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Prediction of Ground Subsidence During Underground Construction of Metro Line 2, Section 1, Ben Thanh - Tham Luong

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Abstract. Urban metro line No. 2 from An Suong station to Thu Thiem is one of the six metro lines that is planned to be built in Ho Chi Minh City (HCMC). The metro line goes through the area in which the stratigraphy consists of many units, distributed from 20-80 m. The hydrogeology mainly has 2 aquifers, namely Holocene, and Pleistocene which affecting the deep excavation. During construction, there will be some problems that will affect the work on the surface such as settlement, cracking, and damage. By finite element method on Plaxis software, the article forecasts the surface settlement during this metro line No.2. The results show that the ground settlement is relatively large in areas with soft ground structures. The settlement results depend on the geological structure characteristics, hydrogeological characteristics, and the shape and size of the tunnels.

Keywords: Ground subsidence, Underground construction, Metro line

1. Introduction

The metro line No. 2 Ben Thanh - Tham Luong is 11,322 km long, including 11 stations, with 9,315 km underground and ten underground stations. The metro line goes through the weak geological areas, low-lying terrain from the South, and gradually increasing to the Northwest.

The tunnel Boring Method (TBM) is commonly used for tunnel excavation. It is applied in complex hydrogeological conditions, weak and unstable soil, long tunnel, constant cross-section. This can be seen as a tunneling method using an excavation shield - a combination machine equipped with mechanized systems for excavation, loading, and unloading soil, assembling tunnel shells. It is also a strong temporary support frame, which has a protective effect when carrying out the main construction and installation stages. The shield can have a circular, rectangular, or elliptical cross-section, etc.

Using TBM, the tunnel is divided into sections and supported by a shell shield structure underneath the tunnel shell shield. It is built by an assembled structure or precast concrete to form a round retaining tunnel shell.

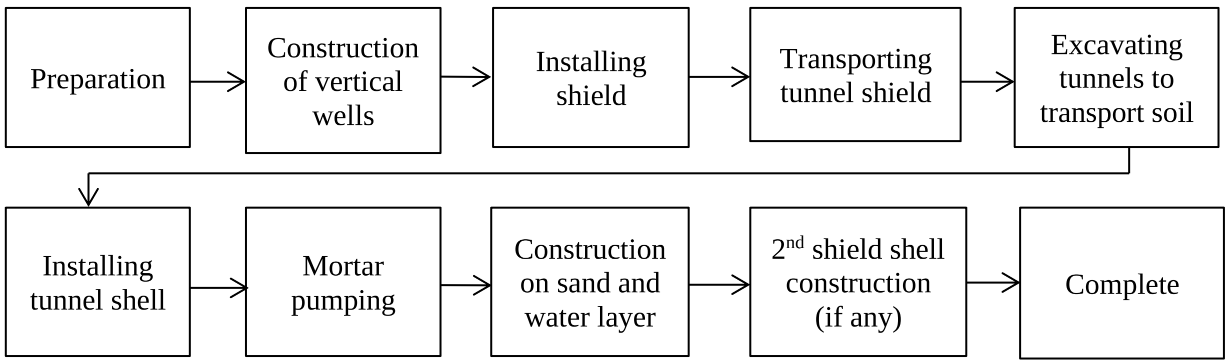

Fig. 1. TBM tunneling method process.

The advantage of this method is that it is unnecessary to divide the excavation face into many parts. Temporary support is not required, the movement of the surrounding soil is minimal, and the soil pressure is slight.

Currently, there have been much kinds of research on ground subsidence caused by tunnel construction in the world, also for Hochiminh City (HCMC) [1-3]. The results are different, but they share some similarities. Some of them showed that the surface settlement characteristics depend on the design, construction method, and technology as well as the geological conditions of the construction area. This paper studies the theoretical basis and selects the methodology to calculate the surface settlement after excavating the double tunnel of Metro line 2 - HCMC by TBM shield in different construction conditions.

2. Methods of calculating surface settlement due to the influence of urban tunnel construction

2.1 Experimental method

There are many different methods to predict surface settlement [4-10].

The experimental method helps estimate these values when changing some data such as the depth, diameter of the tunnel, surface characteristics, and construction properties of soil during construction.

Surface settlement during tunnel construction is represented by the formation of funnel-shaped, which usually appears as a three-dimensional trough (Fig. 2a). The shape and displacement of the settlement conform to Gauss' law, which are characterized by the maximum settlement at the tunnel's center. The settlement decreases with the distance from the inflexion point of the curve outward in the building's horizontal section.

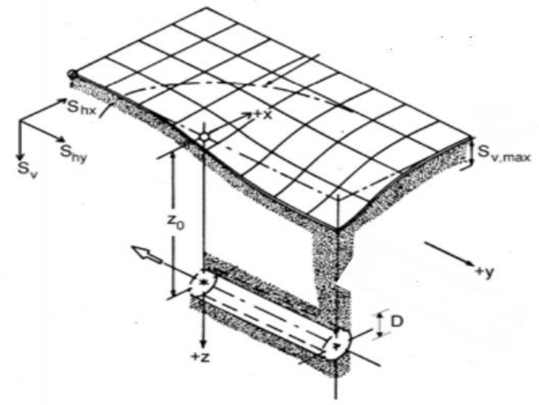

Fig. 2a. Funnel-shaped surface settlement [11]

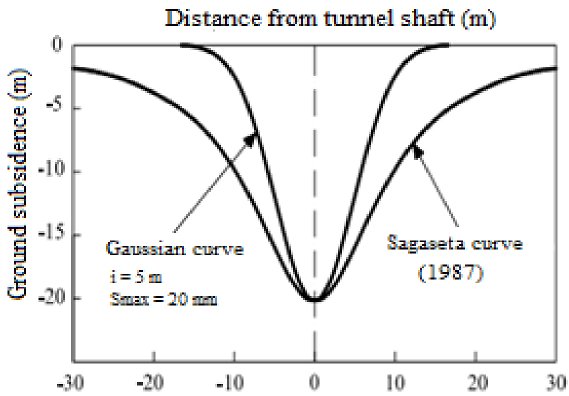

Fig. 2b. Funnel-shaped settlement cross-section [12].

However, in the case of double tunnel construction as of Metro Line 2, the surface settlement caused by the construction of the double tunnel can be predicted using different equations [4, 9, 13] with some adjustments. The surface settlement caused by a double tunnel is usually wider and larger than in a single tunnel (Fig. 3).

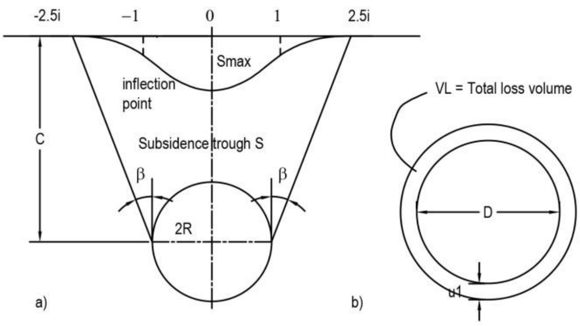

Fig. 3. The shape of the subsidence trough after excavating a single tunnel (a); Total loss volume V_L (b).

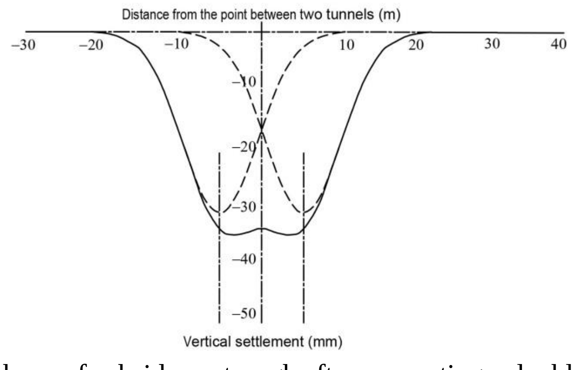

Fig. 4. The shape of subsidence trough after excavating a double tunnel.

In 1969 [4], Peck proposed a formula to calculate surface settlement (S_v) after excavating double tunnels:

$$S_v = S_{max}\left[exp\left(-\frac{x_A^2}{2i^2}\right) + exp\left(\frac{(x_A - d)^2}{2i^2}\right)\right] \quad (1)$$

In which:

d - the horizontal distance between the two centers of the tunnel.

x_A - the horizontal distance from the center of the first tunnel to the point of calculating settlement.

i – the standard deviation of the settlement curve. It is the horizontal distance from the inflection point of the settlement curve to the center of the tunnel, also known as the width of the surface settlement trough. There are various formulas to determine the value of i. Most of them are mainly obtained from the results of field observations. Accordingly, the value of i depends on the size (diameter) of underground constructions, geological conditions, and especially the depth of underground constructions (z_0).

$i = 0.43z_0 + 1.1$ (with consolidated soil) (2)

$i = 0.28z_0 - 0.1$ (with unconsolidated soil) (3)

In which: z_0 is the distance of the tunnel centerline to the ground.

2.2 Numerical Method

Today, with the vigorous development of software technology, numerical methods are increasingly dominant. The application of numerical methods to deal with ground subsidence caused by tunneling is the most appropriate. Numerical methods are not only used to predict surface settlement but also to simulate the entire construction progress, such as the tunneling stages; placement of tunnel segments; the interaction between tunnel segments and the surrounding soil; the influence on neighboring works, and the influence of seepage and consolidation, etc.

The finite element method is the most popular numerical method for estimating surface settlement due to tunnel construction. Simulating and forecasting surface settlement using specialized geotechnical software requires input data, such as geometric dimensions, material properties of the support system, construction methods, and geological conditions. The output results include surface settlement, internal forces in the tunnel shell (vertical pressure and bending moment in designing reinforcement of tunnel shell), and stress distribution diagrams.

The purpose of analysis plays an essential role in determining the model's elements, size, and complexity. Finite elements should be selected so that it is possible to closely simulate the actual process of the ground without being too complicated and beyond the capabilities of conventional calculation tools.

Currently, there are many software for geotechnical analysis and calculation in the world, such as Geostudio, Plaxis, or other software products from Rocscience. Each software has different strengths and weaknesses, which is applicable for various purposes. Plaxis 3D Tunnel software (Netherlands) is used to calculate surface settlement caused by the TBM tunneling process because of its ability to simulate the construction process accurately and calculate the stabilizing pressure at the face during the tunneling process. Therefore, this paper uses a numerical method based on Plaxis 3D Tunnel software to analyze and calculate the surface settlement caused by the influence of underground construction of Metro Line 2.

3. Analysis of surface settlement due to the influence of underground construction of Metro Line 2

3.1. Calculations of surface settlement due to the influence of underground construction of Metro Line 2

3.1.1. Material properties

Geological cross-section (vertical) alongside the center of Metro Line No. 2 is presented in Figure 5, including five soil layers as below:

- Layer 1: Gray clay, liquid to a plastic state.
- Layer 2: Gray, greenish-gray clay, semi-solid state.
- Layer 3: Small to medium sand particles, yellowish-gray, reddish-brown, medium dense sand.
- Layer 4: Patchy color, gray, yellowish-gray clay, semi-solid to solid-state.
- Layer 5: Gray, yellow, dense to the very dense clay-sand mixture.

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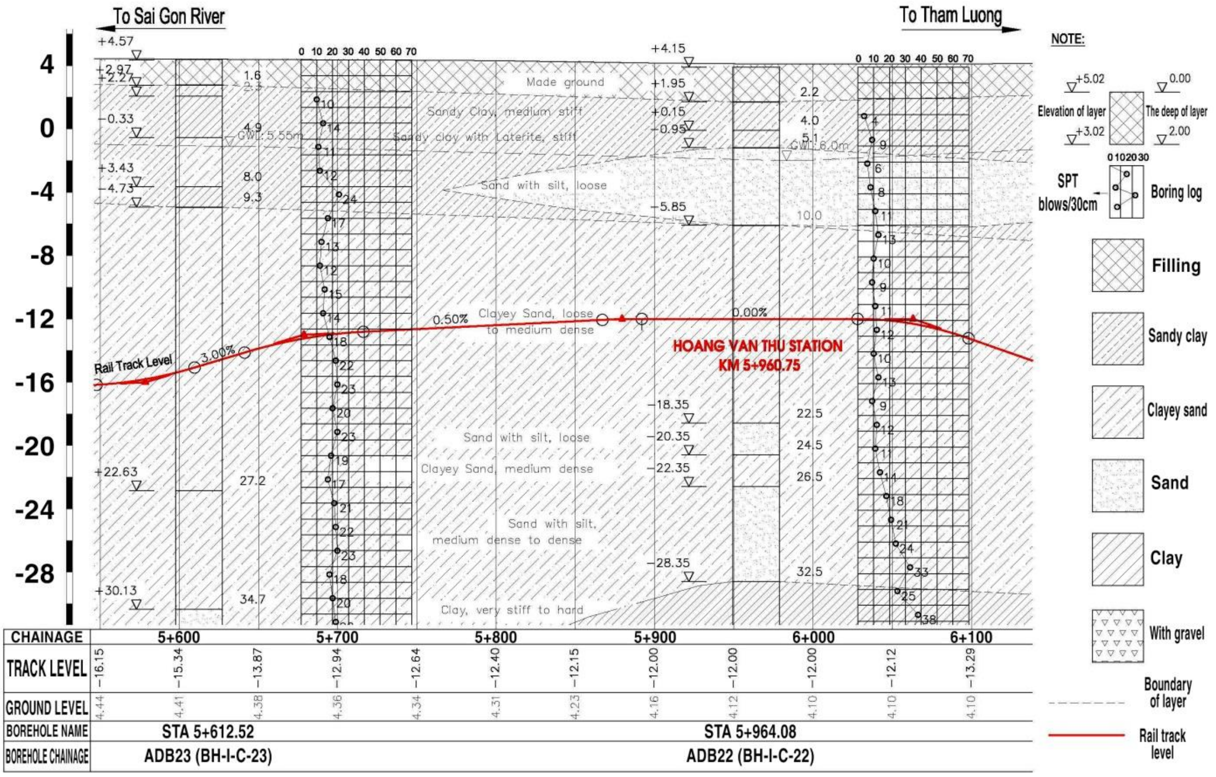

Fig. 5. Typical geological cross-section in location km 5+600 - km 6+100 of Metro Line No. 2.

Geological conditions of construction locations of the double tunnel line at the Km 0+200, Km 3+050, and Km 5+560 are shown in Table 1.

Tab. 1. Properties of soil layers at the location Km 0+200, Km 3+050, and Km 5+560.

No.	Parameters	Symbol	Value			Unit
			Layer 1	Layer 2	Layer 3	
1	Material sample	Model	Morh – Coulomb			-
2	Type of impact material	Type	Drained			-
3	Unit weight of soil above groundwater level	γ_{unsat}	15.8	20.8	19.6	kN/m^3
4	Unit weight of soil below the groundwater level	γ_{sat}	17.8	21	20.5	kN/m^3
5	Horizontal permeability coefficient	k_x	1.81×10^{-5}	0.5	0.5	m/day
6	Vertical permeability coefficient	k_y	0.9×10^{-5}	0.25	0.25	m/day
7	Young's modulus	E_{ref}	1000	30000	120000	kN/m^2
8	Unit adhesive force	c'	8.5	1.1	1.5	kN/m^2
9	Angle of internal friction	φ	15	28	21	degree
10	Dilation angle	ψ	0	4	3	degree
11	Poisson's coefficient	ν	0.33	0.3	0.3	-

Tunnel cross-section: Round tunnel, tunnel diameter D = 6.8m, tunnel cover thickness d = 0.6m. The material parameters of the shield and tunnel shell are shown in Table 2.

Tab. 2. Input parameters for tunnel shell concrete and TBM steel material.

No.	Parameters	Symbol	Value		Unit
			Tunnel shell concrete material	TBM excavator steel material	
1	Material Type	Expression	Elastic		-
2	Axial stiffness	*EA*	2.4×10^{10}	8.2×10^{7}	kN/m
3	Bending stiffness	*EI*	7.2×10^{8}	8.38×10^{4}	kNm^2/m
4	Equivalent thickness	*d*	0.6	0.111	m
5	Weight	*w*	14.4	38.15	kN/m/m
6	Poisson's coefficient	*ν*	0.15	0	-

3.1.2. Simulation using Plaxis 3D Tunnel

Building model using Plaxis 3D Tunnel to calculate the variation of surface settlement with the depth from the surface to the center of the double tunnel (-22.17m at location 0+200 and -11.48m at location 3+050) and the distance between the two centers of the double tunnel (16.5m at location 3+050 and 12.0m at location 5+650).

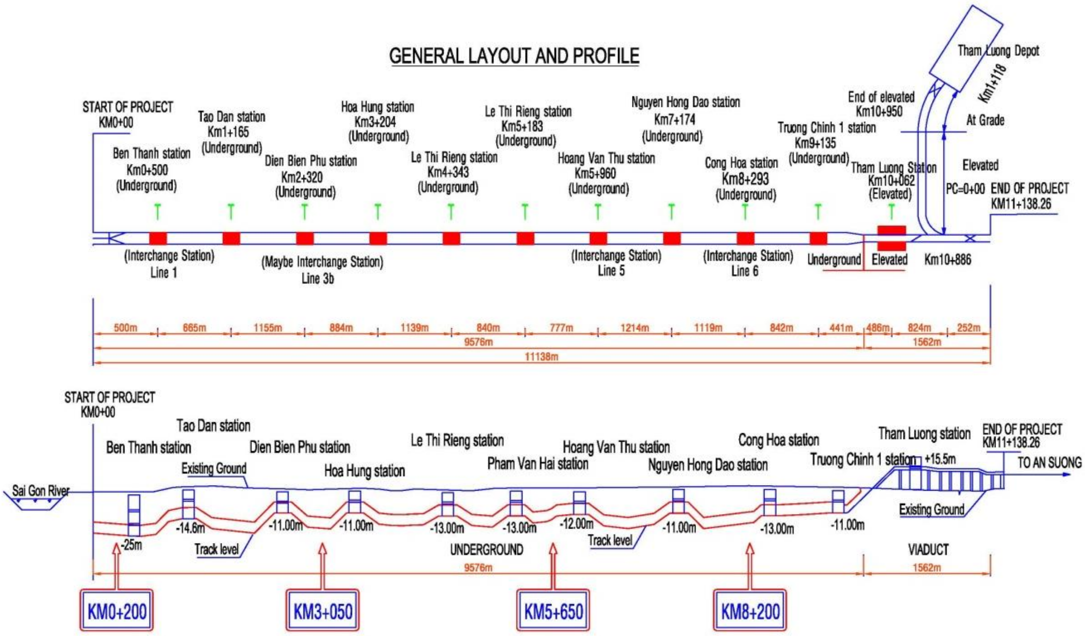

Fig. 6. Map of straight line and study locations.

Simulation process using 3D model includes 3 phases:

- Excavation face installation phase: a balanced pressure must be established for the face to ensure that the effect of volume loss on the face is insignificant. In other words, it can be assumed that this does not affect the surface settlement [14, 15].

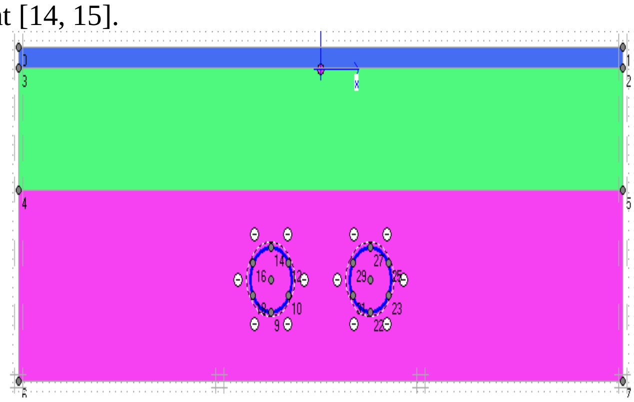

Fig. 7. Excavation face simulation.

- Excavating phase: establish the centripetal loss in the TBM tunneling process. The excavation face removes the soil in phase 1.

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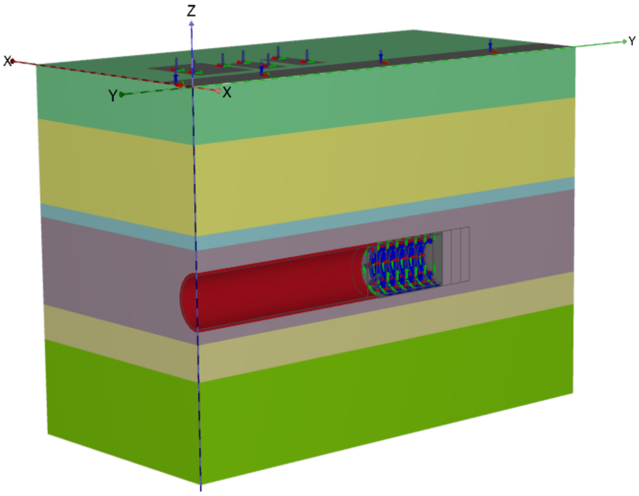

Fig. 8. Excavation process simulation.

- Tunnel shell installation phase: the tunnel shell is installed. Between the tunnel shell and the soil is a layer of mortar to avoid the settlement and waterproofing for the shell. This mortar is pumped into the end of the shield and creates pressure on the surrounding soil.

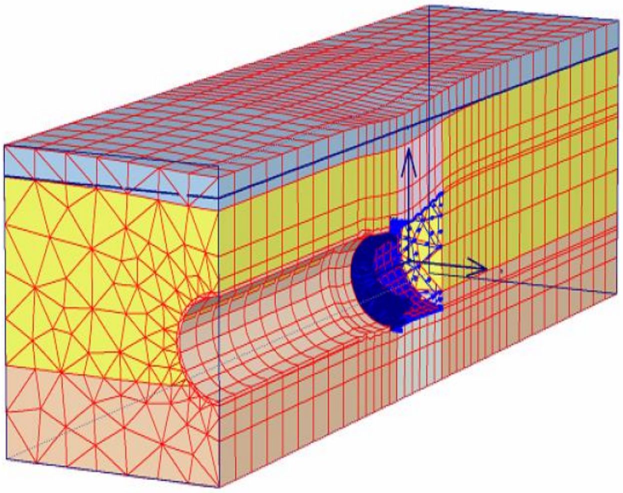

Fig. 9. Tunnel shell installation simulation.

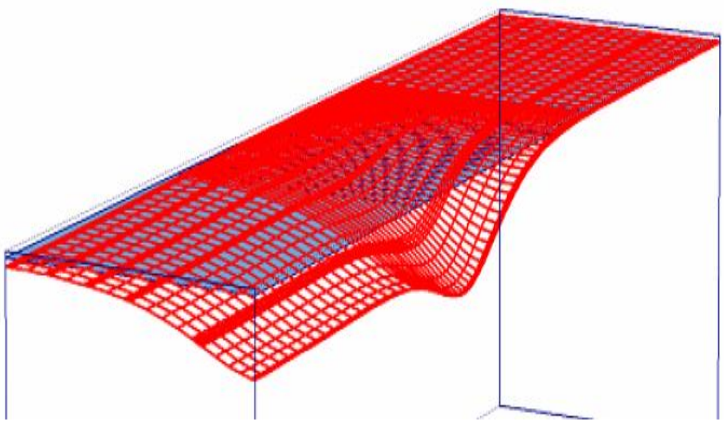

Fig. 10. Funnel-shaped settlement simulation after installing the tunnel shield.

3.2. Calculation results

- When the depth from the surface to the center of the double tunnels is different:

The authors used Plaxis 3D Tunnel software to simulate and calculate the surface settlement of the double tunnel at two locations 0+200 (depth from the surface to the center of the double tunnel is -

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22.17m) and location 3+050 (depth: -11.48m). Together with geological conditions in Table 1, material parameters of the TBM and tunnel shell in Table 2, calculation results are as follows:

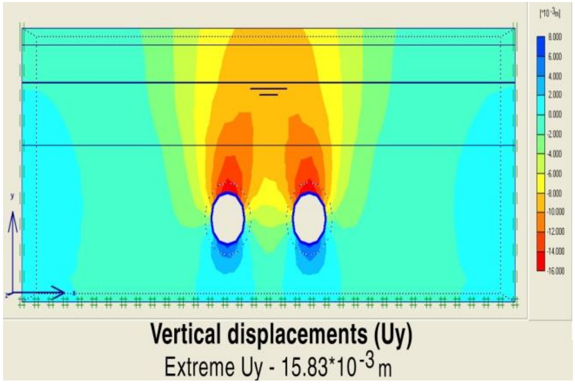

Fig. 11a. The final field of vertical surface displacement in case the distance between the double tunnels is 16.5m and located at a depth of -22.17m (location 0+200).

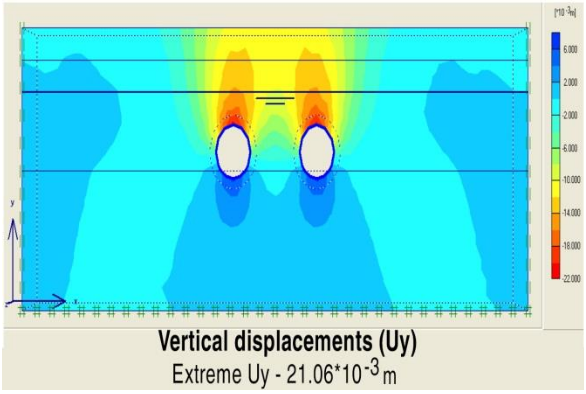

Fig. 11b. The final field of vertical surface displacement in case the distance between the double tunnels is 16.5m and located at a depth of -11.48m (location 3+050).

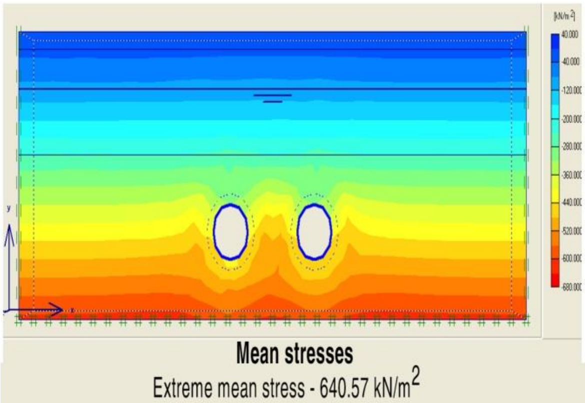

Fig. 12a. Effective stress at the location 0+200.

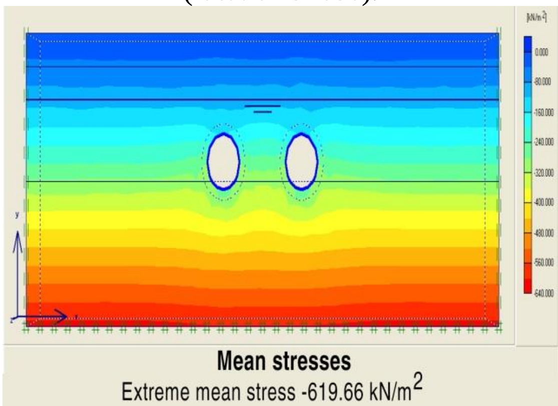

Fig. 12b. Effective stress at the location 3+050.

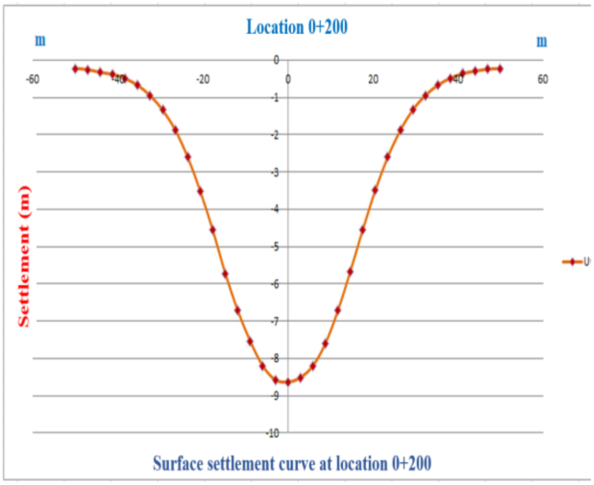

Fig. 13a. The surface settlement curve at location 0+200**.**

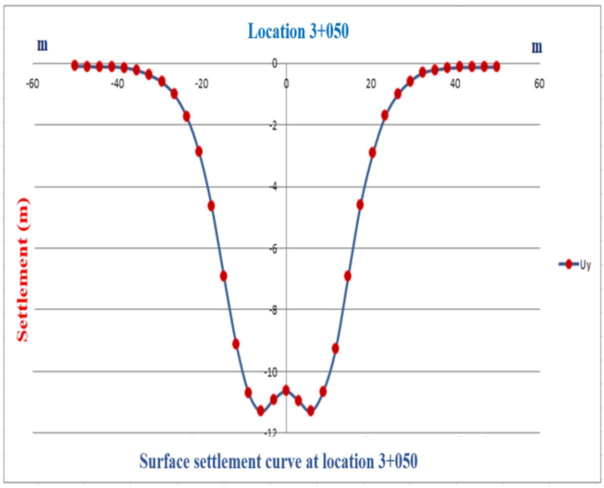

Fig. 13b. The surface settlement curve at location 0+050.

Results of the model analysis show that the deeper the double tunnel, the smaller the surface settlement. This is consistent with the fact that the increase of depth in the same geological conditions will increase the soil stress and reduce the surface settlement. However, the settlement curve shown in Figure 13a (location 0+200) and Figure 13b (location 3+050) are different. The settlement curve at the location 0+200 conforms to the theory of surface settlement of the single tunnel. In contrast, the settlement curve at the location 3+050 conforms to the theory of surface settlement of the double tunnel.

It can be explained that in the case of a double tunnel (Metro line 2) when the depth is too large (depending on geological conditions), the theoretical calculation will be suitable for the single tunnel because of the large soil stress. As a result, the difference in distance between the two tunnels is not significant regarding the influence on the construction work. In contrast, when the depth is suitable, the theoretical calculation perfectly matches with the model on Plaxis 3D Tunnel.

- When the tunnel has the same depth, the distance between the center of the double tunnel is different:

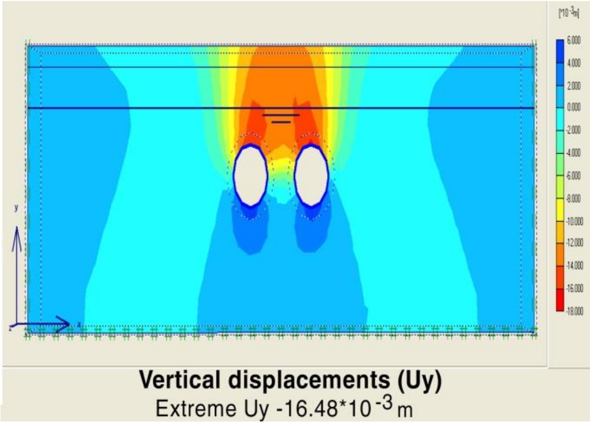

Fig. 14. The final field of vertical surface displacement in case the distance between the double tunnels is 12.0 m and located at a depth of -11.87 m (location 5+650).

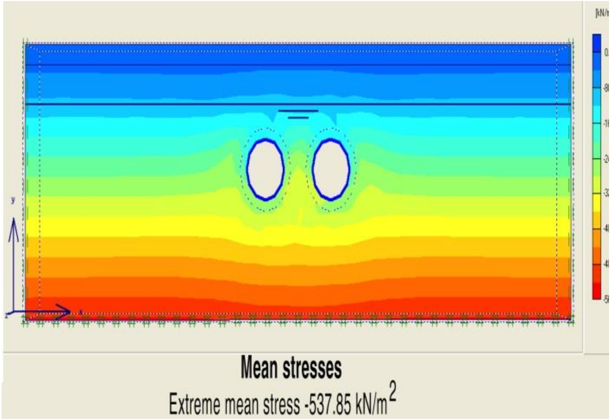

Fig. 15. Effective stress of the double tunnel at the location 5+650.

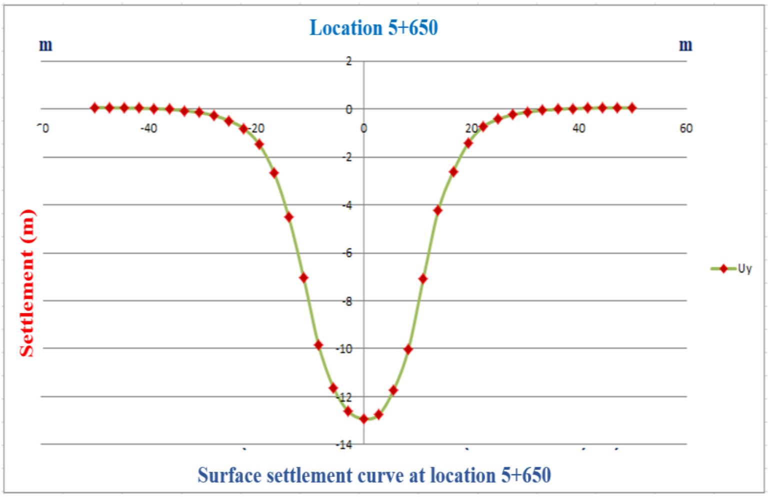

Fig. 16. Surface settlement at the location 5+650.

The results show that the surface settlement increases with the decrease of the distance between two tunnels. It is related to the soil stress at the surrounding location of each tunnel in the double tunnel. The larger the distance between the two tunnels, the greater the soil stress in the opposite case, so the surface settlement after excavating will be smaller (-11.30 mm at location 3+050 and -12.96 mm at location 5+060). The graph also shows that the surface settlement when the two tunnels are located closely to each other will be similar to the theoretical calculation of the single tunnel.

- When the tunnel has the same depth at different geological conditions:

The simulation is conducted at the location 8+200, the depth of the double tunnel is -11.21m, the geological conditions are as in Table 3:

Tab. 3. Properties of the soil layer.

No.	Parameters	Symbol	Value			Unit
			Layer 1	Layer 2	Layer 3	
1	Material sample	Model	Mohr - Coulomb			-

2	Type of impact material	Type	Drained			-
3	Unit weight of soil above ground water level	γ_{unsat}	16.0	17	17	kN/m^3
4	Unit weight of soil below the groundwater level	γ_{sat}	18.0	20	20	kN/m^3
5	Horizontal permeability coefficient	k_x	1.81×10^{-5}	0.5	0.5	m/day
6	Vertical permeability coefficient	k_y	0.9×10^{-5}	0.25	0.25	m/day
7	Elastic modulus	E_{ref}	10000	13000	75000	kN/m^2
8	Cohesion	c'	5	1	1	kN/m^2
9	Angle of internal friction	φ	25	31	31	degree
10	Expansion angle	ψ	0	0	0	degree
11	Poisson's coefficient	v	0.35	0.30	0.30	-

The results of the calculation are as follows:

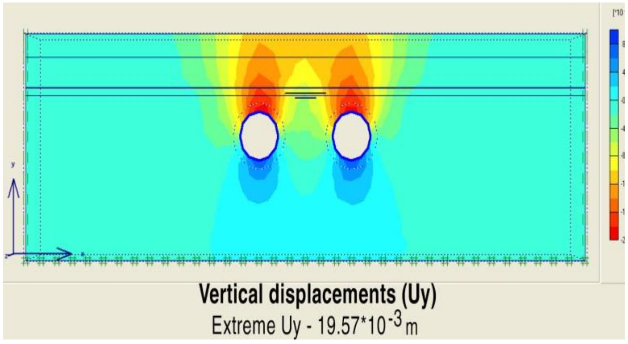

Fig. 17. The final field of vertical displacement of the subsoil in case the distance between the double tunnels is 16.5 m and located at a depth of -11.21 m (8+200).

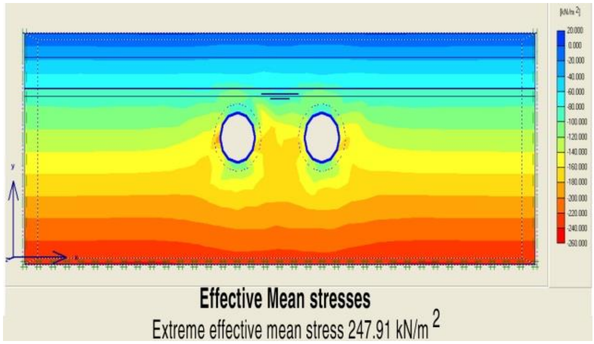

Fig. 18. Effective stress of the double tunnel at location 8+200.

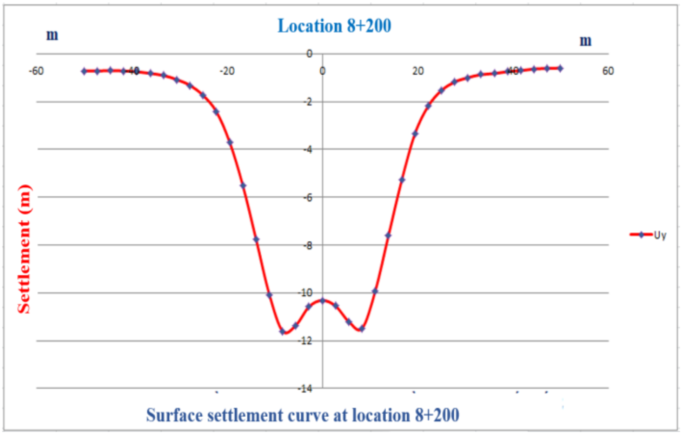

Fig. 19. Surface settlement at location 8+200.

The results show that the calculation of settlement on Plaxis 3D Tunnel model can be performed at many different locations with different geological conditions, and design parameters (depth of tunnel from the ground, distance between the center of the double tunnel two tunnels). Calculation results also show that the increase of the tunnel depth reduces the influence on the surface settlement. The decrease of the distance between the two tunnel centers will increase the surface settlement. These results are consistent with the fact that the soil stress varies when replaced by the tunnel shell volume, causing surface settlement.

Tab. 4. Combined results of the four cases above.

No.	Research location	Location 1	Location 2	Location 3	Location 4
1	Location	0+200	3+050	5+650	8+200

2	Depth of tunnel centerline (m)	-22.17	-11.48	-11.87	-11.21
3	Distance between two centers of double tunnel location (m)	16.5	16.5	12.0	16.5
4	Maximum vertical displacement (mm)	-15.83	-21.06	-16.48	-19.57
5	Maximum ground settlement (mm)	-8.63	-11.30	-12.96	-11.60
6	Maximum horizontal displacement (mm)	5.79	7.05	7.23	5.37
7	Maximum stress (kN/m^2)	-640.57	-619.66	-537.85	-247.91

4. Conclusions

The surface settlement caused by the construction of the double tunnels of Metro Line 2 can be predicted using various methods, including analytical and numerical methods. In particular, using numerical methods via simulation software such as Plaxis 3D gives the most suitable calculation results.

Research on surrounding surface settlement during the construction of metro line 2 in HCMC shows that when geological conditions are different, the surface settlement is different, which is consistent with the bearing capacity of the soil according to each geology area. The above results are only preliminary results. For final results, there must be a combination of calculations on the model, field observations, and laboratory work to determine soil pressure at the construction site and make an adjustment to the model to provide accurate results.

Before construction, investors and the construction contractors should consider the geological conditions of the area, design drafts, and make predictions to protect the existing works within the construction area and other neighboring works, avoiding possible consequences due to the influence of surface settlement.

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