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Finite Element Modeling of Twin tunnel in Milan, Italy

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Abstract
This research paper focuses on the soil-tunnel interaction for a twin tunnel located in Milan Italy (metro-line 5). The analysis is performed using two- and three-dimensional numerical models created using the finite element method (FEM) with PLAXIS 2D and PLAXIS 3D. The elastic-plastic non-linear behaviour is adapted to model the stress-deformation behaviour of soil, both the hardening soil model with small-strain stiffness (HSS) and the Hardening Soil model (HS) are used. The 2D and 3D models for the twin tunnels are validated using the two-dimensional and three-dimensional contraction method. The results are verified with reference field measurements, the comparison reveals that the field measurements and finite element analysis results are remarkably similar.

Keywords: Finite element modelling, Contraction Method, Twin Tunnel, Tunnel-Soil interaction.

1. Introduction

A city's rapid urbanization, high building density within city centers, and limited space are expanding the use of tunnels. However, the construction of tunnels within cities is frequently accompanied by ground surface subsidence, which can cause a variety of damages to existing surface structures [1, 2, 3, 4].

Tunnel design necessitates an accurate estimation of surface settlements. Different design methods are commonly used in engineering practice, ranging from simple empirical and analytical formulas to advanced finite element analyses [5]. Different procedures for modeling the excavation and support sequence are used depending on the tunneling method, such as conventional or closed shield tunneling. These procedures have a significant impact on predicted/calculated deformations and lining forces. The analysis method must consider the effects of the installation on the ground-lining interaction [6]. There are two main tunneling methods: cut and cover, and the closed method. The closed method includes conventional methods, such as the new Austrian tunneling method (NATM), while the other closed method utilizes a tunnel-boring machine (TBM) with or without a shield [6]. A continuous face support to the tunnel face is used in closed face tunneling methods. In comparison to open face tunneling, these methods are designed to reduce ground deformations. This is critically valuable for shallow urban tunneling [6].

This research deals with tunnels excavated by earth pressure balance machines (EBP), which is one of the modern closed face shields tunneling methods. Specifically, tunneling with a shield is ideal for softer ground that requires continuous radial support. The earth pressure balance (EPB) strategy of excavating underground tunnels in soft soils is commonly used [7].

The majority of previous research has focused on the surface settlements observed over twin tunnels in clayey soil. However, less consideration is given to the twin tunnels excavated in gravelly sand, which is the focus of this study.

This paper demonstrates numerically the tunnel-soil interaction of a twin tunnel case study by using PLAXIS 2D version 8.6 and PLAXIS 3D Tunnel version 1.2. A comparison between the field measurements of surface subsidence and predictions of the numerical analysis was conducted. The validation process entails both the validation of model elements (constitutive model, input parameters, boundary conditions, etc.) and the validation of an integral model by contrasting the outcomes of a numerical model and that of field measurements or from software packages that use separate solutions [8,9]. The study's goal was to verify the reliability of the numerical analysis and soil models used in modeling surface settlements caused by the twin tunnel construction, and also to help engineers select the appropriate constitutive models for comparable numerical analysis projects.

2 Milan twin tunnel case study

The twin tunnel (metro-line 5) in Milan (Italy) runs from north to west in the city and has a total length of 12.6 km and 19 access stations [10].

According to Fig. 1, the metro-line portions taken into consideration in this study span a distance of approximately 1.3 km between the station of San Siro and Segesta and nearly 600 m between the stations of Lotto and Portello. The study focuses on the section of the route between the stations of San Siro and Segesta where green-field conditions were found. The situation of the ground section S16 was used as an example, which is distinguished by average values of maximum settlements for the investigated portion of the metro line. The twin tunnels have been partially excavated beneath the water table with a 15-meter distance between axes and a 15-meter mean depth [11]. EPB machines were chosen to effectively minimize ground movements in these densely populated areas. The EPB machine excavates with a rotating cutter-head; the excavated material, maintained under pressure in the bulk chamber, guarantees face stability and limits surface settlements [10]. Metro line 5 is located within the granular unit formation, which is primarily composed of fluvioglacial and alluvial gravel and sand [11]. At the design stage of the project, an extensive geotechnical investigation was conducted along the metro-line, Core drillings with open pipe piezometers, SPT tests, and constant-head Lenfranc-type permeability tests were used in these investigations [11].

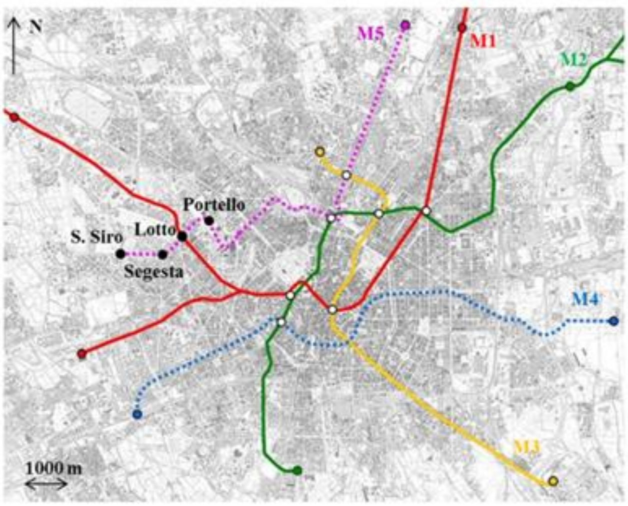

Fig. 1: Milan metro-line system [12].

Fig. 2 represents soil stratigraphy, which refers to the ground conditions encountered at the San Siro-Segesta and Lotto-Portello stations on the Milan metro line 5. In addition, a hydrostatic water table was found 15 m below the ground surface level using open pipe piezometers. The core feature of this deposit is gravelly-sand soil; it is deemed to be homogeneous at the two investigated segments of the route, apart from a 5 m thick sandy-silt layer that was found at depths ranging from 20 m to 25 m just between the stations of Lotto and Portello.

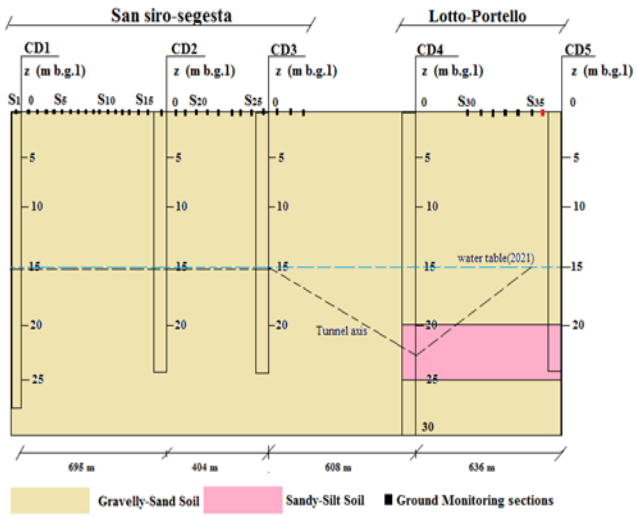

Fig. 2: Soil stratigraphy along the route's reference section and the detected water table (the position of the tunnels and monitoring sections are also shown) [11].

3 Contraction Method

In 1993, two scientists, Vermeer and Brinkgreve, developed a numerical method for simulating ground loss based on specific tunnel contraction [13]. The contraction method does not need a very fine mesh of elements, as in the other methods, which require a special fine mesh between the shell and the shield. Thus, the contraction method is adopted.

3.1 Contraction Method (2D)

The contraction method in the 2D modeling includes two calculation phases to simulate the tunneling influence throughout the excavation, as shown in Fig. 3. The first phase of the calculation began by deactivating the soil cluster inside the tunnel's perimeter, indicating tunnel excavation. The water inside the soil cluster was also removed (cluster dry) and the surrounding groundwater was stopped from flowing into the cluster along with installing a tunnel lining. A defect in the tunnel's stability occurred because of the imbalance between the tunnel lining weight and the excavated soil inside the tunnel, which cause uplifting in the tunnel lining. In phase two, the tunnel was subjected to a prescribed contraction ratio and the tunnel lining was gradually contracted until the prescribed contraction ratio was reached. Equation (1) shows how to calculate the contraction ratio [14].

$$\text{Contraction} = \frac{(\text{Original Tunnel Area} - \text{Tunnel Area At Current Phase})}{\text{Original Tunnel Area}} \quad (1)$$

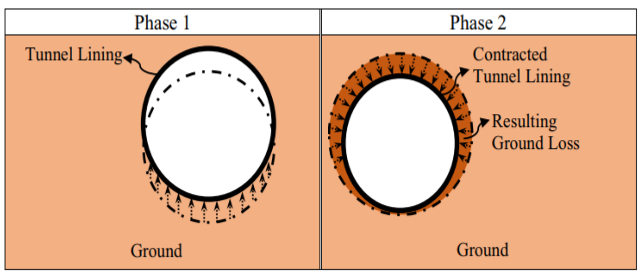

Fig. 3: Contraction Method [14].

3.1 Contraction Method (3D)

AUGARDE procedure relies on prescribing a contraction of the tunnel lining [15]. Augarde's simplified stage-by-stage method for 3D modeling states that elements inside the tunnel are removed in the first stage of calculation, while lining elements are activated along the entire stretch of the tunnel. The first stretch of the lining is subjected to uniform (hoop) shrinkage at the end of this method to generate a prescribed amount of ground loss. Following that, shrinkage is applied to the lining's following stretch, and so on. By reducing the lining stretches to tunnel boring machine strokes, this method approaches the actual shield tunneling process. In fact, closed shield tunneling is a continuous process that includes continuous support pressure and lining segment installation.

4 Tunnel geometry and site conditions

In order to verify the validity of numerical analysis results and to calibrate the behavior of the soil used, a numerical model of the twin tunnel was carried out using the finite element method. This tunnel with an outer diameter of 6.7 m was constructed in 2013. The earth pressure balance shield (EPB shield) with a length of (9.8 m) was utilized in the excavation of the twin tunnel. It relied on permanent support in the front, where the pressure value of 106 kPa at the top of the tunnel increases with depth to reach, at the base of the tunnel, 185 kPa. The lining of the twin tunnel is made of precast reinforced concrete rings (Segments), 0.3 m thick and 1.4 m long.
Several field measurements were carried out with the construction of this project, including measuring the surface settlements above the twin tunnel under green field conditions. In the transverse direction, the measured surface subsidence obtained in the first phase of construction (one tunnel) and second phase (twin tunnel) are illustrated in Fig. 4 respectively.

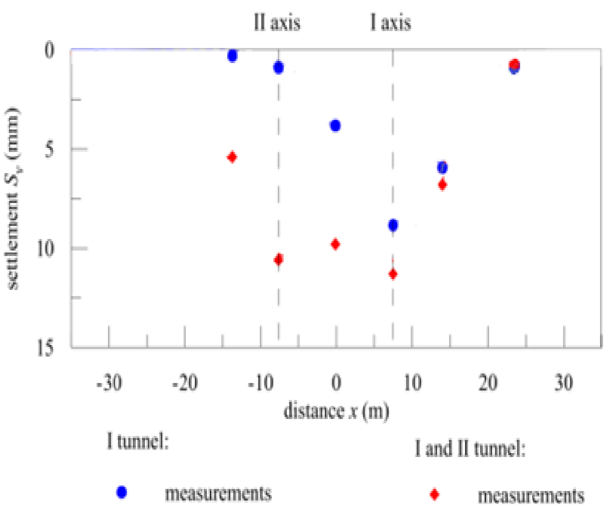

Fig. 4: The measured settlements along transversal direction after the excavation of the first and the second tunnel under green-field conditions [11].

Likewise, in the longitudinal direction within the field measurement region and parallel to the tunnel's axes, the measured settlements under green field conditions in the first phase (first tunnel excavation) are displayed in Fig. 5 and those of the second phase (second tunnel excavation) are displayed in Fig. 6. The twin tunnel is 15 m deep from the ground surface to the tunnel's center; the soil at the site is gravel sandy soil that extends to a depth of (30m).

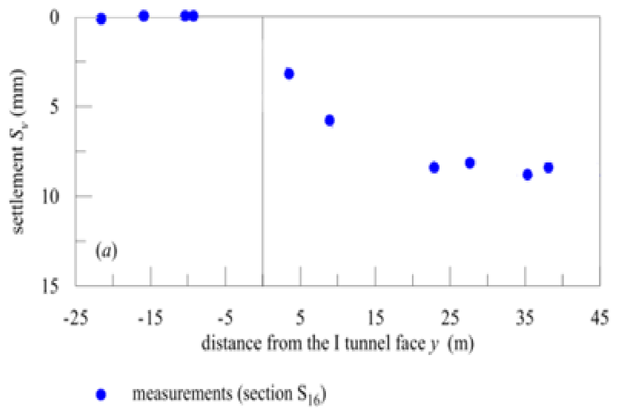

Fig. 5: Measured settlements along the longitudinal direction after the excavation of the first a tunnel under green-field conditions [11].

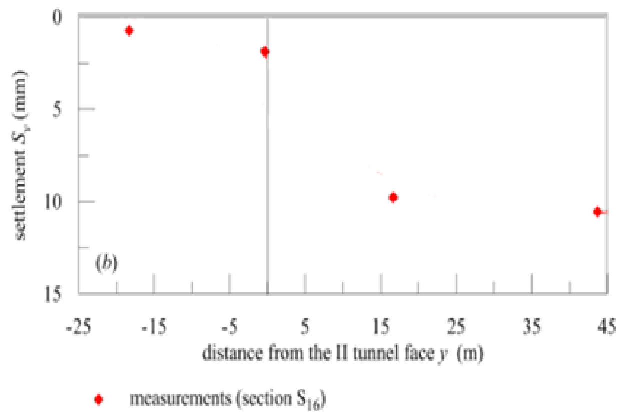

Fig. 6: Measured settlements along the longitudinal direction after excavation of the second tunnel under green-field conditions [11].

5 Finite element modeling

The use of numerical modeling is now required for the simulation of many complex issues. The finite element method is an effective numerical modeling tool used extensively in geotechnical engineering [16].

5.1 3D Model geometry and boundary conditions

The twin tunnel and surrounding soil layers were modeled in 3D in which, geometric dimensions were chosen for the 3D numerical model as a whole model and that it fulfills the German requirements (Meissner, 1996) [17]. To determine the bottom boundary Eq. (2) is applied:

$$h = (1.5 - 2.5) \times D \qquad (2)$$

where h is the distance between the tunnel's center point and the bottom boundary, and D is the tunnel's diameter.
To determine the mesh width, Eq. (3) is applied:

$$w = (4 - 5) \times D \qquad (3)$$

where w is the distance between the tunnel's center point and the vertical boundaries.
Fig. 7 shows the geometric dimensions of the model used, the mesh dimensions are 80 m in the x-direction, 30 m in the y-direction, and 100 m in the z-direction. The model's bottom is fixed in both vertical and horizontal directions [U_x=U_y=0)], while the vertical boundaries are fixed horizontally [U_x = 0,U_y= free]. The model mesh consists of 7638 triangular 15 nodes element.

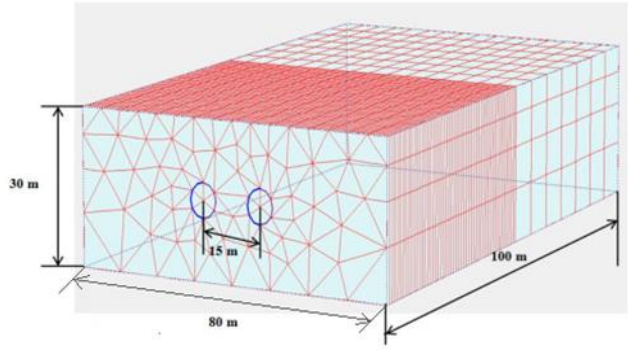

Fig. 7: Sketch of the mesh employed in the 3D numerical study for the twin tunnel case.

5.2 Material Model

The HS model is used to simulate the behavior of the gravelly sand soil surrounding the tunnels. The water table is located at a depth of (15 m) from the ground surface. The properties of the gravelly sand) are summarized in Table 1, As for the lining of the twin tunnel, they were modeled using beam elements with linear elastic behavior and stiffness was reduced in the curves by dividing it by a reduction factor equal to 4 in order to have an effect on the joints between the precast concrete segments taken into consideration (Wood, 1975) and their properties. This is shown in Table 2 [18].

Table 1 The soil properties of the layers around the twin tunnel and the parameters of the material model.

(Hardening soil Model: HS-Model, HS small model) (Gravelly sand)													
R_{inter}	OCR	m [-]	$\gamma_{0.7}$ [%]	G_0^{ref} [Mpa]	E_{ur}^{ref} [Mpa]	E_{50}^{ref} [Mpa]	E_{oed}^{ref} [Mpa]	v_{ur} [Mpa]	Ψ [°]	C' [kpa]	φ' [°]	γ_{sat} [kN/m^3]
0.67	1	0.4	0.0001	250	144	48	48	0.2	0	0	33	20

Table 2 Properties of the tunnel lining.

Lining	Modeling	M-Model	γ [kN/m^3]	EA [GN/m]	EI [M.N.m^2]	v	t [cm]
	Beam elements	Linear Elastic	25	10.5	19.69	0.15	30

5.3 2D model geometry and boundary conditions

The continuous field model was used to simulate the twin tunnel and surrounding soil layers, where the geometric dimensions of the 2D numerical model were chosen as a whole model and it fulfills the aforementioned German requirements (Meissner, 1996) [17].

To determine the bottom boundary, Eq. (5) is applied:

$$h = (1.5 - 2.5) \times D \tag{5}$$

where h is the distance between the tunnel's center point and the bottom boundary, and D is the tunnel’s diameter.

To determine the mesh width, Eq. (6) is applied:

$$\mathrm{w} = (4 - 5) \times D \tag{6}$$

where w is the distance between the tunnel's center point and the vertical boundaries.

Fig. 8 demonstrates the geometric dimensions of the used model; the mesh dimensions are 80 m in the x-direction, 30 m in the y-direction.

The model's bottom is fixed in both vertical and horizontal directions [Ux=Uy=0)], while the vertical boundaries are fixed horizontally [Ux = 0,Uy= free].

The model mesh consists of 703 triangular 15 nodes element.

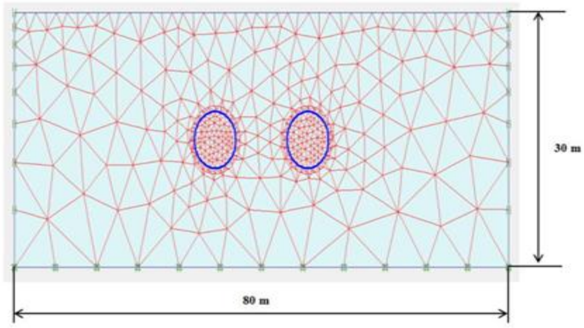

Fig. 8: Sketch of the mesh employed in the 2D numerical study for the twin tunnel case

6 Results and Discussion

6.1 3D model

For the validation procedure, the measured surface settlements during tunnel construction [reference Field section S16] were compared to those calculated by the numerical modeling (HS-model) using the contraction method. Fig. 9 shows the deformed mesh and the vertical settlement using the contraction method as a result of constructing the first tunnel.

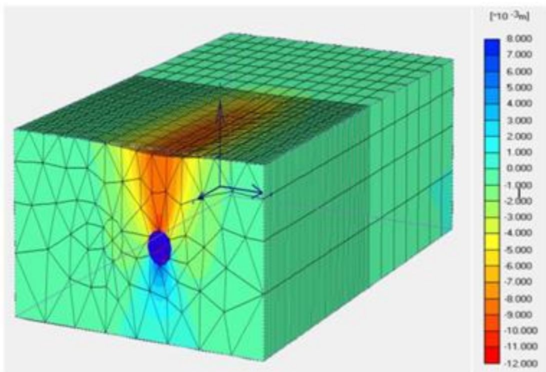

Fig. 9: The deformed shape of the finite elements mesh and the vertical settlements resulting from the construction of the first tunnel using the contraction method.

Likewise, Fig. 10 shows the deformed shape of the mesh and vertical settlements using the contraction method resulting from the construction of the twin tunnel.

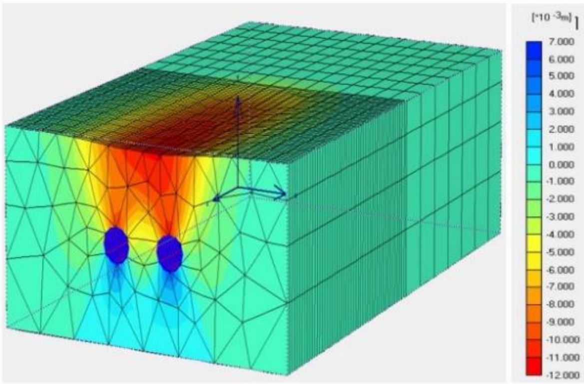

Fig. 10: The deformed shape of the finite elements mesh and the vertical settlement resulting from the excavation of the twin tunnel using the method of contraction.

Fig. 11 clearly shows that the numerical model produces a settlement trough in the transverse direction that substantiates the field measurements; this comparison is based on the hardening soil model (HS-model), where C represents the contraction coefficient value.

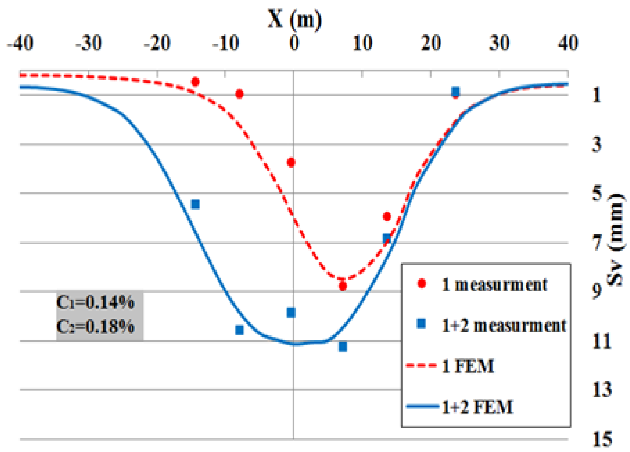

Fig. 11: Transverse settlement trough resulting from the excavation of the first tunnel and after the excavation of the twin tunnel using the HS-model

Fig. 12 and 13 represent the longitudinal settlement trough in which the numerical analysis results clearly substantiate the corresponding field measurements in the monitoring section 16.

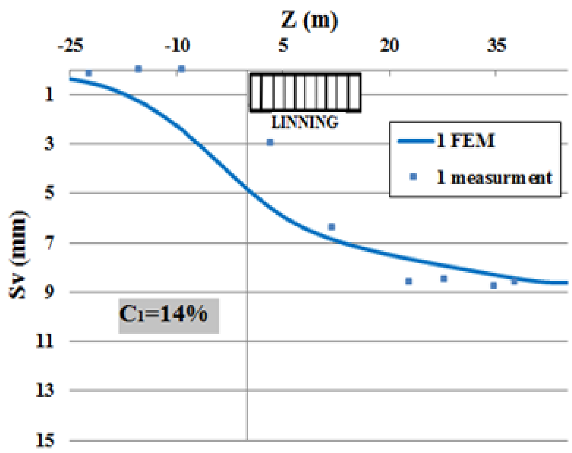

Fig. 12: Longitudinal settlement trough above the axis of the first tunnel resulting from its excavation

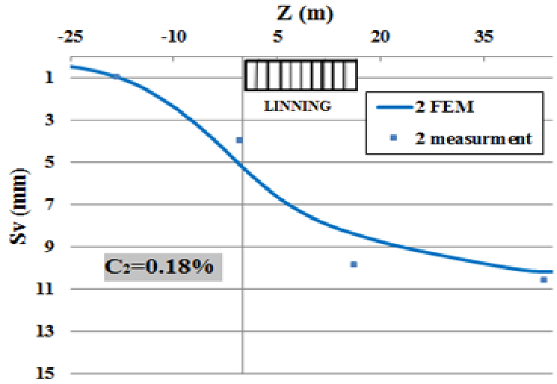

Fig. 13: Longitudinal settlement trough above the axis of the second tunnel, which results after the excavation of the twin tunnel

The results also showed that the settlement ratio above the excavation face to the maximum settlement above the first tunnel is 27%, while for the second tunnel, the ratio is 24% of the maximum settlement, which is close to the results of Mair and Taylor (1997) [19].

6.2 2D model

For the validation procedure, the measured surface settlements during tunnel construction [reference Field section S16] were compared to those calculated by numerical modeling (HSS-model) using the contraction method.

Fig. 14 shows the vertical soil settlement resulting from the excavation of the first tunnel.

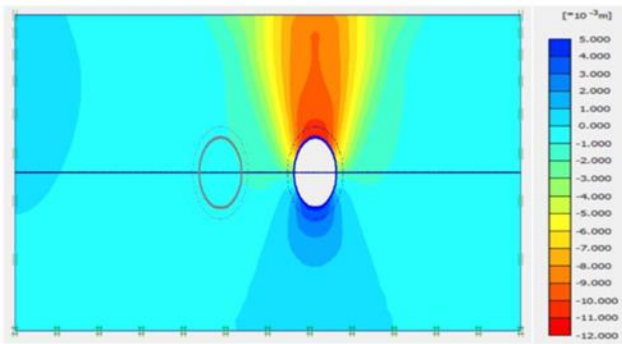

Fig. 14: Resulting vertical settlements of soil using the method of contraction and (HSsmall) soil model after excavating the first tunnel

Fig. 15 shows the resulting vertical settlements of soil after the excavatiing the twin tunnel; it should be noted that the settlements are concentrated above the first tunnel.

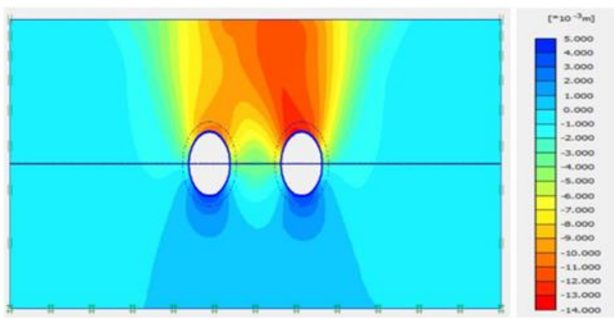

Fig. 15: Resulting vertical settlements of soil using the method of contraction and (HSsmall) soil model after the excavation of the two tunnels

Fig. 16 demonstrates the transversal settlements measured in the field, and calculated using HSS and HS models after the first tunnel (blue curves) and the twin tunnel (red curves) excavation respectively. It is evident that the HSS model yields a settlement trough more consistent with the field measurements.

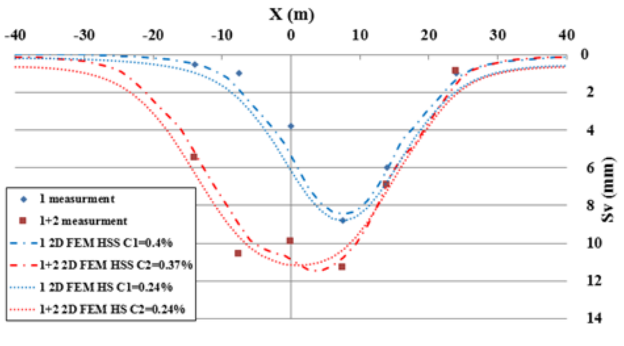

Fig. 16: Transverse settlement trough of the two-dimensional model resulting from the excavation of the first tunnel and after the excavation of the twin tunnel using two different soil models (HS/HSS).

7 Comparison between 2D and 3D modeling results of the twin tunnel

The comparison between the 2D and 3D modeling results demonstrates that the two transverse settlement trough models using the HS-model are close to each other as well as wider than the field measurements, as shown in Fig. 19 and 20, which is consistent with Franzius (2003) [20].

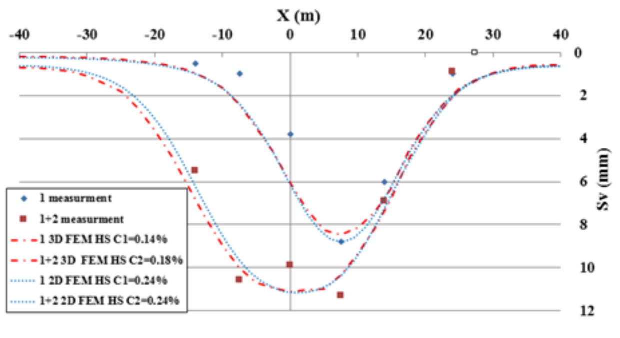

Fig. 17: Comparison of the transverse settlement trough of the 2D and 3D model generated after the twin tunnel is excavated using HS soil model

8 Conclusion

This paper compares field measurements of a twin tunnel case study to the results of numerical modeling. Plaxis 3D tunnel software uses a hardening soil model, while Plaxis 2D 8.6 uses a hardening soil model with small-strain stiffness to simulate the soil behavior and evaluate their performance in forecasting surface settlements. The following are the study's conclusions:

- Combining the developed soil models (HS, HS-small) with the numerical analysis technique to model the excavation progress (using contraction method) leads to the prediction of settlements over the tunnels that are close to field measurements, as is shown in the comparisons between the longitudinal and transverse settlement trough.
- The comparison shows that the field measurements and finite element analysis results are very similar. The behavior of the reference case can thus be successfully predicted using the input data and the finite element simulation procedure.
- The effect of using a different soil model on the accuracy of the results is greater than the effect of modeling the case as a three-dimensional case instead of a two-dimensional case; as a result, the two-dimensional analysis can be used with sufficient accuracy in the preliminary study stage.

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