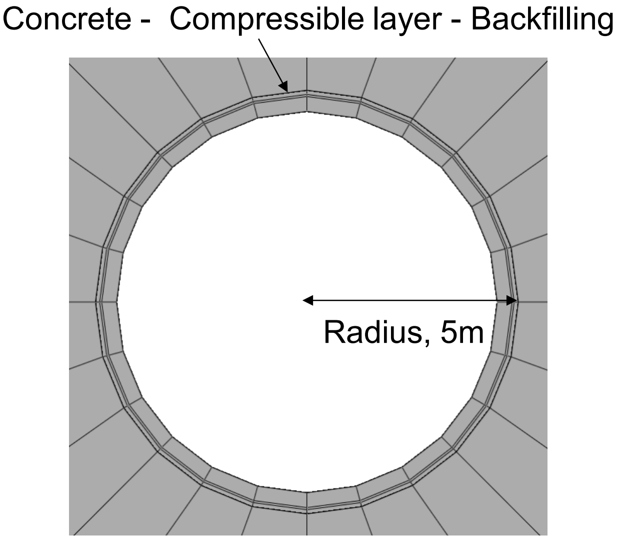
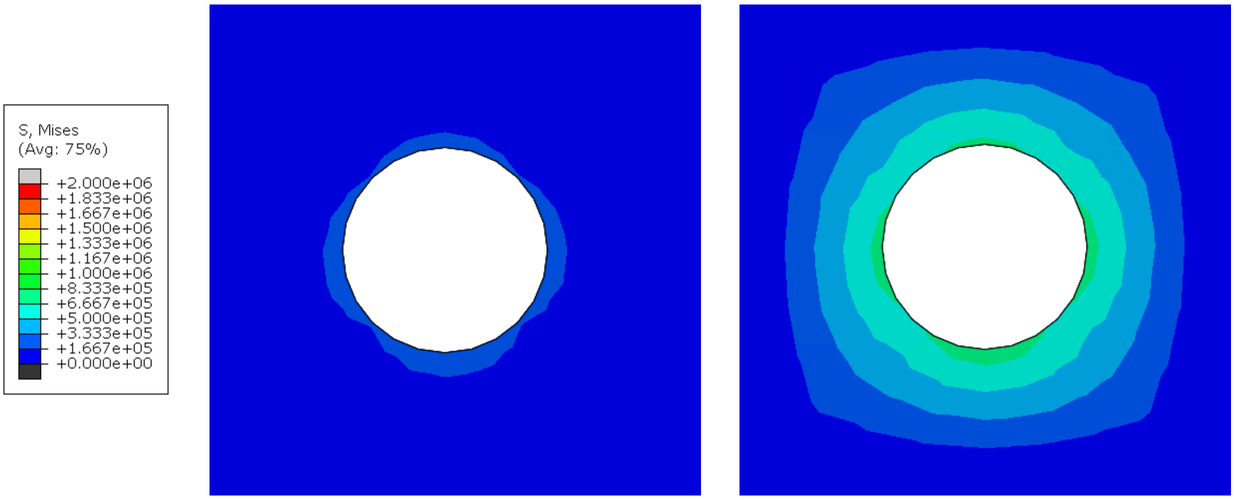


Fig. 4 Cross-section of numerical model

4. Effect on segmental lining

4.1 Stress distribution in surrounding ground

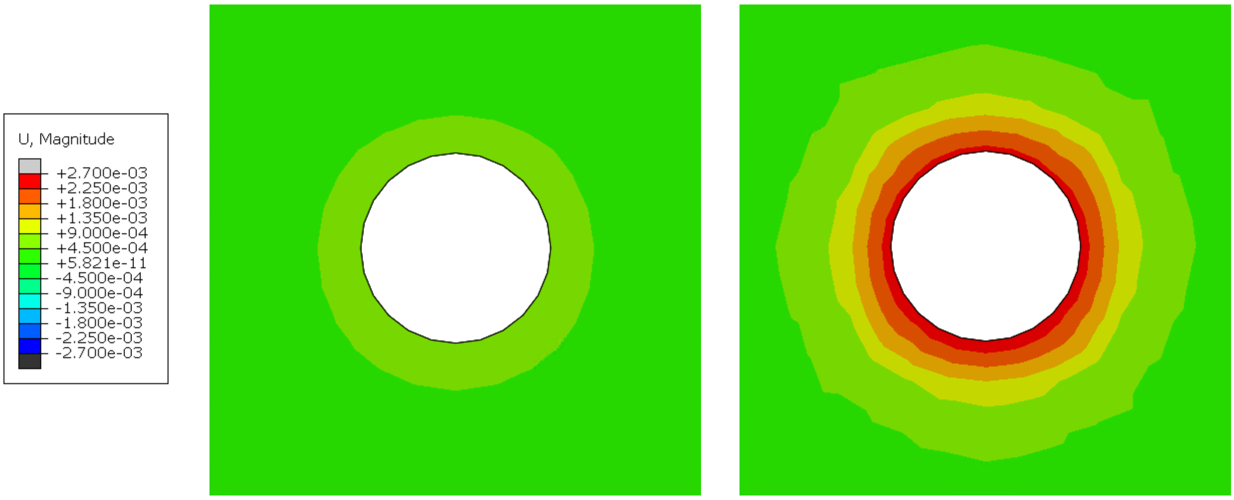
Fig. 13 depicts the stress distribution of the reference case's surrounding ground, which was obtained at ten ring distances from the back of the shielding TBM. It was confirmed that when the compressible layer was applied, the surrounding ground stress increased compared to when the compressible layer was not active.



(a) Support system consisting of backfilling and segmental lining

(b) Support system with compressible layer

Fig. 13 Effect of compressible layer on stress of surrounding ground



(a) Support system consisting of backfilling and segmental lining

(b) Support system with compressible layer

Fig. 14 Effect of compressible layer on displacement distribution of surrounding ground

4.2 Surrounding ground displacement distribution

The displacement distribution of the surrounding ground in the reference case is visualized in Fig. 14, and it was determined that when the compressible layer was applied, the surrounding ground deformed more than in the case without the compressible layer. Therefore, the compressible layer allows the displacement of the surrounding ground, and in the process, it can be confirmed that the stress is concentrated in the interaction with the support system.

4.3 Effect of thickness ratio

Figure 15 demonstrates the stress of the surrounding ground in relation to the change in compressible layer thickness t. As the compressible layer increased thicker, the surrounding ground deformed more, resulting in a stress concentration. This indicates that the design of the thickness ratio is crucial for preventing the collapse of the surrounding ground. Therefore, if a high thickness ratio is designed to relieve the stress of the segmental lining, overstress of the surrounding ground may be induced. This suggests that the stress change of the ground must be considered in the process of designing the thickness, which is the most important parameter of the compressible layer.

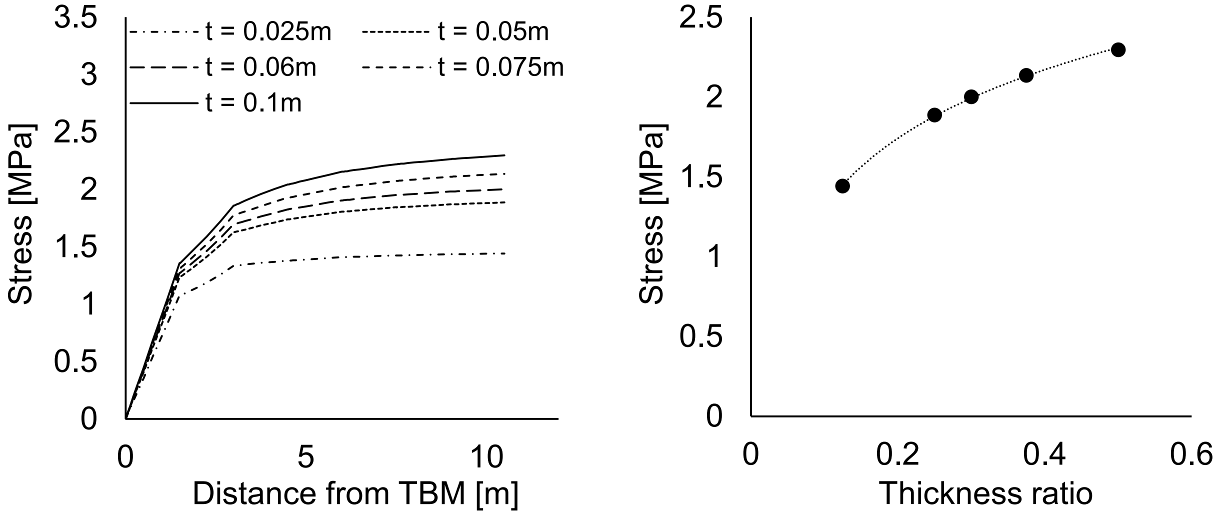


Fig. 15 Stress of ground depending on the thickness ratio of the compressible layer and backfilling

4.4 Effect of rock strength

Figure 16 depicts the stress depending on the variation in Young's modulus of the soft rock surrounding the shield tunnel. As stiffness increases, the soft rock becomes overstressed, as demonstrated by the results. This indicates that it is necessary to consider the concentration of ground stress when a compressible layer is applied to a ground with a high stiffness. Therefore, when designing the compressible layer in the weak rock, it will be preferred to consider the stress concentration of the segmental lining rather than the ground.

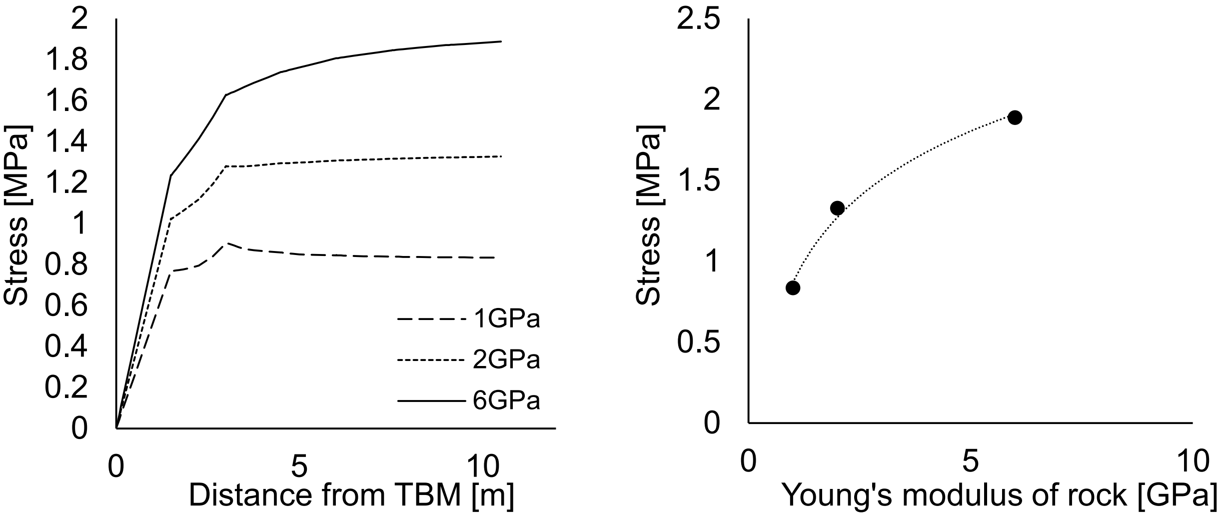


Fig. 16 Stress of ground depending on the stiffness of the rock

4.5 Effect of backfill material stiffness

Figure 17 shows the surrounding ground stress in accordance with the change in stiffness of the backfill material. The results indicate that as the stiffness of the backfill material increases, the stress of the surrounding ground decreases. Therefore, when the compressible layer and the stiffness of the backfill material are designed simultaneously, it suggests that ground stress can be alleviated by increasing the stiffness of the backfill material.

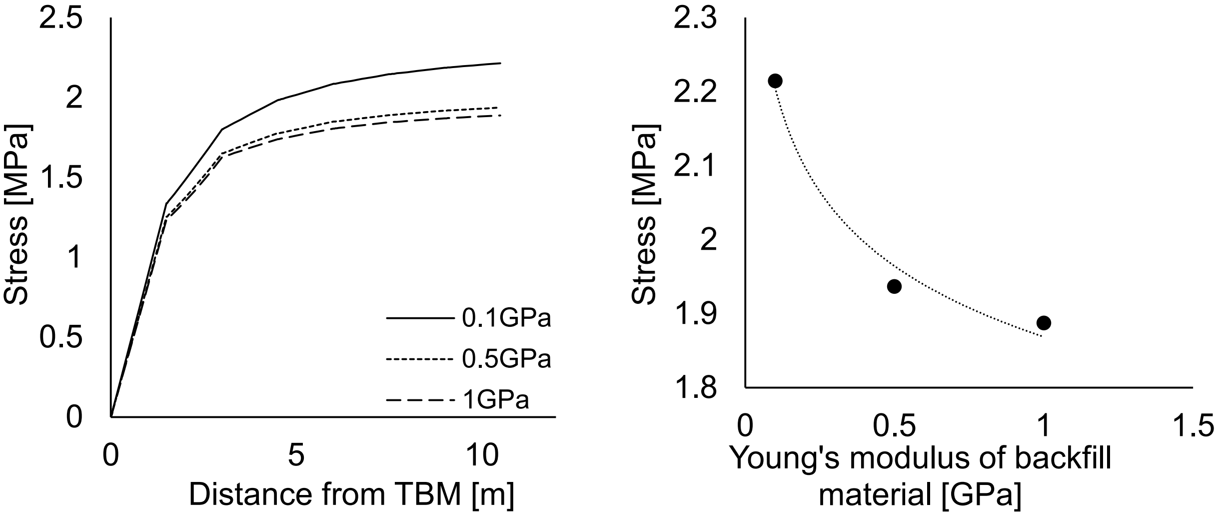


Fig. 17 Stress of ground lining depending on the stiffness of the backfill material

5. CONCLUSIONS

In this study, three-dimensional FEM simulations were performed to analyze numerically the effect of a support system with a compressible layer on the segmental lining and surrounding ground. A simplified FEM model was used to simulate the EPB shield TBM tunneling sequence. On the segmental lining and surrounding ground, the effects of the thickness ratio of the compressible layer and backfilling, the strength of the ground, and the stiffness of the backfill material qualitatively analyzed. The findings of this study can be summarized as follows:

- When a material with yielding deformation phase was used as the compressible layer, it was determined that the stress of the segmental lining was effectively reduced, whereas the stress of the surrounding ground increased.
- During the yielding phase, it was confirmed that the compressible layer deformed while allowing the displacement of the surrounding ground, and that the deformation of the surrounding ground increased.
- As the thickness ratio of the compressible layer and the backfilling increased, the stress on the segmental lining decreased and the stress on the surrounding ground increased.
- It was confirmed that as the strength of rock increased, the stress of segmental lining decreased and the surrounding ground became overstressed. A compressible layer is effective for both the segmental lining and the surrounding ground when the rock strength is low.
- As the stiffness of the backfill material increased, it was determined that the segmental lining was overstressed and that the stress of the surrounding ground was reduced. When designing the stiffness of the backfill material together with the compressible layer, it should have appropriate stiffness to relieve the stress of the ground.
- Therefore, when designing the parameters of the compressible layer in the shield tunnel, the stiffness of the backfill material, the strength of the surrounding ground, and the interaction with the backfilling should be considered simultaneously.
- In this study, only qualitative analysis was performed on the change in stress of the compressible layer segmental lining and the surrounding ground through a simplified numerical model. However, it is expected to be used for experimental research on the interaction with backfill material and surrounding ground.

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REFERENCES

An, J.B., Kang, S.J., Kim, J. and Cho, G.C. (2022), “Numerical evaluation of surface settlement induced by ground loss from the face and annular gap of EPB shield tunneling”, *Geomech. Eng.*, **29**(3), 291-300.

Anagnostou, G. and Cantieni, L. (2007), "Design and analysis of yielding support in squeezing ground", 11th ISRM Congress.

Aydan, Ö., Akagi, T. and Kawamoto, T. (1993), "The squeezing potential of rocks around tunnels; theory and prediction", *Rock Mech. Rock Eng.*, **26**(2), 137-163.

Billig, B., Ebsen, B., Gipperich, C., Schaab, A. and Wulff, M. (2007), "DeCo Grout–innovative grout to cope with rock deformations in TBM tunnelling", Proceedings of the Underground Space–the 4th Dimension of Metropolises, ITA World Tunnel Congress, Prague, Czech Republic.

Brunar, G. and Powondra, F. (1985), "Nachgiebiger Tübbingausbau mit Meypo-Stauchelementen", Felsbau, 3(4), 225-229.

Cai, M. and Kaiser, P. (2014), "In-situ rock spalling strength near excavation boundaries", *Rock Mech. Rock Eng.*, **47**(2), 659-675.

Cantieni, L. and Anagnostou, G. (2009), "The interaction between yielding supports and squeezing ground", *Tunn. Undergr. Space Technol.*, **24**(3), 309-322.

Chu, Z., Wu, Z., Liu, Q., Liu, B. and Sun, J. (2021), "Analytical Solution for Lined Circular Tunnels in Deep Viscoelastic Burgers Rock Considering the Longitudinal Discontinuous Excavation and Sequential Installation of Liners", *J. Eng. Mech.*, **147**(4).

Comodromos, E. M., Papadopoulou, M. C. and Konstantinidis, G. K. (2014), "Numerical assessment of subsidence and adjacent building movements induced by TBM-EPB tunneling", *J. Geotech. Geoenviron.*, **140**(11), 04014061.

Do, D.-P., Vu, M.-N., Tran, N.-T. and Armand, G. (2021), "Closed-Form Solution and Reliability Analysis of Deep Tunnel Supported by a Concrete Liner and a Covered Compressible Layer Within the Viscoelastic Burger Rock", *Rock Mech. Rock Eng.*, **54**(5), 2311-2334.

Galli, M. and Thewes, M. (2014), "Investigations for the application of EPB shields in difficult grounds/Untersuchungen für den Einsatz von Erddruckschilden in schwierigem Baugrund", *Geomechanics and Tunnelling*, **7**(1), 31-44.

Hoek, E. and Marinos, P. (2000), "Predicting tunnel squeezing problems in weak heterogeneous rock masses", *Tunn. Tunn. Int.*, **32**(11), 45-51.

Hu, X.-Y., He, C., Lai, X.-H., Walton, G. and Xu, G.-W. (2020), "Study on the interaction between squeezing ground and yielding supports with different yielding materials", *Tunn. Undergr. Space Technol.*, **97**.

Jang, D.-I., Kim, J.-I., Kwak, C.-W. and Park, I.-J. (2017), "Study on flexible segment efficiency for seismic performance improvement of subsea tunnel", *Journal of Korean Tunnelling and Underground Space Association*, **19**(3), 503-515.

Kaiser, P. K. and Cai, M. (2012), "Design of rock support system under rockburst condition", *J. Rock Mech. Geotech. Eng.*, **4**(3), 215-227.

Kovári, K., Amstad, C. and Anagnostou, G. (1988), "Design/construction methods-Tunnelling in swelling rocks", The 29th US Symposium on Rock Mechanics (USRMS).

Lambrughi, A., Medina Rodríguez, L. and Castellanza, R. (2012), "Development and validation of a 3D numerical model for TBM–EPB mechanised excavations", *Comput. Geotech.*, **40**, 97-113.

Liu, H., Small, J. C. and Carter, J. P. (2008), "Full 3D modelling for effects of tunnelling on existing support systems in the Sydney region", *Tunn. Undergr. Space Technol.*,

23(4), 399-420.

Mezger, F., Ramoni, M. and Anagnostou, G. (2018), "Options for deformable segmental lining systems for tunnelling in squeezing rock", *Tunn. Undergr. Space Technol.*, **76**, 64-75.

Mezger, F., Ramoni, M., Anagnostou, G., Dimitrakopoulos, A. and Meystre, N. (2017), "Evaluation of higher capacity segmental lining systems when tunnelling in squeezing rock", *Tunn. Undergr. Space Technol.*, **65**, 200-214.

Moeinossadat, S. R. and Ahangari, K. (2019), "Estimating maximum surface settlement due to EPBM tunneling by Numerical-Intelligent approach – A case study: Tehran subway line 7", *Transp. Geotech.*, **18**, 92-102.

Ramoni, M. and Anagnostou, G. (2010), "Tunnel boring machines under squeezing conditions", *Tunn. Undergr. Space Technol.*, **25**(2), 139-157.

Ramoni, M., Lavdas, N. and Anagnostou, G. (2011), "Squeezing loading of segmental linings and the effect of backfilling", *Tunn. Undergr. Space Technol.*, **26**(6), 692-717.

Schneider, E., Rotter, K., Saxer, A. and Röck, R. (2005), "Compex support system", *Felsbau*, **23**(5), 95-101.

Shahriar, K., Sharifzadeh, M. and Hamidi, J. K. (2008), "Geotechnical risk assessment based approach for rock TBM selection in difficult ground conditions" *Tunn. Undergr. Space Technol.*, **23**(3), 318-325.

Tarkoy, P. J. and Byram, J. E. (1991), "The advantages of tunnel boring: a qualitative/quantitative comparison of D&B and TBM excavation", *Hong Kong Engineer*, **19**(1), 30-36.

Tian, H., Chen, W., Tan, X., Tian, Y. and Zhang, N. (2022), "Investigating polymeric foam materials as compressible layer for tunnelling in squeezing ground conditions", *Tunn. Undergr. Space Technol.*, **122**.

Tian, Y., Chen, W. Z., Tian, H. M., Tan, X. J., Li, Z. and Lei, J. (2021), "Parameter design of yielding layers for squeezing tunnels", *Tunn. Undergr. Space Technol.*, **108**.

Wu, K. and Shao, Z. (2019), "Study on the Effect of Flexible Layer on Support Structures of Tunnel Excavated in Viscoelastic Rocks", *J. Eng. Mech.*, **145**(10).

Wu, K., Shao, Z., Qin, S., Wei, W. and Chu, Z. (2021), "A critical review on the performance of yielding supports in squeezing tunnels", *Tunn. Undergr. Space Technol.*, **115**.

Wu, K., Shao, Z., Sharifzadeh, M., Hong, S. and Qin, S. (2022), "Analytical computation of support characteristic curve for circumferential yielding lining in tunnel design", *J. Rock Mech. Geotech. Eng.*, **14**(1), 144-152.

ABAQUS/CAE (2022), http://www.simulia.com