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PARAMETRIC AND MECHANISM-BASED EVALUATION OF ANCHORED DIAPHRAGM WALL DISPLACEMENT IN SOFT CLAY

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ABSTRACT: Anchored diaphragm walls are widely used to control ground deformation and maintain stability in deep excavations in soft ground. Motivated by these challenges, this study investigates the lateral displacement of an anchored diaphragm wall system in soft clay in Thu Duc City, Ho Chi Minh City. The system consists of 800-mm-thick barrette diaphragm walls and prestressed ground anchors installed within a 13-m-thick soft clay layer, where the undrained shear strength ranges from 15 to 25 kPa. A two-dimensional finite element model using 15-node triangular elements in PLAXIS 2D is employed to simulate staged excavation and soil–structure interaction. A parametric study is conducted by varying prestressing force (0–100% of design load), anchor spacing (1.5–3.0 m), inclination angle (25°–45°), and the number of anchor levels. To support interpretation, an integrated FEM–XGBoost framework is adopted to quantify parameter importance and provide a mechanism-consistent ranking using a surrogate model. The results indicate that prestressing force is the dominant factor controlling wall displacement, reflecting the mobilization of tensile resistance. Displacement decreases significantly with increasing prestress, but improvement becomes marginal beyond approximately 80% of the design load. Inclination angle also has a strong influence through the horizontal component of anchor force, whereas spacing and number of anchor levels have limited effects within the investigated ranges. These findings provide a rational basis for optimizing anchor design in soft clay. The results are derived from two-dimensional numerical analysis and should be interpreted as indicative trends rather than exact field predictions.

Keywords: Deep Excavation, Soft Clay, Prestressed Ground Anchors, Finite Element Method, XGBoost

1. INTRODUCTION

Rapid urbanization has increased the demand for underground space, leading to more deep excavations in densely built environments. In Ho Chi Minh City, these excavations are typically constructed in thick soft clay with high compressibility and low undrained shear strength, as documented for Mekong Delta soils [1,2]. Under such conditions, excessive lateral wall deformation may threaten adjacent structures and surrounding infrastructure [3,4].

Finite element methods (FEM) are widely used to analyze wall deformation in deep excavations [4–6]. However, system behavior is governed by multiple interacting design parameters, while most studies consider variables independently.

Anchored diaphragm wall systems are commonly used to control ground deformation by transferring loads to deeper, stiffer soil layers [7]. Their performance depends on anchor design, including prestressing force, spacing, inclination angle, and number of anchor levels. Previous studies have shown that appropriate configurations improve excavation performance, with increased anchor stiffness reducing wall displacement and anchor arrangement influencing deformation patterns [8–11].

Despite these advances, the relative importance of design parameters and their combined effects on wall displacement remain insufficiently quantified. Recently, machine learning techniques, particularly XGBoost, have demonstrated strong capability in capturing nonlinear relationships and ranking variable importance [12–15], yet their integration with FEM-based parametric studies for anchored excavation systems remains limited.

This study investigates the lateral displacement behavior of an anchored diaphragm wall in soft clay in Thu Duc City using a two-dimensional FEM framework combined with a full-factorial parametric analysis. A total of 360 simulations are performed by varying prestressing force, inclination angle, anchor spacing, and number of anchor levels. An XGBoost-based surrogate model is employed to quantify parameter importance and approximate FEM responses. The proposed approach provides a systematic and computationally efficient framework for evaluating design variables and improving interpretation of parameter interactions in anchored excavation systems.

The remainder of this paper is organized as follows. Section 2 describes the site conditions, and Section 3 presents the anchor system and design parameters. Section 4 outlines the numerical modelling approach, while Section 5 discusses the parametric results. Section 6 provides the XGBoost-based interpretation, and Sections 7 and 8 present the study limitations and conclusions, respectively.

2. PROJECT DESCRIPTION AND GEOLOGICAL CONDITIONS

2.1 Project Description

The project is located on Luong Dinh Cua Street, Thu Duc City, Ho Chi Minh City. It comprises a high-rise building with three basement levels and one mezzanine, covering approximately 14,000 m² of underground area.

The excavation is supported by 800-mm-thick barrette diaphragm walls (DW800) embedded to a depth of 22.7 m, with a maximum excavation depth of -15.0 m at the elevator pit. Up to five levels of prestressed ground anchors are installed at the deepest section.

In the numerical model, construction is simulated using staged excavation and anchor installation procedures consistent with the site layout (Fig. 1) and excavation cross-section (Fig. 3). Excavation proceeds in successive lifts from -3.0 m to -15.0 m, with each stage followed by installation and prestressing of the corresponding anchor level, as summarized in Table 1.

Table 1. Simplified construction sequence adopted in the FEM simulation

Stage	Excavation Level (m)	Support Installation
1	-	Construction of DW800
2	-3.0	First anchor layer
3	-4.3	BS anchor layer
4	-6.1	Second anchor layer
5	-9.1	Third anchor layer
6	-11.9	Fourth anchor layer
7	-15.0	Final excavation to elevator pit

2.2 Geological Description

The site layout and borehole locations (BH-01 to BH-07) are shown in Fig. 1. The investigation included seven boreholes drilled to depths of 90–100 m to characterize subsurface conditions across the site. Vane shear tests were conducted at selected depths to evaluate the undrained shear strength of the soft clay layers, and standard laboratory tests were performed to determine key soil properties. The soil profile, together with the main laboratory and in-situ test results within the upper 36 m, which governs excavation behavior, is presented in Fig. 2.

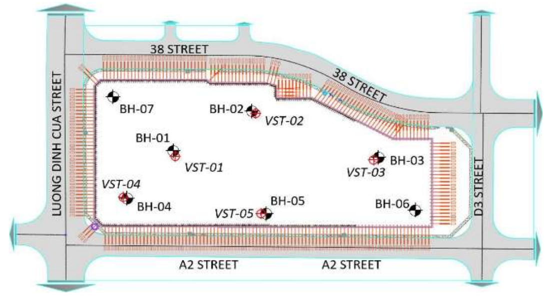


Fig. 1 Site layout showing borehole locations and anchor layout.

The borehole layout was defined within the geotechnical investigation plan in accordance with TCVN 9363:2012. The locations were selected based on the project footprint, excavation extent, and subsurface variability to ensure adequate coverage. The boreholes are distributed across the site to capture lateral and vertical variations of the soft clay layer and identify underlying stiffer strata governing anchor performance.

The excavation is primarily located within Layer 2, consisting of organic silty clay with very low SPT N-values (1–2). The undrained shear strength increases with depth from approximately 10–20 kPa near the surface to about 73 kPa at greater depths. This layer is characterized by low unit weight (14.4–15.0 kN/m³) and high natural water content (67–94%), indicating high compressibility and low stiffness.

The bonded lengths of the anchors extend into deeper and stiffer strata, mainly Layers 3A, 4, and 5, characterized by higher SPT N-values (12–13) and greater unit weights (17.0–19.3 kN/m³). These layers provide favorable conditions for load transfer and enhance system performance by mobilizing higher shaft resistance.

The soil profile exhibits significant variation in strength and stiffness with depth, particularly within the soft clay layer, which strongly influences excavation-induced deformation. Representative soil parameters for numerical modelling were derived from laboratory tests, in-situ measurements, and empirical correlations.

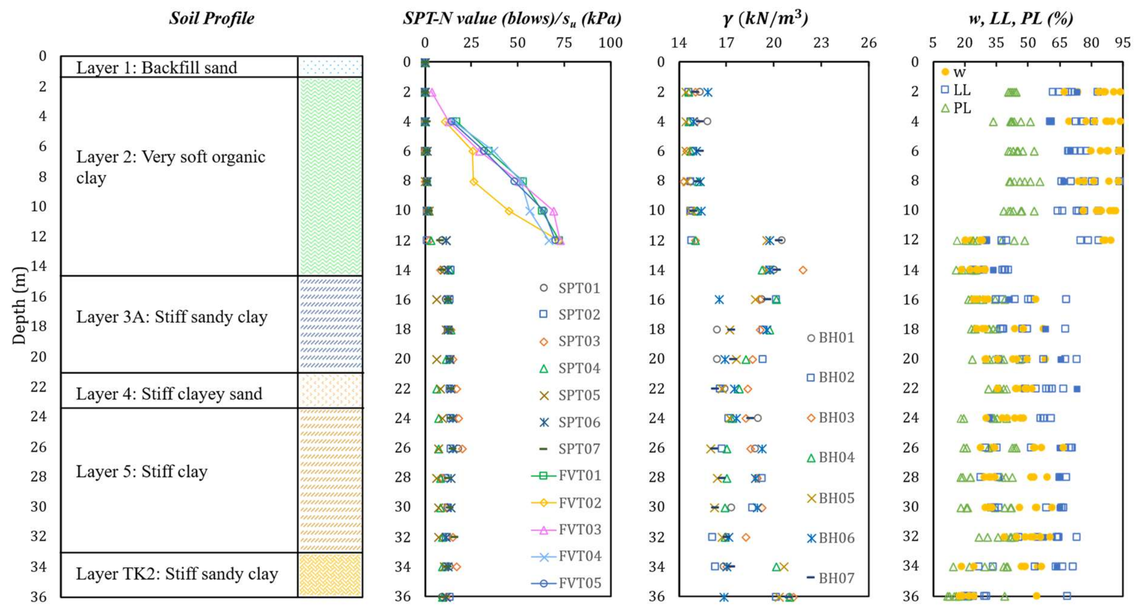


Fig. 2 Results of field and laboratory geotechnical tests

The adopted averaged values for each layer are summarized in Table 3, while details of parameter selection are presented in Section 4.

2.3 Research Significance

This study investigates the lateral displacement behavior of anchored diaphragm walls in soft clay using a combined FEM–XGBoost framework. A full-factorial parametric analysis is performed to evaluate the effects of prestressing force, anchor inclination, anchor spacing, and number of anchor levels on wall deformation. Unlike previous studies that mainly considered individual variables, the present study quantifies their relative importance and combined effects within a unified framework. The study also integrates staged-construction FEM simulations with a machine-learning-based surrogate model for a real excavation project in Ho Chi Minh City, providing an efficient approach for interpretation and preliminary design assessment of anchored excavation systems.

3. ANCHOR SYSTEM AND PARAMETER DEFINITION

The anchors considered in this study are prestressed grouted ground anchors using multi-strand steel tendons. Each anchor consists of high-strength prestressing strands (nominal diameter 12.7 mm) installed in a drilled hole and bonded to the surrounding soil through cement grout. The bonded length is embedded in competent strata, while the free length allows load transfer.

This anchor type is widely used in deep excavations in soft ground due to its high load-carrying capacity and compatibility with staged construction. In addition, the prestressing force can be adjusted during excavation to improve deformation control and system stability.

According to FHWA (2015) [7], the recommended inclination angle for ground anchors ranges from 13° to 45°, with values between 15° and 35° commonly adopted in practice [8]. In this study, angles from 25° to 45° were selected based on site-specific conditions. At smaller inclination angles (<25°), the bonded length may remain within the soft clay layer or require excessive extension to reach competent strata, which is impractical for the excavation geometry. Inclination angles ≥25° ensure that the bonded length penetrates Layers 3A, 4, and 5, which provide higher stiffness and shear strength for reliable anchorage (Fig. 3).

Anchor spacing is determined based on load transfer and group interaction considerations. To avoid overlapping stress zones between adjacent anchor bulbs, the spacing should generally exceed 1.5 m [7,9]. However, excessively large spacing reduces support stiffness and increases lateral wall deformation. In practice, spacing is commonly limited to about 4.0 m [7]. Based on these considerations, spacing values between 1.5 and 3.0 m were selected to balance group effects and system stiffness, thereby maintaining stable and efficient excavation performance while ensuring adequate load transfer to the surrounding ground.

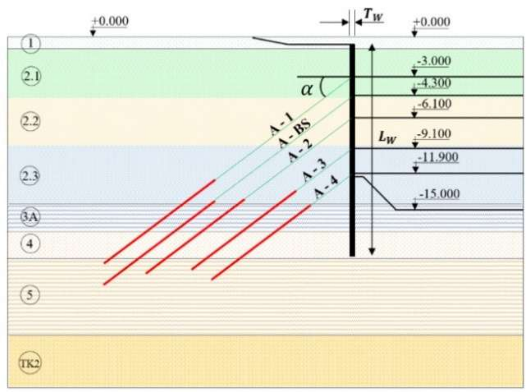


Fig. 3 Excavation cross-section for the anchor inclination case of α = 35°

The prestressing force was varied from 0% to 100% of the design load to represent the full range of anchor behaviour. The number of anchor levels was defined based on the layout in Fig. 3. The five-level system includes all anchors (A-1, A-BS, A-2, A-3, and A-4), while the four- and three-level systems are obtained by progressively omitting deeper anchors. This reflects practical scenarios in which anchor levels may be reduced under lower excavation demand or site constraints [7-9].

The anchors are modelled as linear elastic structural elements without explicit consideration of tip resistance, and the prestressing force is defined as a normalized proportion of the design load. This simplified representation is adopted to ensure numerical stability and to focus on the relative influence of design parameters on wall displacement. Within the investigated loading range, the anchors are assumed to operate under serviceability conditions, where linear elastic behaviour provides a reasonable approximation.

The selected values of inclination angle, anchor spacing, prestressing force, and number of anchor levels were combined to generate a full-factorial parametric matrix, as summarized in Table 2, where denotes the design load of the ground anchor. This resulted in 360 finite element simulations. The dataset was used to evaluate the relative influence of design parameters on wall displacement and to train the surrogate model.

Table 2. Values of the four input parameters

Parameter	Values
α (deg)	25°, 30°, 35°, 40°, 45°
L_s (m)	1.5, 2.0, 2.5, 3.0
F_p (%T_s)	0, 20, 40, 60, 80, 100
n	3, 4, 5

4. NUMERICAL MODELLING AND PARAMETRIC SETUP

The Hardening Soil parameters used in the numerical model are summarized in Table 3. To account for stratigraphic variability, Layer 2 is subdivided into three sublayers (2.1–2.3), reflecting the variation in soil properties with depth.

The effective strength parameters c′ and ϕ′ for the clay and silty clay layers (Layers 2, 3A, 4, 5, and TK2) were derived from consolidated undrained (CU) triaxial tests, while the reference secant stiffness was interpreted from the corresponding stress-strain responses. For layers without direct laboratory measurements, empirical correlations were adopted. The selected parameters represent the average strength and stiffness characteristics of each soil layer.

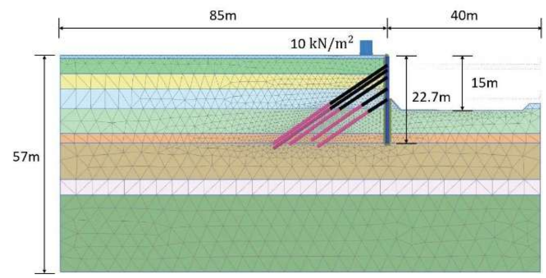


Fig. 4 Finite element model layout and mesh used in the parametric analyses.

The remaining stiffness parameters are assigned following standard Hardening Soil model assumptions in PLAXIS, with $\boldsymbol{E_{ur}^{ref}} = \boldsymbol{3E_{50}^{ref}}$ and $\boldsymbol{E_{oed}^{ref}} = \boldsymbol{E_{50}^{ref}}$. Interface elements are defined along the wall and anchor boundaries to represent soil-structure interaction, ensuring consistent stiffness representation.

The numerical model configuration, including geometry, boundary conditions, and mesh discretization, is illustrated in Fig. 4. A refined triangular mesh is adopted near the diaphragm wall and anchor system, where stress and displacement gradients are significant. The mesh density is selected through preliminary trials to ensure stable displacement results while maintaining computational efficiency. Further refinement produces negligible changes in predicted wall displacement, indicating that the adopted mesh is sufficiently fine for the present analysis, consistent with common finite element practice [16].

The analysis is based on a two-dimensional plane strain assumption representing a typical excavation cross-section. The plan layout is elongated, and the analysed section is located along the central portion of the longer side, where boundary effects are limited. Under these conditions, the behaviour can be reasonably approximated as plane strain.

The retaining system consists of an 800-mm-thick barrette diaphragm wall embedded to a depth of 22.7 m. The wall is modelled as a linear elastic structural element with an elastic modulus E = 25,673 MPa and a Poisson's ratio of 0.2. The axial and flexural stiffnesses are defined as EA = 20,538,381 kN/m and EI = 1,095,381 kN·m²/m, respectively, while the unit weight is taken as 6.8 kN/m³. The wall is supported by up to five levels of prestressed ground anchors, modelled as linear elastic node-to-node elements with embedded bond zones. Prestress is applied as an initial axial force normalized by the bonded-length capacity, while tip resistance is neglected. Maximum lateral wall displacement is adopted as the response variable.

A parametric analysis is performed by varying the prestressing force F_p, inclination angle α, anchor spacing L_s, and number of anchor levels n within the ranges defined in Table 2, resulting in 360 simulations under a full-factorial framework.

The numerical model is established using the Hardening Soil (HS) formulation with parameters derived from site investigation data, as shown in Fig. 4. The HS model captures nonlinear stress-strain behaviour and stress-dependent stiffness, which are important for representing soil response under staged excavation and anchor loading. Previous studies show that the HS model is widely applied in deep excavation analysis and can be calibrated through back-analysis using laboratory and field measurements [17]. Although more advanced models (e.g., HSsmall) may improve accuracy at very small strain levels, they require additional parameters not available in the present study.

Table 3. Soil parameters for the Hardening Soil model

Parameters	Layers	1	2.1	2.2	2.3	3A	4	5	TK2
Drainage type	Type	Drained	UndrA	UndrA	UndrA	UndrA	UndrA	UndrA	UndrA
Thickness	(m)	1.5	4.0	4.0	5.0	6.5	2.5	9.5	4.0
Unsaturated unit weight	γ_{unsat} (kN/m^3)	18.5	15	15	15	19.3	18.8	17	20.6
Saturated unit weight	γ_{sat} (kN/m^3)	19	15.1	15.1	15.1	19.5	18.9	17.1	20.7
Secant stiffness	E_{50}^{ref} (kPa)	10000	9500	9500	10000	23000	26000	24000	19300
Oedometer stiffness	E_{oed}^{ref} (kPa)	10000	9500	9500	10000	23000	26000	24000	19300
Unloading/reloading stiffness	E_{ur}^{ref} (kPa)	30000	28500	28500	30000	69000	78000	72000	57900
Power exponent parameter	m	0.5	0.9	0.9	0.9	0.7	0.7	0.7	0.75
Effective cohesion	c' (kPa)	1	25.5	13.8	21.5	37.0	15.3	30.2	21.6
Effective internal friction angle	φ' (°)	25	26.4	26.7	27.7	25.8	26.6	23.8	28.0
Interface coefficient	R_{inter}	0.80	0.75	0.75	0.75	0.75	0.70	0.75	0.75

The lateral loading acting on the diaphragm wall arises from in-situ soil stresses, excavation-induced stress redistribution, and surface surcharge, as illustrated in Fig. 4. A uniform surcharge load of 10 kN/m² is applied at the ground surface to represent adjacent construction activities and other temporary loads near the excavation during construction stages. Pore water pressures are incorporated within an effective stress framework. This study focuses on lateral wall behaviour, which governs excavation performance in soft clay. Vertical displacement is therefore not explicitly considered, as vertical movements are relatively small and have limited influence on wall deformation under the investigated conditions.

5. PARAMETRIC ANALYSIS OF WALL DISPLACEMENT

Figure 5 presents the influence of prestressing force, anchor spacing, inclination angle, and number of anchor levels on diaphragm wall displacement. Prestressing force has the greatest effect, with wall displacement decreasing as prestress increases. The reduction rate becomes marginal beyond approximately 70–80% of the design load (Fig. 5a), indicating diminishing efficiency at higher prestress levels. Within the investigated range, prestress levels of 80–90% provide effective deformation control with limited additional benefit.

Anchor spacing has a moderate influence on wall displacement (Fig. 5b), with larger spacing increasing displacement due to reduced support stiffness and lower restraint provided to the retaining wall system. Inclination angle shows higher sensitivity (Fig. 5c), as steeper anchors provide a smaller horizontal restraint component. Increasing the number of anchor levels reduces displacement (Fig. 5d), although its effect remains limited because additional levels mainly redistribute system stiffness.

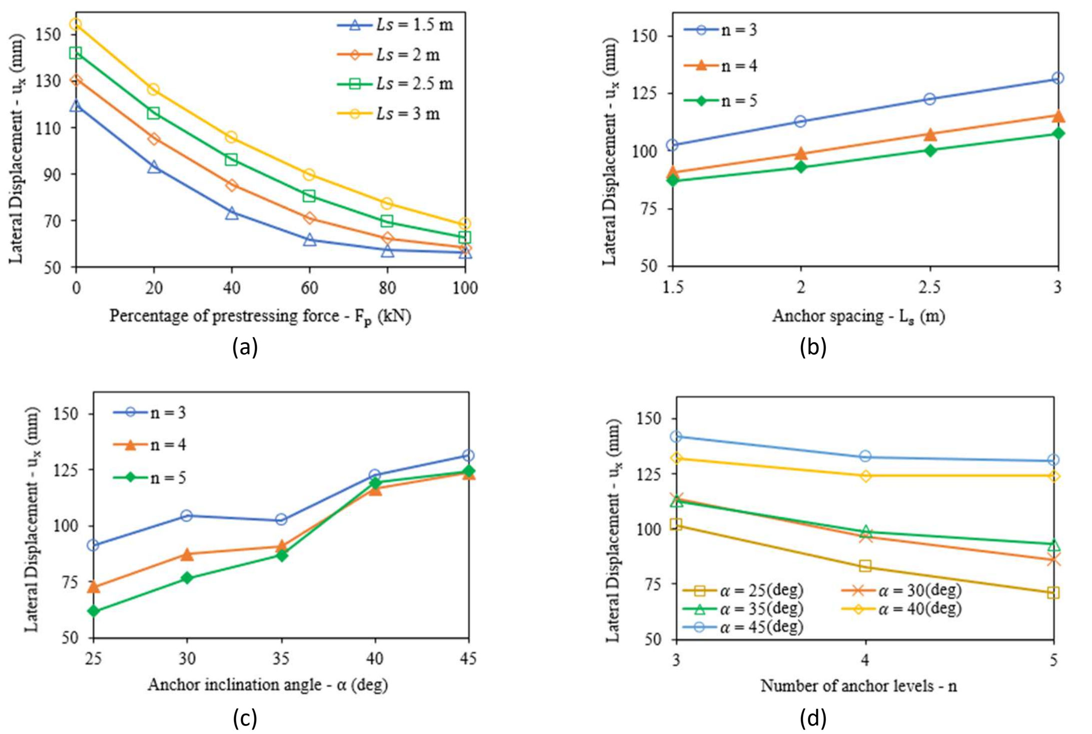


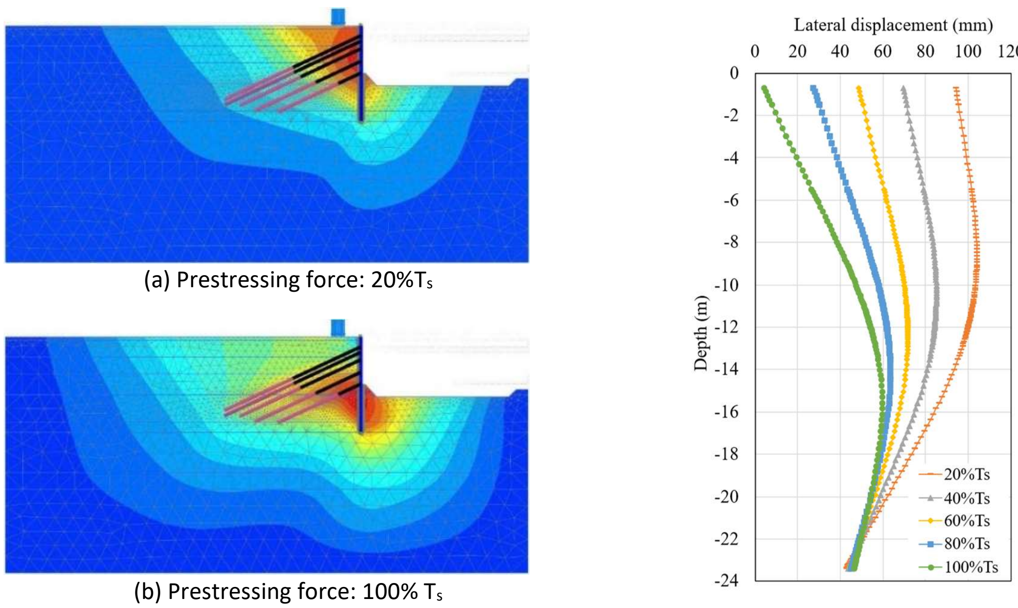
Fig. 5 Influence of anchor design parameters on diaphragm wall lateral displacement: (a) prestressing force percentage, (b) anchor spacing, (c) inclination angle, and (d) number of anchor levels.

The deformation mechanisms are illustrated in Figs. 6 and 7. Owing to the low stiffness of the soft clay, excavation-induced stress release produces significant lateral strain. Deformation is concentrated in the upper soft layers, while deeper strata provide restraint to the anchored wall system.

Higher prestress confines the large displacement zone and shifts it upward, producing a more localized deformation pattern near the ground surface due to increased system stiffness. Increasing anchor spacing slightly enlarges the deformation zone but does not significantly alter the displacement pattern. Anchors transfer loads to deeper, stiffer layers, thereby limiting wall movement. Overall, prestressing force and inclination angle are the primary controlling parameters, while anchor spacing and number of anchor levels have secondary influence.

6. SURROGATE-BASED SENSITIVITY ANALYSIS

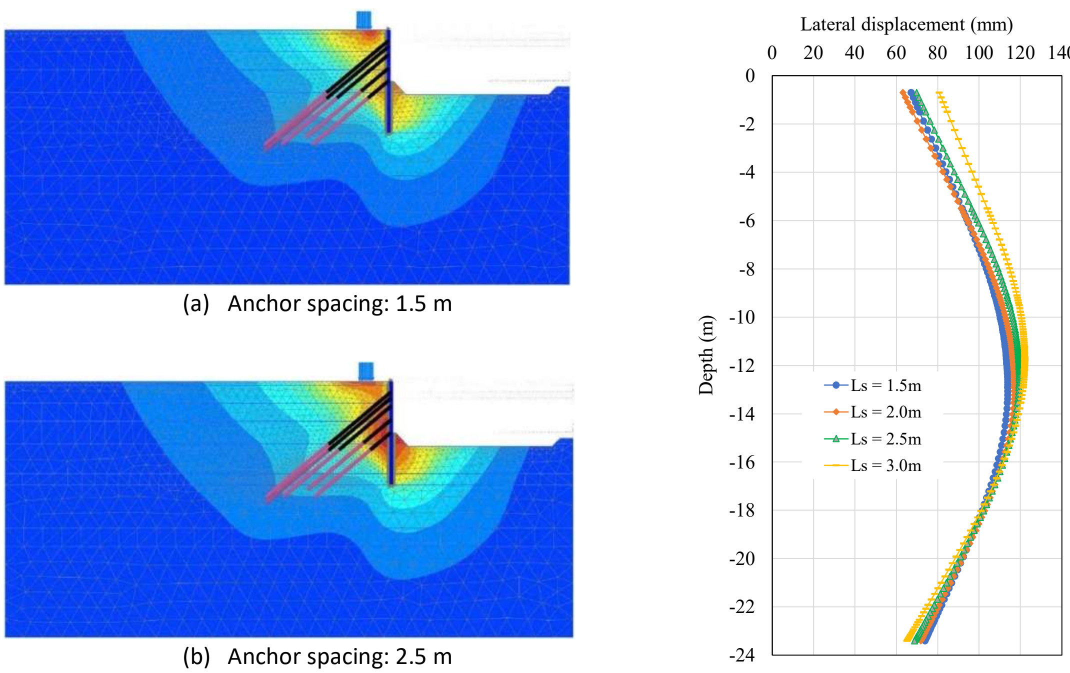
An XGBoost surrogate model was developed using the 360 PLAXIS 2D simulations to quantify the relative importance of prestressing force F_p, anchor spacing L_s, inclination angle α, and number of anchor levels n. The FEM-derived lateral wall displacement was used as the response variable. The main hyperparameters and optimal values obtained through grid search are summarized in Table 4.



(a) Prestressing force: 20%T_s

(b) Prestressing force: 100% T_s

Fig. 6 Effect of Anchor Prestress Level on Ground Displacement Field and Diaphragm Wall Lateral Displacement (α = 25°, n = 5, L_s = 2.0 m)



(a) Anchor spacing: 1.5 m

(b) Anchor spacing: 2.5 m

Fig. 7 Effect of Anchor Spacing on Ground Displacement Field and Diaphragm Wall Lateral Displacement (α = 40°, n = 5, F_p = 100%T_s)

The training and testing errors converge to similar stable values, indicating good generalization without noticeable overfitting. The predicted displacements agree closely with the FEM results (Fig. 8), with a testing R^2 of 0.992. The feature-importance results (Fig. 9) reproduce the same parameter hierarchy observed in the FEM analysis, with prestressing force identified as the dominant factor, followed by inclination angle, while anchor spacing and number of anchor levels exhibit comparatively smaller contributions. This consistency indicates that the surrogate model captures the key response patterns observed in the numerical simulations.

Table 4. Main XGBoost Model Hyperparameters

Hyperparameter	Range	Optimal value
Learning_rate	[0, 1]	0.3
Max_depth	[0, ∞)	6
*n*_estimators	[0, ∞)	100
Reg_lambda	[0, ∞)	1

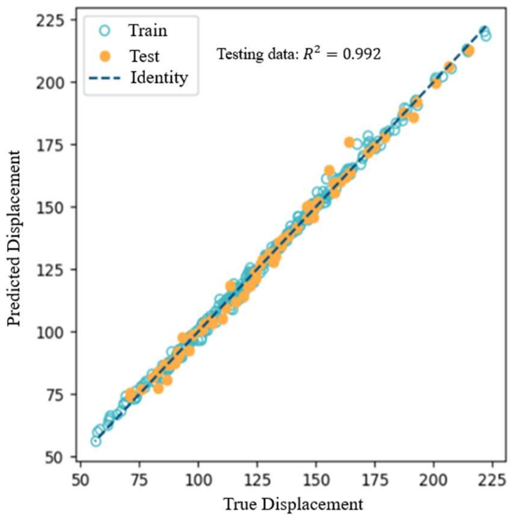


Fig. 8 Comparison of predicted and actual lateral displacements for the training and testing datasets of the XGBoost model

The trained surrogate model enables rapid evaluation of wall displacement for different parameter combinations and supports preliminary design and sensitivity assessment. It is used to interpret parameter influence and complements, rather than replaces, the physics-based FEM analysis.

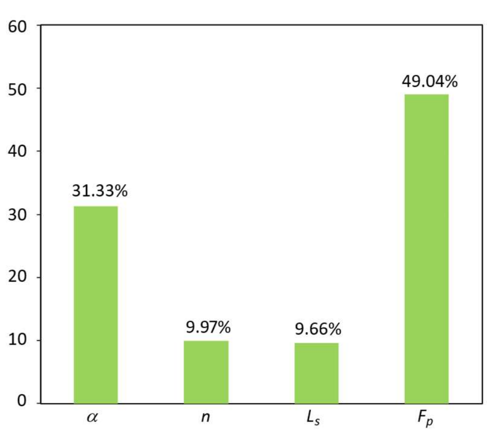


Fig. 9 Relative feature importance of the four input parameters in the XGBoost model

7. STUDY LIMITATIONS

The analysis is based on two-dimensional plane strain modelling of a typical excavation cross-section; therefore, three-dimensional effects such as staggered anchor layout and spatial load redistribution are not captured. Soil parameters are derived from site investigation data and empirical correlations, which may introduce uncertainty. Anchors are represented by a simplified linear elastic model without considering nonlinear load-displacement behaviour or bond degradation.

The study is entirely numerical and lacks validation against field monitoring data. The results should therefore be interpreted as relative trends rather than exact field predictions. Explicit uncertainty analysis and quantitative evaluation of parameter interaction effects were not performed and remain topics for future work.

8. CONCLUSION

This study evaluates the influence of anchor design parameters on the lateral displacement of anchored barrette diaphragm walls in thick soft clay using a combined FEM-surrogate framework. Prestressing force is the dominant parameter, followed by inclination angle, while anchor spacing and number of anchor levels have comparatively smaller effects within the investigated ranges.

Wall displacement decreases markedly with increasing prestress, with diminishing improvement beyond approximately 80% of the design load. Prestress levels of approximately 80% or higher provide effective deformation control with limited additional benefit at higher levels. Inclination angle affects the horizontal component of anchor force, whereas spacing and anchor levels mainly redistribute system stiffness. The surrogate model reproduces the FEM-derived parameter hierarchy and provides an efficient tool for sensitivity assessment.

From a practical perspective, optimizing prestressing force and inclination angle is more effective than increasing anchor quantity for controlling wall displacement. However, the results are based on a two-dimensional numerical model without field validation and should therefore be interpreted as relative trends rather than exact predictions.

9. ACKNOWLEDGMENTS

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