Proc. of the 8th International Symposium on Geotechnical Safety and Risk (ISGSR)
Edited by Jinsong Huang, D.V. Griffiths, Shui-Hua Jiang, Anna Giacomini and Richard Kelly

Published by Research Publishing, Singapore.
doi: 10.3850/978-981-18-5182-7_05-007-cd

ISGSR 2022

Effect of Soil Mechanical Properties on Shield Tunnel Deformation

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Abstract: Surcharge load frequently threatens the serviceability and even safety of urban metro shield tunnels by causing excessive deformations and associated structural defects. This paper aims to characterize the development pattern of tunnel deformation under increasing surcharge load considering the effect of random migration and mechanical properties of tunnel surrounding soil. For this purpose, a meso-scale discrete element model is developed to delicately simulate the macro- and meso-mechanical behaviors of soil-tunnel interaction system. The numerical simulation results show that tunnel transversal convergence develops in a nonlinear growth trend with the increase of surcharge load. This trend is accompanied by a certain degree of dispersion due to random movement of granular soil. Moreover, soil parametric sensitivity analysis is carried out. The results demonstrate that soil elastic modulus plays a role in affecting the overall trend of tunnel transversal convergence, while the internal friction coefficient of soil has influence on the variability. Results from the numerical model are compared with real data and show the promising possibilities of the model to predict tunnel deformation under varying load conditions.

Keywords: Soil-tunnel interaction; mesoscopic analysis; discrete element method; shield tunnel; transversal convergence.

1 Introduction

Within a life-cycle context, existing shield tunnels are exposed to potentially excessive deformations due to adjacent construction activities (Zhang et al., 2018). Particularly, with the acceleration of urbanization progress in China, surcharge load is commonly found in a large scale above metro tunnels. The surcharge load on ground surface imposes additional pressure on the existing tunnel and its surrounding soil, leading to unexpected large transversal deformation of tunnel linings (Huang et al., 2020). With respect to the influence of surcharge load on the existing shield tunnel, many studies focus on the tunnel mechanical responses in terms of stress conditions in segment concrete and joint bolts, transversal deformation, and joint opening (Wu et al., 2018), but mostly neglect the soil-tunnel interaction effect and the role of soil properties.

Narunat et al. (2018) analyzed the influence of adjacent loaded pile row on the existing tunnel located in soft clay and stiff clay, respectively, and revealed that the tunnel deformation mechanism is primarily due to the soil displacement. Tunnel surrounding soil, as the co-stressed body against the action of external surcharge load, produces coordinated movements together with tunnel deformation. The mechanical properties of tunnel surrounding soil also play an important role in the tunnel deformation extent and associated uncertainties. However, the mechanical and deformational interaction between tunnel structure and surrounding soil under surcharge load is still not clearly understood from the mesoscopic viewpoint (Jiang and Yin, 2014). Especially, very limited investigations have been made to address the mechanism of soil properties influencing tunnel deformation development.

In order to overcome these limitations, this work aims to characterize the development pattern of tunnel deformation under increasing surcharge load considering the effect of random migration and mechanical properties of tunnel surrounding soil. The discrete element method (DEM) is chosen as the numerical tool to gain mesoscopic insight into the influence of soil properties on tunnel transversal deformation. The mesoscopic mechanisms of soil displacement and its mutual action with tunnel deformation are analyzed from particle-scale characterization of soils and upscaling to its macroscopic behaviors. Moreover, soil parametric sensitivity analysis is carried out to study the influence of soil mechanical properties on the development of tunnel deformation and associated uncertainties.

2 Numerical Model

DEM is a powerful tool to simulate mechanical behaviors of granular assemblies. By using the MatDEM software (Liu et al., 2021), discrete element modelling is performed to analyze the soil-tunnel interaction behavior in response to surcharge load and the effect of soil properties on tunnel transversal deformation. First of all, a DEM-based numerical model of the soil-tunnel system is built up in the following three steps.

Step 1: Generate the stratum model. The soil stratum is simplified as a 40 m × 40 m homogeneous soil layer, which is composed of a total of 10, 492 spherical particles, as shown in Figure 1. The radius of spherical particles is set to randomly fluctuate around 0.2 m in a range where the ratio of the maximum radius to the minimum radius is less than 1.44. Soil particles are spatially randomly arranged by generating a random seed. Then the gravity force is applied to all soil particles to pre-balance the soil layer, thus realizing the construction of the original stratum model.

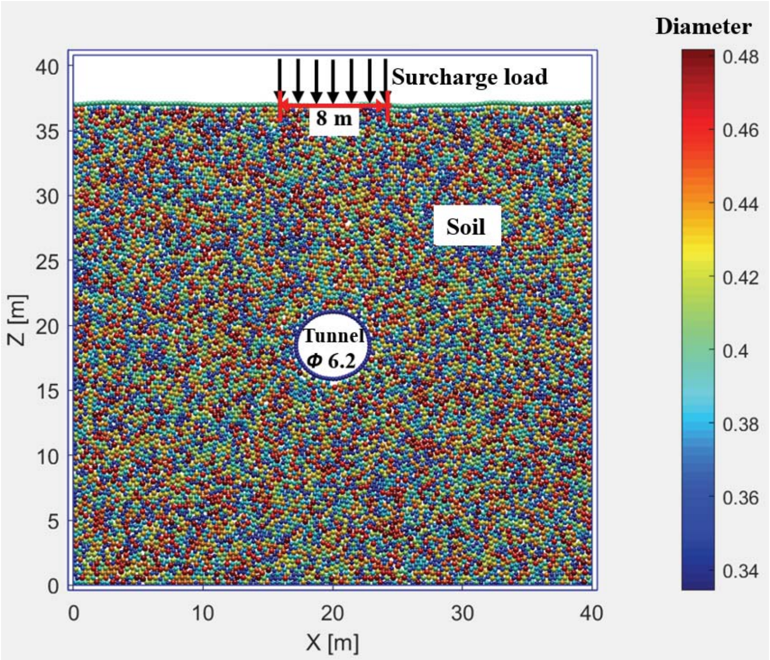

Figure 1. The simulation model of soil-tunnel system.

Step 2: Create the shield tunnel. The shield tunnel is located in the center of the established stratum model. It is simplified equivalent to a homogeneous rigid ring, which is simulated by a single layer of particles with a diameter of 0.35 m. The outer diameter of the tunnel cross section is 6.2 m. The soil particles in the tunnel excavation zone are removed, and meanwhile the shield tunnel elements are activated. Finally, the simulated tunnel and soil layer are closely attached by accumulation under gravity.

Step 3: Set up material properties. According to the well-documented tunnel structural design information and borehole data of the tunnel case presented by Huang et al. (2017), the physical and mechanical properties of the tunnel lining and its surrounding soil are determined and given in Table 1, including density, elastic modulus, Poisson’s ratio, tensile and compressive strength, and internal friction coefficient.

Table 1. Material properties of soil and tunnel lining.

Material	Elastic modulus (Pa)	Poisson’s ratio	Tensile strength (Pa)	Compressive strength (Pa)	Internal friction coefficient	Density (kg/m^3)
Soil	8.30×10^{6}	0.300	8.00×10^{3}	2.50×10^{4}	0.67	2000
Tunnel lining	2.31×10^{10}	0.167	1.96×10^{6}	2.53×10^{7}	0.80	2500

It should be noted that the DEM simulation of the complex large-scale soil-tunnel system entails making reasonable simplifications in terms of soil grains and tunnel structure due to the limitations of computer resources currently available. In addition, since the actual longitudinal joints between concrete segments have a lower stiffness than the concrete segments, the tunnel lining simulated by a homogeneous rigid ring is supposed to properly reduce the stiffness and strength based on the modified routine method (Sun et al., 2016). In this numerical model, the input elastic modulus and tensile/compressive strength of the tunnel lining are reduced to one tenth of the original values, which ensures that the simplified soil-tunnel system shows the similar mechanical behaviors as the real tunnel.

3 Results and Analyses

Based on the established DEM simulation model of the soil-tunnel system, surcharge load on the ground surface above tunnel is further simulated, and a series of discrete numerical simulations are performed under varying surcharge load. According to the simulation results, the macro characteristics of tunnel deformation development with increasing surcharge load are explored, and the related mesoscopic mechanism is revealed through analysis of force chains. In addition, soil parametric sensitivity analysis is carried out to discover how soil mechanical properties influence the development of tunnel deformation and associated uncertainties.

3.1 Meso-mechanical analysis of tunnel deformation under surcharge load

Surcharge load will result in the imposition of an extra pressure on the tunnel structure. In order to simulate the surcharge load above the shield tunnel, the vertical pressure is applied incrementally onto the 8 m wide zone in the middle of the ground surface in the established model, as shown in Figure 1. Based on the simulation results, the meso-mechanical analysis is performed to capture the mechanical and deformational responses of the soil-tunnel system. Figure 2 shows the displacement field and stress field of the soil-tunnel model under a surcharge load of 0.10 MPa. The interaction between the shield tunnel and its surrounding soil is manifested by the coordination between shield tunnel deformation and surrounding soil displacement.

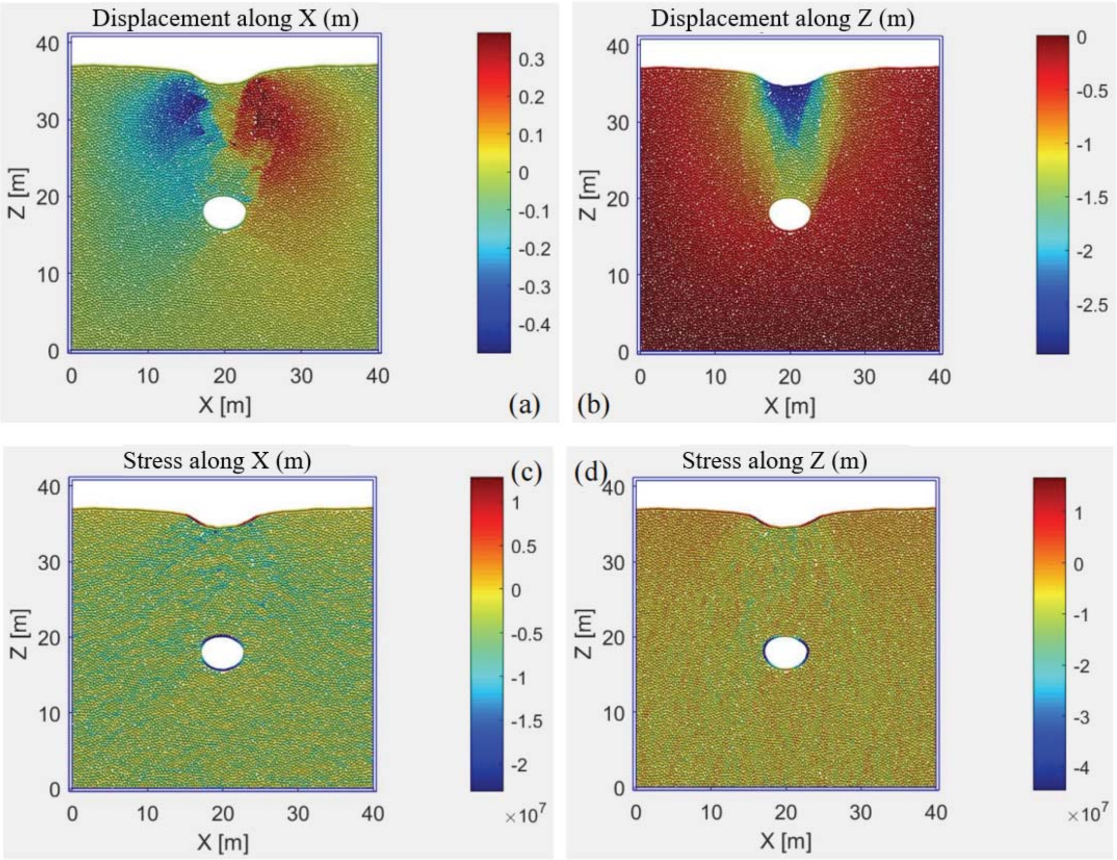
Displacement along X (m)
Displacement along Z (m)
Stress along X (m)
Stress along Z (m)

Figure 2. Stress and deformation fields of the model under 0.10 MPa surcharge: (a) Horizontal displacement; (b) Vertical displacement; (c) Horizontal normal stress; and (d) Vertical normal stress.

Compared with the initial condition in the displacement field, the tunnel surrounding soil particles are squeezed and transported to tunnel lateral sides under the action of the external surcharge load. Forces are transmitted from one particle to the next via their contacts. Deformation of the simulated soil-tunnel system is accompanied by significant changes in the magnitude of contact forces. As seen in the stress field, the color of particles represents the magnitude of the contact force. The force chains corresponding to the actual strong contact force pathways are observed. The force chains characterize the direction and magnitude of force propagation, which captures the mechanical response of the soil layer against the external surcharge load, and further explains the mesoscopic mechanism of the macroscopic behaviors in terms of soil displacement and tunnel deformation. As illustrated in Figure 2(d), the particles colored green trace the transmission of interparticle force chains induced by the 0.10 MPa surcharge load. The force chains appear in a divergent distribution downward from the ground surface and propagate onto the tunnel structure. The formation of these force chains control the development of displacement field of the soil-tunnel model. Consequently, the circular shaped tunnel lining in the initial stress condition is deformed into a distorted ellipse in shape with significant vertical compression and transversal expansion.

As soil is a granular material, soil particles have the random walking mechanism in nature. The random walking mechanism of soil particles is considered and imitated by stochastic acceleration applied with downward gravity. On this basis, under the initial set of soil property parameters, the development and variation features of tunnel transversal deformation with the increase of surcharge load are analyzed. Figure 3 shows the development pattern of the tunnel transversal convergence versus the applied growing surcharge load. For each load level, a total of 30 random simulations are performed with stochastic acceleration applied with downward gravity. The deformation-load relationship exhibits a non-linear growing trend with an enlarging deviation. At each load level, the tunnel transverse convergence values obtained from the 30 random simulations follow a normal distribution. Figure 4 presents the change of the mean and standard deviation of tunnel convergence with increasing surcharge load. It is observed that the mean value-surcharge load relationship and the standard deviation-surcharge load relationship can be best fitted by a quadratic polynomial curve (with a R-squared value of 0.9974) and a cubic polynomial curve (with a R-squared value of 0.9940), respectively.

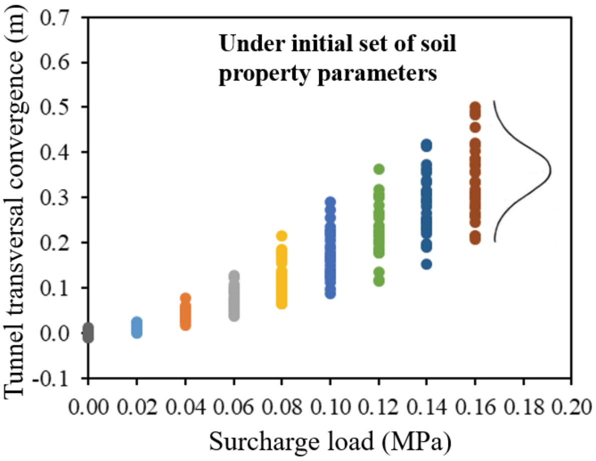

Figure 3. Tunnel transversal convergence versus growing surcharge load (30 realizations of random simulation undertaken at each load level).

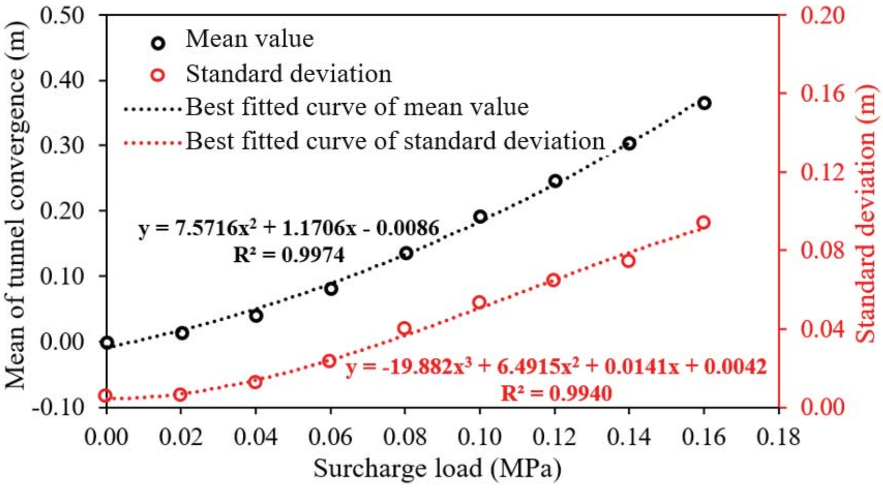

Figure 4. Change of the mean and standard deviation of tunnel convergence with increasing surcharge load.

3.2 Sensitivity analysis of soil properties affecting tunnel convergence

To understand how soil mechanical properties will influence the evolution of tunnel transversal convergence and associated uncertainties, a parametric sensitivity analysis of the input soil mechanical parameters (including elastic modulus, Poisson’s ratio, tensile and compressive strength, and internal friction coefficient) is performed. A straightforward sensitivity analysis using the One-Factor-At-A-Time method is applied to test the influence of each parameter over the results of tunnel transversal convergence. Each time, only one soil mechanical parameter is changed by increasing or decreasing its initial value by 20%, respectively, and other parameters are kept the same as initial values given in Table 1. Then the updated parameter serves as the new input to the established DEM-based numerical model of the soil-tunnel system, and corresponding simulations are carried out at increasing load levels. For each reset parameter at each load level, similar random simulations are performed with 30 realizations.

Based on the simulation results under each setting of soil mechanical parameters, similarly, it is tested that the tunnel transverse convergence values obtained from the 30 random simulations also follow a normal distribution. The mean and standard deviation of tunnel transversal convergence at each load level are calculated, as shown in Figures 5 and 6. After changing soil elastic modulus, the mean value of tunnel transversal convergence clearly deviates from the initial value. The higher the surcharge load, the greater the amount of deviation. To quantitatively measure the influence of the change of each soil mechanical parameter, the sum of squares of deviations (*SS*) is calculated over all surcharge load levels. The statistical results show that when the elastic modulus changes, the calculated *SS* for the mean of tunnel transversal convergence is significantly larger than that of the other three parameters. The result indicates that soil elastic modulus plays a significant role in affecting the general development trend of tunnel deformation. The increase/decrease of soil elastic modulus leads to the decrease/increase of the average tunnel transversal convergence. This can be attributed to the fact that soil layer bears the surcharge load and produces the coordinated deformation together with tunnel structure, and the ability of soil to resist deformation is mainly characterized by elastic modulus.

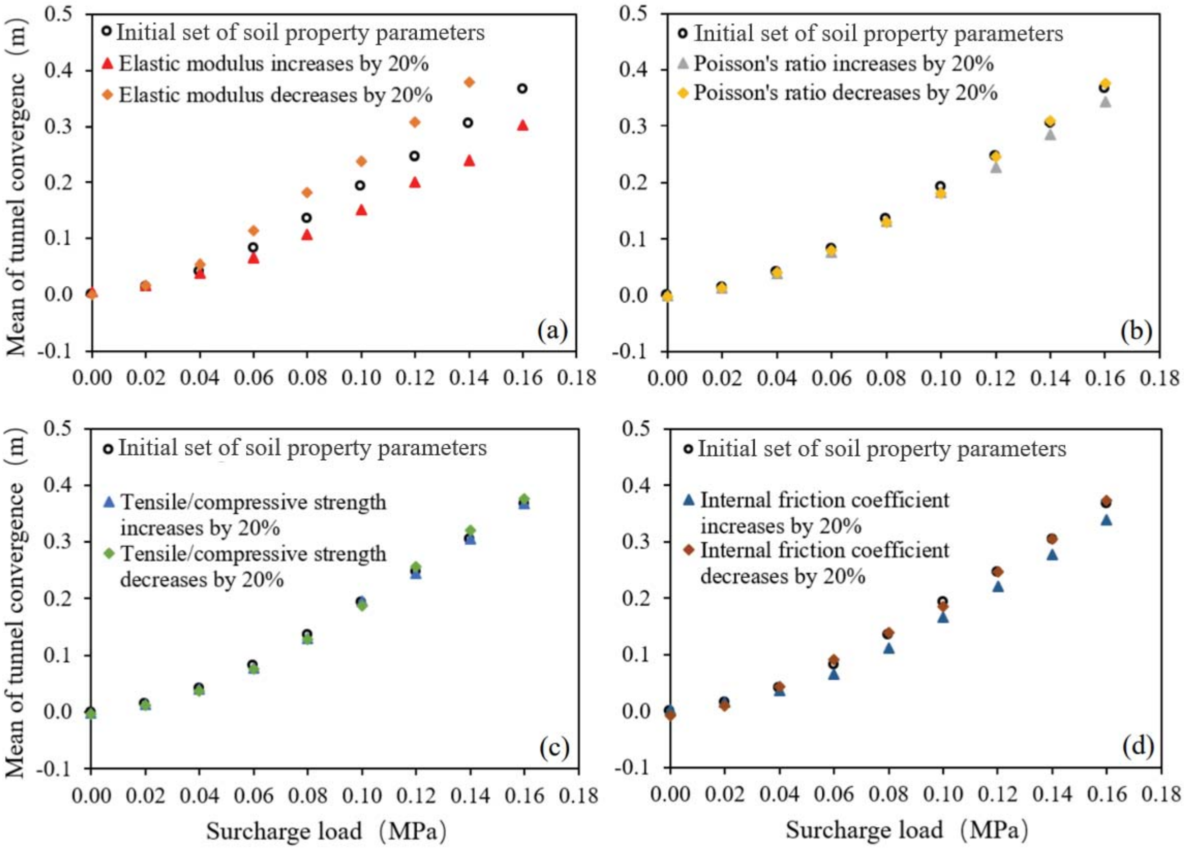

Figure 5. The mean of tunnel transversal convergence under varying soil mechanical parameters: (a) Elastic modulus; (b) Poisson's ratio; (c) Tensile/compressive strength, and (d) Internal friction coefficient.

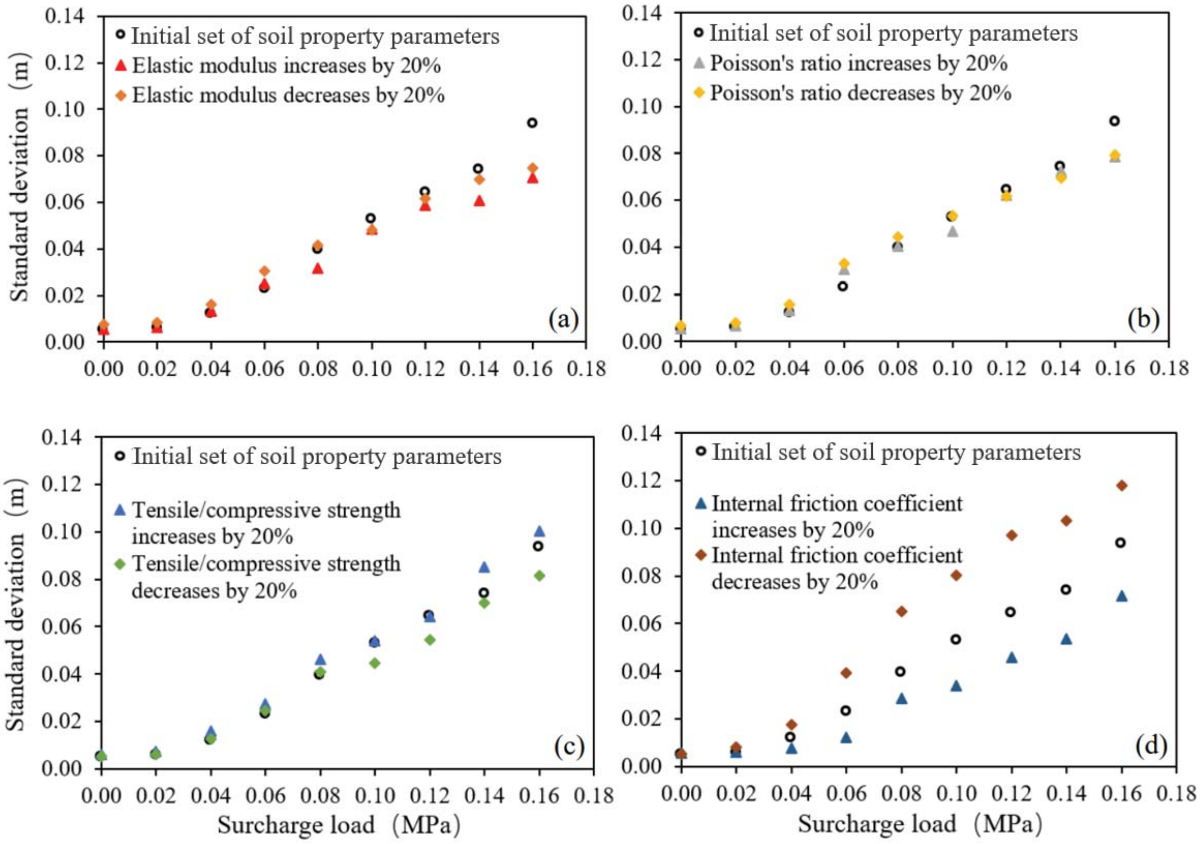

Figure 6. The standard deviation of tunnel transversal convergence under varying soil mechanical parameters: (a) Elastic modulus; (b) Poisson's ratio; (c) Tensile/compressive strength; and (d) Internal friction coefficient.

As shown in Figure 6, the standard deviation of tunnel transversal convergence correlates much better with soil internal friction coefficient than with the change of other parameters. When soil internal friction coefficient changes, the calculated *SS* for the standard deviation value is significantly larger than that of the other three parameters. The standard deviation increases/decreases as the internal friction coefficient decreases/increases. The internal friction coefficient reflects the friction characteristics of soil, including the surface friction of soil particles and the connection force caused by the embedding and interlocking between particles. Therefore, relatively large internal friction coefficient tends to hinder the relative migration of soil particles, and thus leads to small variability of tunnel deformation.

Overall, the sensitivity analysis results demonstrate that soil elastic modulus is the main factor that affects the general development trend of tunnel transversal convergence under surcharge load, while soil internal friction coefficient exerts influence on its variability. Both the mean and standard deviation of tunnel transversal convergence are much less influenced by Poisson's ratio and tensile/compressive strength.

4 Conclusions

This paper uses a discrete modelling technique to investigate the macro- and meso-mechanical behaviors of the soil-tunnel interaction system under external surcharge. Considering the random migration of soil particles, multiple random simulations are carried out under different surcharge load levels, and the main soil mechanical parameters that influence over tunnel transversal convergence are identified. The results show that among the input soil mechanical properties, soil elastic modulus is the main factor affecting the general trend of tunnel convergence, while soil internal friction coefficient has a significant effect on the magnitude of variability. Because of the cooperative deformation of soil layer and tunnel structure under surcharge load, it is not surprising that the average tunnel convergence increases with the decrease of soil elastic modulus. Soil internal friction coefficient characterizes the surface friction of soil particles and the connection force due to the embedding and interlocking between particles. Therefore, relatively large internal friction coefficient tends to hinder the relative migration of soil particles, and thus macroscopically reduces the variability of tunnel deformation.

Acknowledgments

The research work was founded by the Fundamental Research Funds for the Central Universities, China University of Geosciences (Wuhan) (Grant No. CUGGC09), and the Engineering Research Center of Rock-Soil Drilling & Excavation and Protection, Ministry of Education (Grant No. 202103). These financial supports are gratefully acknowledged.

References

Huang, H.W., Zhang, Y.J., Zhang, D.M. and Ayyub, B.M. (2020). Field data-based probabilistic assessment on degradation of deformational performance for shield tunnel in soft clay. *Tunelling and Underground Space Technology*, 67, 107-119.

Huang, Z., Zhang, H., Fu, H.L., Ma, S.K. and Liu, Y. (2020). Deformation response induced by surcharge loading above shallow shield tunnels in soft soil. *KSCE Journal of Civil Engineering*, 24(2).

Jiang, M.J. and Yin, Z.Y. (2014). Influence of soil conditioning on ground deformation during longitudinal tunneling. *Comptes rendus - Mécanique*, 342(3), 189-197.

Liu, C., Liu, H. and Zhang, H. (2021). MatDEM-Fast matrix computing of the discrete element method. *Earthquake Research Advances*, https://doi.org/10.1016/j.eqrea.2021.100010.

Narunat, H., Pornkasem, J., Prateep, L. and Suchatvee, S. (2018). Investigation on pile-soil-tunnel interaction due to adjacent loaded pile row by 3D FEM. *MATEC Web of Conferences*, 192, 02051.

Sun, B., Helin, F.U. and Zhang, J. (2016). Internal force analysis of underwater shield segment based on modified routine method. *Journal of Railway Science and Engineering*.

Wu, H.N., Shen, S.L., Yang, J. and Zhou, A. (2018). Soil-tunnel interaction modelling for shield tunnels considering shearing dislocation in longitudinal joints. *Tunnelling and Underground Space Technology*, 78, 168-177.

Zhang, D.M., Phoon, K.K., Hu, Q.F. and Huang, H.W. (2018). Nonlinear subgrade reaction solution for circular tunnel lining design based on mobilized strength of undrained clay. *Canadian Geotechnical Journal*, 55(2), 155-170.