■Ngày nhận bài: 14/02/2024 ■Ngày sửa bài: 04/3/2024 ■Ngày chấp nhận đăng: 08/4/2024

Design of urban tunnels in soft soil using tunnel boring machine (TBM) application for the umrt line no.3 in Hanoi

Thiết kế hầm trong đất yếu sử dụng máy đào hầm (TBM) ứng dụng cho tuyến đường sắt đô thị số 3 tại Hà Nội

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ABSTRACT
Metro systems are integral to modern infrastructure and are in a constant process of development. Designing tunnels in soft soil demands consideration of various factors to optimize construction costs and ensure safety. This article addresses the challenges of constructing urban tunnels in soft ground using tunnel boring machines, emphasizing geological behavior, tunnel lining loads, and soil displacement. FEM analytical and simulation methods are employed to calculate surface settlements, face-support pressure, and lining load, with a focus on evaluating geological influences on subway line design. TBM-driven tunnel construction induces short- and long-term ground deformations in soft soil, influenced by heading face support, shield skin friction, and gap grouting. Realistic 3D simulations are increasingly essential to understanding the interaction between TBM-driven tunneling and surrounding soil, providing reliable estimates of settlements and associated risks, especially in urban tunnel projects.
Keywords: Soft soil; geological behavior; lining load; soil displacement; surface settlements; face-support pressure; tunnel boring machine.

TÓM TẮT
Hệ thống tàu điện ngầm là một phần không thể thiếu trong cơ sở hạ tầng hiện đại và đang trong quá trình phát triển không ngừng. Thiết kế hầm trong đất yếu đòi hỏi phải xem xét nhiều yếu tố để tối ưu hóa chi phí thi công và đảm bảo an toàn. Bài báo này đề cập đến những thách thức khi xây dựng đường hầm đô thị trong đất yếu bằng máy đào hầm TBM, nhấn mạnh đến đặc điểm địa chất, tải trọng tác động lên vỏ hầm và chuyển vị của đất đá xung quanh đường hầm. Các phương pháp phân tích và mô phỏng phần tử hữu hạn FEM được sử dụng để tính toán độ lún bề mặt, áp lực chống đỡ gương đào và tải trọng tác động lên vỏ hầm, tập trung vào việc đánh giá ảnh hưởng của địa chất đến thiết kế tuyến tàu điện ngầm. Việc xây dựng đường hầm bằng máy đào hầm gây ra các biến dạng ngắn hạn và dài hạn trong đất yếu, bị ảnh hưởng bởi áp lực cân bằng gương đào ở đầu máy, ma sát bề mặt khiên và đất đá và áp lực phun vữa lấp đầy ở khe hở đuôi khiên. Mô phỏng 3D thực tế ngày càng cần thiết để hiểu được sự tương tác giữa đường hầm thi công bằng máy đào hầm và đất đá xung quanh, cung cấp các ước tính đáng tin cậy về độ lún và các rủi ro liên quan, đặc biệt là trong các dự án đường hầm đô thị.
Từ khoá: Đất yếu; ứng xử địa chất; tải trọng tác động lên vỏ hầm; chuyển vị của đất đá; lún bề mặt; áp lực chống đỡ gương đào; máy đào hầm.

1. INTRODUCTION
Ground behavior is one of the most essential characteristics in urban tunnel construction, as stability and deformation can cause serious problems. When choosing a tunneling system for soft soil using a tunnel boring machine (TBM) with earth pressure compensation (EPB), the system offers significant advantages in overcoming major issues related to ground behavior. When using TBM, consider particular aspects: shallow overburden due to cost and functionality, structures on the ground surface, foreign objects in the ground such as drainpipes, foundations, anchors, etc., and alignment and constraints regarding material transport and TBM access.

Appropriate planning and geotechnical exploration may help overcome these difficulties. The design of TBM tunnels must consider the previous aspects; the main problems regarding design are summed up in the following points: Measures to control ground behavior loads on the liner, structural design, and prediction of ground displacements.

The following sections will discuss the existing methods to assess these three focuses. In addition, geology, changing conditions in the ground due to lenses, boulders, etc., and the presence of groundwater must be considered for tunnel design to select the best construction method and reduce risk scenarios. Soft soils represent a challenging condition for tunnel construction.

Realistically modeling shield-driven tunneling processes, particularly excavation and Tunnel Boring Machine (TBM) advancement, poses challenges in existing finite element models. Understanding interactions between the shield machine and surrounding soil is crucial for tunnel construction insight. Existing models face challenges in simulating the excavation process and often lack a realistic kinematics model for the shield machine. A three-dimensional finite element model prototype has been successfully developed for simulations in soft soil, enabling systematic numerical studies. This model has been extended for soft soils and advanced constitutive models, contributing to an integrated design support system for mechanized tunneling. Various finite element models have been proposed to address excavation process simulation difficulties, including removing finite elements from the excavated volume before the machine and applying the nodal forces necessary to preserve equilibrium.

2. GEOLOGICAL AND HYDROGEOLOGICAL CHARACTERISTICS OF THE AREA WHERE UMRT HANOI LINE NO.3 IS LOCATED

2.1. Geological characteristics

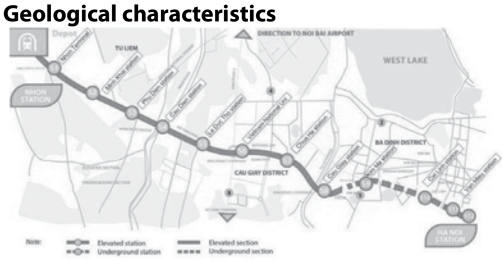

Figure 1. Description of UMRT Line No.3 (Urbanist Hanoi 2018)

Package CP03 includes four underground stations and the central tunnel along the inter-stations stretches, apart from auxiliary structures like the Emergency Shaft and the Ramp connecting the elevated system to the underground section. The main tunnel comprises +two single-track tubes linking the stations together, summing up to 2.6 km of mechanized tunnel. The segmental lining consists of a 5700 mm inner diameter ring with a thickness of 300 mm (resulting in an outer diameter of 6300 mm). Tunnel depth is from 15 to 30m.

Table 1. Geotechnical properties of soil layers [5]

Soil layer		Grain size (%)				Atterberg limits			UW	e0	SPT	Su (kPa)
No	Description	Gravel	Sand	Silt	Clay	Wc (%)	LL (%)	PL (%)	(kN/m^3)			
1	Filling soil	-	-	-	-	-	-	-	-	-	-	-
2	Stiff to very stiff clay (CL)	-	11.5	57	31.5	24.2	33.5	18.7	19.9	0.67	6.4	26.34
3	Soft clay	-	7.1	54.5	38.5	50.1	52.61	31.03	17	1.46	3.7	16.7
4	Medium dense silty sand	-	78	20.9	0.7	-	-	-	-	-	24.8	-
5	Fine medium gravelly sand	-	74.4	16	-	-	-	-	-	-	47	-
6	Dense poorly graded gravel with sand	-	33.4	7.3	-	-	-	-	-	-	>50	-

The area where the metro tunnel line 3 of the Hanoi metro project is located in the central region of Hanoi is on the Red River basin. Through survey documents and experimental drilling samples, it can be concluded that the area from The ground to a depth of about 50 m is soil and is divided into six characteristic layers. A durable bedrock layer is below a depth of 50 m in the central area of Hanoi. Because the tunnel of Hanoi's subway system is designed at a depth ranging from H = 15 to 30 m, the research focuses on fixing the tunnel depth at H = 18m. The soil layers in the area where the metro tunnel line 3 of the Hanoi metro project is located have the characteristics determined through experiments, as shown in Table 1. Vertical geological survey of metro line 3 (according to Giao et al.., 2018) [2] is shown in Figure 2, and according to (Young-Jin Shin et al., 2019) [3] is shown in Figure 5 - Figure 7.

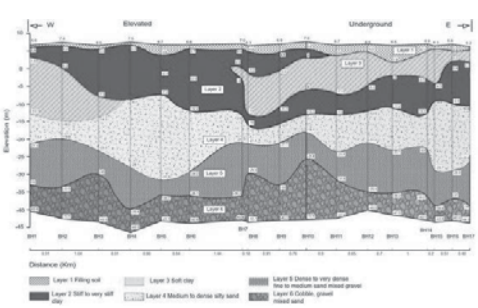

Figure 2. Soil profile along UMRT line No.03 [1-2]

2.2. Hydrogeological characteristics

The Hanoi aquifer system (see Fig. 3) consists of the Holocene aquifer, the aquitard, the Upper and Lower Pleistocene aquifer, and the Neogene sandstone bedrock.

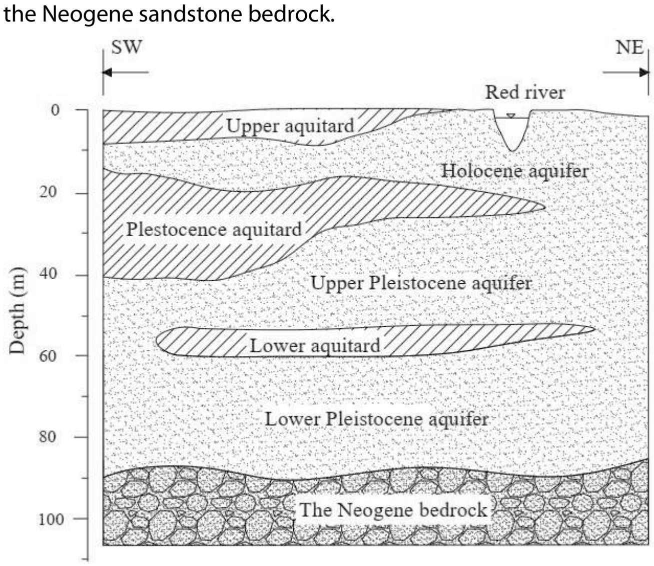

Figure 3. Sketch of Hanoi Aquifer System [2]

In Hanoi city, there are 80 monitoring observation wells, among which 19 observation wells were stopped (K2 2004) [4]. Most of the observation wells are distributed in the South of Hanoi. In this study, four observation wells, i.e., P9a, P32a, P29a, and P35a, were selected as they are near UMRT line No.3. The groundwater levels observed at these wells are shown in Fig. 5. The maximum drawdown is at in P9a about 12 m from 1991 to 2017. The drawdowns for P29a, P32a, and P35a were about 10 m, 6 m, and 6 m, respectively.

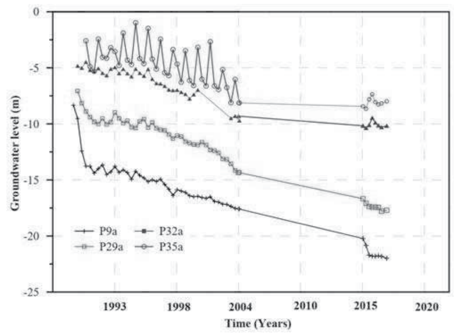

Figure 4: Groundwater levels monitored at some observation well nearby UMRT line No.03 [4]

In this scientific article, Hanoi's groundwater level at UMRT line No. 3 is -6m.

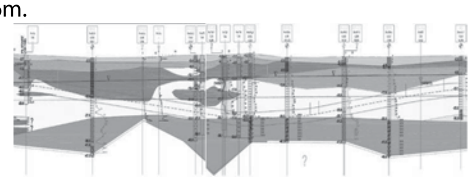

Figure 5: Geological profile between St09 and St10 [3]

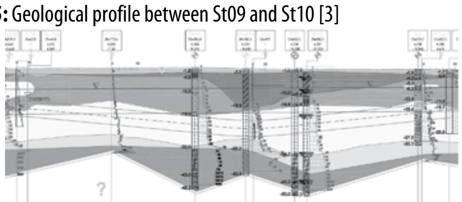

Figure 6: Geological profile between St10 and St11 [3]

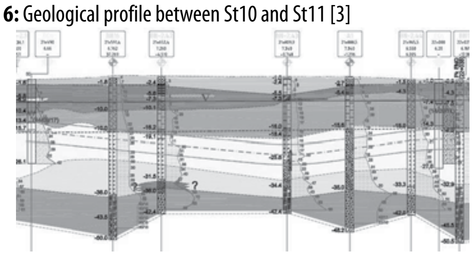

Figure 7: Geological profile between St11 and St12 [3]

3. SIMULATE THE UMRT LINE NO.03, HANOI METRO PROJECT BY MIDAS GTS NX SOFTWARE

3.1. Model parameters

Simulate the construction of a tunnel located on soft soil using TBM. The tunnel to be analyzed will have a double lining; the first will be elaborated with prefabricated segments, and the second will be constructed as a continuous element modeled as a sliding formwork.

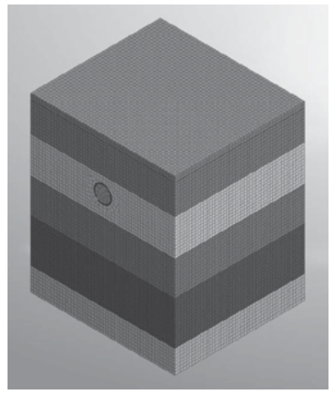

Figure 8: Tunnel design model using Midas GTS NX software

To simulate the construction process of the (6.3M outer diameter) tunnel, a section of 45m in length is considered, in which 3d precast segments of 1.5 each are installed. Likewise, both the pressure of the front and the pressure around the shield are simulated, thereby obtaining efforts and displacements for each stage considered.

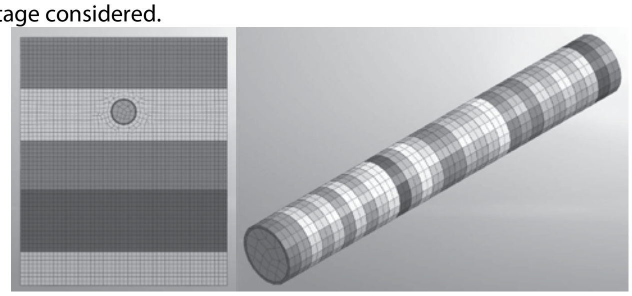

Figure 9: Cross-section and overall tunnel model

The model includes six soil layers according to the results of the actual geological survey at borehole 12, where the subway line passes. The geological data declared in the model is presented in Table 2:

Table 2. Geotechnical properties of soil layers in BH12 input the software

Name	Filling soil	Stiff to very stiff clay (CL)	Soft clay	Medium dense silty sand	Fine medium gravelly sand	Dense poorly graded gravel with sand	Segment
Thickness	2	10.3	12.7	11.9	15	8.1	
Material	Isotropic	Isotropic	Isotropic	Isotropic	Isotropic	Isotropic	Isotropic
General	Mohr Coulomb	Soft Soil	Soft Soil	Mohr Coulomb	Mohr Coulomb	Mohr Coulomb	Elastic
Elastic Modulus (E) (KN/m^2)	9250	15300	7680	35020	53900	65000	2.1E+07
Poisson's Ratio (v)	0.41	0.38	0.35	0.33	0.32	0.3	0.3
Unit Weight kN/m^3	17.5	17.6	18.1	17.8	18.3	18.6	24
K0	0.5	0.5	0.5	0.5	0.5	0.5	1
Unit Weight (Saturated) kN/m^3	17.5	21	21	21	21	21	24
Initial Void Ratio (e0)	0.5	0.67	1.46	0.5	0.5	0.5	0.5
Drainage Parameters	Drained	Undarined	Undarined	Drained	Drained	Drained	Drained
Cohesion (C)	20	1	1	40	50	50	-
Frictional Angle	30	36	36	30	30	30	-
Slope of Consol Line (λ)	-	1.947	1.822	-	-	-	-
Slope of Over Consol Line (K)	-	0.195	0.1822	-	-	-	-
K0nc	-	0.5	0.426	-	-	-	-

Table 3. Technical specifications of Shield and Grouting

Name	Steel	Grout
Material	Isotropic	Isotropic
General	Elastic	Elastic
Elastic Modulus (E) (KN/m^2)	2.5E+08	1.0E+07
Poisson's Ratio (v)	0.2	0.3
Unit Weight kN/m3	78	22.5

Table 4. Property of material

Name	Filling soil	Stiff to very stiff clay (CL)	Soft clay	Medium dense silty sand	Fine medium gravelly sand	Dense poorly graded gravel with sand	Segment	Shield	Grout
Type	3D	3D	3D	3D	3D	3D	3D	2D-Plate	2D-Plate
Material	Filling soil	Stiff to very stiff clay (CL)	Soft clay	Medium dense silty sand	Fine medium gravelly sand	Dense poorly graded gravel with sand	Segment	Steel	Grout
Section Size	-	-	-	-	-	-	-	TH=0.06	TH=0.06

The soft clay layer is located at a depth of -12.7 to -25m, and the tunnel's center is at a depth of -18m, so the tunnel is entirely in the soft clay layer.

3.2. Load during tunnel construction

During tunnel construction, six types of loads appear earth and water pressure, drilling pressure loads, jack thrust loads, shield external pressure loads, and segment external pressure loads.

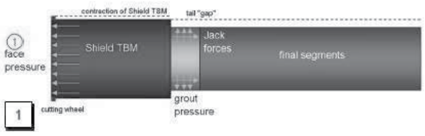

Figure 10: Forces appear during tunneling

Earth and water pressure continuously impact the tunnel throughout construction and after completion. And they are calculated automatically by the software.

- Drilling pressure loads

Drilling pressure loads generated during the process of TBM moving forward in the soil, the force has the effect of supporting and stabilizing the digging surface. In this research, the author takes the drilling pressure load value as 200 kN/m^2

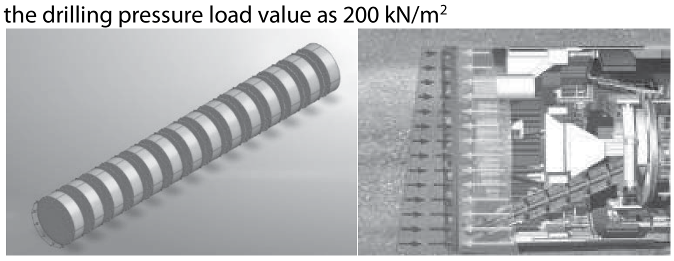

Figure 11: Drilling pressure loads

- Jack thrust loads

The jack thrust load is a temporary load acting on the linings as a reaction force to move the shield forward and is one of the most essential construction loads on the linings. In this research, the author takes the jack thrust load value as 4500 kN/m^2

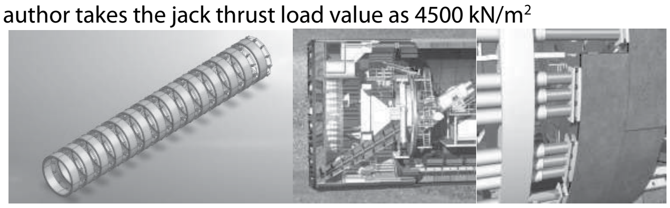

Figure 12: Jack thrust loads

- Shield external pressure loads

Shield external pressure (S) is used in tunnel engineering to describe the pressure applied around the shield excavation face of a tunnel boring machine (TBM). It is usually assumed to be a percentage of the total vertical and horizontal pressure acting on the tunnel. In this research, the author takes the shield external pressure loads value as 50 kN/m^2

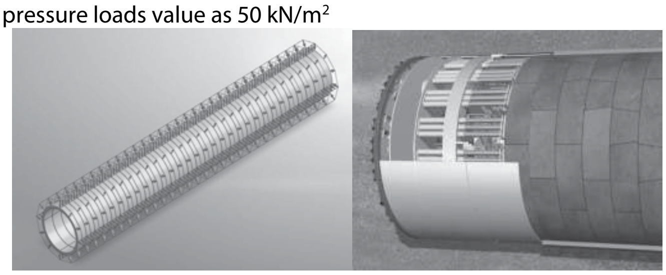

Figure 13: Shield external pressure loads

- Segment external pressure loads

Segment external pressure (E) is applied on the segments of a tunnel boring machine (TBM) from the surrounding soil or rock. It depends on the tunnel's depth, soil type, and groundwater conditions. It affects the stability and safety of the TBM and the tunnel lining. In this research, the author takes the segment external pressure loads value as 1000 kN/m^2

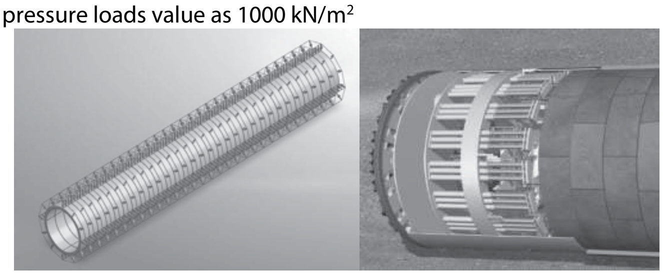

Figure 14: Segment external pressure loads

3.3. Construction stages summary

Simulating the tunnel construction process is summarized in the image below.

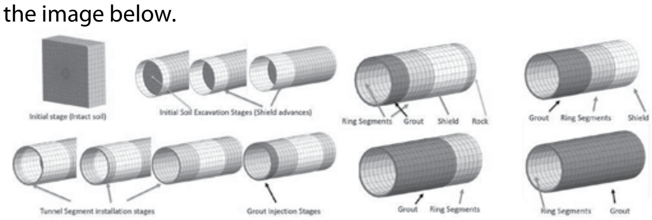

Figure 15: Tunnel construction process using TBM

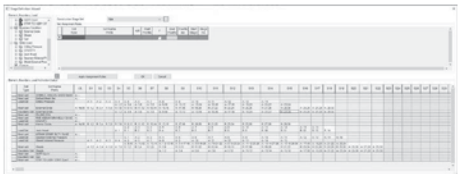

Figure 15: Tunnel construction stages

4 RESULT
4.1. Displacement
4.1.1. Soil displacement

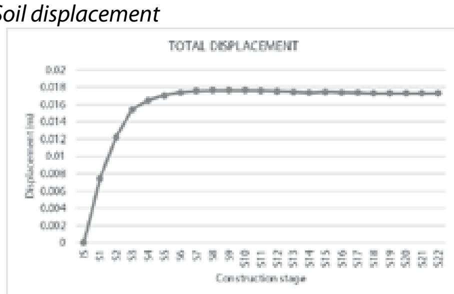

Figure 16: Chart of maximum displacement value at each construction stage

The maximum displacement occurs at the intersection between the tunnel lining and soil because when the shield is boring the soil, the excavation diameter will be larger than the outside diameter of the tunnel lining so that a void will form. This is overcome by injecting pressure grouting to fill the gap to prevent displacement as well as enhance the bearing capacity of the tunnel lining.

The maximum displacement reached a value of 17.67cm at the 9th construction phase (S9), and by the time the tunnel was completed (S22), the displacement value reached 17.29cm, a decrease of 2.15%. The displacement value is relatively large because the tunnel is in the soft soil layer.

Figure 17: Displacement at S9

Figure 18: Displacement at S22

4.1.2. Surface settlements

Surface settlement is mainly distributed around the area where the tunnel passes through, in which the largest settlement is concentrated along the tunnel's center. The chart shows that the maximum surface settlement is - 0.0430866815149784 m (=4.3cm) at node 228594 at the 22nd construction stage.

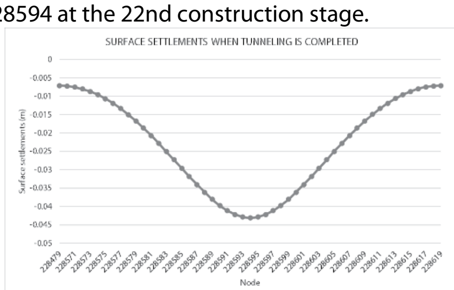

Figure 18: Chart of surface settlements when tunneling is completed (S22)

Figure 18 shows the distribution of surface settlement at the section with the largest settlement when the tunnel was completed.

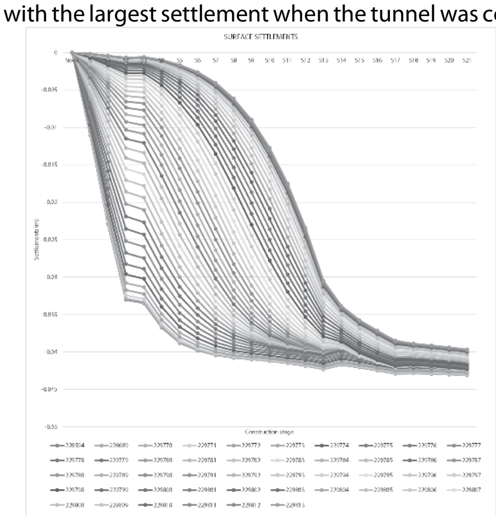

Figure 19: Chart of surface settlement along the tunnel

4.2. STRESS
4.2.1. Shield Stress

During tunnel construction using the TBM method, the maximum and minimum principal stresses acting on the excavator are not only located in the section with the most unfavorable geology but also change according to the construction stage's different cross-sectional positions. So, when designing a mechanical tunnel, we need to take the maximum stress value that appears during the construction phase as the initial calculation and design value.

Looking at the chart as shown in the figure, we can see that the maximum (σ1) and minimum (σ3) principal stresses in the excavated shield appear at the 4th construction stage (S4) with values of 367626.3 kN/m², respectively. and 408165.1 kN/m².

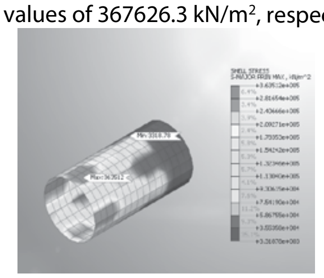

Figure 20: Maximum principal stress of shield in S4

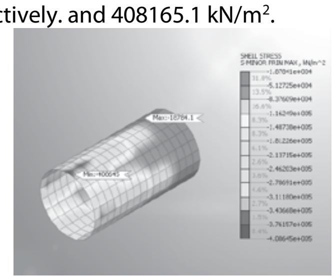

Figure 21: Minimum principal stress of shield in S4

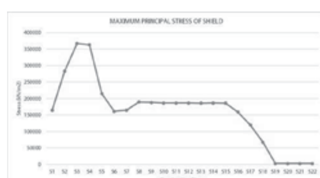

Figure 22: Chart of maximum principal stress of shield at each construction stage

Figure 23: Chart of minimum principal stress of shield at each construction stage

4.2.2. Segment Stress

Similar to the segments, the maximum and minimum principal stresses on the segments change according to each construction phase. We take the construction phase with the maximum stress as the value for calculating and designing the segments.

According to the chart shown in figure 25 and 27, we see that the maximum principal stress (σ1) in the segments at the 15th construction stage (S15) with a value of 18889.1kN/m^2, and the minimum principal stress (σ3) in segments appears at the 17th constructions stage (S17) with a value of 30049.4 kN/m^2.

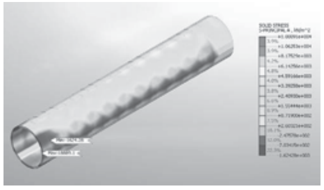

Figure 24: Maximum principal stress of the segment in 15

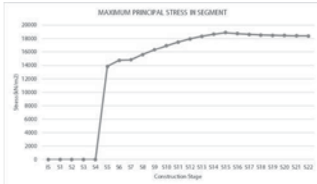

Figure 25: Chart of the value maximum principal stress in the segment at each construction stage

Figure 26: Minimum principal stress of the segment in S17

Figure 27: Chart of the value minimum principal stress in the segment at each construction stage

4.3. STRAINS

4.3.1. Shield strains

The strains of the shield continuously change in value and position at each construction stage.

The maximum principal strains of the shield at the 4th construction stage (S4) reached a value of 0.00144176 m (=1.144176mm).

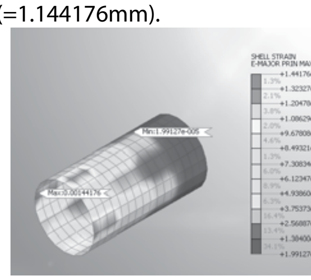

Figure 28: Maximum principal strains of the shield in S4

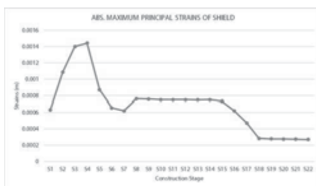

Figure 29: Chart of the value maximum principal strains of shield at each construction stage

4.3.2. Segment strains

Construction stages S1, S2, S3, and S4 are the initial excavation stages; stage 5 activates the tunnel lining components, so strains in the tunnel lining appear at this stage. The strains of the tunnel lining continuously change in value and location at each construction stage.

The maximum principal strains in the segments appeared at the 15th construction stage (S15), reaching a value of 0.00109612 m (=1.09612mm).

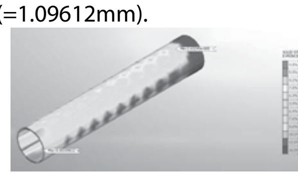

Figure 30: Maximum principal strains of the segments in S15

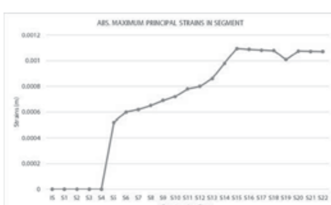

Figure 31: Chart of the value maximum principal strains of segment at each construction stage

5. CONCLUSION

The results of surface settlement, as well as displacement of soil around the tunnel, are relatively large (4.3cm and 17.67cm) because the tunnel is wholly located in the soft soil layer. Therefore, it is necessary to set up displacement monitoring stations to continuously monitor and control displacement so treatment and recovery plans can be promptly proposed.

From the design results stated above, we can see that the maximum values of surface settlement, soil displacement, stresses, and strains of the tunnel lining and shield are not located on one fixed section or fixed construction stage like the 2D simulation we often do, the value and position change continuously at each construction stage, so when designing the mechanized tunnels, it is necessary to simulate 3D tunnel in as much detail as possible to provide accurate and realistic data, to calculate and control risks that may occur during construction.

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