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Practical Calculation of Diaphragm Wall Deflection using Plaxis 3D Software

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KEYWORDS

Plaxis 3D
Deep excavation
Diaphragm wall
Mathematical models
Deflection

ABSTRACT

In this article, the mathematical models within the Plaxis 3D software were used to simulate and assess the deflection of diaphragm walls, comparing with data collected from a real project. This scientific and effective approach is crucial, as analyzing and simulating the excavation stages before constructing diaphragm walls for underground levels becomes essential for controlling wall displacement and preventing potential soil erosion issues in the surrounding deep excavation, which could have serious consequences for neighboring structures. The numerical modeling results demonstrate that the deflection of the diaphragm wall varies inversely with its thickness, but this variation is relatively small and quite compatible with the observed data.

1. Introduction

Underground structures or part of them often need to be deeply embedded into the soil, which is inherently complex and subject to various impacts, including horizontal pressure and uplift pressure from the soil. In fact, many excavation landslide incidents stem from inaccurate calculation and estimation of the displacement of diaphragm walls, without fully considering all factors of the soil. Figure 1 illustrates a reinforced concrete diaphragm wall stabilized by brace system [1, 2]. Some notable studies [3- 7] have researched the structure of soil retaining walls and identified three main methods for analyzing the lateral displacement of retaining walls in deep excavations: analytical method, beam-on-elastic-foundation method, and finite element method (FEM). Among these, the FEM is the most complex method with the highest requirements for the accuracy of input parameters and reliable results. Its advantage is that the behavior of soil can be relatively accurately and reasonably simulated during excavation, which is suitable for practical use and is widely applied.

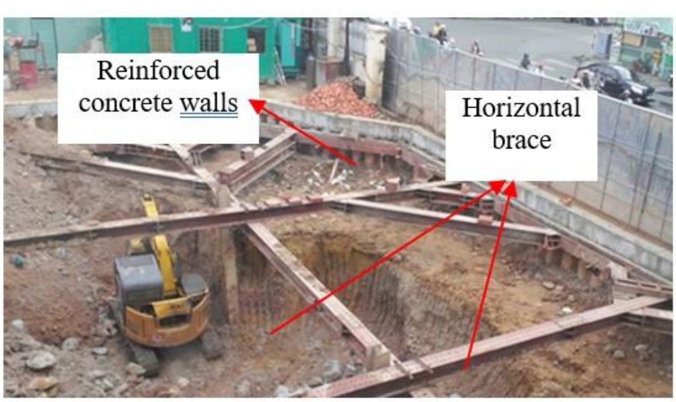

Figure 1. Reinforced concrete diaphragm walls [1, 2].

Plaxis 3D, a popular commercial program in analyzing geotechnical problems, integrates many different types of models, suitable for the calculation scope, accuracy requirements, and many different types of soil [8, 9]. Studying and evaluating the Plaxis calculation models to find the appropriate model for each problem is necessary to help the process of calculating, designing, and constructing deep foundation excavation.

Phan [10] and Jim S., et al [11] analyzed the influence of soil models on the analysis results of the lateral displacement of the diaphragm wall by using Plaxis 2D software on two soil models, Morh Coulomb (MC) and Hardening Soil Model (HS). They noted that one of the most sensitive parameters in the HS Model that affects the lateral displacement of the wall is the soil stiffness parameter, E_{ref}^{50}. Nguyen Ba Ke [12, 13] conducted a study on the appropriate method for calculating soil pressure for the diaphragm wall of a deep excavation. The results showed that the internal forces and displacements of the diaphragm wall calculated with both Morh Coulomb (MC) and Hardening Soil Model (HS) were not significantly different.

Thang [14] proposed formulas to estimate the stiffness or deformation modulus of the soil, it can be seen that empirical formulas for estimating the stiffness of the soil depend on the type of soil. For clayey soil, the stiffness is derived from the value of the undrained shear strength Su, while for sandy soil, the value of the standard penetration test number NSPT is used. Chau Ngoc An and Le Van Pha [15] used the correlation between the SPT-N index and the parameter E in the MC Model to analyze the interaction between the soil and the diaphragm wall structure and obtained results that were quite consistent with the monitoring data.

In this study, the author used Plaxis 3D to simulate the calculation of diaphragm walls for the Pullman SaiGon Center hotel project at 148 Tran Hung Dao Street, Ben Nghe Ward, District 1, Ho Chi Minh City, using two soil models of Hardening Soil (HS) Model and Mohr Coulomb (MC) Model. The survey results with different wall

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thicknesses show that the calculation according to the HS Model is close to the observed value, tending towards a safer value compared to the calculation according to the MC Model.

2. Mathematical models in Plaxis

2.1. Hardening Soil Model

The Hardening Soil (HS) Model is a hyperbolic type of nonlinear elastic model. This advanced soil model uses the theory of plasticity instead of elasticity theory and considers the plastic behavior and failure characteristics. The model can simulate both strain hardening due to tangential stress and normal stress. When subjected to primary shear stress, the soil will decrease in stiffness while simultaneously undergoing plastic deformation. The relationship between axial strain and shear stress can be described by a hyperbolic curve. The parameters of model include: E^{ref}_{50}: the secant stiffness determined from the triaxial compression test at a loading level of 50% of the failure strength with a confining pressure of P^{ref}; E^{ref}_{oed}: the tangent stiffness determined from the oedometer test at a pressure level of P^{ref}; E^{ref}_{ur}: the reloading stiffness; m: a power coefficient indicating the dependence of strain modulus on the stress state of the soil element; P^{ref}: the confining pressure (σ_3) when the triaxial compression test is conducted; K_o^{NC}: the stress ratio; and ν_{ur}: the Poisson's ratio, which Plaxis takes as default 0.2 [8, 9].

2.2. Mohr Coulomb Model

The Mohr Coulomb (MC) Mode is an approximate model of soil behavior. This is an elastic-plastic model based on the Hook's law combined with the Mohr-Coulomb failure criterion. In this model, deformation and deformation rate are analyzed into two components: elastic and plastic. The Hook's law is used to express the relationship between stress increase and deformation. The model consists of five basic parameters: elastic modulus E, Poisson's ratio ν, soil cohesion c, internal friction angle φ, and soil dilation angle ψ [8, 9]. The physical parameters of soil are obtained from geotechnical experiments according to current standards.

3. Lateral displacement of diaphragm walls

3.1. The Project Overview

The project analyzed in this study is the Pullman SaiGon Center hotel located at 148 Tran Hung Dao Street, Ben Nghe Ward, District 1, Ho Chi Minh City. The building consists of 3 basement levels with an average excavation depth of 12.6m, and the deepest excavation pit is -15.6m, used as a parking basement and technical area. The basement is designed and constructed using the Bottom-up method. The ground floor level is 0.00m, the basement 1 level is -3.3m, the basement 2 level is -6.9m, the basement 3 level is -9.3m, and the foundation bottom level is -12.5m (for the elevator pit bottom area is -15.6m). The structure used 4 main bracing levels to support the excavation pit during the soil excavation and basement construction process, and the 5th bracing level only supports locally in the elevator core pit area. The diaphragm wall system used a 1.2m thick diaphragm wall with a depth of 30m and a soil layer of 5th layer. The soil characteristics with an average thickness shown in Table 1 below.

Table 1. Soil layer characteristics at the construction site.

Nº	Description	Condition	Depth (m)	Thickness (m)	N_{SPT}
-	Fill soil	-	1.1	1.1	0
1	Clay, gray-brown	Liquid	3.0	1.9	0
2	Clay sand, reddish-brown	Firm	7.0	4.0	11
3	Sandy, yellow	Firm	15.0	8.0	17
4	Clay sand, sandy, yellow	Firm	29.0	14.0	18
5	Sandy, yellow-brown	Firm	43.0	14.0	21

The displacement will be determined at all points of the retaining wall where the Inclinometer tube is placed, and the data is collected through specialized software. The software used for processing horizontal displacement data, called Inclinometer_SiteMaster, is one of the products that the Vietnam Geological and Environmental Monitoring Equipment Joint Stock Company has purchased and distributed in Vietnam (illustrated in Figures 2 and 3).

Figure 2. Inclinometer Equipment [16].

Figure 3. Monitoring the Wall Deformation [16].

3.2. 3D Plaxis Modeling

The construction sequence of the project includes the following stages: Stage 1: Construction of diaphragm walls, Barrette piles, wall beams; Stage 2: Construction of Kingpost columns; Stage 3: Excavation to a depth of -1.1m; Stage 4: Installation of level 1 reinforcement system (-1.1m); Stage 5: Excavation to a depth of -3.3m; Stage 6: Installation of level 2 reinforcement system (-3.3m); Stage 7: Excavation to a depth of -6.9m; Stage 8: Installation of level 3 reinforcement system (-6.9m); Stage 9: Excavation to a depth of -9.3m; Stage 10: Installation of level 4 reinforcement system (-9.3m); Stage 11: Excavation to a depth of -12.5m; Stage 12: Installation of level 5 reinforcement system in the elevator shaft area (-12.5m); Stage 13: Excavation to a depth of -15.6m, and finally the localized excavation for the foundation pit construction. The diaphragm wall and bracing systems are modeled in Plaxis 3D, as shown in Figure 4.

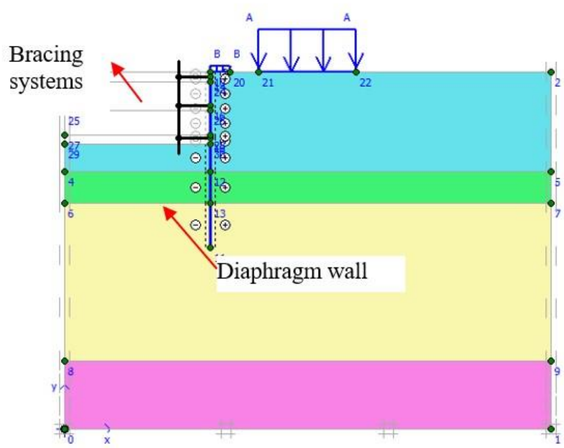


Figure 4. The 3D Model (Walls with Bracing system).

The parameters of the retaining wall and strut system for each level are listed in Table 2 and Table 3 respectively.

Table 2. Wall specifications.

Component	Material characteristic	Icon	Value	Unit
Wall 1200mm	Material properties	Material Type	Elastic	
	Elastic modulus	E	$3.25x10^7$	kN/m^2
	Compressive	EA	$3.90x10^7$	kN/m
	Flexural	EI	$46.8x10^5$	kNm^2/m
	Poisson's ratio	ν	0.15	

Table 3. Specification of Bracing beams.

Component	Material characteristic	Icon	Value	Unit
H 350x350	Material properties	Material Type	Liner Elastic	-
	Elastic modulus	EA	$3.795x10^7$	kN/m^2
	Compressive	L_s	7	m
H 350x350	Material properties	Material Type	Liner Elastic	-
	Elastic modulus	EA	$4.505x10^7$	kN/m^2
	Compressive	L_s	7	m

Table 4 shows the input parameters for Hardening Soil and Mohr Coulomb Models, in which the parameters are determined from the physical characteristics of soil layers from 1st to 5th layer (the section containing diaphragm wall).

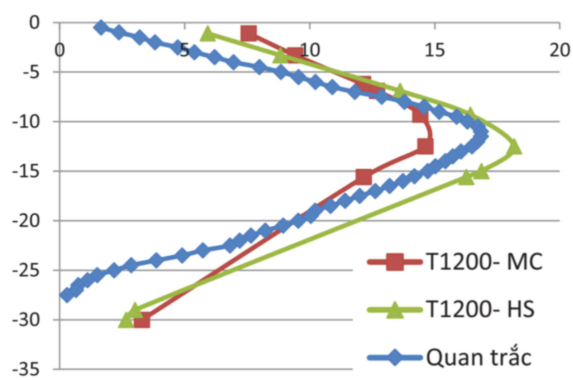
Table 4. Soil parameters of Hardening Soil (HS) and Mohr-Coulomb (MC) models.

Model	Soil Layer	Fill soil	1st layer	2nd layer	3rd layer	4th layer	5th layer	Unit
Hardening Soil (HS) Model	Behavior	Drained	Undrained	Drained	Drained	Drained	Drained	-
	γ_{unsat}	22	15.5	20.2	20.9	20.6	20.3	kN/m^3
	γ_{sat}	22	15.8	20.6	21.3	21	21.1	kN/m^3
	k_x, k_y	0.5	$1.05x10^{-5}$	$3.45x10^{-5}$	1	$5.79x10^{-5}$	$4.94x10^{-5}$	m/day
	E_{oed}^{ref}	E_{50}^{ref}	E_{50}^{ref}	E_{50}^{ref}	E_{50}^{ref}	E_{50}^{ref}	E_{50}^{ref}	kPa
	E_{50}^{ref}	1500	$a \times S_u$	$1000 \times N$	$1000 \times N$	$1000 \times N$	$1000 \times N$	kPa
	E_{ur}^{ref}	$3xE_{50}^{ref}$	$3xE_{50}^{ref}$	$3xE_{50}^{ref}$	$3xE_{50}^{ref}$	$3xE_{50}^{ref}$	$3xE_{50}^{ref}$	kPa
	c'	1	1.12	1	1.11	4.0	11.2	kPa
	φ'	22	22	30	31	34.9	31.4	(°)
Mohr – Coulomb (MC) Model	N_{SPT}	0	0	11	17	18	21	-
	k	1000	1500	3500	3500	3500	3500	-
	E^{ref}	k x N	k x N	k x N	$k \times N$	$k \times N$	$k \times N$	kPa
	E^{eod}	1000 x N	1000 x N	1000 x N	1000 x N	1000 x N	1000 x N	kPa

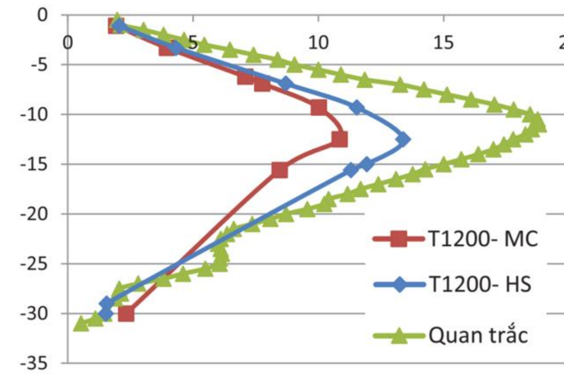
4. Results and analysis

4.1. Results

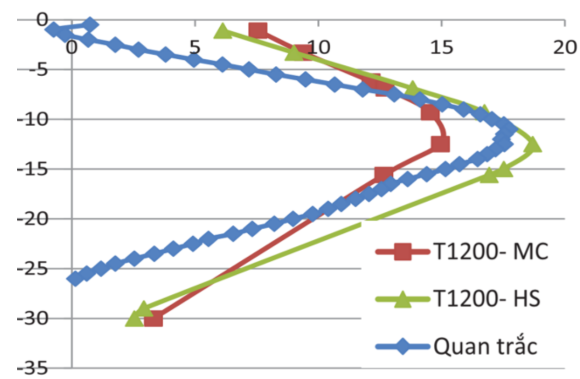
Figure 5 illustrates a comparison of the lateral displacement of T1200 (thickness of 1200mm) wall calculated by HS and MC Model with the collected data. Measuring points labeled of A01, A02, A03 respectively correspond to the midpoints of 3 long edges of the retaining wall, and the measurement devices are vertically arranged along the depth of the wall. The calculated displacement results according to the two models at measuring points are different, which can be explained by the different lengths of the wall at each face resulting in different stiffness of corresponding wall faces.



a) Point A01



b) Point A02



c) Point A03

Figure 5. Displacement according to HS Model and MC Models and measured data.

Table 5. Results of displacement of T1200 wall according to HS and MC models.

Depth (m)	Measurement Point A01				Measurement Point A02				Measurement Point A03			
	HS Model	MC Model	Actual data (mm)	Devia-tion (%)	HS Model	MC Model	Actual data (mm)	Devia-tion (%)	HS Model	MC Model	Actual data (mm)	Devia-tion (%)
-3.3	8.82	9.42	6.2	34.1	4.33	3.96	6.48	-49.7	9.01	9.39	3.81	57.7
-6.9	13.61	12.13	11.8	13.3	8.70	7.09	13.26	-52.4	13.83	12.13	11.8	14.7
-12.5	18.17	14.42	9.2	9.66	13.39	10.02	17.78	-32.76	18.69	14.54	17.55	6.12

Table 6. Results of displacement of wall with different thicknesses using the HS models.

Depth (m)	Measurement Point A01				Measurement Point A02				Measurement Point A03			
	HS Model	MC Model	Actual data (mm)	Devia-tion (%)	HS Model	MC Model	Actual data (mm)	Devia-tion (%)	HS Model	MC Model	Actual data (mm)	Devia-tion (%)
-12.5	18.99	19.91	21.02	9.66	13.80	13.87	13.98	12.87	19.49	20.45	21.6	9.77

However, the obtained curves all show similar variations and are consistent with the actual collected data (see Figure 5). The maximum displacement values are approximately 18.17 mm, 13.39 mm, and 18.69 mm, respectively, at a depth of approximately 12.5m, as shown in Table 5, summarizes the calculated displacement results of the T1200 wall according to different models and the measured data at various depths on the wall.

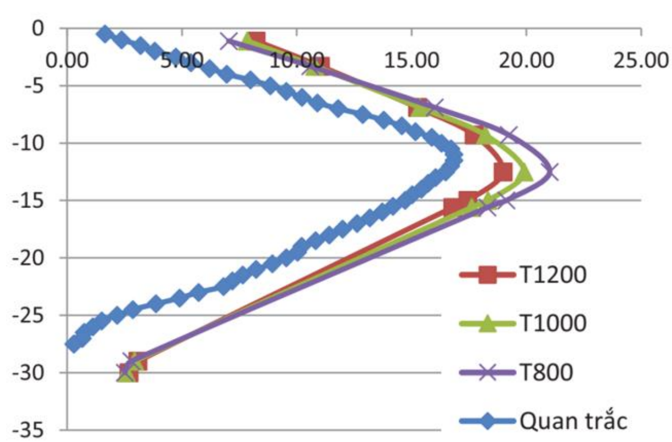
Table 5 shows that the deviation between the displacement results from the two models compared to the collected monitoring data varies depending on the model and the depth of the comparison position on the retaining wall. This deviation is often quite large at the two ends of the retaining wall but tends to decrease at the maximum displacement position. At monitoring positions A01 and A03, the measured values are both higher than the calculated results using the MC Model (from 6.12 % at A03 to 9.66 % at A01) and lower than the calculated values using the HS Model (-32.76 % at A02).

On the other hand, at monitoring position A02, the displacement values from both theoretical models are smaller than the measured data. This indicates that when calculating with the HS Model, the displacement is larger than when calculating with the MC Model, tending towards safety conditions. This analysis result is consistent with the previous research findings on [10- 13].

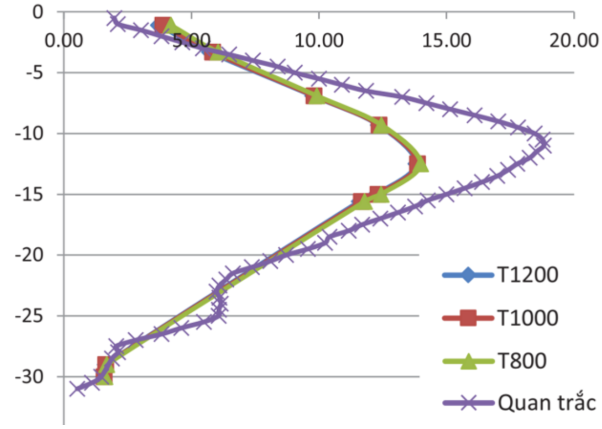
4.2. The influence of the thickness of the retaining wall on horizontal displacement

To evaluate the influence of the thickness of the retaining wall on the lateral displacement, a simulation was carried out to calculate the displacement according to the HS Model for retaining walls with thicknesses of 1200mm, 1000mm, and 800mm (denoted as T1200, T1000, and T800, respectively). The parameters of the model used are as in section 3.2 above. The calculated results were compared with the measured displacement data at the measurement positions A01, A02, and A03.

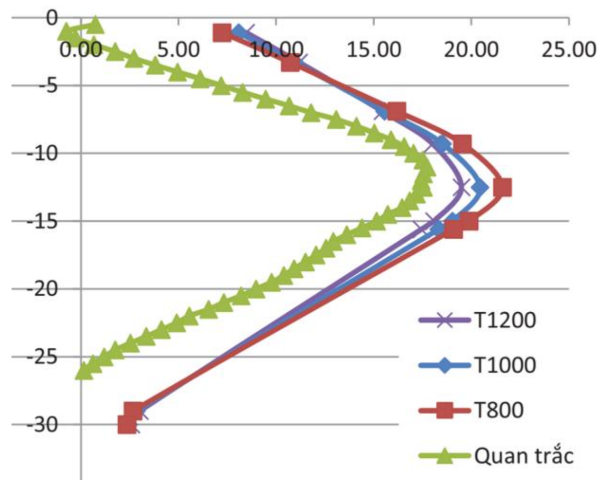
Figure 6 shows the displacement diagram calculated according to the HS Model for the corresponding wall thicknesses, and the displacement values at a depth of 12.5m are summarized in Table 6. The results in Figure 6 show that the deformation of the retaining wall for different wall thicknesses is quite consistent with each other, with the values increasing as the wall thickness decreases and vice versa. However, the degree of variation in deformation of the wall is not the same at different depths. This variation is also different at different measurement points, and at a depth of -12.5m, the displacement of the wall is the largest, reaching 21.6mm, 20.45mm, and 19.5mm corresponding to wall thicknesses of 800mm, 1000mm, and 1200mm at the deformation measurement point A03.



a) Point A01



b) Point A02



c) Point A03

Figure 6. Displacement with HS Model and Measured data.

Similar results were obtained for the corresponding positions of A01 and A02, which were (21.02mm, 19.91mm, and 18.99mm) and (13.98mm, 13.87mm, and 13.8mm), respectively. Thus, as the thickness of the diaphragm wall increases, its stiffness also increases, resulting in a decrease in its displacement. However, the degree of this variation is quite small, ranging from only 9.77% (at measurement point A03) to 12.87% (at measurement point A02). This shows that in the design of diaphragm walls for deep excavations, the wall thickness should be selected according to the displacement calculation model that is appropriate, while considering reducing the wall thickness to meet technical requirements as well as economic requirements.

5. Conclusions

The results of calculating the displacement of the retaining wall using Plaxis 3D simulated with two common soil models, Hardening Soil (HS) and Mohr Coulomb (MC) Model, show fairly compatible results with actual measured data. However, the HS Model provides safer and more consistent results with actual data. In the case of having complete soil mechanics indicators, simulating with the HS

Model will accurately describe the stiffness parameters of the soil and consider the dependence on the stress of the stiffness coefficient.

On the other hand, the research results also indicate that the influence of the thickness of the retaining wall on the horizontal displacement variation is quite small. Therefore, when selecting the thickness of the wall, the requirements for bending stiffness and waterproofing should be the basis for determining the appropriate thickness.

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