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Review article

Geotechnical Responses of Soils and Nearby Structures to Deep Excavations: Review and Case Study Analysis

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Abstract
Deep excavation projects within city environments often provoke significant shifts in the earth's mass, particularly in stratified layers containing weak soils such as; silty sand and soft clay, which can pose risks to neighboring structures. This article presents a comprehensive review of the application of spatial variability in tunneling and deep excavation and provides useful references in understanding the degradations and damage generated by excavation methods. The paper also presents a two-dimensional finite element analysis of a deep excavation supported by sheet piles, recently constructed in Tripoli, Libya, using the code PLAXIS 2D. The research integrates computer simulations with real-world observations to understand how soil and built structures interact during excavations. Findings of the study reveal that the way the ground deforms depends heavily on soil characteristics, layered formations, the shape of the excavation, and the construction techniques employed. Besides, a 2D soil model effectively simulates the complex behavior between soil and neighboring structures. Furthermore, previous works have proven that the performance of tunnels and deep excavations can be better captured by considering the spatial variability and compared with conventional deterministic analysis methods. Nonetheless, current research still faces many factual scientific problems. Therefore, this paper identifies some research gaps, as well as some recommendations and proposals for future work. Ultimately, the study highlights the importance of developing better predictive tools and practical techniques to carry out deep excavations safely, efficiently, and sustainably within urban settings.
Keywords. Deep Excavation, Soil Behavior, Sheet Pile, Soil-structure Interaction.

Introduction

The rapid pace of urbanization and the rising need for underground spaces, such as those for transportation systems, commercial centers, and the basements of high-rise buildings, have made deep excavations a crucial part of modern civil engineering projects. Nevertheless, these excavations often occur near existing constructions and sensitive infrastructure, which can seriously shift the stress distribution in the ground. This shift in stress can cause ground movements, such as the lateral deflection of retaining walls and the displacement of the surrounding surface [1]. If these movements are not properly predicted and controlled, they can jeopardize the safety and functionality of adjoining structures, resulting in costly damages and delays in projects. Consequently, being able to accurately anticipate and control the deformations caused by excavation has become a crucial concern for geotechnical engineers.

To tackle these challenges, numerical approaches, especially the Finite Element Method (FEM), have appeared essential for analyzing and designing deep digging projects [2]. Conversely, traditional limit equilibrium methods that primarily focus on stability, FEM provides a more holistic approach by analyzing the entire construction process. It catches the complex, non-linear, and time-dependent attitude of soil, enabling detailed simulations of soil-structure interactions. This method considers various support systems, complex soil layers, and groundwater conditions with impressive accuracy [3]. However, the effectiveness of finite element analysis mostly hinges on the option of the constitutive model utilized to represent soil behavior and the precision of the input factors [4]. The natural variability of soil deposits and the limitations of site investigation methods create uncertainties in determining these parameters, presenting a significant challenge in numerical modeling.

Acknowledging the challenges posed by uncertainties in parameters, modern engineering practices increasingly focus on combining numerical analysis with field monitoring programs. On-site instruments like inclinometers, extensometers, and piezometers collect real-time data about how well the excavation support system is performing. This data is essential for validating and fine-tuning numerical models [5]. Through a process known as back-analysis, engineers can adjust initial soil parameter estimates until the model's predictions closely match actual field observations. This calibration process boosts the model's reliability, turning it from a theoretical tool into a practical resource that can confidently simulate future construction stages [6]. A well-calibrated model serves as a solid basis for evaluating design modifications and assessing potential risks. Beyond simply checking predictions for one project, a well-calibrated numerical model becomes a valuable tool for exploring how different factors influence excavation performance. Through parametric sensitivity analyses, engineers can adjust key inputs—such as soil strength, stiffness, support system characteristics, or groundwater levels—to see how each one affects outcomes like wall movements and ground settlement [7]. Looking at these variables one at a time helps

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highlight which parameters matter most in controlling excavation behavior. This insight is especially useful for improving design efficiency, directing geotechnical investigations toward the most important properties, and building stronger risk assessment strategies [8]. By testing a range of "what-if" scenarios, parametric studies offer a clearer understanding of soil–structure interaction than field observations alone can typically provide.

Despite significant advances in analysis and monitoring techniques, accurately predicting soil–structure interactions SSI around deep excavations remains challenging, particularly in non-homogeneous or highly changeable ground conditions, and managing the influence zone is still critical to preventing damage to nearby structures. This article seeks to inspect the geotechnical impacts of deep excavations in detail, offering insights relevant to both practicing engineers and researchers. It highlights the key parameters that control excavation stability, evaluates current approaches for reducing associated risks, and outlines best practices for the safe design and execution of deep excavations. The overarching aim is to support safer and more efficient underground construction while minimizing adverse effects on the surrounding environment and built infrastructure.

Ground Movements Induced by Deep Excavations

The development of deep excavation systems can be traced back to the early 20th century. Early projects relied on relatively simple supporting walls, but as excavation depths rose and urban environments became more constrained, more progressive systems such as braced excavations, diaphragm walls, and underpinning were introduced. Excavation activities inevitably generate changes in lateral earth pressures and cause ground deformations, including settlement, tilting, and lateral displacement [9]. Nearby constructions react to ground movements via uneven settling and horizontal stresses, potentially resulting in cracking, leaning, or collapse [10,11]. The extent of these movements is affected by factors such as soil conditions, excavation depth, support system stiffness, and the sequence of construction phases. In soft clay, for instance, displacements can propagate several meters beyond the excavation footmark, posing risks to structures located at significant distances [12].

Research consistently demonstrates that field monitoring and performance evaluation play a critical role in the successful execution of deep excavations in soft soils. Observing excavation behavior and tracking ground movements around the site [13-15] provides essential information for understanding how the soil responds during construction. Equally important is assessing how these movements affect nearby structures, as highlighted in foundational studies by Refs. [16,17]. For design engineers, such observations offer a means to verify design assumptions, refine predictive models, and improve decision-making. Case histories and documented excavation performance have repeatedly proven valuable in reducing construction risk and enhancing reliability throughout the excavation process [18-23].

Over the last few decades, the finite element method (FEM) has become the go-to tool for this work. Yet the accuracy of FEM simulations hinges on three key factors: realistically modeling how soil and support systems interact, choosing the right soil behavior model (constitutive laws), and validating predictions against real-world performance data. This review explores the latest advances in these critical areas, setting the groundwork for our study. Despite its challenges, Ref. [24] investigated how stresses develop around a deep excavation in soft clay supported by a diaphragm wall and cross-bracing. By applying an advanced soil model, they were able to capture important features of soil behavior, including anisotropic stress–strain responses, nonlinear deformation, and hysteresis. Their analysis provided insight into how lateral earth pressures change during excavation and clarified the mechanisms of load transfer and soil arching, such as shear reversals prompted by ground movement and stress arching below the lowest bracing level. Comparisons with field measurements from Taiwan showed that the numerical predictions closely matched the observed stress paths, lending confidence to their modeling approach. Likewise, Lam [25] developed a practical predictive tool for deep excavation design, drawing on centrifuge model tests and a newly devised actuation system. The authors reported that wall deformations follow an O'Rourke-type cosine bulge shape and proposed an updated deformation mechanism that accounts for wall fixity and geometry. By validating energy conservation principles and refining the strength-based approach, the method was able to predict wall displacements with accuracy comparable to more advanced numerical models. The results also revealed that wall stiffness plays a major role in floating-wall excavations but has only a modest effect when the wall is firmly supported. Overall, the research underscores the importance of accurately characterizing soil stiffness to achieve reliable predictions of ground movements.

Besides, Yang et al. [6] examined ground pressures acting on a deep-buried shield tunnel using the Levenberg–Marquardt method and found it to be both accurate and efficient. Their results show that earth pressure gradually increases over time and is strongly affected by soil arching. These observations emphasize the need for precise load evaluation to ensure the safe design of deep underground structures.

Soil-Structure Interaction SSI

Deep excavation projects naturally entail a sophisticated exchange between the earth materials and the supporting structures put in place. This phenomenon, referred to as soil-structure interaction (SSI), oversees

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how the system functions, influencing how much and in what manner the retaining wall moves, how the ground surface settles, and the stresses experienced by reinforcement components. Such interactions are fluid rather than fixed, changing throughout different phases of construction—including excavation activities, water removal, and the placement of braces or anchors—rendering the behavior significantly dependent on the progression of work. Precisely modeling this ever-changing process remains the primary challenge in computational simulations of deep excavations.

Nonetheless, numerous researchers have tried to understand this sensitive phenomenon governing the dynamic relationship between soil and structural behaviour, such as [26-33]. Nearby constructions react to ground movements via uneven settling and horizontal stresses, potentially resulting in cracking, leaning, or collapse [10,11]. The extent of their reaction depends on factors such as the firmness of the underground base, the closeness to digging activities, and the severity of ground movement. Research indicates that structures with greater flexibility are more prone to harm, highlighting the importance of a comprehensive assessment of their dynamic interactions. The main signs of soil-structure interaction (SSI) include the distortion of the retaining structure and the corresponding shifting of the soil it holds back [34]. Real-world examples, such as a case from Vietnam, have clearly shown that damage to nearby buildings is directly related to ground movements and wall deflections caused by a nearby deep excavation [35]. These instances emphasize the importance of reliable predictive tools capable of estimating ground shifts accurately.

Since the 1960s, the numerical simulation of Soil-Structure Interaction (SSI), mainly using the Finite Element Method (FEM), has become a common technique. This method involves dividing both the ground and the structural components into smaller, manageable parts, allowing engineers to analyze the entire system cohesively [36]. A vital element of an accurate SSI model is correctly capturing how the soil and the structure come into contact. The interface component permits relative movements like sliding or separation, which can greatly affect how loads are transferred and how the system deforms over time. Ignoring or oversimplifying this interface can result in mistaken estimates of earth pressures and wall displacements. In summary, a thorough understanding and precise numerical representation of SSI, covering the behavior of the retaining wall, the soil mass, and their interface, is essential for confidently predicting how deep excavations will behave.

Bryson and Kotheimer [37] employed 3D finite-element modeling to investigate how ground movements affect a structure situated close to an excavation site. They discovered that the cracks appearing in the walls were the result of a combination of the building's own weight settling and the shifts caused by the excavation, rather than solely the excavation itself. Their study provided valuable insights into the key stress levels that could lead to structural harm. This research established a connection between underground ground motions and how structures respond during excavation activities. Similarly, Son and Cording [38] examined how different types of buildings, such as load-bearing brick walls, open-frame designs, and brick-filled frames, react to minor ground shifts caused by nearby excavation work. Through computer simulations, they assessed how these structures behave under various soil conditions and explored how aspects of their design influence their tendency to deform or crack. Their results emphasize the necessity of factoring in both the properties of the soil and the building's construction to accurately forecast how structures will perform when subjected to ground movements associated with excavation.

Dhadse and colleagues [36] explored how different types of interfaces, such as those experiencing separation or non-linear behavior, affect SSI. The authors used an innovative modified five-node interface element with zero thickness within FE models. Their study, limited to static loads, demonstrated that including this interface enhanced building performance by lowering the stress on the base, increasing sway or sideways movement, and allowing for precise redistribution of moments within the structure.

Meanwhile, Amari and Houhou [39] investigated how single piles and groups of piles respond to soil shifts caused by deep excavation in soft clay layers resting on dense sand. The analysis started with observing how a single vertical pile reacts, looking at the bending forces it experiences, its side-to-side movement, the axial load it carries, the distribution of resistance along its surface, and how much it settles. The insights gained provided a clearer picture of how piles behave and how SSI plays a role during such excavations. The results indicated that deep digging can induce significant bending stresses, lateral shifts, and axial forces on nearby piles. Additionally, their parametric study revealed that these pile responses are greatly affected by factors such as how deep the excavation is, where the pile is positioned relative to the excavation, the density of the sand, the support system used during excavation, and the length of the pile itself.

Integration of Field Monitoring and Numerical Back-Analysis

Geotechnical engineering naturally involves an element of unpredictability due to the changing and diverse nature of ground materials, coupled with the constraints of investigative methods used on-site. To narrow the divide between theoretical computer models and real-world conditions, combining thorough on-site monitoring with post-event analysis has become a vital aspect of contemporary deep excavation projects. This blended approach, often called the observational method, enables engineers to fine-tune and confirm their predictions, ultimately resulting in safer and more economical designs.

Monitoring the progress of a project on-site involves carefully recording key performance metrics at various stages of construction. Typically, for deep excavation operations, a set of instruments is used to gather

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important data: inclinometers to measure lateral wall deflections, settlement markers and extensometers to track vertical and horizontal ground movements, and piezometers to monitor changes in pore water pressure. The information collected from these tools creates a detailed record of how the soil and structure behave in real-time. Such real-world data is crucial for confirming that initial design assumptions are holding true and for alerting engineers to any unforeseen issues early on. Numerous research efforts have highlighted the significance of comparing on-site measurements from different instruments with computer-based simulations to develop a thorough understanding of how the excavation is proceeding [34].

Back-analysis, also known as inverse analysis, involves leveraging data collected from field monitoring to fine-tune the inputs of a computational model. The main aim is to carefully adjust uncertain parameters, most notably the soil's strength and stiffness characteristics, until the model's predictions align closely with real-world observations, such as the movement of retaining walls or the pattern of ground settlements. This approach helps to personalize and adapt the model to the specific conditions of the site. When successful, back-analysis transforms a generic, one-size-fits-all model into a tailored, site-specific tool that accurately represents local behavior. This calibrated model then becomes a reliable resource for predicting future ground responses during construction phases or for evaluating the potential effects of design changes. Many studies have emphasized the importance of this approach, where numerical models are verified and improved based on experimental or in-situ measurements, thereby enhancing the precision of deformation forecasts [40].

In this context, Houhou et al. [34] investigated a deep excavation at Toulouse's Saint-Agne subway station, supported by a diaphragm wall and steel struts, built in over-consolidated molassic geology. The authors compared monitoring data with 3D finite difference simulations that included dewatering effects, finding good agreement. The model provided insights into the 3D behavior of the excavation and its influence on nearby structures, with short comments on differences between 2D and 3D analysis results.

With the rise of powerful computing technology, engineers now have greater access to advanced 3D numerical modeling techniques for back-analysis. Sometimes, practitioners translate 2D finite element simulation outcomes into 3D models, but this approach isn't as robust as performing a comprehensive 3D analysis from the start [41]. Ultimately, by continuously monitoring, comparing results, and refining models through an iterative back-analysis process, engineers can better understand uncertainties and effectively control risks during the entire project. This approach shifts the focus from mere theoretical predictions to practical, data-driven engineering decisions.

Previous Studies on Parametric Analysis of Excavation Performance

While the existing literature mainly concentrates on creating and validating models for specific case studies [34-40], these validated models are essential for performing meaningful parametric analyses. The insights gleaned from monitoring excavation-related damage to adjacent buildings highlight the importance of understanding which factors can lead to significant movements [41].

Parametric analyses usually focus on three major categories of factors: geotechnical properties, structural system characteristics, and construction-related elements. When it comes to geotechnical parameters, researchers often look into the soil's effective cohesion (c'), friction angle (φ'), and stiffness (Young's modulus, E, or more advanced stiffness moduli). The attitude of an excavation can be particularly sensitive to these properties, which often carry the greatest level of suspicion. Structural parameters encompass aspects like the stiffness of the retaining wall, influenced by the material and thickness, as well as the spacing and pre-stress levels of struts or anchors, and the depth at which the wall is embedded. Additionally, construction-specific factors such as the depth of each excavation phase and the effect of water removal (dewatering) on the underground water levels are also common considerations in these evaluations.

In a study conducted by ref. [42] to explore the effectiveness of buttress walls in improving excavation stability and reducing basal heave in soft clays using 3D finite element analysis with reduced shear strength. The authors discovered that the friction between the wall and soil is crucial; longer or deeper buttresses significantly enhance stability. Their work also revealed different failure modes based on elastic and elastic-plastic behaviors and introduced simplified methods, validated through finite element results and case studies, for assessing basal heave risks and designing buttress dimensions.

By quantifying how sensitive the system's response is to each parameter, engineers can set performance limits, conduct probabilistic risk assessments, and create designs that are more robust and resilient, accommodating the inherent uncertainties in geotechnical engineering. These analyses bridge the gap between the details of individual projects and the development of broader design principles and guidelines.

Case Study Selection: Site Conditions and Support System

The chosen location for this case analysis is a construction site within a densely developed part of Tripoli, Libya (TR1, TR2, TR3, and TR4) (see Figure 1). The area is characterized by thick layers of silty sediments. Four extensive deep excavation projects were examined, with particular attention to how the ground moved, how the structures responded, and how effective the support systems were. These excavations reached depths of up to 4.0 meters, with a width of 1.5 meters, and were carried out in three distinct phases. The

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groundwater table remained well below the excavation zone. To ensure safe excavation procedures, ground improvement techniques were implemented. Support walls made of sheet piles were used to reinforce the excavation sides, a method well-suited to the site's specific conditions. This project mainly involves a numerical assessment of how deep excavations in silty sands perform, utilizing PLAXIS 2D software (plane-strain approach). The finite element model predicts how underground retaining structures will shift, how the surrounding ground may settle or move, and the effects of excavation activities on nearby structures. Overall, this study highlights the crucial role of accurately forecasting ground movements during deep excavations in soft soil environments.

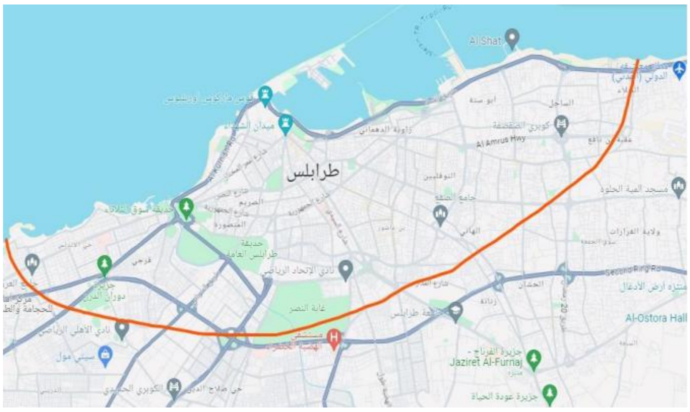

Figure 1. Site of the selected case study

Data Collection and Soil Stratigraphy

A detailed geotechnical investigation was carried out at the selected sites, involving in-situ (CPT and Cross-Hole tests) and laboratory tests performed on undisturbed samples retrieved from deep boreholes. (Table 1) summarizes the main results from the geotechnical investigation and the soil properties at various depths.

Table 1. summarizes the soil properties, derived from in-situ testing.

Site		**TR1**			**TR2**		**TR3**		**TR4**	
Depth (m)		Layer 1	Layer2	Layer3	Layer 1	Layer2	Layer 1	Layer2	Layer 1	Layer2
		3.5	6	5.5	3	12	4	11	4	11
MC		Silty Sand Loose	Silty Sand mid to dense.	Silty Sand Loose	Silty Sand (SM)	Silty Sand (ML)	Silty Sand (SM)Mid	Silty Sand (SM)	Silty Sand (SM)	Silty Sand with GR
Type		Drained	Drained	Drained	Drained	Drained	Drained	Drained	Drained	Drained
□	kN/	17.5	19	17.5	18	16.5	17	19	17.5	19
□	kN/	17.5	19	17.5	18	16.5	17	19	17.5	19
E	kN/	$25*10^3$	$30*10^3$	$25*10^3$	$30*10^3$	$40*10^3$	$30*10^3$	$40*10^3$	$20*10^3$	$28*10^3$
□	□	0.25	0.3	0.3	0.25	0.3	0.35	0.35	0.3	0.35
C	kN/	1	1	1	1	1	1	1	1	1
□	□	28.88	34.17	29.27	29.46	33.16	30.9	36.41	29.8	34.6
□	□	0	4.17	0	0	3.16	0.9	6.41	0	4.6

Finite Element Model Development

For many decades, the linear elastic-perfectly plastic Mohr-Coulomb (MC) model has been a popular choice in geotechnical engineering because of its straightforward nature and the relatively small set of input parameters needed, such as Young's modulus, Poisson's ratio, cohesion, friction angle, and dilatancy angle. In this investigation, a finite element method was utilized to perform a numerical simulation of soil response during deep excavation activities to identify key factors responsible for extensive deformations. The simulation framework was constructed using a linear elastic perfectly plastic material model based on the Mohr-Coulomb failure criterion. This criterion in PLAXIS requires the input of five parameters: Young's modulus (E) and Poisson's ratio (ν) to characterize elastic behavior, as well as cohesion (c), internal friction angle (ϕ) for the yielding condition, and dilation angle (ψ) for plastic flow. (Table 1) presents the geotechnical properties employed in the modeling process. The analysis was executed using PLAXIS 2D, employing a plane strain assumption with a mesh composed of 15-node triangular elements. To improve the precision during the initial consolidation phase, a fine mesh was implemented. Standard boundary conditions were applied, with fixed constraints on both lateral and bottom boundaries. The effects of neighboring structures were incorporated into the simulation; the left boundary was positioned 15 meters away from the sheet pile wall, while the bottom boundary was aligned with the base of the 15-meter-deep silty sand stratum. Before the excavation, sheet pile walls were installed to uphold geostatic stability, modeled as elastic-plastic steel with a yield strength of 430 N/mm^2 and a unit weight of 1.808 kN/m^3. To reduce boundary effects at the

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model base, the overall height was set to twice the maximum excavation depth, following recommendations by ref. [43]. (Figure 2) depicts the mesh configuration and boundary conditions adopted in the study. The excavation process was simulated in three progressive stages, with depths controlled at 2 meters, 3 meters, and 4 meters, respectively.

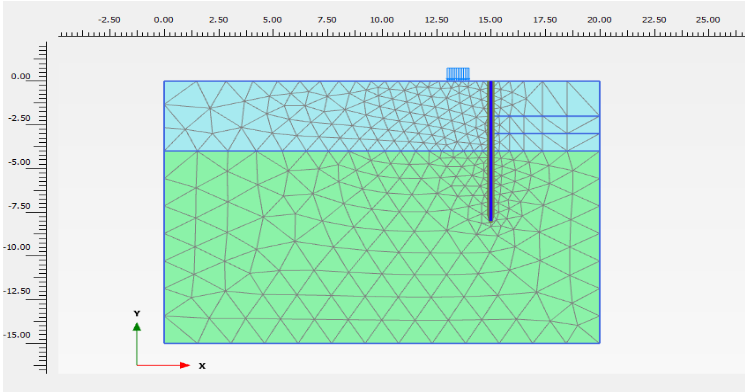

Figure 2. A finite element mesh is used in the analysis modeling.

Predicted performance

The results of the numerical analysis are presented in terms of sheet pile and soil displacements computation. The predicted ground movements are influenced by soil stratigraphy and soil model parameters used [40]. Key findings include the critical role of soil properties in deformation patterns and the importance of tailored support systems.

Ground Deformation Patterns

Generally, the soft clay strata experienced considerable settlements, frequently surpassing 300 millimeters, which in turn impacted the adjacent structures. These soft soil layers tend to intensify ground movements, as noted by Burland [44]. In the present research, the simulation data revealed that the maximum horizontal displacements occurred near the excavation face, with lateral spreading diminishing progressively with increased distance from the face, as depicted in Figure 3. When comparing the four locations under investigation, the largest displacement observed at the final stage was recorded at Site TR4, reaching 12.6 millimeters. In contrast, the displacements at the other sites ranged from 8.4 to 9.9 millimeters, as illustrated in Figure 4 below. This outcome aligns with expectations, considering that the elastic modulus at Site TR4 is over 30% lower than at the other sites, underscoring the significant influence of this property on soil strength and its capacity to resist deformation.

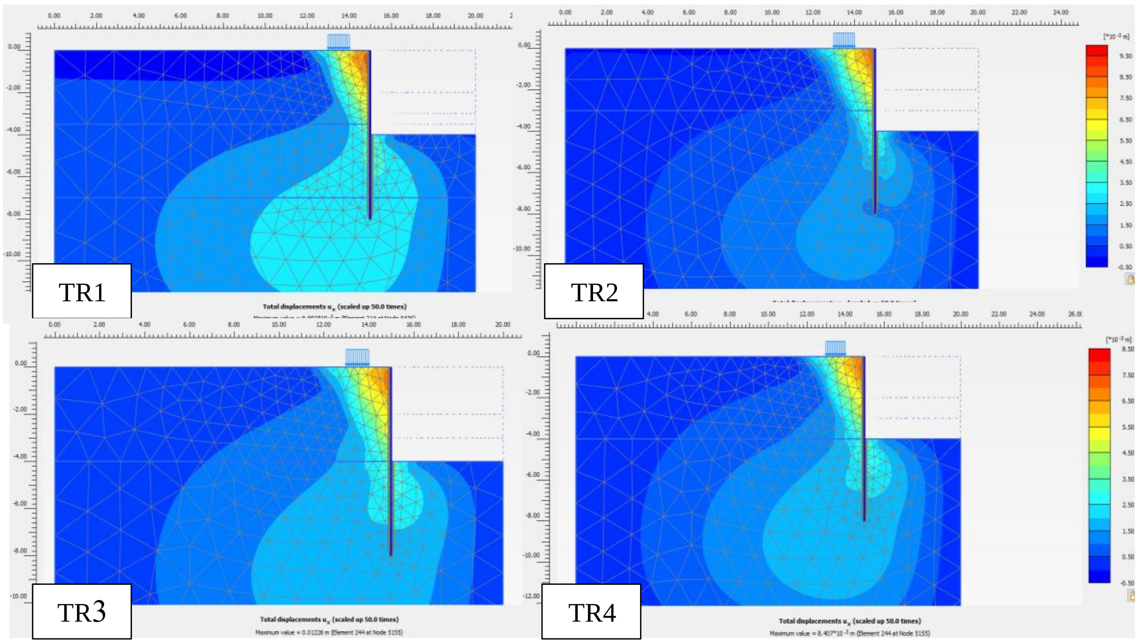

Figure 3. Distribution of horizontal displacement in the four locations

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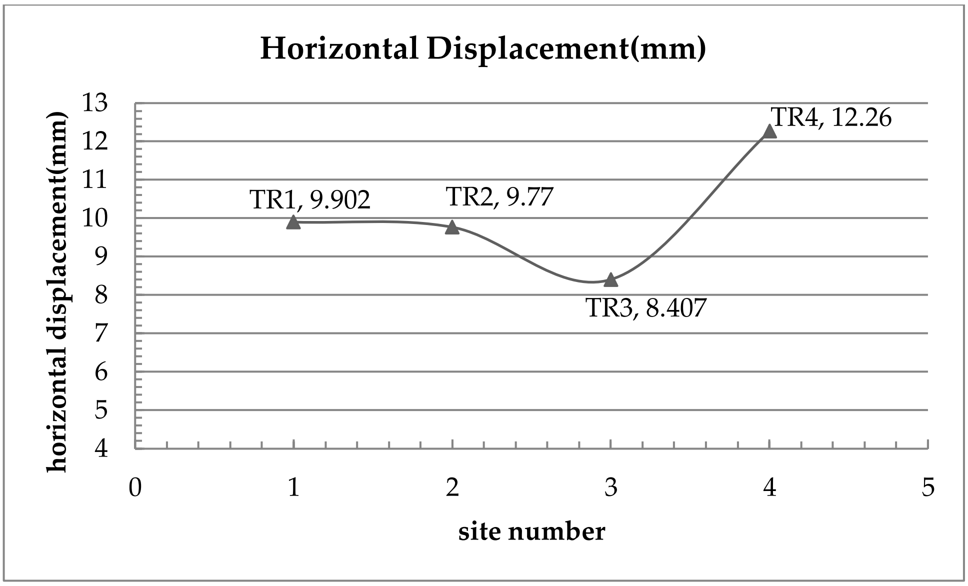

Figure 4. Comparison of horizontal displacement at the four studied locations

(Figure 5) illustrates the deformed mesh generated from the numerical simulation at the completion stage of the two representative cases, TR1 and TR4. The analysis indicates that the peak horizontal displacement of the soil adjacent to the top of the sheet pile at site TR1 closely aligns with the results observed at other locations, albeit with a marginally conservative estimate at the critical site TR4. Additionally, enhancement in ground settlement mitigation was achieved by assigning a higher elastic modulus (E) to the lower soil strata, where the combined thickness of these layers approximates the excavation depth. Overall, the findings demonstrate a substantial improvement in ground settlement behavior as a result of the applied measures.

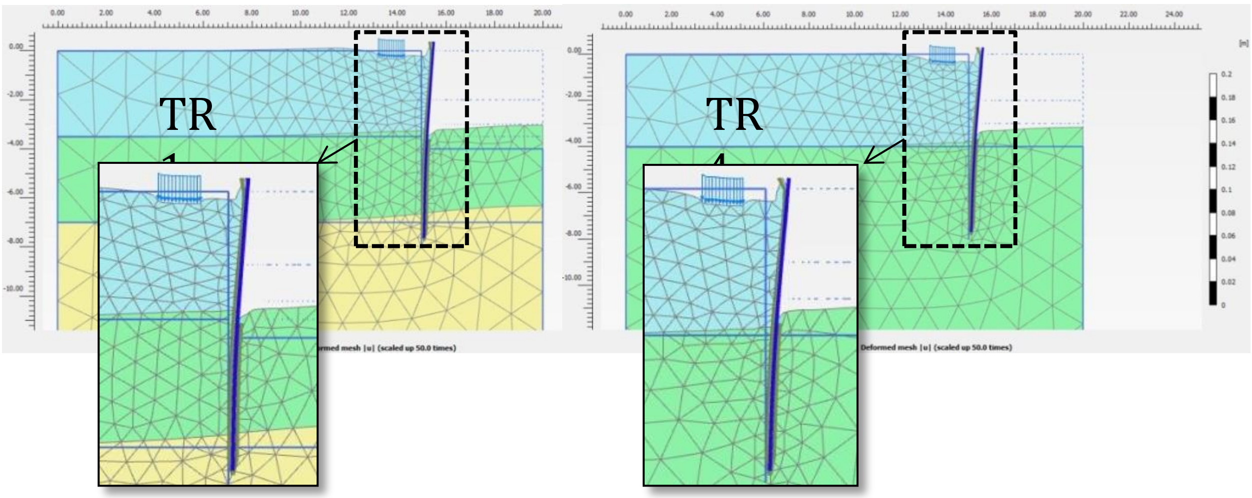

Figure 5. Deformation mesh with the total displacements of the sheet pile at TR1 & TR4

Structural Responses

Retaining structures embody intricate interactions between the soil and the constructed elements. Accurate prediction of their performance necessitates the use of advanced numerical modeling techniques, which facilitate detailed simulation of the complex system comprising the retaining element, the foundational substrate, and adjacent edifices. Despite employing such sophisticated methods, the outcomes may still exhibit notable deviations from actual behavior. In the context of full-site excavation, observations indicate that as the depth of excavation increases, the lateral stresses exerted on the sheet pile also escalate. Greater excavation depths tend to amplify horizontal earth pressures, as noted by refs. [9]. Additionally, regions where the underlying strata possess higher stability tend to experience reduced shear forces and bending moments. Furthermore, fluctuations in soil layer thickness and the vertical distribution of stress significantly influence the response and performance of the sheet pile system.

Adjacent structures experienced uneven settlements of up to 56 mm, resulting in tilting and, in certain instances, cracking [45]. The implementation of sheet piles proved highly effective in mitigating lateral displacements and minimizing structural deterioration, thereby underscoring the significance of support system configuration. The shear force exerted on sheet piles constitutes a vital consideration in design,

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originating from lateral earth pressures that impose internal shear stresses and bending moments on the retaining wall. (Figure 6) demonstrates the influence of shear forces on the behavior of sheet piles, depicting their responses across four designated case studies. Additionally, (Figure 7) indicates that the peak shear force was observed at the TR4 location, reaching a value of 40.41 KN, whereas the lowest shear force, approximately 37 KN, was recorded at TR3. At TR4, the applied load was predominantly concentrated on the uppermost layer, characterized by a lower friction angle and reduced elastic modulus, rendering it more susceptible to slippage. Subsequently, the shear forces at TR1, TR2, and TR3 measured approximately 39.63, 38.94, and 36.94 KN, respectively. The interaction between the layers plays a crucial role, as the lower layers with better properties will support the upper layers.

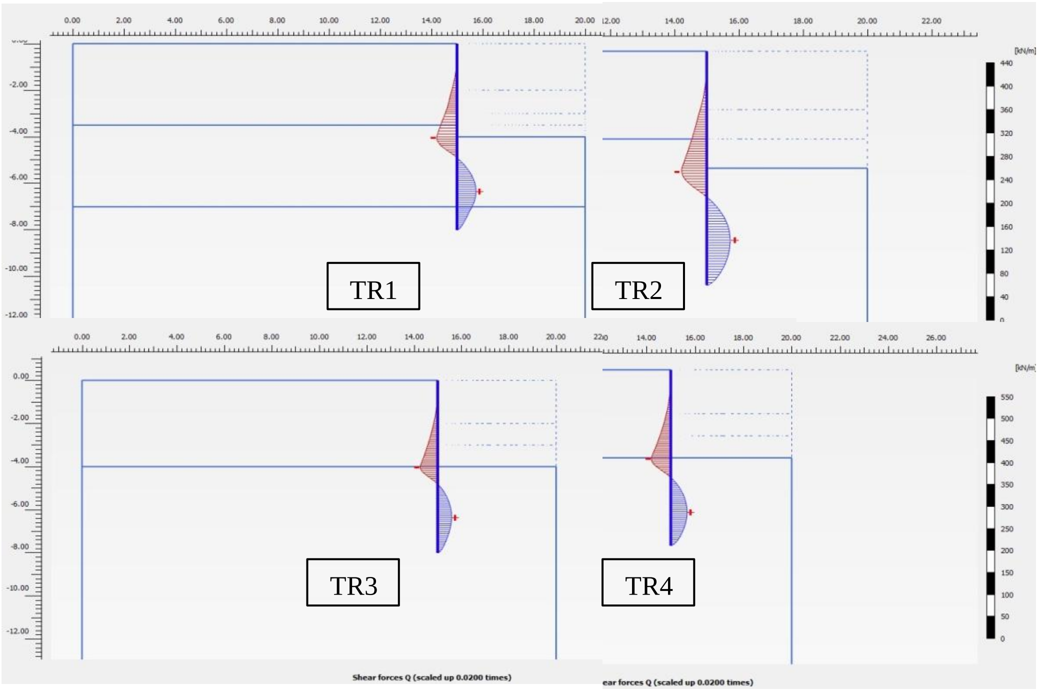

Figure 6. Shear force along the sheet pile at four locations

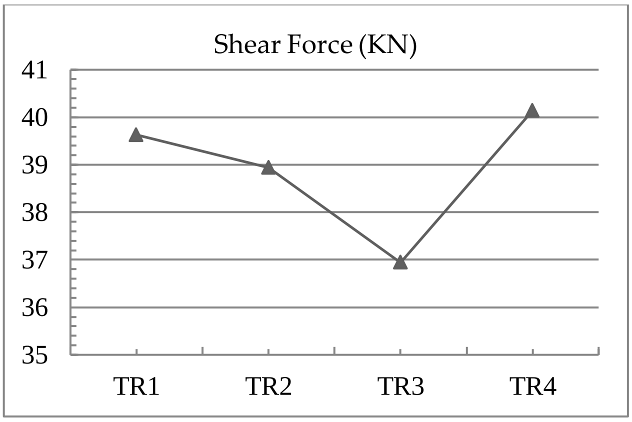

Figure 7. Comparison of the maximum shear force of the sheet pile at four locations

The values of bending moment along the sheet pile at the end of construction (phase 4) are reported in (Figures 8 and 9). From these figures, the bending moment increases due to the increase of soil properties until a value approximately equal to 77.7 kN.m/m.

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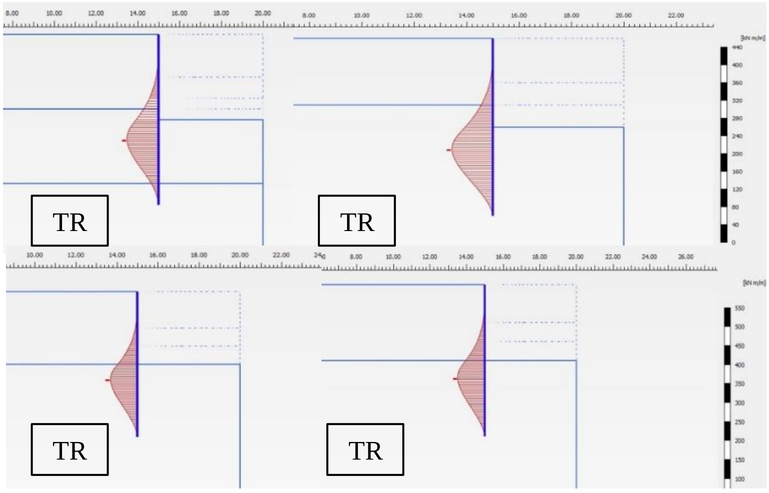

Figure 8. Bending moment along the sheet pile at four locations

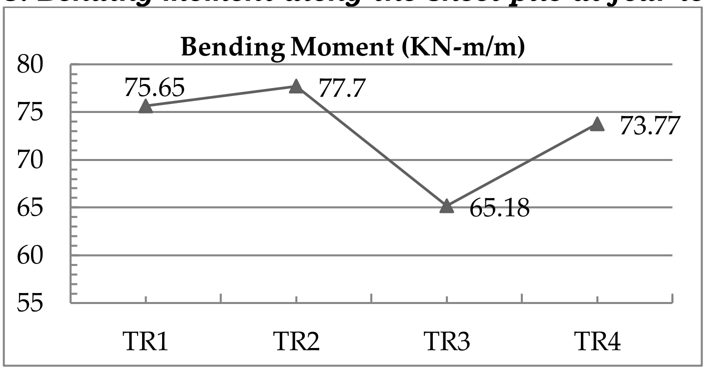

Figure 9. Comparison of the maximum bending moment of the sheet pile at four locations

Factors Influencing Stability

The location where the greatest settlement occurs potentially exerts a considerable influence on the performance and stability of nearby structures. Nonetheless, multiple parameters significantly impact the magnitude of maximum surface settlement, and understanding the influence of these factors can greatly enhance the precision of maximum surface settlement assessments obtained through finite element method (FEM) analysis [40]. Both numerical simulations and experimental studies identify key parameters such as cohesion, internal friction angle, depth of diaphragm walls, Poisson's ratio, Young's modulus, unit weight, and face support pressure as primary determinants. Notable factors include soil characteristics, specifically elastic modulus and friction angle, as well as the design of support systems and the sequence of construction activities. Properly designed and implemented support mechanisms effectively reduce associated risks. Employing staged excavation procedures enables controlled ground deformation, thereby minimizing unforeseen settlement issues. The significance of conducting early geotechnical evaluations coupled with ongoing monitoring was also underscored. In the current research, the Young's modulus was assessed utilizing observed deformation data collected from four study sites. As illustrated in (Figure 10), the elastic modulus markedly influences soil settlement, underscoring its critical role. Specifically, an increase in the Young's modulus from 20 MPa to 30 MPa resulted in approximately a 28% reduction in soil settlement.

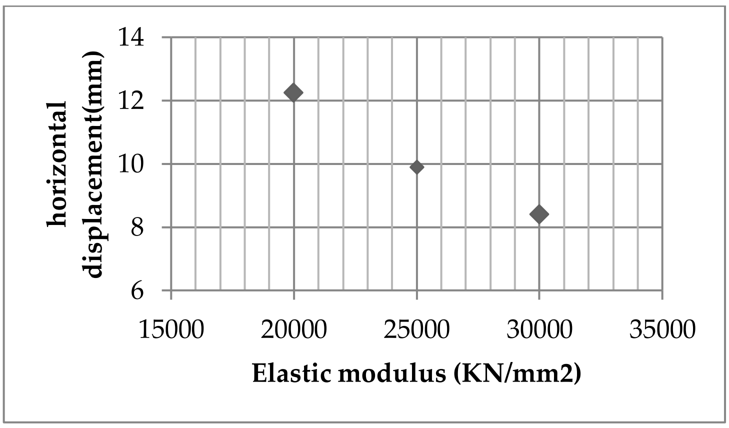

Figure 10. Relationship between horizontal displacement and elastic modulus

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Conclusion

This study demonstrates that deep excavations induce significant soil movements that can adversely affect adjacent structures, particularly in layered soils with soft clay components. Key findings include:
The behavior of soil and adjacent structures during deep excavations represents a complex interplay of geological conditions, excavation geometry, construction methods, and the characteristics of nearby buildings. Soil layering and its properties play a decisive role in shaping deformation patterns, influencing how the ground responds to excavation activities. To capture this complexity, the Hardening Soil model is often employed, as it effectively simulates the nonlinear and stress-dependent behavior of soils under excavation conditions. Equally important is the design of ground support systems, which directly impacts excavation stability and requires careful consideration of soil-structure interaction. Among the various support techniques, the use of steel sheet piles has proven particularly effective. By providing lateral resistance, these piles reduce stresses in critical areas and help distribute loads more evenly, thereby enhancing overall soil stability.

A thorough understanding of wall movement and its interaction with ground pressures is essential for engineers in designing retaining walls that ensure both structural safety and excavation stability. Looking ahead, advancing predictive capabilities and developing practical mitigation strategies will be key to improving the safety, efficiency, and sustainability of deep excavation projects. Such progress will not only support urban development but also safeguard existing infrastructure, striking a balance between growth and preservation.

Mitigation strategies and recommendations

The design of support systems in deep excavation projects requires tailored solutions that respond to the specific conditions of each site. This often involves the use of diaphragm walls, braces, and techniques to enhance ground strength, all of which work together to maintain stability and minimize risks. To complement these structural measures, continuous monitoring plays a vital role. By implementing real-time sensors and instruments, engineers can quickly detect any ground or structural movements, allowing for immediate intervention when necessary. A phased excavation approach is also essential, as the careful and sequential removal of soil helps control deformation rates and reduces the likelihood of sudden instability. Before any excavation begins, thorough pre-construction evaluations must be carried out to assess the soil and structural conditions of the site, ensuring that potential risks are identified and addressed in advance. Even after construction is complete, post-construction surveillance remains critical. Ongoing monitoring ensures long-term stability and provides early warnings of minor movements that could otherwise develop into significant issues. Looking toward the future, further research should focus on integrating advanced 3D modeling with real-time data collection. This combination has the potential to greatly improve prediction accuracy, offering engineers more reliable insights into soil-structure interaction and enabling safer, more efficient, and sustainable excavation practices.

Conflicts of Interest

The authors declare no conflicts of interest.

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