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Implementation of Staged Excavation with Strut Wall Under Different Surcharge Load

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Abstract: Deep excavations in urban areas require robust support systems to maintain stability and serviceability under varying surcharge loads. Staged excavation supported by strut walls is a widely used technique to control ground movements and wall deformations during construction. However, accurate prediction of excavation behavior remains challenging due to the complex soil–structure interaction and stress redistribution occurring at each excavation stage. In this study, the implementation of staged excavation with strut wall systems under different surcharge load conditions is investigated using the Finite Element Method (FEM). A numerical model is developed to simulate staged excavation sequences, strut installation, and surcharge loading. The FEM analyses focus on evaluating wall deformation, bending moments, strut axial forces, and overall excavation stability throughout the construction stages. Parametric studies are performed to examine the influence of surcharge magnitude and excavation depth on system performance. The results demonstrate that FEM provides a reliable and effective framework for capturing the nonlinear behavior of soil–structure interaction and for optimizing strut wall design parameters. The findings contribute to safer and more efficient design practices for staged excavations subjected to varying surcharge loads.

Keywords: Excavation, Strut, Diaphragm wall, Finite element analysis.

1. INTRODUCTION

Excavation is considered as one of the most hazardous phases of constructions which may cause collapses. Excavations are carried out for reasons such as ensuring the location of the footings regarding soil bearing capacity, protecting the foundation from external impacts, construction of road embankments considering slope stability and obtaining a tunnel cut-and-cover area within the ground. The design process is classified as staged excavation, deep excavation, or shallow excavations according to dimensions of the excavation. Before the excavation process, the condition of the groundwater level, the size of the surcharge loads arising from the existing structures, the distance to the excavation area, the relative distance of the load strut gain importance in the design to prevent damage to the surrounding structures and existing infrastructures. Staged excavation with strut wallis a method of deep excavation that involves the excavation of vertical shafts in a staged manner. This method is commonly used in urban areas where buildings and other structures are located close to the excavation site, and where soil and groundwater conditions require additional support to maintain stability during construction. The use of strut walls helps to strut the excavation and prevent the inward movement of soil and water pressure, ensuring that the excavation remains stable and safe.

Despite the effectiveness of staged excavation supported by strut walls, several challenges arise during the design and construction processes, requiring the use of advanced numerical methods. These challenges include determining optimal excavation stages, selecting appropriate strut wall and support system parameters, and ensuring excavation stability and safety under different surcharge load conditions throughout construction. In this study, the implementation of staged excavation with strut walls under varying surcharge loads is investigated using the Finite Element Method (FEM). The numerical analyses enable detailed simulation of staged construction sequences, soil–structure interaction, and surcharge-induced stress redistribution, providing a reliable framework for evaluating excavation performance. In any geotechnical design of an excavation case is required, the stability of the system should be ensured by using Retaining system such as shotcrete, pile curtain, buttress, permanent coating, suspension etc. to support excavations. Sheet piles designed with or without strut are more frequently used geotechnical structural elements that provide stability during and after excavation. Strut systems can be used to support sheet piles in the geotechnical designs of foundation pit, trench, highway, tunnel, or gallery. Ensuring the stability of excavation systems is a fundamental requirement in geotechnical engineering design, particularly for deep excavations carried out in urban environments. Excavations must be supported by appropriate retaining systems to prevent excessive ground deformation, structural failure, and damage to adjacent infrastructure. Various support systems have been developed and widely applied in practice, including shotcrete walls, pile curtains, buttresses, permanent linings, and suspended retaining systems (Peck, 1969; Clough & O'Rourke, 1990; Potts & Zdravkovic, 1999). The selection of a suitable retaining system depends on several factors such as excavation depth, soil conditions, groundwater level, construction sequence, and external loading conditions.

Among the available retaining systems, sheet pile and diaphragm walls are commonly used due to their structural efficiency and ease of construction. These walls may be designed with or without additional support systems such as tie-back anchors or internal struts. In situations where space limitations, property boundaries, or underground utilities restrict the use of tie-back anchors, internally braced systems using struts become a preferred solution (Kim et al., 2008; Finno & Kim, 2012). Strut-supported retaining systems are frequently applied in the design of foundation pits, trenches, highways, tunnels, and underground galleries, providing adequate lateral support during staged excavation processes (Ou, 2006; Kim & Lee, 2010; Cho et al., 2017). Previous studies have demonstrated that the performance of strut wall systems is strongly influenced by excavation sequence and staging. Staged excavation allows for gradual stress redistribution in the surrounding soil, reducing the risk of sudden instability and excessive wall deformation (Ou et al., 1993; Potts & Zdravkovic, 2001). However, improper staging or delayed installation of struts can lead to increased bending moments in retaining walls and significant ground settlements. Therefore, determining optimal excavation stages and strut installation levels is a critical aspect of design (Kim et al., 2008; Tang et al., 2015). External surcharge loads acting near excavation boundaries further complicate the behavior of supported excavation systems. Surcharge loads may arise from nearby buildings, traffic loads, construction equipment, or material stockpiles. Several researchers have reported that surcharge loads significantly increase lateral earth pressures, resulting in higher wall deflections and internal forces in struts

(Ou & Lai, 1994; Kim & Lee, 2010; Cheng et al., 2016). The magnitude and location of surcharge loads play a key role in excavation performance, particularly in deep excavations where stress redistribution is highly nonlinear. Despite this, surcharge effects are often simplified or neglected in conventional design approaches (Peck, 1969; Clough & O'Rourke, 1990). Traditional methods for analyzing braced excavations are primarily based on classical earth pressure theories and empirical design charts. While these approaches offer simplicity and practicality, they rely on idealized assumptions regarding soil behavior, wall rigidity, and loading conditions (Clough & O'Rourke, 1990). Such simplifications may lead to conservative or unconservative designs, especially for complex excavation geometries and staged construction under varying surcharge loads. Consequently, the limitations of conventional methods have motivated the use of advanced numerical techniques in excavation analysis.

In recent years, the Finite Element Method (FEM) has been increasingly employed to analyze staged excavations supported by strut walls. FEM enables detailed simulation of soil–structure interaction, nonlinear soil behavior, construction sequencing, and installation of support systems (Ou, 2006; Kim et al., 2008; Potts & Zdravkovic, 2001; Tang et al., 2015). Numerical studies using FEM have shown that this approach provides more accurate predictions of wall deformation, bending moments, strut axial forces, and ground settlements compared to traditional analytical methods (Ou et al., 1993; Kim & Lee, 2010; Cho et al., 2017). FEM-based analyses also allow parametric investigations to evaluate the influence of excavation depth, strut spacing, wall stiffness, and surcharge load magnitude on system performance (Finno & Kim, 2012; Cheng et al., 2016). Several FEM studies have focused on the effect of strut configuration and stiffness on excavation behavior, highlighting the importance of support system optimization (Kim et al., 2008; Tang et al., 2015). Others have examined the influence of surcharge loads on lateral earth pressure distribution and wall response, demonstrating that surcharge-induced stress redistribution can significantly alter excavation performance (Ou & Lai, 1994; Kim & Lee, 2010; Cheng et al., 2016). More recent research has also explored advanced constitutive models and coupled soil–structure interaction analyses to improve the prediction of excavation behavior under complex loading (Potts & Zdravkovic, 2001; Cho et al., 2017). However, most existing studies consider either staged excavation or surcharge loading independently, and comprehensive investigations addressing their combined effects remain limited.

Therefore, further research is required to systematically evaluate the behavior of staged excavations supported by strut walls under different surcharge load conditions. Advanced FEM-based modeling provides a robust framework for capturing the complex interactions between soil, retaining structures, and external loads throughout the construction process. The findings from such studies can contribute to improved design guidelines and safer, more efficient excavation practices in geotechnical engineering (Ou, 2006; Kim & Lee, 2010; Potts & Zdravkovic, 2001). This study investigates an excavation supported by a strut-braced diaphragm wall using the finite element method (FEM). Five different excavation scenarios were analyzed by varying the magnitude of surcharge loads and the distance from the excavation, creating a set of parametric combinations to assess the behavior of the wall system under different conditions. The use of strut-supported diaphragm walls has become increasingly popular due to their advantages, including reduced construction time, cost-effectiveness, accessibility, and enhanced safety. FEM was employed to simulate the excavation process and evaluate the structural performance of the walls under the five scenarios, ensuring stability and reliability during staged excavation.

2. MATERIALS AND METHODS

Numerical analysis of the sheet pile and struted retaining systems observed in this study was carried out to ensure the stability of the soil after excavation. This method uses the primary unknowns (displacement, current potential, etc.) and their dependent secondary unknowns (stress, strain, current amount, etc.) speed etc.) together and provide convenience in solving integrated problems [such as stress-strain (static) and consolidation (dynamic)]. PLAXIS (Finite Element Code for Soil and Rock Analysis), a computer software designed for the analysis of deformation and stability problems in geotechnical engineering with the finite element method, is equipped with important features for the analysis of geotechnical applications with a versatile and complex structure. In this study, PLAXIS version 8.2 was used. Analyzes were made in 2D plane deformation geometry conditions. In the software, the stress-strain behavior of the material is modeled with nonlinear solution techniques. For this purpose, a parametric study of the staged excavation problem was carried out with the PLAXIS program. The baseline problem geometry is depicted in Figure (1).

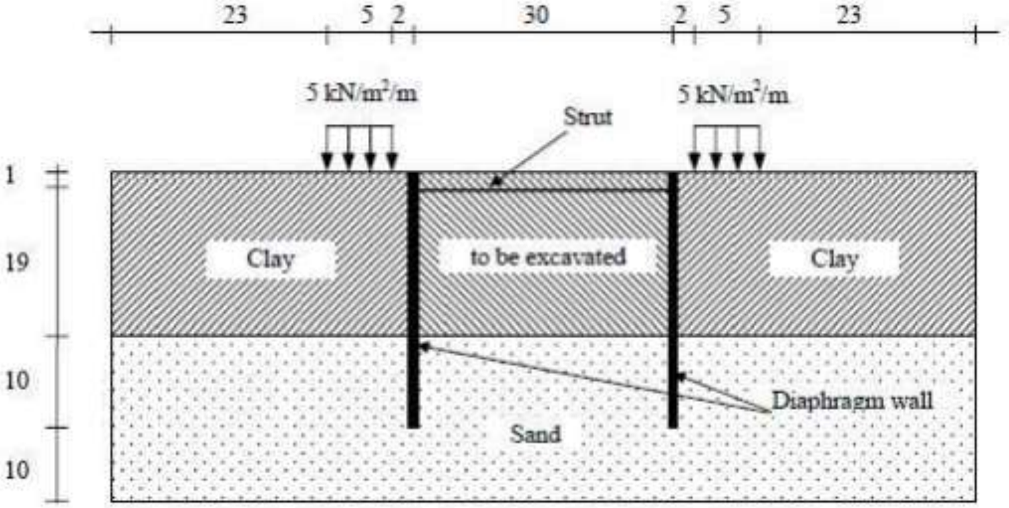

Figure 1. Baseline geometry of the staged excavation problem analyzed using the PLAXIS program.

In the baseline model analysis, Mohr-Columb Model were used, and the problem was handled under plane strain conditions. The finite element mesh was chosen with medium density. The proposed solution is derived by modifying the numerical solution obtained for a specific mesh density of the studied object with a suitable proportionality coefficient determined through the analysis of simple bodies subjected to different external forces. It is assumed that the elastic displacement of various bodies follows a similar trend as the mesh density increases, and that the proportionality coefficients are approximately equal for identical mesh densities. Subsequently, medium-sized finite element meshes were selected as there was no significant change in results when the mesh density was increased from medium to very fine.

A two-dimensional finite element model was developed using PLAXIS software to simulate the excavation process and the construction of a strut-diaphragm wall system. The diaphragm wall was modeled as a rigid structural element with appropriate support nodes to represent its interaction with the surrounding soil. The soil mass was represented using the Mohr–Coulomb constitutive soil model, which is commonly employed to capture the elastic–plastic behavior of soils under excavation-induced loading conditions.

The material properties of the soil layers were selected based on laboratory test results to ensure realistic representation of in-situ conditions (Tuskan and Yiğit, 2025). Key parameters incorporated into the model included soil density, Young's modulus, and Poisson's ratio. These parameters were carefully selected to reflect the mechanical behavior of the soil strata encountered at the site and to improve the reliability of the numerical predictions. Boundary conditions were defined to replicate actual site constraints and loading conditions. The numerical model was established under plane strain assumptions, which are appropriate for long excavation sections where out-of-plane deformations are negligible. This approach enabled accurate simulation of both vertical and horizontal stress distributions within the soil mass during excavation. The excavation process was modeled in a staged construction sequence to reflect field practices. Initially, the diaphragm wall was installed, followed by the first-stage excavation and the installation of the initial set of strttss. This procedure was subsequently repeated for the second excavation stage, allowing the progressive development of stresses and deformations to be captured throughout the construction process.

Finally, the model was analyzed to evaluate stress redistribution and deformation behavior during excavation. Stress concentrations in both the soil and the diaphragm wall were examined, while horizontal and vertical deformations were monitored at various excavation levels. This analysis provided insights into the structural performance and stability of the excavation system under staged construction conditions. In the analysis, five different scenarios were considered by varying the magnitude of the surcharge load and the distance of the distributed load from the excavation, as presented in Table 1.

Table 1. Parameters for the Analyzed Strut Reinforced Wall-Excavation Scenarios

Parameter/Scenario	1	2	3	4	5
Number of Struts (N)	8	8	8	8	8
Strut Length (L), m	30	30	30	30	30
Sheet Pile Length (H), m	30	30	30	30	30
Distributed Load (Y) (kN/m^2)	5	5	10	5	15
Number of Excavation Stages	6	6	6	6	6
Relative Distance of Distributed Load, m	5	15	15	15	10
Distance of Distributed Load from Excavation, m	2	2	2	4	6

The upper elevation of the pier is 0.50 m deep from the ground surface. A total of 5 different analyses were carried out in the study. The characteristics of the soil used in the analysis are given in Table 2.

Table 2. Soil Constitutive Model Parameters for Sand and Clay Layers

Parameters	Sand Layer	Clay Layer
γ_n(kN/m^3)	17	16.00
γs (kN/m^3)	20	18.00
E_{50}^{ref} (kN/m^2)	4.0 x 10^4	1.0 x 10^4
E_{oed}^{ref} (kN/m^2)	4.0 x 10^4	1.0 x 10^4
C (kN/m^2)	1.00	5.00
Φ (°)	32.00	25.00
ψ(°)	2.00	0.00

3. RESULTS

Five different FEM scenarios were analyzed to investigate the effects of distributed load magnitude and its distance from the excavation on the structural response of the retaining system. In all scenarios, the number of struts, strut length, sheet pile length, and number of excavation stages were kept constant to isolate the influence of surcharge-related parameters. The distributed load magnitude was varied between 5 and 15 kN/m², while both the relative distance of the load and its absolute distance from the excavation were systematically changed. As shown in Figure 2, the uniform distributed load is applied at a distance of 15 m. The horizontal spacing between the sheet pile walls is taken as 2 m, and the magnitude of the applied uniform load is 5 kN/m²/m. The behavior of the strut–sheet pile system under these conditions is examined.

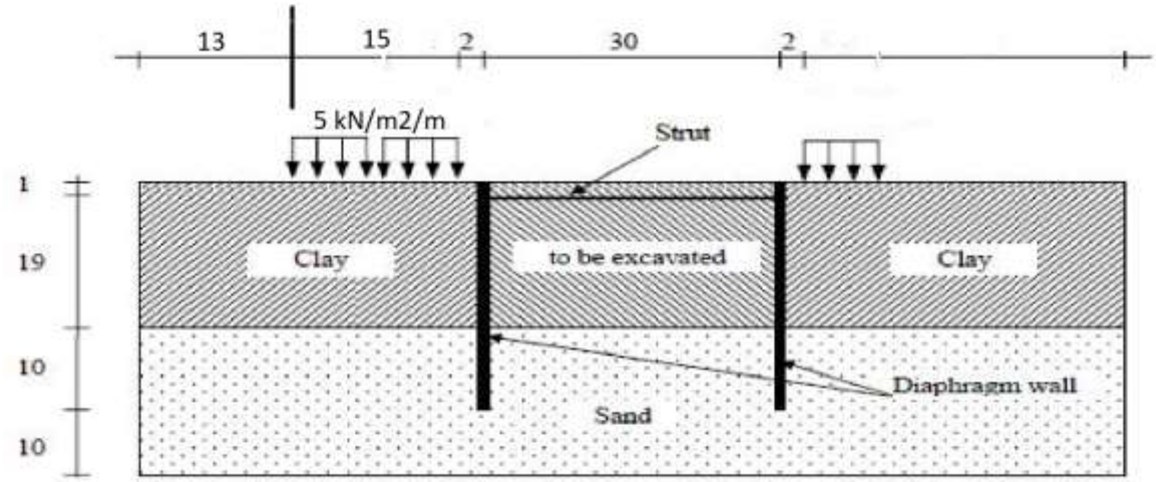

Figure.2 Configuration of the strut–diaphragm wall system with a uniform distributed load of 5 kN/m²/m applied at 15 m from the excavation and a wall spacing of 2 m.

The results are presented in terms of total displacement and effective principal stresses, highlighting the deformation characteristics and stress response of the strut–diaphragm wall system (Figure 3.).The results indicate that increases in distributed load magnitude lead to higher total displacements and bending moments in the diaphragm wall when the load is applied close to the excavation. Scenarios with higher surcharge loads acting at shorter distances from the excavation exhibited the largest wall deformations and peak bending moments due to intensified stress transfer within the retained soil mass. Conversely, relocating the distributed load farther away from the excavation resulted in a noticeable reduction in total wall displacement and bending moment, even when higher surcharge magnitudes were applied.

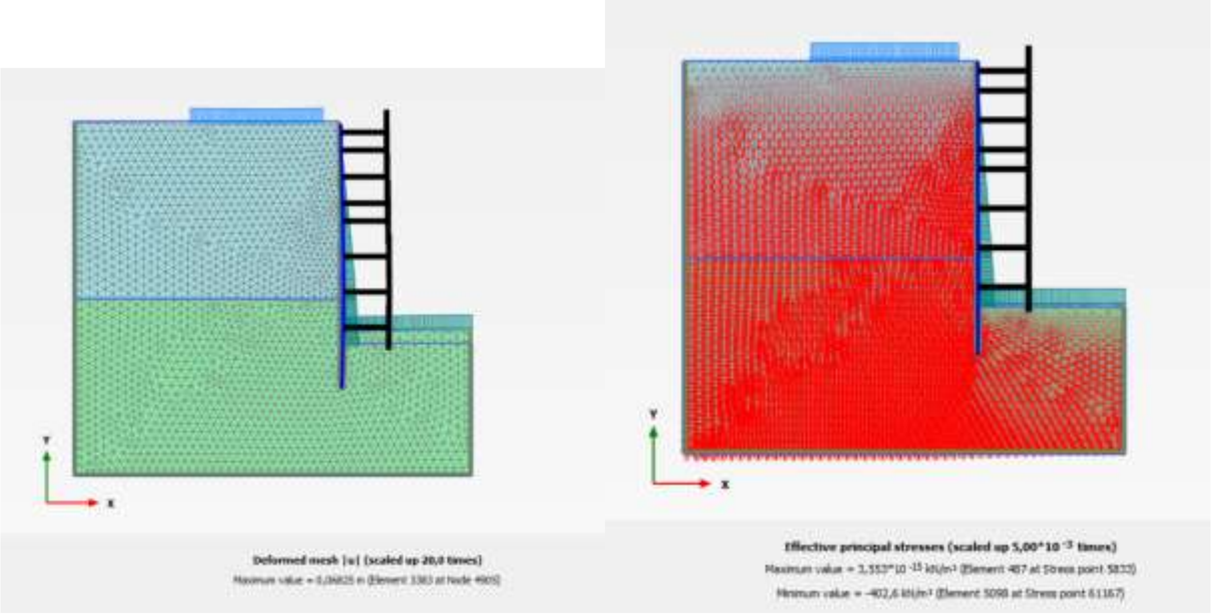

Figure 3. Total displacement and effective principal stresses for the strut–diaphragm wall system under a uniform distributed load of 5 kN/m²/m applied at a distance of 15 m, with a wall spacing of 2 m.

Comparative evaluation of the scenarios shows that the distance of the distributed load from the excavation has a dominant influence on wall behavior. For instance, scenarios with identical load magnitudes but greater load distances exhibited significantly lower total displacements and bending moments than those with loads applied closer to the excavation. These findings highlight that increasing the distance between the surcharge load and the excavation boundary is an effective measure for mitigating deformation and reducing structural demand on the retaining wall system. The FEM results provide valuable insight into the combined effects of surcharge magnitude and load distance on excavation performance and can support safer and more economical design decisions. In this example (see Figure 4), a uniform distributed load of 10 kN/m²/m is applied at a distance of 15 m, with a diaphragm wall spacing of 2 m, and the corresponding results are presented.

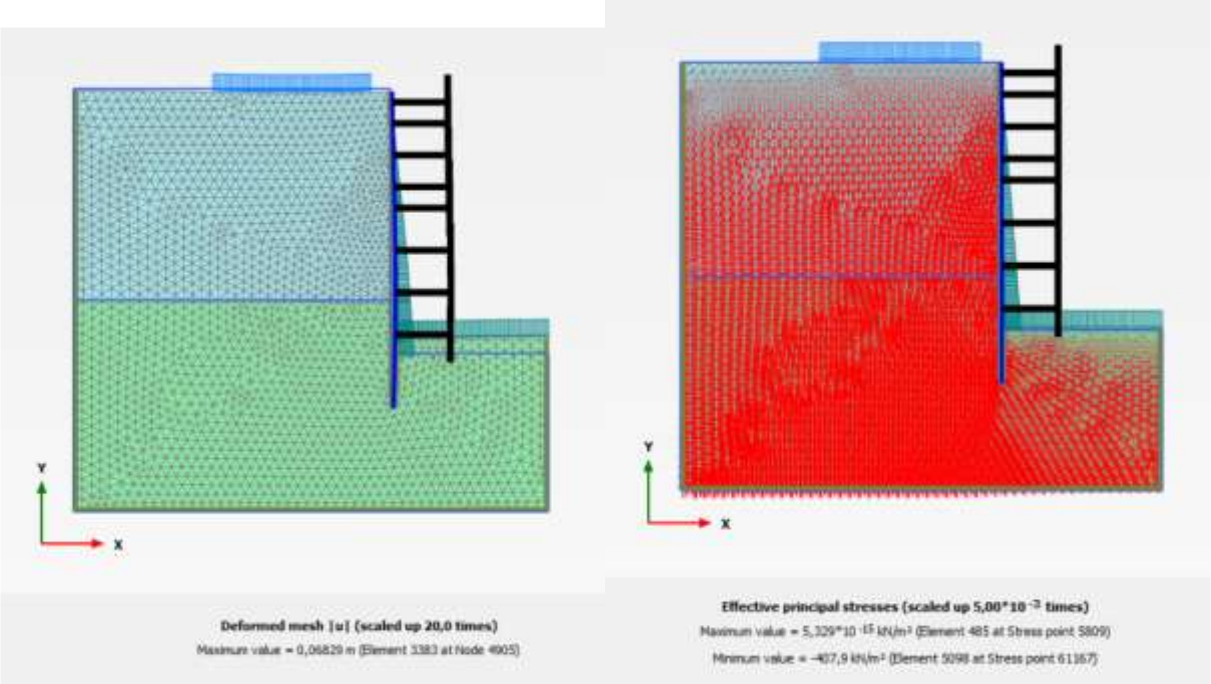

Figure 4. Total displacement and effective principal stress distributions for the strut–diaphragm wall system with a uniform distributed load of 10 kN/m²/m applied at 15 m, and a wall spacing of 2 m.

In Figure 5, finite element analyses are presented for a uniform distributed load of 10 kN/m²/m is applied at a distance of 15 m, with a diaphragm wall spacing of 4 m, and the resulting total displacement and effective principal stresses are presented.

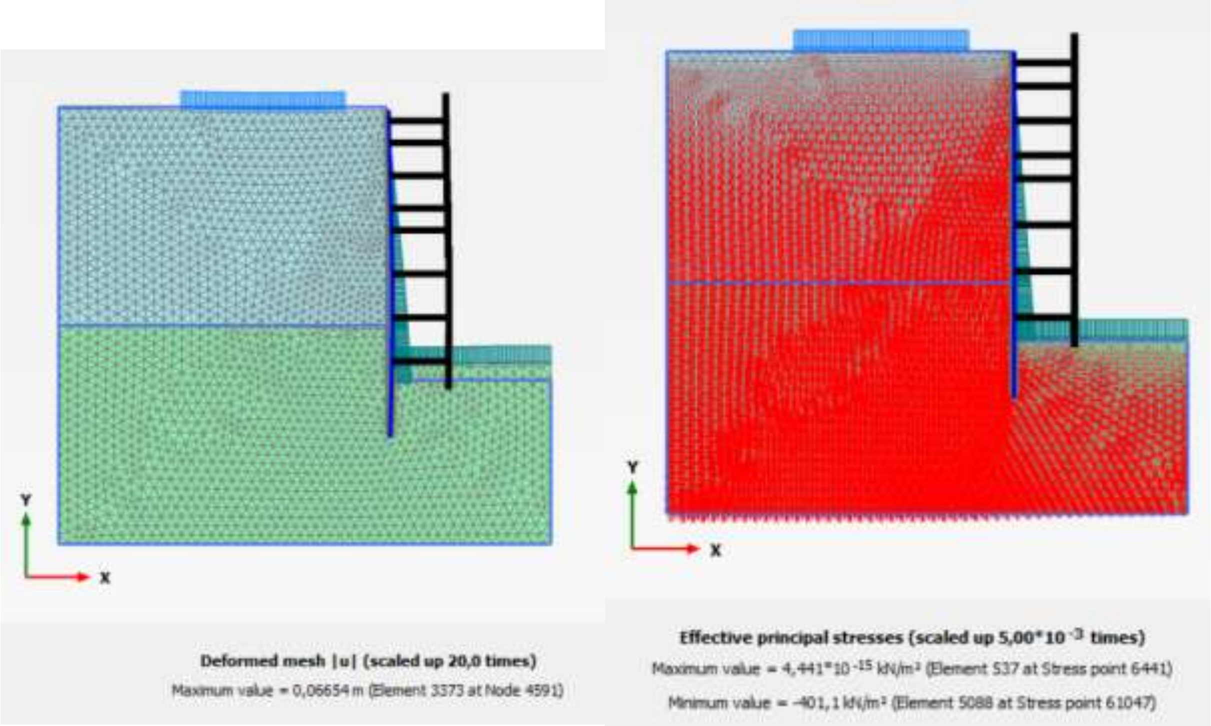

Figure 5. Total displacement and effective principal stress distributions of the strut–diaphragm wall system under a uniform distributed load of 10 kN/m²/m applied at 15 m, with a wall spacing of 4 m.Disturbed load:

In this study, a series of finite element analyses were performed to investigate the effect of distributed load magnitude on the behavior of the excavation system. Analyses were conducted for the no-load condition and for different distributed load levels ranging from 5 kN/m² to 15 kN/m², with increments of 5 kN/m², while all other parameters were kept constant.

The results indicate that the magnitude of the distributed load applied to the soil behind the sheet pile has a significant influence on the stability and structural performance of the system. As the distributed load increased, a proportional increase was observed in the lateral and vertical displacements of the sheet pile, as well as in the bending moments and shear forces developed along the wall. In addition, the axial forces in the struts and the settlement of the soil behind the sheet pile increased consistently with increasing load magnitude. It was observed that the excavation system experienced structural failure when the distributed load reached 15 kN/m², indicating that this load level exceeds the bearing and structural capacity of the support system under the given conditions. A relatively uniform distribution of axial forces among the struts was observed for increasing load levels, suggesting that the strut system effectively shared the surcharge-induced loads.

4. CONCLUSION

Deep excavations in urban areas require carefully designed support systems to ensure stability and serviceability under varying surcharge loads. This study investigated staged excavations supported by strut wall systems using the Finite Element Method (FEM), focusing on wall deformation, and overall excavation stability. The FEM analyses demonstrated that both the magnitude and the location of surcharge loads significantly influence the deformation and stress response of the diaphragm wall–strut system. Smaller relative distances of the surcharge load or closer proximity to the wall result in higher total displacements and larger effective principal stresses, whereas increasing the relative distance or moving the load farther from the wall reduces structural demand.

Parametric studies highlighted that FEM is a reliable and effective tool for capturing the nonlinear soil–structure interaction and for optimizing strut wall design under varying construction and loading conditions. Finite element analyses were carried out to evaluate the influence of the relative distance of the distributed load on the strut–diaphragm wall system, keeping all other parameters constant. Analyses were performed for relative distances of 5, 10, and 15 m and uniform distributed loads of 5, 10, and 15 kN/m²/m. The results show that smaller relative distances (closer to the wall) lead to higher total displacements and larger effective principal stresses. For example, for a particular load case, the total displacement reached 0.068 m at a relative distance of 5 m, whereas it decreased slightly to 0.066 m at a relative distance of 15 m. This indicates that increasing the relative distance reduces both displacement and stress, improving the overall stability of the system. The effect of the absolute distance of the distributed load from the diaphragm wall was studied for distances of 2, 4, and 6 m, with loads of 5, 10, and 15 kN/m²/m. The results indicate that loads applied closer to the wall generate higher total displacements and larger effective principal stresses. For instance, for one scenario, the total displacement was 0.068 m when the load was 2 m from the wall, decreasing to 0.066 m when the load was positioned 6 m away. This demonstrates that increasing the distance from the wall reduces structural demands, resulting in lower displacements and stress concentrations.

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