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THE EFFECT OF DEEP EXCAVATION ON THE ADJACENT BUILDINGS

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ABSTRACT

Excavation activities are essential to access foundation levels in construction projects. However, when such operations occur near existing buildings, they can pose significant risks to adjacent structures. Uncontrolled excavation may lead to ground movements that compromise the structural integrity of nearby facilities. This study investigates the impact of deep excavation on surrounding buildings through a series of parametric analyses, aiming to provide insight into safe design strategies. A total of 20 numerical case studies were developed using PLAXIS 2D finite element software under the Mohr-Coulomb model. All cases involved a two-layer soil profile - an upper cohesionless layer overlying a cohesive stratum - with the groundwater table artificially lowered to the excavation base level to simulate dewatering. The cases were grouped to examine the influence of: (1) increasing excavation depth; (2) varying cohesive strength of the lower soil layer. Each scenario was evaluated under single and double strut configurations. Key results show that increasing the excavation depth significantly amplifies wall bending moments, lateral deflections, ground settlements, and strut reactions. For instance, in single-strut systems, a 57% increase in excavation depth led to a 136% rise in bending moment and a 53% increase in wall deflection. In double-strut systems, deeper struts experienced up to 483% increase in axial force, highlighting their sensitivity. Conversely, enhancing cohesive strength of the deep soil by 80% effectively reduced bending moments, displacements, and strut loads - though its influence diminishes at greater depths. The findings emphasize that excavation depth is the dominant factor influencing deformation and structural demand, while deep soil cohesion improvement is a practical mitigation strategy. Surface soil compaction, however, offers limited benefit. The research provides valuable guidance for optimizing excavation

design to minimize adverse effects on adjacent buildings, especially by highlighting the critical performance of lower struts in multi-level support systems.

1. INTRODUCTION

Deep excavation is a fundamental operation in most construction projects, as it is often required to reach the design foundation level. However, when excavation is carried out, a major concern is the risk associated with uncontrolled excavation, where inadequate support, inappropriate construction sequences, or insufficient monitoring may lead to excessive wall movements, loss of stability of the excavation face, and severe effects on neighboring structures, resulting in significant economic losses and safety hazards.

Long (2001) [1] compiled a large database of deep excavation case histories to improve prediction of retaining wall and ground movements and to reassess existing empirical design charts. The study classified nearly 300 cases by soil conditions, wall/support type and basal stability, and analysed trends in normalized maximum wall deflection and surface settlement. The results showed that excavations in stiff soils with adequate basal stability generally experience smaller movements than predicted by common charts, whereas walls retaining thick soft clays or with low base-heave safety factors exhibit much larger displacements controlled mainly by soil conditions at dredge level. Long concluded that current design for excavations in stiff soils is often conservative, while careful attention to basal stability is critical for controlling movements in soft ground.

Moormann (2004) [2] analyzed a new worldwide database of deep excavations in soft soils to quantify retaining-wall and ground movements and refine empirical prediction methods. Case histories were normalized and grouped by soil profile, support type and basal stability, then evaluated statistically in terms of maximum wall deflection and surface settlement. The study showed that excavations in soft clays experience much larger movements than those in stiffer soils, with deformations strongly controlled by soft-layer thickness, strength and system stiffness, and concluded that commonly used charts derived from stiffer ground are not directly applicable to soft soils, for which revised empirical correlations were proposed.

Leung et al. (2007) [3] analyzed field monitoring data from 14 multipurposed deep excavations in Hong Kong supported by cast in situ diaphragm walls in mixed ground, with no numerical software involved. The cases were grouped by mid-depth SPT N and assessed in terms of normalized maximum wall deflection and ground settlement. They found mean maximum wall deflections of about 0.23%H in softer profiles and 0.13%H in stiffer profiles, with settlements generally below 0.15%H and extending to roughly 2.5H behind the wall, and concluded that in these relatively stiff mixed ground conditions movements are modest and mainly governed by soil conditions and basal stability rather than system stiffness.

Wang et al. (2010) [4] compiled and analyzed field monitoring data from about 300 deep excavations in Shanghai soft soils to quantify retaining-wall displacements and ground settlements for various support systems and to compare local performance with worldwide experience. Using normalized deformation measures for different wall types (top-down diaphragm walls, bottom-up diaphragm/contiguous/compound DSM walls, sheet piles, DSM and compound soil-nail walls), they reported mean maximum wall deflections of 0.27-0.40%H for relatively stiff systems and much larger values up to about 1.5-2.4%H for flexible or non-strutted systems, with maximum ground settlements averaging 0.42%H and extending 1.5-3.5H behind the wall. The study showed only a weak trend of decreasing normalized wall movement with increasing system stiffness and factor of safety against basal heave, and a settlement-deflection ratio typically between 0.4 and 2.0 (average ≈0.9), leading to the conclusion that existing empirical envelopes can be used as conservative upper bounds for Shanghai conditions and that performance is strongly influenced by wall type and basal stability.

Xiao et al. (2019) [5] investigated how excavation width affects wall deflection, ground settlement and basal heave for 92 braced deep excavations in soft soils in the Yangtze River Delta, using field monitoring data supplemented by PLAXIS 2D analyses. They showed that normalized maximum wall deflections and settlements increase with excavation depth and width but tend to stabilize beyond a critical width of about 50 m, and are generally smaller than earlier published values due to stricter deformation control and improved construction. The study found that retaining wall type and increased embedded depth have limited influence once overall stability is ensured, and proposed a width-based classification of foundation pits (narrow, normal and wide) to support deformation control in design.

Zhang et al. (2018) [6] analyzed four deep braced excavations for Mass Rapid Transit (MRT) stations in Bukit Timah Granite residual soils, using detailed monitoring of wall deflections, ground settlements, groundwater pressures and strut forces under significant groundwater drawdown. They found that maximum lateral wall deflections were very small, typically between about 0.03% and 0.15% of the excavation depth, whereas maximum ground settlements were larger, between about 0.09% and 0.9% of the excavation depth, so that settlements were often several times greater than the corresponding wall movements. The study showed that stiff retaining walls can effectively limit lateral movement, but that groundwater drawdown in permeable residual soils strongly controls surface settlements, and it proposed modified design recommendations for apparent earth pressures and settlement envelopes in such conditions.

Zhang et al. (2021) [7] built on the same Downtown Line database to develop semi-empirical design charts for wall deflections and ground settlements of braced excavations in Bukit Timah Granite residual soils subjected to groundwater drawdown. After summarizing field performance at four MRT stations, they calibrated a two-dimensional PLAXIS 2D model with a hardening-soil constitutive law and performed a parametric study varying residual-soil thickness, groundwater drawdown, system stiffness, excavation depth and width, and rockhead level. The results showed that groundwater drawdown and the thickness/strength of the residual soil have a strong influence on maximum ground settlements, whereas wall deflections are less sensitive once a reasonably stiff bracing system is adopted, and they led to base design charts with modification factors that predict deformations in good agreement with monitoring data and provide a practical, conservative tool for similar excavations in residual granitic soils.

Shi et al. (2019) [8] analyzed a deep foundation pit project in Shanghai soft soils using real-time monitoring of retaining-wall displacements, support axial forces, column uplift, ground settlement and deformation of adjacent pipelines, in order to study the so-called time-space effect of excavation. They found that wall displacement, support forces and column uplift increase rapidly during excavation and then stabilize once the base slab is constructed; the maximum lateral wall displacement is about 0.15% of the excavation depth, occurring at a depth of roughly 0.8 times the excavation depth, pipeline settlement is greatest within about 1.35 times the excavation depth from the wall, and ground settlement peaks at a distance of about 1.15 times the excavation depth before decreasing. Based on the observed relationship between soil and pipeline settlements, they modified an existing soil-settlement prediction formula by introducing a stiffness correction factor so that it can be used to estimate settlement of different types of buried pipelines near deep foundation pits in soft soil areas.

Bai et al. (2021) [9] investigated an extra-large deep excavation in soft clay in downtown Shanghai constructed using the frame top-down method, combining comprehensive field monitoring with a three-dimensional finite element model with a hardening-soil law. They showed that maximum wall deflections and ground settlements were relatively small - less than about 0.3% and 0.25% of the excavation depth, respectively - thus meeting local protection criteria and confirming the good deformation control of the method in dense urban conditions. They concluded that 3D finite element analysis can reasonably reproduce wall deflections and overall trends of ground and structural deformation, but that simplifications in modelling (such as ignoring dewatering and concrete shrinkage) can cause discrepancies, so numerical predictions should be interpreted together with monitoring and engineering judgement.

Mei et al. (2022) [10] investigated a specially shaped deep excavation in Hangzhou soft clay using extensive field monitoring and ABAQUS modelling with a Mohr-Coulomb soil model. They found a clear spatial effect, with maximum lateral wall deflections on the long side about 2.6 times those on the short side and of the order of 0.14-0.17% of the excavation depth, while maximum ground surface settlements were larger, about 0.29-0.50% of the excavation depth, giving settlement-to-deflection ratios between roughly 1.3 and 3.7. The authors concluded that the numerical model reproduced the overall deformation pattern reasonably well and proposed a surface-settlement envelope that can be used as a reference for deformation control in similar soft-clay excavations.

Son et al. (2005) [11] investigated damage to nearby masonry bearing-wall buildings caused by excavation-induced ground movements and proposed a strain-based damage assessment method. They combined field case histories, large-scale physical model tests and distinct-element numerical analyses (UDEC) in which individual bricks and mortar joints were modelled to capture cracking and stiffness loss. They showed that cracking makes buildings deform more like the free-field ground, and concluded that a maximum tensile strain criterion, incorporating soil-structure interaction, can reasonably predict observed damage levels for excavations near masonry structures.

Cording et al. (2010) [12] reviewed excavation case histories, physical model tests and numerical analyses to develop a practical, strain-based framework for assessing building damage due to excavation-induced ground movements. They showed that damage levels depend not only on the magnitude of ground movement, but also on wall stiffness, basal stability, building stiffness, geometry and condition, and that stiff foundations and floor diaphragms can significantly reduce building strains compared with free-field values. The paper proposed a step-by-step procedure for estimating ground movements, converting them into building distortions and classifying likely damage to support risk assessment and design of mitigation measures.

Piciullo et al. (2021) [13] proposed the GIBV (Ground-work Impact and Building Vulnerability) method as a rapid screening tool to assess potential building damage from excavation-induced displacements. They combined empirical models for short- and long-term settlements with a vulnerability index based on building geometry, structural system, foundation type and condition, and implemented the approach in a GIS environment. Application to two Norwegian deep excavation case studies showed good agreement with observed damage and a generally conservative tendency, indicating that GIBV is useful for identifying buildings most at risk, provided it is calibrated to local conditions.

Zhang et al. (2021) [14] developed a numerical procedure to evaluate building damage risk from deep excavations using ground-surface deformation profiles obtained from FLAC3D analyses with a hardening-soil model. They applied strain-based damage criteria (after Burland) to buildings adjacent to a simulated cut-and-cover metro excavation and found all to be in the negligible damage range. They concluded that the method offers a practical way to link numerically predicted ground movements to building damage risk at the design stage, provided the soil model and parameters are well calibrated.

Zheng et al. (2023) [15] studied excavations supported by inclined-vertical framed retaining walls and proposed a simplified method to predict ground movements and building damage. Using PLAXIS 3D with a hardening-soil small-strain model, they ran a large parametric study and derived regression equations for maximum settlements and lateral displacements, which they validated against three case histories with prediction errors mostly within about ±20%. By combining these predictions with a damage potential index, they concluded that the method provides a practical tool for preliminary risk assessment of building damage for this type of retaining system.

Hsu et al. (2024) [16] examined how nearby buildings affect wall deformation and ground settlement in a top-down deep excavation in soft ground, using field monitoring and PLAXIS 3D analyses. After calibrating several soil models, they showed that adjacent buildings significantly increase wall displacement and settlement when located within about twice the excavation depth, with the strongest influence when neighboring basements are about half as deep as the excavation. They concluded that nearby underground structures must be modelled explicitly with an appropriate small-strain soil model to realistically assess excavation impacts.

Bovolenta et al. (2021) [17] reported a forensic case of a three-level parking excavation only about 2 m from an existing masonry building, where flexible temporary retaining structures and inadequate management of the construction stages led to significant slope deformation, cracking and building evacuation. Using geological investigation, monitoring data and back-analyses with limit-equilibrium and PLAXIS 2D models, they showed that excavation-induced deformations markedly reduced foundation safety margins even without full collapse. They concluded that the damage resulted from a combination of design and management errors and highlighted the need for realistic nonlinear soil-structure interaction analysis and careful interpretation of monitoring during temporary as well as final stages.

Hulagabali et al. (2022) [18] used PLAXIS 2D with Mohr-Coulomb and Hardening Soil models to study how deep excavations supported by contiguous pile walls and anchors affect nearby structures. Through a parametric study varying pile stiffness, anchor spacing and pre-stress, excavation depth and adjacent building loading, they found that flexible piles, wider anchor spacing and lower pre-stress lead to larger lateral wall deflections, and that the Mohr-Coulomb model predicts about 40% greater deflections and bending moments than the Hardening Soil model. They concluded that realistic stiffness modelling and careful selection of wall geometry and anchor layout are essential for controlling deformations and limiting the impact of deep excavations on neighboring buildings.

Wang et al. (2023) [19] used a three-dimensional finite-difference model of a deep foundation pit to study how excavation affects a nearby piled building, varying building height, distance from the pit and orientation. They found that internal forces and horizontal displacements in the piles increase with building height and are most critical for buildings within about one excavation depth of the pit (with maximum horizontal pile displacement at about 1.3 times the excavation depth) but become negligible beyond roughly three times that distance, and that the worst uneven deformation occurs when the building is oriented at about 45° to the pit, so these positional effects must be explicitly considered in design.

Mohamed et al. (2019) [20] used PLAXIS 2D with a Hardening Soil model to analyze a 14.1 m deep braced diaphragm-wall excavation in Sudan, modelling adjacent buildings as surface loads. They obtained a maximum lateral wall deflection of about 0.27% of the excavation depth, a maximum ground settlement of about 6.5 cm extending roughly two excavation depths behind the wall, and an estimated building angular distortion of about 1/500, below common damage limits. They concluded that increasing wall stiffness gives only limited additional reduction in movements, whereas reducing strut stiffness significantly increases wall deflection, so realistic stiffness modelling and appropriate strut layout are essential for controlling deformations.

Based on the literature, most existing studies concentrate on empirical deformation envelopes and simplified building-damage assessment methods for braced deep excavations in soft soils, whereas only limited research has developed systematically calibrated finite-element models to examine, in a consistent manner, how key factors such as excavation, groundwater level, and adjacent-building loads would affect the deformations and structural response of nearby buildings.

2. CASE STUDY

2.1 Problem description

The behavior of an anchored PZ27 sheet pile wall (ASPW) reported by Debnath et al. (2023) [21] is adopted in this case study. In their work, the wall response was analyzed using three-dimensional finite-element modelling in ABAQUS, with the sand foundation soil idealized by a Mohr-Coulomb constitutive model. The wall geometry and soil stratigraphy were taken from Bilgin (2010) [22], who examined the same configuration in plane strain using PLAXIS 2D; the soil parameters adopted in the present study are summarized in Table 1, and the examined section is shown in Figure 1. Debnath et al. (2023) [21] validated their 3D results by comparing the bending-moment distribution and wall-deflection profiles with Bilgin's 2D numerical predictions and with measurements from their small-scale laboratory model for the medium-dense sand case without surface loading (their Figures 4(a)-4(c)). Good agreement was reported. In the present study, these published moment and deflection profiles are used as benchmark curves to validate the finite-element model.

Table 1. Soil parameters of case study 1

Soil	Unit weight (KN/m^3)	Friction angle	Cohesion (KPa)	Elasticity modulus (MPa)
Medium dense Sand	18	36	--	30.00

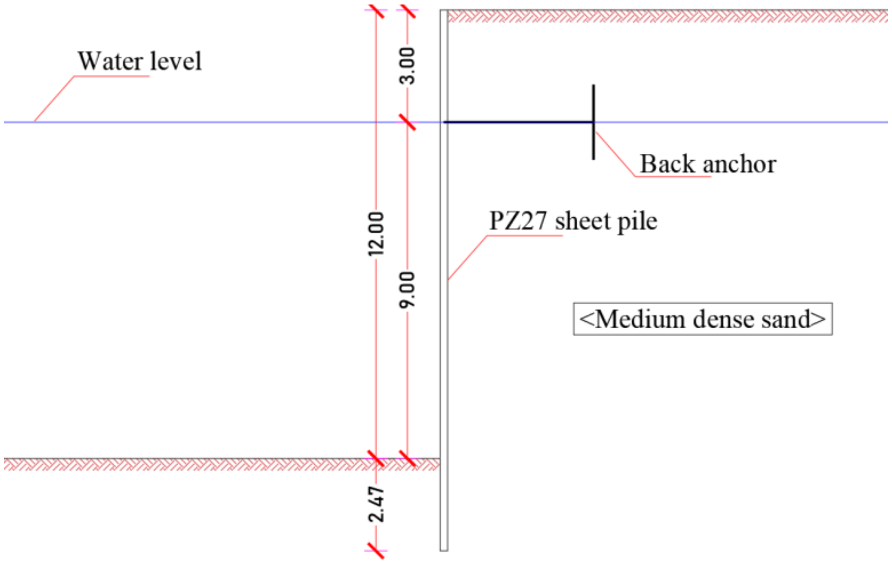


Figure 1: Case study 1, examined cross-section

2.2 Numerical model

Using the bending-moment and deflection charts reported by Debnath et al. (2023) [21], the finite-element model was validated. The analysis was carried out with the FE program

PLAXIS, which is widely used for geotechnical simulations. Since the problem can be idealized as a plane-strain condition, the calibrated model was implemented as a two-dimensional continuum in PLAXIS 2D. The model extensions are presented in Figure 2. The extensions were chosen to reduce boundary conditions effect on the results.

The sheet pile wall was modelled as a plate element, and the anchorage was modelled as fixed end anchor, with the groundwater table set at the anchor level following the geometry described within Debnath et al. (2023) [21] work.

The sheet-pile and anchor elements were assigned linear-elastic steel properties with a Young's modulus of 200 GPa, and the axial stiffness of the tie rod/anchor was taken as 47.5 GN/m. All soil layers were modelled using the Mohr-Coulomb elastoplastic constitutive model, which was selected for its simplicity, modest parameter requirements, and widespread use in practical geotechnical finite-element analysis.

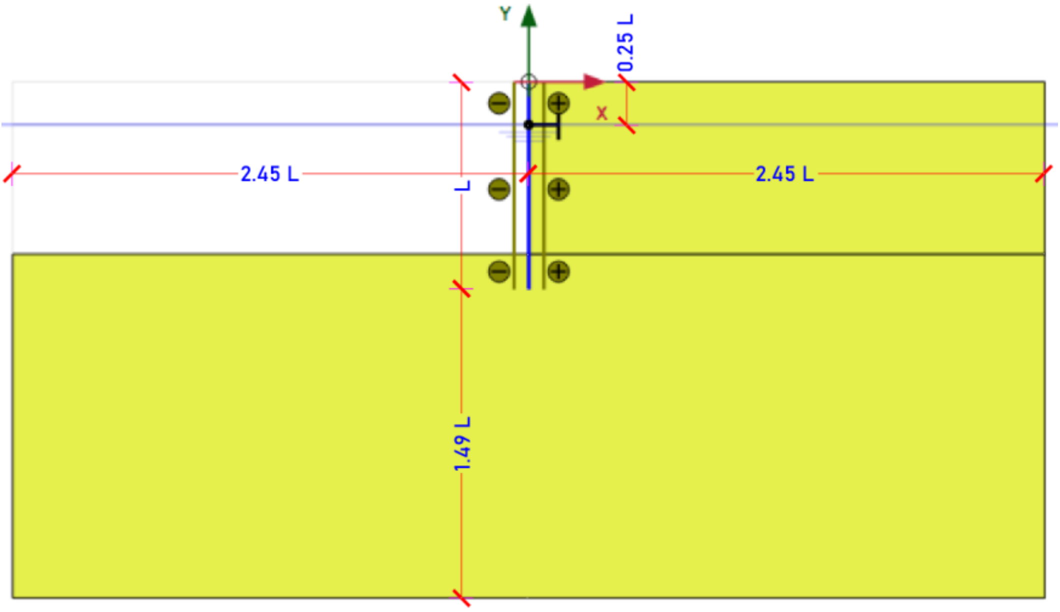
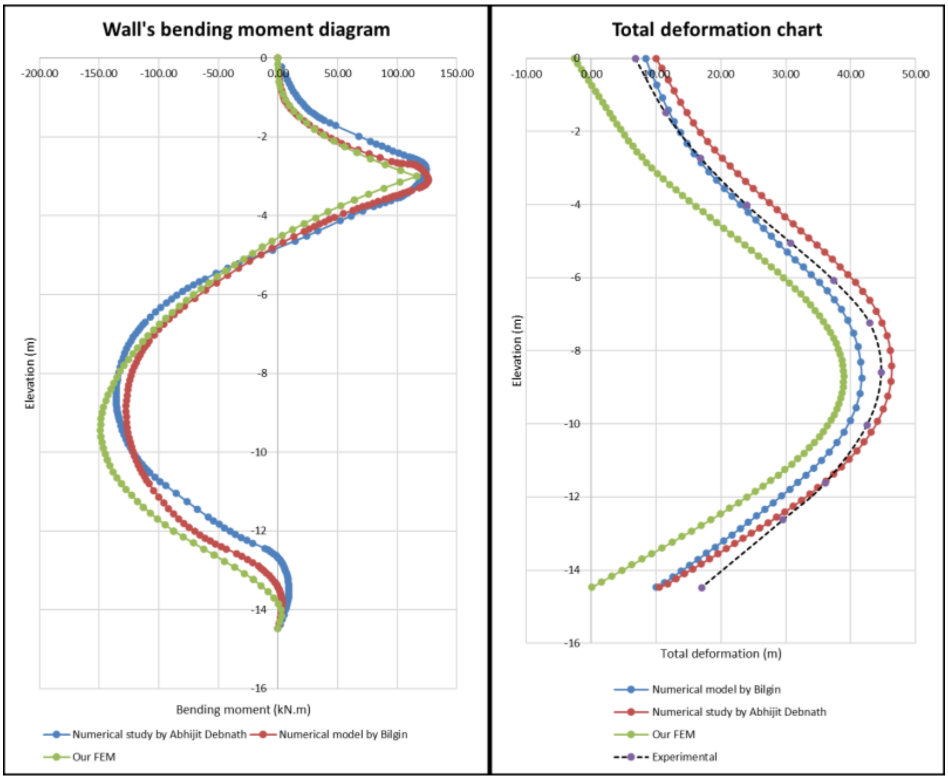


Figure 2: Geometry of the FE model

2.3 Model verification

For model verification, the bending-moment and wall-deflection results reported by Debnath et al. (2023) [21] for the medium-dense sand case without surcharge, as shown in their Figures. 4(a)-4(c), were adopted as reference. These figures compare the response of the front wall obtained from 2D and 3D finite-element analyses and from a small-scale laboratory model.



(a) (b)

Figure 3: Verification results: (a) bending moments, (b) lateral displacements

The corresponding results from the present FE model are plotted in Figure 3, and show good agreement with the numerical and experimental data of Debnath et al. (2023) [21] as well as with the earlier 2D analysis of Bilgin (2010) [22].

3. PARAMETRIC STUDY

The parametric study comprises 20 finite-element cases arranged in two series. In all analyses, the retaining system is a secant pile wall with a constant pile diameter of 0.50 m and center-to-center spacing of 0.70 m, supporting a uniform surface surcharge of 10 kPa to represent existing adjacent structures and personnel loads. The soil profile consists of a 5 m thick upper granular layer (φ_1 = 32°, c = 0) overlying a cohesive stratum idealized with φ_2 = 0° and cohesion c_2. Groundwater is lowered to the excavation level in every case to represent dewatering; consequently, the depth to the groundwater table coincides with the retained height H (defined as the full excavation depth from road level to excavation level). A single row of anchors is provided for excavation depths up to 5.5 m, while a second row is introduced once the excavation depth exceeds 5.5 m.

Cases 1-10 are designed to investigate the influence of increasing excavation depth while keeping soil properties constant. In this series, H (and thus the groundwater level) is varied from 3.5 m to 8.0 m in 0.5 m increments, with c_2 fixed at 40 kPa. Cases 11-20 explore the effect of cohesive strength of the lower layer at two representative excavation depths. For cases 11-15, H = 5.0 m (one anchor level) and c_2 is varied from 25 to 45 kPa, whereas for cases 16-20, H = 7.0 m (two anchor levels) and the same range of c_2 values is adopted. Together, these two series allow the separate assessment of excavation depth and cohesive strength on the behavior of the anchored secant-pile wall and the adjacent ground. The layout of the parametric study is summarized in Table 2, Table 3. The response quantities examined are the wall bending moment, lateral deformation, ground-surface settlement behind the wall, and strut forces.

Table 2. Parametric studies layout, cases 1-10

Parametric study Case	GWT, retained height measured from Top (m)	Friction angle of Layer -1	Cohesive strength of Layer -2 (KPa)	Number of struts
Case 1	3.50	32	40	1
Case 2	4.00	32	40	1
Case 3	4.50	32	40	1
Case 4	5.00	32	40	1
Case 5	5.50	32	40	1
Case 6	6.00	32	40	2
Case 7	6.50	32	40	2
Case 8	7.00	32	40	2
Case 9	7.50	32	40	2
Case 10	8.00	32	40	2

Table 3. Parametric studies layout, cases 11-20

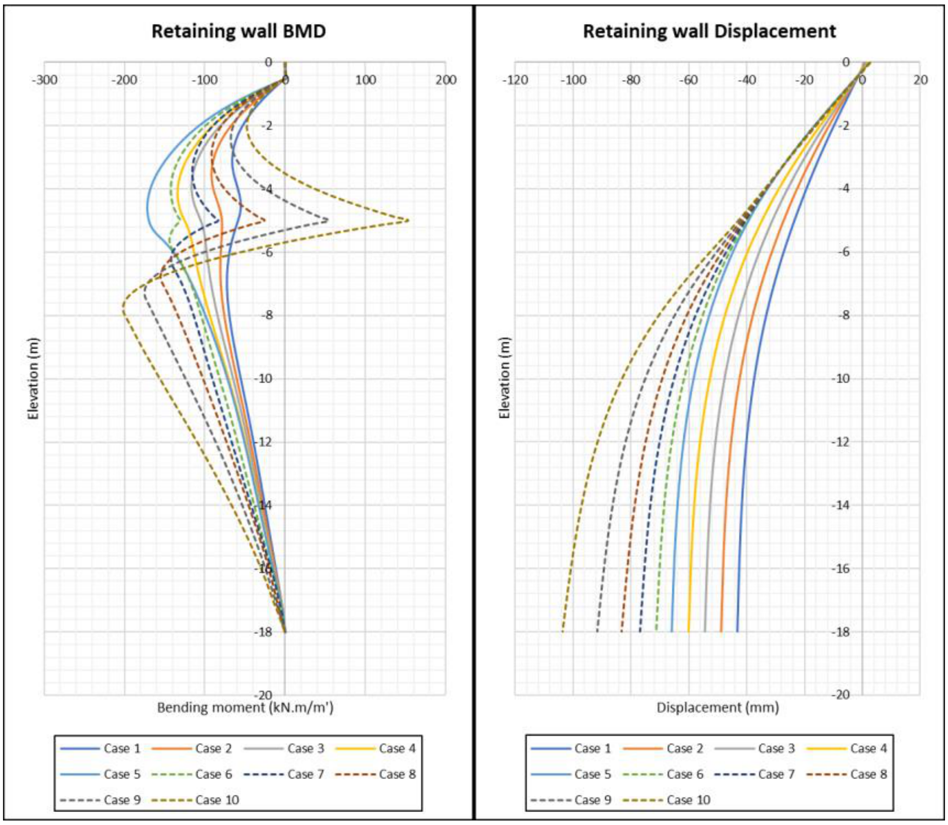
Parametric study Case	GWT, retained height measured from Top (m)	Friction angle of Layer -1	Cohesive strength of Layer -2 (KPa)	Number of struts
Case 11	5.00	32	25	1
Case 12	5.00	32	30	1
Case 13	5.00	32	35	1
Case 14	5.00	32	40	1
Case 15	5.00	32	45	1
Case 16	7.00	32	25	2
Case 17	7.00	32	30	2
Case 18	7.00	32	35	2
Case 19	7.00	32	40	2
Case 20	7.00	32	45	2

3.1 Cases 1-10: Effect of increasing excavated depth

The results indicate that increasing the excavation depth has a pronounced effect on the internal forces and deformations of the retaining system. For the range with a single row of struts, increasing the excavation depth by about 57% led to an increase of 136% in the maximum bending moment of the front wall, while the maximum lateral deformation increased by 57%. The corresponding ground-surface settlement in the backyard increased by 48%, and the axial force in the struts increased by 113%. When a second row of struts was introduced and the excavation depth was further increased by about 33%, the general increasing trend persisted but with a modified response: the maximum bending moment still increased, but at a lower rate (about 40%), and the maximum wall deformation increased by 45%. In this deeper configuration, the axial force in the upper strut decreased by 35%, whereas the axial force in the newly installed lower strut increased sharply, by approximately 483%. The results are illustrated in Figure 4, and Figure 5(a-b).

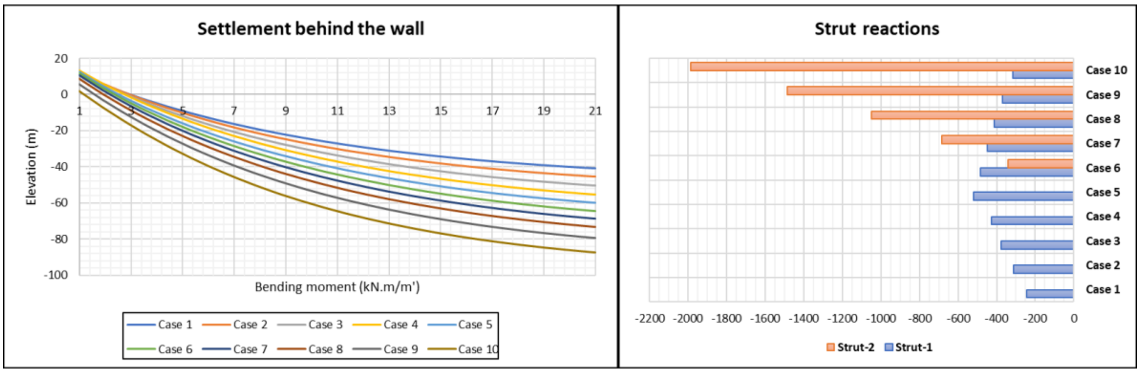
3.2 Cases 11-20: Effect of increasing cohesive strength

The results show that increasing the clay cohesion by about 80% (a change that would be difficult to achieve in practice) has only a modest influence on the response of the wall when a single strut is used. In this configuration, the maximum bending moment in the front wall decreases by 14%, the maximum lateral deformation by 16%, the backyard settlement by 13%, and the strut reaction by 24%. For the deeper excavation where a second strut is installed, the same increase in clay cohesion produces only a small reduction (4%) in the maximum wall bending moment, while the maximum deformation and backyard settlement decrease by 16% and 18%, respectively. In this case, the axial force in the upper strut reduces by 32%, and that in the lower (newly added) strut decreases by 19%. The results are shown in Figure 6, and Figure 7(a-b).



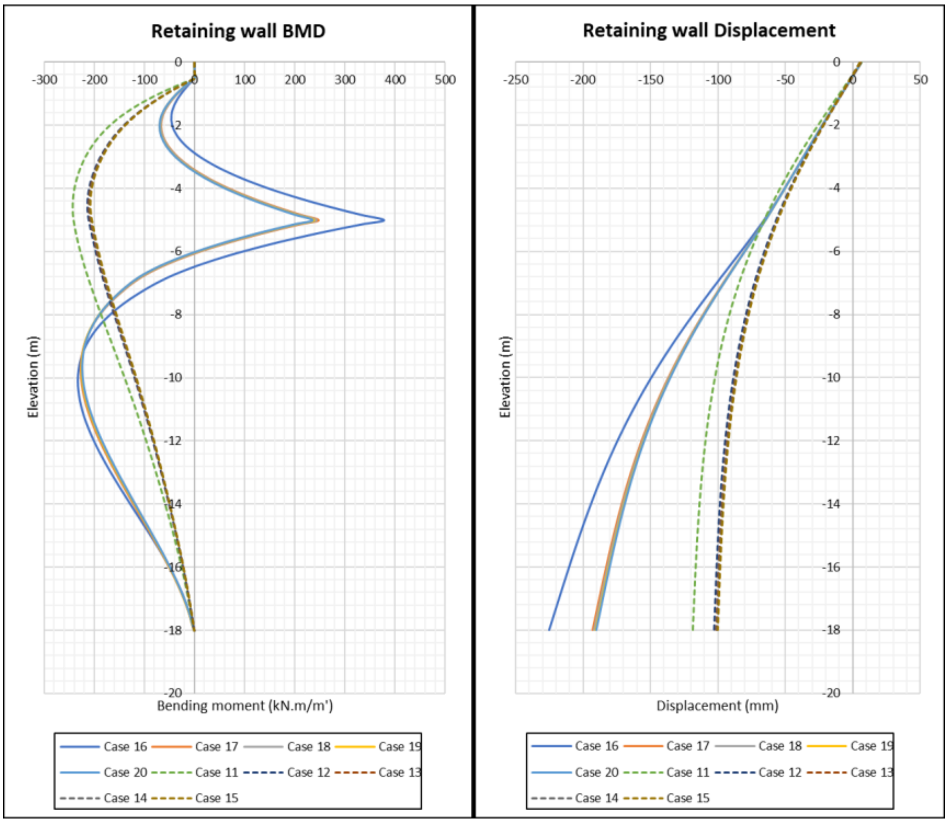
(a) (b)

Figure 4: Front wall impact for cases 1-10: (a) bending moments, (b) lateral displacements



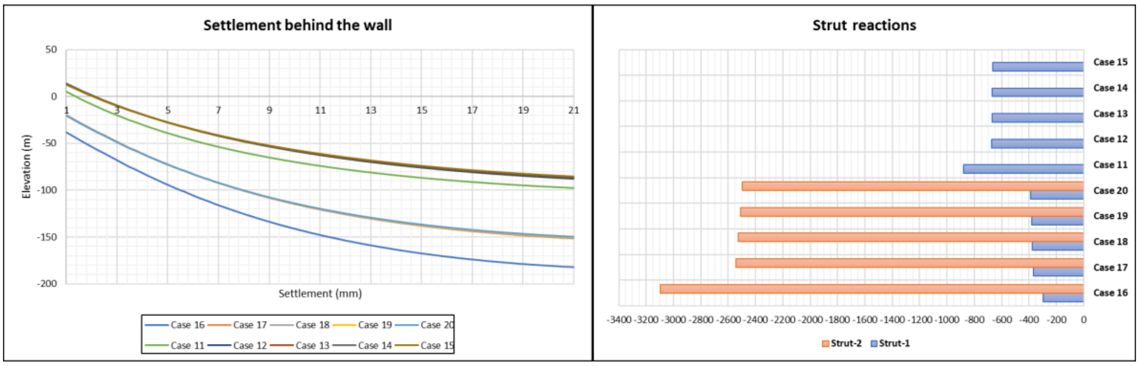
(a) (b)

Figure 5: Backyard and struts impact for cases 1-10: (a) settlement in the backyard, (b) struts reactions



(a) (b)

Figure 6: Front wall impact for cases 11-20: (a) bending moments, (b) lateral displacements



(a) (b)

Figure 7: Backyard and struts impact for cases 11-20: (a) settlement in the backyard, (b) struts reactions

3.3 Discussion of the results

The results for increasing excavation depth highlight the dominant influence of this parameter on the overall behavior of the system. This outcome is expected, as deeper excavations generate substantially higher lateral earth pressures on the retaining wall - the primary source of loading in braced excavations. Consequently, the axial force in the tie rods increases significantly, reflecting the higher mobilized support required to maintain stability. When a second strut is introduced, the magnitude of bending moment in the wall still increases with depth, but at a reduced rate due to the additional restraint. However, this redistribution of load leads to a pronounced increase in the axial force carried by the newly added lower strut, as it directly resists the larger component of the lateral pressures acting at greater depth. Despite the change in support configuration, the trends in wall deflection and ground-surface settlement remain generally consistent, showing similar proportional increases with excavation depth. This behavior reinforces the well-established principle that excavation depth governs both structural demand and ground deformation patterns in braced retaining systems.

In contrast to excavation depth, increasing the cohesive strength of the lower clay layer has only a limited influence on the overall behavior of the retaining system. This is consistent with the fact that, for the studied geometry, lateral earth pressures are primarily governed by the vertical effective stress, while the contribution of cohesion becomes relatively small, especially at greater depths. Increasing cohesion in the single-strut configuration leads to only modest reductions in wall bending, lateral deformation, and backyard settlement, together with a slight relief in the strut force. When a second strut is introduced for the deeper excavation, the effect of cohesion becomes even less pronounced with respect to wall bending, although some reduction in strut forces is still observed. This behavior indicates that improvements in clay cohesion are more effective near the ground surface, where vertical stresses are lower, and progressively less effective with depth as the overburden stress and corresponding lateral pressures dominate the response. The observed changes in wall deformation and ground settlement remain comparatively small for all cohesion levels, confirming that excavation depth and support configuration are the primary drivers of system performance, while cohesion plays a secondary, moderating role.

4. CONCLUSIONS

This study investigated the behavior of strutted secant piles wall to support excavation sides through series of twenty FE analyses, focusing on the influence of excavating on the area around the excavated zones, the walls, and the struts. The following conclusions can be drawn:

(1) Excavation depth is the dominant factor controlling wall behavior. Increasing the retained height produced substantial growth in bending moments, lateral deformation, ground settlement, and strut forces. This is consistent with the fundamental increase in lateral earth pressures with depth, confirming excavation geometry as the primary driver of structural and geotechnical demand.

(2) Additional struts reduce bending moment but significantly redistribute forces. Introducing a second strut at deeper excavation stages moderated wall bending but shifted a large portion of the load to the lower support. This redistribution highlights the importance of proper strut spacing and stiffness selection, as lower supports may experience disproportionately high axial forces.

(3) Variations in clay cohesion have only a secondary influence on system behavior. Even large increases in cohesive strength produced only modest reductions in wall bending, deformation, settlement, and strut forces. This limited sensitivity reflects the governing role of vertical effective stress in determining lateral earth pressures, particularly at depth.

(4) Cohesion improvements are more effective near the ground surface. The influence of cohesion diminished with depth, indicating that any practical ground-improvement strategy would yield the greatest benefit at shallower levels where overburden stresses are lower.

These trends highlight the importance of properly designing the excavation system (wall and struts) while accounting for ground movements and settlements in the surrounding area, in order to limit deformations and reduce the potential impact on nearby buildings.

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