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Numerical study on stability and deformation of retaining wall according to groundwater drawdown

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Abstract. In this study, the ground settlement in backside of retaining wall and the behavior of the retaining wall were analyzed according to the method of groundwater drawdown due to excavation by using two-dimensional(2D) finite element analysis. Numerical analysis was performed by applying 1) fixed groundwater level, 2) constant groundwater drawdown, and 3) transient groundwater drawdown. In addition, the behavior of the retaining wall according to the initial groundwater level, ground conditions, and surcharge pressure in backside of retaining wall was evaluated. Based on the numerical analysis results, it was confirmed that the initial groundwater level is at 0.5H from the ground surface (H: Excavation soil height), the wall displacement and ground settlement are not affected by the method of groundwater drawdown, regardless of soil conditions (dense or loose) and surcharge pressure. On the other hand, when the initial groundwater level is at 0.1H from the ground surface, the method of groundwater drawdown was found to have a significant effect on wall displacement and ground settlement. In this case, the difference in ground settlement presents by up to 4 times depending on the method of groundwater drawdown, and the surcharge load could increase the ground settlement by up to 1.5 times.

Keywords: adjacent ground settlement; excavation; finite element method; groundwater drawdown; retaining wall

1. Introduction

The rapid growth of population and urban development has led to numerous deep excavation projects for high-rise buildings and subways. In Korea, deep excavation and tunnel construction are subject to the Special Law on Underground Safety Management in 2018 to prevent damage caused by excavation work. To facilitate the prediction of ground settlement due to deep excavation, which is a crucial task in conducting an underground safety impact assessment, Park (2018) proposed a settlement evaluation chart.

The process of deep excavation alters the stress state around the excavation site, resulting in subsequent deformations of retaining walls and ground movements that can strain adjacent properties. The extent and magnitude of these movements depend on various factors such as soil profile, excavation geometry, wall type, supporting system, and construction process, as reported in previous studies (Ou *et al.* 1998; Poh and Wong 1998, Wong and Poh 2000, Zhang *et al.* 2015, 2018a). With the increasing number of construction activities in urban environments, public concerns regarding the potential impact on their properties have also grown. Many studies have investigated the wall and ground movements associated with excavation, including settlement envelope near the ground, ground movements behind the wall, and the apparent influence range to assess the damage to adjacent properties (Clough and O'Rourke 1990, Ou *et al.* 1993; Hsieh and Ou 1998, Goh *et al.* 2017b, Bahrami *et al.* 2018, Zhang *et al.* 2018b, Li *et al*. 2022). Studies on the analysis of groundwater level have been carried out in the field of temporary earth retaining structures or tunnels. Furthermore, various types of research have been conducted for underground excavations such as tunnels, indirectly considering the groundwater level (Yang *et al.* 2007, Shin *et al.* 2005, Yoo *et al.* 2004). Generally, the effect on the groundwater level has been analyzed for various factors (Kim *et al.* 2011, Lee *et al.* 2007), but comparative research on the methods of lowering the groundwater level is insufficient. Additionally, Jang (2007) conducted a study comparing the unsteady flow behavior, considering time, with the design water pressure by numerical analysis for retaining structures. However, studies on behavior analysis considering various influencing factors are limited.

The study examined the behavior of the retaining wall and the ground settlement on the backside of the structure in terms of groundwater drawdown caused by excavation using two-dimensional (2D) finite element analysis. Three

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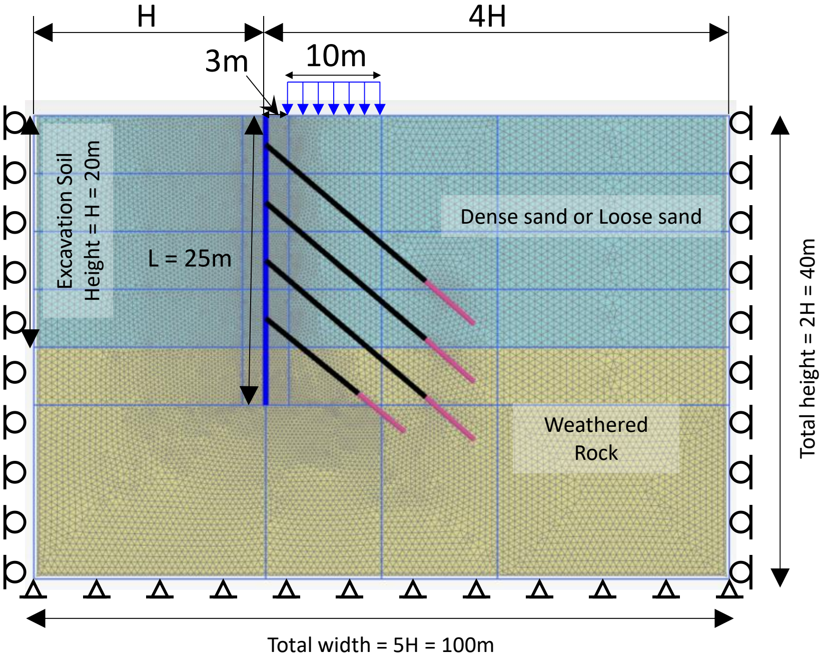


Fig. 1 Typical 2D FE model for a retaining wall and earth anchor

types of groundwater drawdown were used in the numerical analysis: a fixed groundwater level, constant groundwater drawdown, and transient groundwater drawdown.

2. Finite element analysis

The main objective of the numerical analysis was to investigate the effect of controlled groundwater conditions on wall displacement in dense (or loose) sand and weathered rock, as well as to evaluate any ground settlement nearby due to excavation. The numerical approach offered a significant advantage over in-site and laboratory experiment due to its ability to more precisely control test parameters. To analyze the behavior of the retaining wall, a numerical method that could accurately predict wall displacement and nearby ground settlement while considering groundwater conditions was needed. The numerical analysis also took the excavation process into account.

2.1 FE mesh and boundary conditions

The earth anchor is modeled using a node to node anchor and embedded beam element, while the retaining wall is modeled using a plate element under two-dimensional (2D) plane strain conditions. The numerical analysis utilizes the commercial FE software PLAXIS 2D (2022). The typical 2D FE model used in this study is shown in Fig. 1. The soil and rock are composed of 15-node triangular elements, while the retaining wall is modeled using 5-node plate elements. The model employs fourth-order interpolation for displacements and twelve Gauss points for numerical integration (stress points). The interfaces consist of five pairs of 10-node interface elements that can connect with 15-node soil elements.

The numerical model has a total height equal to the height of the retaining wall (L) plus an additional 0.7L below the retaining toe level, and extends four times the excavation width (H) from the retaining wall center. These dimensions were chosen to minimize boundary effects on the retaining wall's behavior. A finer mesh was used near the retaining wall and surrounding soil interface, while a coarser mesh was used further away. The typical retaining wall had a width of 0.3 m and a length of 25 m. The bearing end of the wall was on weathered rock and continued into a layer of dense or loose sand. The mesh consisted of 217,419 nodes and 26,797 fifteen-node triangular elements.

Assuming a rigid, unyielding strata, such as a rock layer, the vertical boundaries are allowed to move only in the vertical direction, while the bottom boundary is fixed in both the horizontal and vertical directions. The initial stress distributions were matched with a calculation based on the material's weight. After the first phase, soil lifts were removed to simulate excavation. For retaining walls of 5, 10, 15, and 20 m, the soil was removed in 1, 2, 3, and 4 steps, respectively. Earth anchors were installed simultaneously with the incremental excavation.

2.2 Constitutive model and material parameters

In contrast to the surrounding soil and rock layer, which are modeled using a non-associated Mohr-Coulomb flow rule, the retaining wall is modeled as a linear-elastic material. This study simulated the ground settlement of soil layers using Mohr-Coulomb constitutive models of soils, which are commonly used in finite element modeling of retaining structures (Potts and Fourie, 1984; Day and Potts, 1993, Grande *et al.* 2002, Jeong and Seo 2004, Karlsrud and Andresen 2005, Krabbenhoft *et al.* 2005, Tan and Paikowsky 2008).

Using the bilinear Mohr-Coulomb model, the retaining wall-soil contact is simulated with an interface element (Kim and Jeong 2011). The element at the interface is processed as a virtual thickness zone. Prior to slipping, it behaves as if it shares the same material properties as the nearby soil elements. When slippage occurs on the interface element, a lower shear modulus value is assigned to it. A strength reduction factor R_{inter} in PLAXIS represents the reduction of the interface element's strength. The following equation is used to determine the interface properties.

$$c_{inter} = R_{inter} c_{soil}, \tan \phi_{inter} = R_{inter} \tan \phi_{soil} \qquad (1)$$

where c_{inter} and ϕ_{inter} are the cohesion and friction angle of the interface, respectively, and c_{soil} and ϕ_{soil} are the cohesion and friction angle of the soil mass, respectively.

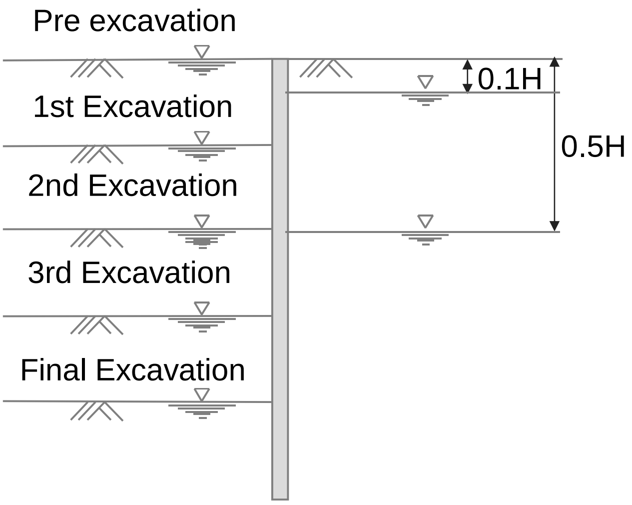
2.3 Numerical simulation procedure

In the numerical simulation procedure of this study, the initial stress distribution of the soil and rock was set in the initial stage, followed by the installation of the retaining wall in the next stage. Then, the first-stage excavation was performed, and simultaneous first-stage earth anchors were installed. The numerical analysis process for the groundwater level was applied differently for each condition, as shown in Fig. 2.

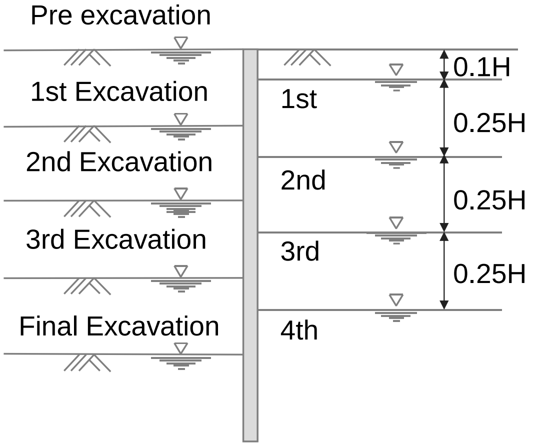
Under the fixed groundwater level condition, the numerical analysis was performed while assuming that the position of the initial groundwater level remained unchanged at each excavation stage, and there was no groundwater runoff due to excavation. Under the constant groundwater drawdown condition, numerical analysis was performed while lowering the groundwater level to a constant depth for each excavation stage, assuming that there was groundwater runoff. Finally, under the transient groundwater drawdown condition, the numerical analysis was performed with a parabolic drop in the groundwater level at each excavation stage, assuming that there was groundwater runoff. The parabolic shape was described by fixing the starting point of the groundwater level and the location of the excavation stage in the same way as Caspe's settlement formula (1966).

2.4 Validation of FE Analysis

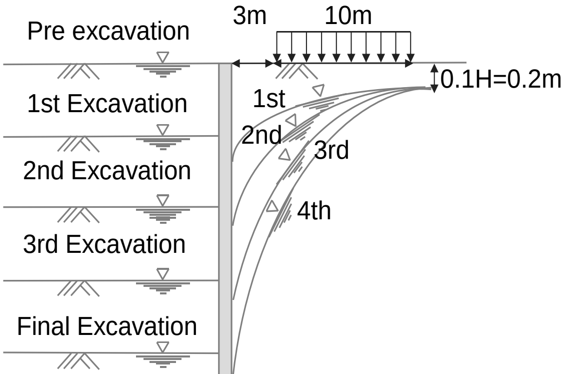
To validate the FE analysis for excavation in this study, field monitoring data was adopted and compared with predicted results using the FE analysis. The excavation depth was 20 m with four stages of excavation and three level of earth anchor at of 3, 8.2, 12.8 m. The ground profile showed five layers, including three sandy soil layers and two rock layers. The material parameters for the FE analysis were the same as those given in site investigation. The elastic modulus (E) values for the sand and rock layers were in the range of 15~50 and 100~500 MPa, respectively. The internal friction angle (ϕ′), cohesion (c′), and Poisson's ratio (ν) were equal to 26°~35°, 0 kPa, and 0.3 for the sand layers and 35°~40°, 30~40 kPa, and 0.25 for rock layers, respectively. Fig. 3 shows the lateral wall deflection profiles measured from the field monitoring and predicted using the FE analysis. As compared in Fig. 3, close agreements were observed between the measured and the FE predicted results in the displacement profile shape and magnitude.



(a) Fixed groundwater level



(b) Constant groundwater drawdown



(c) Transient groundwater drawdown

Fig. 2 Numerical simulation procedure in this study

Table 1 Material properties used in the analyses

Type	γ (kN/m^3)	E (MPa)	ϕ	c (kPa)	ν	R_{inter}	Model
Dense sand	20.0	50	35	0	0.3	0.67	M.C
Loose sand	18.0	15	30	0	0.3	0.67	M.C
Weathered rock	21.0	150	40	35	0.25	1.0	M.C
Retaining wall	50	51,683 EA: 6,785,913 kN	-	-	0.2	1.0	L.E
Earth anchor	75	204,000 EA: 30,136kN	-	-	0.2	1.0	L.E

*M.C: Mohr-Coulomb, L.E: Linear Elastic, EA : Elastic modulus × Area

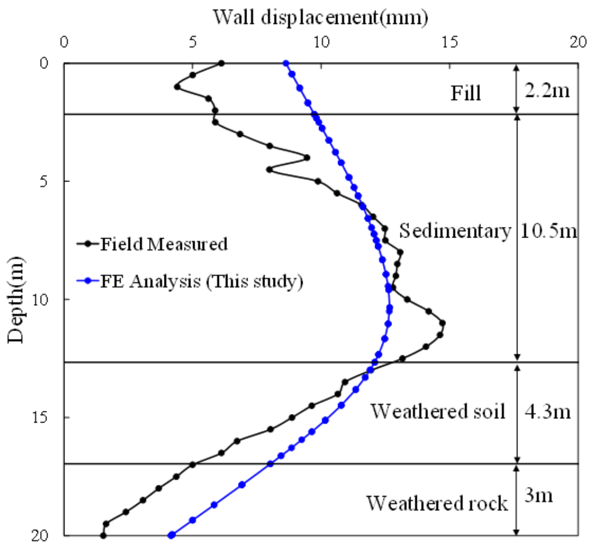


Fig. 3 Measured and FE predicted results

3. Parametric study

A comprehensive parametric study was conducted to investigate the impact of wall displacement on the retaining wall and surrounding ground settlement. The study involved a series of FE analyses on a retaining wall in dense (or loose) sand and weathered rock, under different groundwater conditions, including 1) fixed groundwater level, 2) constant groundwater drawdown, and 3) transient groundwater drawdown. Additionally, numerical analysis was performed with and without surcharge pressure on the back of the retaining wall. Tables 1 and 2 describe the parametric material properties used in the analysis studies.

3.1 Without surcharge pressure (No P) – 0.1H

Fig. 4(a) shows the wall displacement versus the soil depth for several groundwater conditions (fixed, constant and transient; initial groundwater level: 0.1H) and soil conditions (dense and loose). The largest wall displacements were observed for both loose and dense sand under fixed groundwater conditions. It was confirmed that the denser the sand, the smaller the displacement of the wall because of the greater soil stiffness. Fig. 4(b) represents the adjacent ground settlement under various conditions on the retaining wall's backside. Similar to the characteristics of wall displacement, the largest ground settlement was observed in the fixed groundwater condition for both loose and dense sand. However, unlike the characteristics of wall displacement, it was found that there was no significant difference in settlement between the constant condition and the transient condition under dense sand.

Table 2 Summary of numerical analyses conducted

Parameters	Case
Soil conditions	Dense, Loose
Surcharge pressure (kPa)	24, 0
Initial groundwater level	Ground level(G.L) – 0.1H, -0.5H
Method of groundwater drawdown	Fixed, Constant, Transient

3.2 With surcharge pressure(P) – 0.1H

Fig. 5(a) shows the wall displacement versus the soil depth for several groundwater conditions (fixed, constant and transient; initial groundwater level: 0.1H) and soil conditions (dense and loose) with surcharge pressure. The largest wall displacements were observed for both loose and dense sand under fixed groundwater conditions.

Unlike the results without surcharge pressure, it was confirmed that the difference in wall displacement according to the soil condition was not large under the constant groundwater condition and the transient groundwater condition. It was also confirmed that the displacement of retaining wall appeared large under the condition of the groundwater level fixed at the upper part due to the influence of the surcharge pressure.

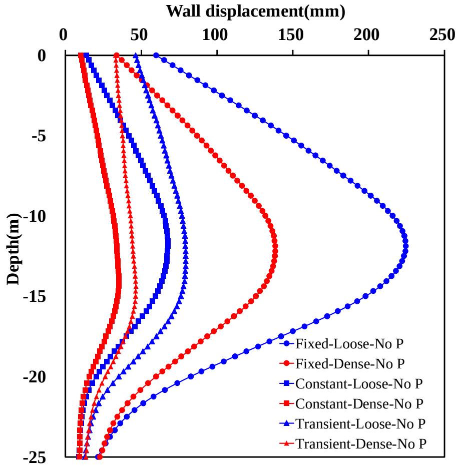
According to various conditions, the adjacent ground settlement is represented in Fig. 5(b) on the retaining wall's backside. It was confirmed that there was a significant difference in adjacent ground settlement according to the ground conditions and groundwater level conditions due to the influence of surface surcharge pressure. In addition, it was found that the adjacent ground settlement was up to 1.5 times larger than the case without surcharge pressure.

3.3 Without surcharge pressure – 0.5H

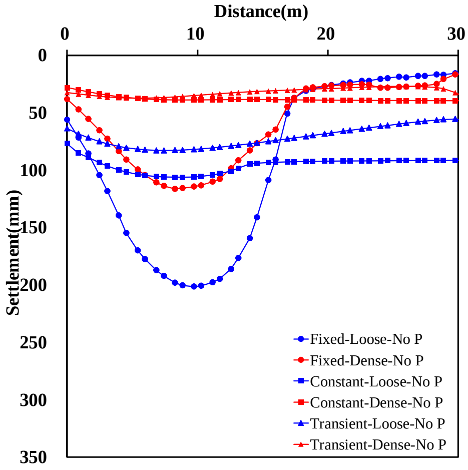
Fig. 6(a) displays the relationship between soil depth and wall displacement for multiple groundwater conditions (fixed, constant, and transient) and soil conditions (dense

Table 3 Maximum wall displacement Unit : mm

Wall displacement		0.1H		0.5H	
		Pressure	No Pressure	Pressure	No Pressure
Fixed	Loose	247	224	68	58
	Dense	146	138	37	29
Constant	Loose	87	67	75	62
	Dense	41	35	42	34
Transient	Loose	82	79	66	60
	Dense	46	46	41	33

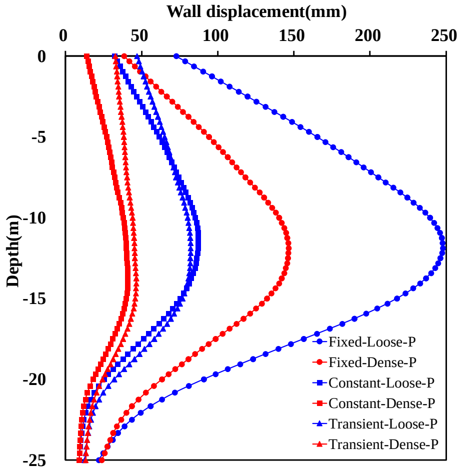


(a) Wall displacement

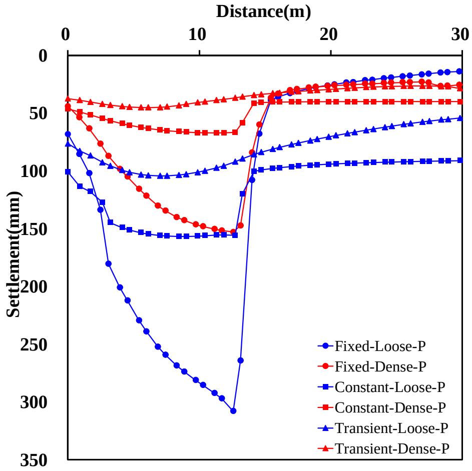


(b) Ground settlement

Fig. 4 Results of without surcharge pressure – 0.1H



(a) Wall displacement



(b) Ground settlement

Fig. 5 Results of with surcharge pressure – 0.1H

and loose) with an initial groundwater level of 0.5H located at the excavation surface's center. The study concluded that while the groundwater level condition had minimal impact on wall displacement under the 0.5H condition, ground conditions significantly affected wall displacement.

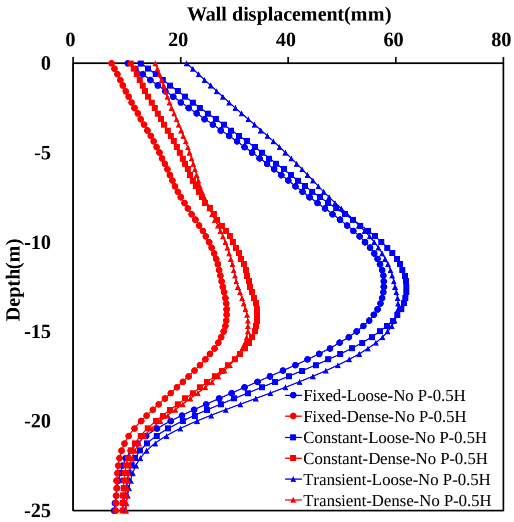
Fig. 6(b) show the adjacent ground settlement on the retaining wall's backside under various conditions. The study verified that the ground conditions had a greater impact on adjacent ground settlement than the groundwater level condition, particularly when the groundwater level was situated near the wall's toe at 0.5H.

3.4 With surcharge pressure – 0.5H

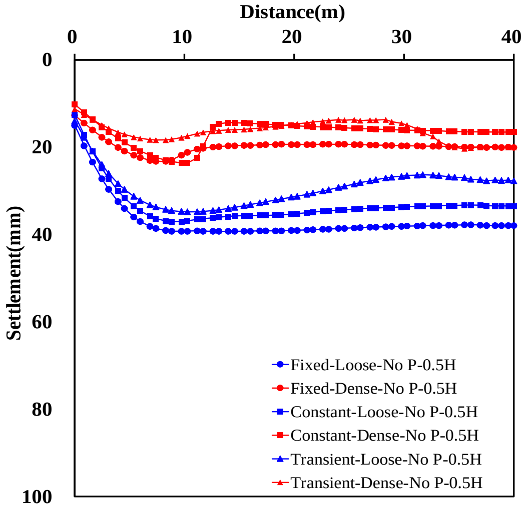
Fig. 7(a) shows the relationship between wall movement and soil depth for different groundwater and soil conditions with surcharge pressure, starting at a groundwater level of 0.5H. Fig. 7(b) illustrates the adjacent ground settlement under various conditions. The study found that wall movement and ground settlement were more significant with surcharge pressure than without. However, since the groundwater level was close to the final excavation surface, the study confirmed that ground conditions had a more significant impact than the groundwater level.

Table 4 Maximum ground settlement Unit : mm

Ground Settlement		0.1H		0.5H	
		Pressure	No Pressure	Pressure	No Pressure
Fixed	Loose	308	202	76	39
	Dense	153	116	43	23
Constant	Loose	157	106	77	37
	Dense	67	40	42	23
Transient	Loose	117	119	59	34
	Dense	69	71	39	20

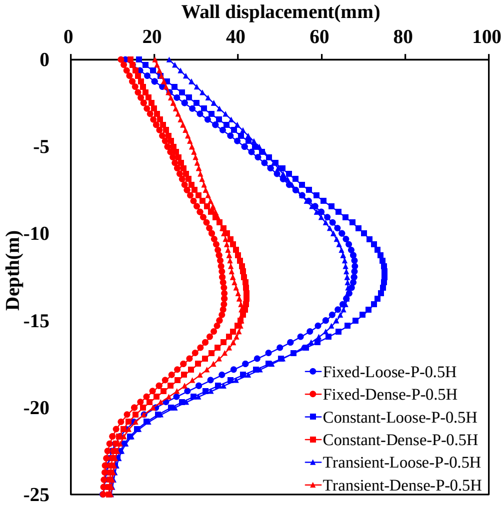


(a) Wall displacement

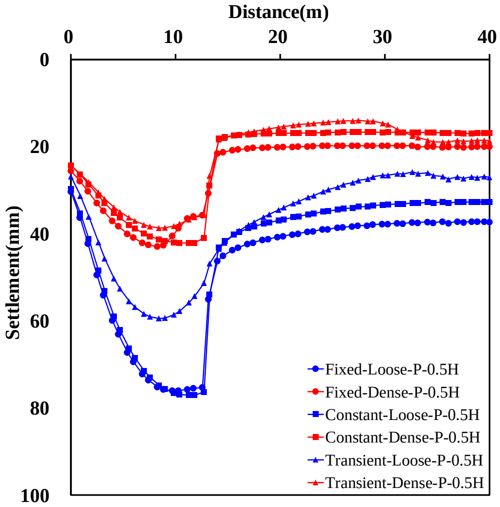


(b) Ground settlement

Fig. 6 Results of without surcharge pressure – 0.5H



(a) Wall displacement



(b) Ground settlement

Fig. 7 Results of with surcharge pressure – 0.5H

4. Results and discussion

Table 3 shows a comprehensive summary of maximum wall displacements. It can be seen that the difference in wall displacement according to the presence or absence of surcharge pressure is large in the order of fixed groundwater, constant groundwater, and transient groundwater conditions. It can be seen that the difference in wall displacement according to the soil conditions is also large in the order constant groundwater, fixed groundwater, and transient groundwater conditions. This result show that when the water table is fixed, the pressure exerted by the water significantly increases the displacement of the wall. However, if the water table is consistently lowered, the effect of water pressure is reduced, resulting in less displacement of the wall. Additionally, in transient cases, the effect of water pressure on the wall due to the lowering of the water table is found to be the smallest. These findings provide valuable insights for ensuring safe and effective excavation practices, particularly with regard to the planning and implementation of appropriate measures to mitigate the impact of water pressure on diaphragm wall excavation.

Table 4 shows a comprehensive summary of maximum adjacent ground settlement. It can be seen that the difference in wall displacement according to the presence or absence of surcharge pressure is large in the order of constant groundwater, fixed groundwater, and transient groundwater conditions. This is equivalent to the results of maximum wall displacement. However, it was found that the maximum adjacent ground settlement difference according to the soil conditions depended on the constant groundwater, transient groundwater conditions, and fixed groundwater in the order.

5. Conclusions

This study's primary objective was to examine into how retaining walls affected by loose or dense sand and weathered rock are affected by wall displacement. To investigate the effects of groundwater conditions and ground surcharge pressure on the backside of the retaining wall, a series of 2D finite element studies were performed. These conclusions can be drawn in consideration of the study's findings.

- The study found that denser soil results in smaller wall displacement and that ground conditions have a more significant impact than groundwater levels on wall displacement and adjacent ground settlement.
- The difference in the ground settlement depending on the groundwater level is up to about 4 times different, so the initial groundwater level is important during excavation.
- Surcharge pressure was found to have a significant impact on wall movement and ground settlement, causing adjacent ground settlement to increase by up to 1.5 times.
- It was confirmed that the effect on the surrounding structures was very important as the difference in ground settlement was larger than the wall displacement in the review according to the ground condition.
- Therefore, depending on the initial groundwater level, the method of the groundwater drawdown should be considered.

Acknowledgments

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