Application of constitutive model in simulation analysis of tunnel construction

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There are great difficulties in tunnel construction. In order to improve the effect and safety of tunnel construction, this paper establishes the basic method of rock elasto-viscoplastic constitutive model. On the basis of drawing lessons from the under-load surface model of over-consolidated soil, according to the idea of relative over-stress, with the lower load surface adjusted to the rock as the reference yield surface, an elastic-viscoplastic constitutive model that can characterize the characteristics of rock softening time-dependent deformation is established. Moreover, this paper uses the newly established elastic viscoplastic model to calculate and simulate the rate sensitivity test results of quartz sandstone and argillaceous sand-stone respectively. In addition, this paper combines the actual needs of tunnel construction to conduct a simulation analysis of the tunnel construction process, and statistics related data to analyze the reliability of the method, and analyze the satisfaction of the method proposed in this paper. The research results show that the model constructed in this paper has certain practical effects and can provide theoretical references for related research.

Keywords: Constitutive model, Tunnel construction, Simulation analysis, Machine learning

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1. Introduction

Although our country's tunnels have made considerable progress in the design and construction of tunnels, and have improved the safety and reliability of tunnel construction to a higher level, there is still a considerable gap in the long-term stability, safety and reliability of the tunnel surrounding rock and supporting structure compared with developed countries. As academician Wang Mengshu proposed, the safety and reliability assessment of highway tunnels should be strengthened. In the process of tunnel excavation, the instability of the surrounding rock is mainly due to the stress caused by the excavation being greater than the strength of the surrounding pressure to cause excessive deformation of the surrounding rock. From a mechanical point of view, when the stress of the surrounding rock is equal to or exceeds the strength of the rock, a plastic zone will be formed in the rock mass, and the deformation of the plastic zone will extend to the crack surface, which leads to damage and destruction of the rock mass and excessive deformation of the surrounding rock [1].

After the tunnel excavation is completed, the creep phenomenon of the surrounding rock is the main factor leading to the deformation of the rock mass. The reason is that after the initial support and the secondary lining are constructed, the creep deformation of the surrounding rock is restricted. According to the interaction of forces, the primary support and the secondary lining will be subjected to the load generated by the creep of the surrounding rock. When the load stress on the secondary lining is greater than its ultimate strength, the surrounding rock will deform and the lining will be destroyed.

However, in the current tunnel design, the deformation of the secondary lining is generally only considered in the elastic range, and the influence of creep on the secondary lining is ignored. This hypothesis cannot effectively explain the nature of the tunnel support system damage. Therefore, creep is a non-negligible factor in the study of tunnel stability [2].

At present, the main method for studying rock creep is indoor rock creep test. The reason is that the indoor creep test can strictly control the conditions, exclude secondary factors, and can be repeated many times for long-term observation. Usually, the rock creep model can be established by the rock creep test data, and the test parameters can also be provided for the application of the creep model in rock engineering.

However, the test results of the indoor rock test are limited by factors such as sample size, test technology level, etc., and cannot reflect the actual project conditions well. For example, natural geology contains defects such as joints, cracks and faults, and indoor rock samples will be specially processed into "complete rock samples" (rock samples without visible cracks). As a heterogeneous material, the size of the rock has a greater impact on the mechanical properties of the rock, so the mechanical properties of a certain size of rock often cannot be directly applied in geotechnical engineering. At the same time, the construction of geotechnical engineering is often a complicated loading and unloading process, which is different from the simple stress loading and unloading process in the indoor rock test. Therefore, obtaining rock mechanical parameters based on on-site monitoring in-formation (such as monitoring displacement, stress) through the use of reverse thinking and reverse analysis is an effective solution to solve the difficulty of indoor test results in practical rock engineering [3].

This study establishes an elasto-viscoplastic constitutive model that can consider time effects and can be used to simulate the strain softening characteristics of rock mass. Moreover, this paper carries out a numerical simulation of actual engineering, which has great practical significance and application value for understanding the mechanical behavior of rock and predicting the failure law of rock engineering.

2. Related work

At present, commonly used rock creep constitutive models are combinations of linear elements, which cannot describe the nonlinear creep characteristics of rocks. Therefore, many scholars have discussed and put forward some nonlinear rheological models and put forward some effective methods for the description of accelerated creep stage [4].

The literature [5] proposed a nonlinear creep model, which uses a stress-triggered Hooke body to describe the instantaneous plastic strain and a strain-triggered nonlinear viscous dashpot element to describe the third stage of accelerated creep. The literature [6] replaced the linear viscous dashpots in the traditional Nishihara model with nonlinear viscous dashpots. The stress on the viscous damping is proportional to its acceleration. Moreover, it established a nonlinear creep constitutive equation and verified that it can describe the rheological properties of salt rock well. The literature [7] introduced a new nonlinear viscous damper, and combined it with the traditional model describing deceleration and constant velocity creep to establish a composite mechanical model, which can simultaneously describe three kinds of creep deformation.

The literature [8] used the Nishihara model to describe the non-attenuating creep of soft rock and corrected the viscosity coefficient to nonlinearity. The literature [9] proposed two nonlinear elements, creep body and cracked plastic body. Moreover, it combines them with the Kelvin form describing the attenuation creep characteristics and the Hooke form describing the instantaneous elasticity to establish a new com-pound rheological model that can describe soft rock.

The literature [10] used non-Newtonian viscous elements to form an improved Nishihara Masao model with five elements, and discussed the time-dependent creep equation of soft rock. Based on the improved Nishihara Masao model, the literature [11] established a parametric nonlinear creep model by using the corresponding relationship between the rock's entire stress-strain curve and the parameters in the creep equation. The literature [12] proposed a nonlinear viscoplastic NVPB and a five-element linear viscoelastic rheological model to reflect the accelerated creep characteristics of rock in series. The literature [13] proposed a software component based on the theory of fractional calculus. It can describe materials between ideal solids and fluids, and can effectively describe the rheological constitutive characteristics of rock and soil in series and parallel with spring elements, and has a simple structure and few parameters. The disadvantage is that the accelerated creep characteristics of rock and soil cannot be described.

The literature [14] proposed a strain-triggered nonlinear viscous element, which can better describe the accelerated creep of rock. The above research ideas are mainly to use nonlinear rheological elements to re-place linear rheological elements, or to use series nonlinear elements to form a nonlinear rheological model of rock. This method is flexible and simple, and is widely used. The disadvantage is that in the process of re-placing and connecting components in series, the parameters of the model increase more, and the physical meaning of multiple parameters is not clear enough.

The literature [15] used fractional derivatives to describe the dynamic frequency response of viscoelastic bodies. The literature [16] proposed a fractional derivative model for viscoelastic materials, and used numerical analysis and graphical fitting methods to determine the rheological parameters of the model. The literature [17] used the time-dependent fractional calculus model to describe the viscoelastic creep and stress relaxation of materials. The literature [18] unified the theory of fractional calculus with the classical model to propose a new model. The model has few parameters and the physical concept of the parameters is clear. The literature [19] proposed soft-ware components based on the theory of fractional calculus. The literature [20] used the theory of fractional calculus to study the rheological constitutive of salt rock, and adopted a dimensionless treatment for the model. The literature [21] replaced the Newtonian dashpot in the Nishihara model with the Abel dashpot based on the fractional calculus theory, and combined the results of the indoor shear creep test to in-verse the parameters in the model. The literature [22] replaced the Newtonian dashpot and viscoplastic body in the Nishihara model with Abel dashpot and NVPB models. The literature [23] used a software component based on the theory of fractional calculus to replace the Newtonian viscous components in the traditional Nishihara model, and used simplified SN components and damage variables considering stress and time to further improve the viscous co-efficient of the software components.

3. Application of constitutive model in tunnel construction simulation analysis

In order to evaluate the influence of the lateral pressure coefficient and azimuth angle on the failure mode formed by the excavation of the phyllite circular tunnel, the value of the in-situ stress level under each group of working conditions was deter-mined through trial calculation.

The basic principle of the value is to fully expose the plastic failure characteristics of the rock mass within a certain range of the surrounding rock tunnel under the corresponding conditions due to the pressure release caused by excavation. The specific working conditions and stress values are shown in Table 1. From the distribution of working conditions in Table 1, it can be seen that the stress levels under different horizontal-vertical ground stress ratios and joint inclination angles are quite different, and it is difficult to make quantitative horizontal comparisons in the analysis. Therefore, the analysis in this paper focuses on comparing the distribution characteristics of surrounding rock mechanics indexes.

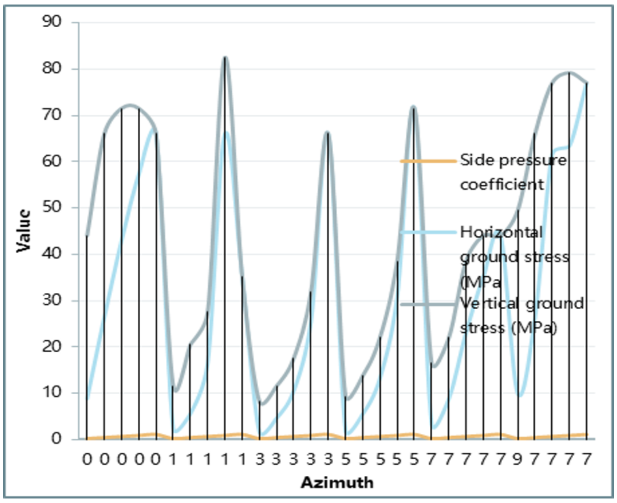

Fig. 1. Statistical diagram for calculation of working conditions of tunnel excavation.

Because the confining pressure failure mode and displacement distribution chara-teristics are quite different under different working conditions, in order to facilitate analysis, the relative positional relationship between the initial stress state, joint plane direction and surrounding rock is specified and explained, as shown in Fig. 2.

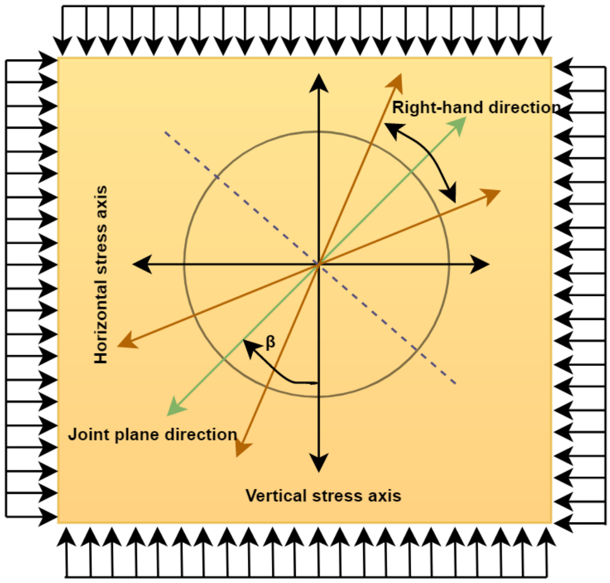

Fig. 2. Rules of analysis of mechanical behavior of surrounding rock.

After the tunnel is excavated, the maximum principal compressive stress (minimum principal stress) of the surrounding rock represents the stress concentration caused

Table 1. Statistical table for calculation of working conditions of tunnel excavation.

Serial number	Azimuth	Side pressure coefficient	Horizontal ground stress (MPa)	Vertical ground stress (Mpa)
1	0	0.22	8.8	44
2	0	0.44	26.4	66
3	0	0.66	42.9	71.5
4	0	0.88	57.2	71.5
5	0	1.1	66	66
6	1	0.22	2.31	11.55
7	1	0.44	5.61	20.46
8	1	0.66	16.5	27.5
9	1	0.88	66	82.5
10	1	1.1	35.2	35.2
11	3	0.22	1.65	8.25
12	3	0.44	4.62	11.55
13	3	0.66	10.56	17.6
14	3	0.88	25.52	31.9
15	3	1.1	66	66
16	5	0.22	1.87	9.35
17	5	0.44	5.5	13.75
18	5	0.66	13.2	22
19	5	0.88	30.8	38.5
20	5	1.1	71.5	71.5
21	7	0.22	3.3	16.5
22	7	0.44	8.8	22
23	7	0.66	23.1	38.5
24	7	0.88	35.2	44
25	7	1.1	44	44
26	9	0.22	9.9	49.5
27	7	0.44	26.4	66
28	7	0.66	61.6	77
29	7	0.88	63.36	79.2
30	7	1.1	77	77

by the excavation of the rock mass. The cloud diagram of the maximum principal compressive stress (minimum principal stress) of the surrounding rock after the tunnel excavation is completed is shown in Fig. 3. It can be seen that due to the large horizontal in-situ stress, the tunnel invert and the surrounding rock outside the dome have a large compressive stress concentration phenomenon, which is the cause of the rock matrix shear failure of the dome and invert surrounding rock.

In summary, it can be seen that the failure of the surrounding rock of an unsupported circular tunnel in the phyllite strata is dominated by joint shear type failure and rock matrix shear type failure. However, the joint tension type failure mainly occurs in the shallow surrounding rock, and the rock matrix tension type failure is difficult to occur in the excavation of the cavern. The distribution law of plastic zone for the three main types of failure is:

1. Joint shear failure zone: its distribution pat-tern is very complicated, and can be divided into four categories in general. The first type is that when the azimuth angle of the weak plane is 0 °, the joint shear failure zone is distributed in an "X" shape symmetrical about the initial principal stress axis. With the increase of the lateral pressure coefficient, the development direction of the plastic zone gradually evolved from extending along the direction of large principal stress to extending along the direction of small principal stress. In the second category, when the azimuth angle of the weak plane is small (the azimuth angle is 18 °) and the lateral pressure coefficient is small, the joint shear-type plastic zone develops along the direction of the joint plane. With the increase of the lateral pressure

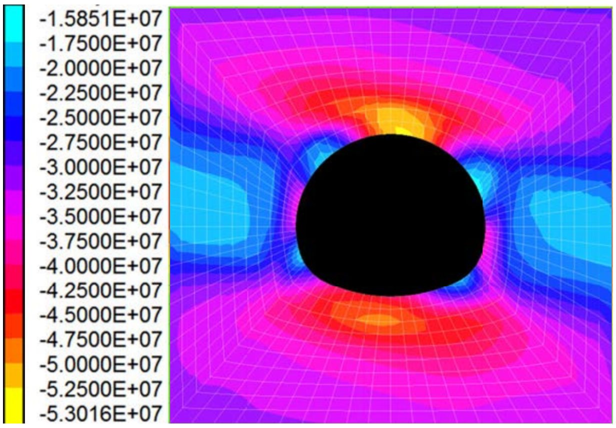

Fig. 3. Distribution of maximum principal compressive stress of surrounding rock.

coefficient, the joint shear-type plastic zone evolved into a symmetrical "X"-shaped distribution about the direction of the joint plane. The third type is when the azimuth angle of the weak plane is medium or large and the lateral pressure coefficient is small, the plastic zone is mainly distributed in the direction perpendicular to the joint plane. As the lateral pressure coefficient increases, the distribution of the plastic zone gradually evolves into a symmetrical "X"-shaped distribution in the direction perpendicular to the joint plane. The fourth category is that when the azimuth angle of the weak plane is 90 °, the plastic zone of the surrounding rock is distributed in an "X" shape, and the development direction of the plastic zone of the surrounding rock is always along the direction of the large principal stress. It can be seen that the distribution of the joint shear failure plastic zone has a dual dependence on the initial ground stress and the azimuth angle of the joint plane.

2. Shear failure of rock matrix: Under different lateral pressure coefficients, the location of the shear failure of the rock matrix shows the followability of the joint plane orientation, that is, it is always distributed along the joint direction and perpendicular to the joint direction and is distributed in a "cross" shape. When the direction of the joint plane is parallel to the main axis of the initial stress, the range of the shear failure zone of the rock matrix is equivalent to the distribution range of the joint shear failure zone. At this time, the proportion of the plastic zone area in the direction of the large principal stress increases with the in-crease of the lateral pressure coefficient. When the direction of the joint plane is not parallel to the main axis of the initial in-situ stress, the proportion of the area of the shear failure zone of the rock matrix perpendicular to the joint plane and along the direction of the joint plane increases with the increase of the initial ground stress side pressure coefficient, and tends to be consistent with the proportion of the plastic zone of the joint shear failure.

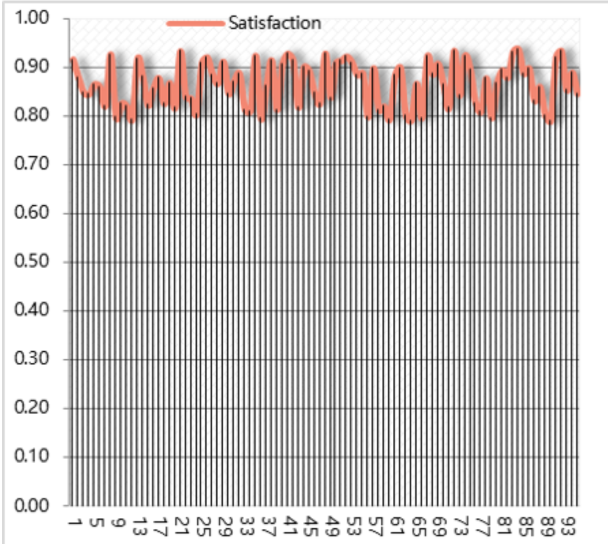

Fig. 4. Statistical diagram of user satisfaction survey of simulation system.

From the above analysis, the constitutive model proposed in this paper has a good application effect in construction simulation analysis, and user satisfaction is high.

4. Conclusion

In this paper, from the perspective of anisotropic elastoplastic mechanics, a constitutive model suitable for tunnel construction simulation of layered rock mass is developed in the finite difference program. Moreover, this paper perfects the evaluation model of strength anisotropy and deformation anisotropy of layered rock mass in engineering. At the same time, this paper conducts research on unsupported circular tunnels under different lateral pressure coefficients and rock formation conditions in the rock formation, and systematically analyzes the mechanical behavior of the secondary stress state. In addition, this paper introduces the basic method of establishing rock elasto-viscoplastic constitutive model. On the basis of drawing lessons from the underload surface model of over-consolidated soil, according to the idea of relative over-stress, with the lower load surface adjusted to the rock as the reference yield surface, an elastic-viscoplastic constitutive model that can characterize the characteristics of rock softening time-dependent

Table 2. Statistical table of user satisfaction survey of simulation system.

Number	Satisfaction	Number	Satisfaction	Number	Satisfaction	Number	Satisfaction	Number	Satisfaction
1	0.92	21	0.93	41	0.93	61	0.89	81	0.90
2	0.88	22	0.84	42	0.92	62	0.90	82	0.88
3	0.85	23	0.84	43	0.82	63	0.80	83	0.93
4	0.85	24	0.81	44	0.90	64	0.79	84	0.94
5	0.87	25	0.91	45	0.89	65	0.87	85	0.89
6	0.86	26	0.92	46	0.85	66	0.80	86	0.90
7	0.82	27	0.89	47	0.83	67	0.92	87	0.83
8	0.93	28	0.87	48	0.93	68	0.89	88	0.86
9	0.80	29	0.91	49	0.84	69	0.91	89	0.80
10	0.83	30	0.85	50	0.91	70	0.87	90	0.79
11	0.82	31	0.87	51	0.92	71	0.82	91	0.92
12	0.80	32	0.89	52	0.92	72	0.94	92	0.94
13	0.92	33	0.82	53	0.91	73	0.84	93	0.86
14	0.88	34	0.81	54	0.89	74	0.93	94	0.89
15	0.82	35	0.93	55	0.89	75	0.90	95	0.85
16	0.86	36	0.80	56	0.80	76	0.83		
17	0.88	37	0.86	57	0.90	77	0.81		
18	0.83	38	0.92	58	0.81	78	0.88		
19	0.87	39	0.82	59	0.82	79	0.80		
20	0.82	40	0.81	60	0.80	80	0.87		

deformation is established. Finally, this pa-per uses the newly established elasto-viscoplastic model to simulate the rate sensitivity test results of quartz sandstone and argillaceous sandstone.

References

[1] G. Andreotti and C. G. Lai. A nonlinear constitutive model for beam elements with cyclic degradation and damage assessment for advanced dynamic analyses of geotechnical problems. Part II: validation and application to a dynamic soil–structure interaction problem. *Bulletin of Earthquake Engineering*, 15(7):2803–2825, jul 2017.

[2] Qiang Huang, Hongwei Huang, Bin Ye, Dongmei Zhang, and Feng Zhang. Evaluation of train-induced settlement for metro tunnel in saturated clay based on an elastoplastic constitutive model. *Underground Space (China)*, 3(2):109–124, 2018.

[3] Hanpeng Wang, Yong Li, Shucai Li, Qingsong Zhang, and Jian Liu. An elasto-plastic damage constitutive model for jointed rock mass with an application. *Geomechanics and Engineering*, 11(1):77–94, 2016.

[4] Mingnian Wang, Yucang Dong, and Li Yu. Analytical Solution for a Loess Tunnel Based on a Bilinear Strength Criterion. *Soil Mechanics and Foundation Engineering*, 57(4):296–304, sep 2020.

[5] Xi bing Li, Shi ming Wang, Lei Weng, Lin qi Huang, Tao Zhou, and Jian Zhou. Damage constitutive model of different age concretes under impact load. *Journal of Central South University*, 22(2):693–700, 2015.

[6] Thayanan Boonyarak and Charles W.W. Ng. Effects of construction sequence and cover depth on crossing-tunnel interaction. *Canadian Geotechnical Journal*, 52(7):851–867, oct 2014.

[7] Shuling Huang, Chuanqing Zhang, and Xiuli Ding. Hardening–Softening Constitutive Model of Hard Brittle Rocks Considering Dilatant Effects and Safety Evaluation Index. *Acta Mechanica Solida Sinica*, 33(1):121–140, feb 2020.

[8] M. Mousivand and M. Maleki. Constitutive Models and Determining Methods Effects on Application of Convergence–Confinement Method in Underground Excavation. *Geotechnical and Geological Engineering*, 36(3):1707–1722, jun 2018.

[9] M Javadi, S Sayadi, and M. Sharifzadeh. Evaluation of Soil Constitutive Model Effects on Numerical Modeling of Set-tlement Induced by Tunneling in Urban Area, Case Study of the Amirkabir Tunnel. *Journal of Analytical and Numerical Methods in Mining Engineering*, 10(24):119–136, 2020.

[10] Heyam H Shaalan, Romziah Azit, and Mohd Ashraf Mohamad Ismail. Numerical Analysis of TBM Tunnel

Lining Behavior using Shotcrete Constitutive Model. *Civil Engineering Journal*, 4(5):1046, 2018.

[11] C. W.W. Ng, H S Sun, G H Lei, J W Shi, and David Mašín. Ability of three different soil constitutive models to predict a tunnel's response to basement excavation. *Canadian Geotechnical Journal*, 52(11):1685–1698, apr 2015.

[12] Hui Wang, Wei zhong Chen, Qing biao Wang, and Peng qiang Zheng. Rheological properties of surrounding rock in deep hard rock tunnels and its reasonable support form. *Journal of Central South University*, 23(4):898–905, 2016.

[13] Kang Bian, Jian Liu, Wei Zhang, Xiaoqing Zheng, Shaohu Ni, and Zhenping Liu. Mechanical Behavior and Damage Constitutive Model of Rock Subjected to Water-Weakening Effect and Uniaxial Loading. *Rock Mechanics and Rock Engineering*, 52(1):97–106, 2019.

[14] Hua bing Zhao, Yuan Long, Xing hua Li, and Liang Lu. Experimental and numerical investigation of the effect of blast-induced vibration from adjacent tunnel on existing tunnel. *KSCE Journal of Civil Engineering*, 20(1):431–439, 2016.

[15] Ningyu Zhao and Haifei Jiang. Mathematical methods to unloading creep constitutive model of rock mass under high stress and hydraulic pressure. *Alexandria Engineering Journal*, 60(1):25–38, 2021.

[16] Hossain Md Shahin, Teruo Nakai, Kenji Ishii, Toshikazu Iwata, and Shou Kuroi. Investigation of influence of tunneling on existing building and tunnel: Model tests and numerical simulations. *Acta Geotechnica*, 11(3):679–692, jun 2016.

[17] Alessandra Paternesi, Helmut F. Schweiger, and Peter Schubert. Verification of a rheological constitutive model for shotcrete through back-analysis. *Geomechanik und Tunnelbau*, 9(4):356–361, aug 2016.

[18] E. Soranzo, R Tamagnini, and W Wu. Face stability of shallow tunnels in partially saturated soil: Centrifuge testing and numerical analysis. *Geotechnique*, 65(6):454–467, jun 2015.

[19] Tomáš Janda, Michal Šejnoha, and Jiří Šejnoha. Applying Bayesian approach to predict deformations during tunnel construction. *International Journal for Numerical and Analytical Methods in Geomechanics*, 42(15):1765–1784, oct 2018.

[20] Arash Alimardani Lavasan, Chenyang Zhao, Thomas Barciaga, Alexander Schaufler, Holger Steeb, and Tom Schanz. Numerical investigation of tunneling in saturated soil: the role of construction and operation periods. *Acta Geotechnica*, 13(3):671–691, jun 2018.

[21] Guan lin Ye and Bin Ye. Investigation of the overconsolidation and structural behavior of Shanghai clays by element testing and constitutive modeling. *Underground Space (China)*, 1(1):62–77, 2016.

[22] Osamah Ibrahim Khalaf, Kingsley A. Ogudo, and Manwinder Singh. A fuzzy-based optimization technique for the energy and spectrum efficiencies trade-off in cognitive radio-enabled 5g network. *Symmetry*, 13(1):1–14, 2021.

[23] Osamah Ibrahim Khalaf, F Ajesh, A. A. Hamad, Gia Nhu Nguyen, and Dac Nhuong Le. Efficient Dual-Cooperative Bait Detection Scheme for Collaborative Attackers on Mobile Ad-hoc Networks. *IEEE Access*, 2020.