European Journal of
Engineering and Applied Sciences

ISSN: 2651-3412 (Print) & 2667-8454 (Online)
Journal homepage: http://dergipark.gov.tr/EJEAS
Published by Çorlu Faculty of Engineering, Tekirdağ Namık Kemal University

European J. Eng. App. Sci. 7(1), 35-43, 2024

Research Article

Investigation of the Contribution of First Row Rock Anchors to the Retaining System by Variation of Anchor Bond Length

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Geliş: 24.05.2024 *Kabul: 08.07.2024* *DOI: 10.55581/ejeas.1485894*

Abstract: In deep foundation excavations, inclined, prestressed soil/rock anchors are commonly used as lateral support elements. During the construction of multi-row anchored excavation systems, sometimes it may not be possible to manufacture anchors in the first row. This situation is often encountered in the production of rock anchors. The presence of discontinuities, karstic voids, and/or historical water channels in the rock environment where these anchors will be manufactured, hinders the injection of the anchor bond length. Additionally, the presence of hard rock units or igneous intrusions in the rock environment prevents the anchor hole from being drilled to the desired length. The application of anchors that could not be drilled to the desired length or those that could not achieve the desired quality of bond zone injection is canceled and usually left as an empty hole. In this study, the usability of canceled rock anchors in the first row, as at least anchors with a short bond length has been investigated. A rock anchor designed to support a 5.0-meter excavation pit to be created in a weathered rock environment, with a prestressing load of 500 kN and a bond length of 6.0 meters, was analyzed using Plaxis 3D software for situations with shorter bond lengths. Accordingly, the function of the related rock anchor can also be fulfilled by an anchor with a bond length of 4.0 meters. When the bond length is 4.0 meters, the entire anchor bond length operates at full efficiency. In anchors with bond lengths smaller than 4.0 meters, the prestressing load of 500 kN causes pull-out failure. However, for example, an anchor with a bond length of 2.0 meters continued to contribute to the overall stability of the retaining system under the effect of a prestressing load of 250 kN.

Keywords: *Retaining wall, Rock anchor, Anchor bond length, Efficiency, Plaxis 3D, Overall slope stability.*

İlk Kademe Kaya Ankrajlarının İksa Sistemine Katkısının Ankraj Kök Boyu Değişimi İle İncelenmesi

Öz. Derin temel çukuru kazılarında, yatay destek elemanı olarak eğimli, öngermeli zemin/kaya ankrajları yaygın olarak kullanılmaktadır. Çok sıra ankrajlı iksa sistemlerinin inşaası sırasında, bazen ilk kademede bulunan ankrajların imalatı mümkün olmamaktadır. Bu durum genellikle, kaya ankrajlarının üretiminde karşılaşılır. Bu ankrajların imal edileceği kaya ortamında, ayrışma süreksizliklerinin, karstik boşlukların ve/veya tarihi su kanallarının olması, ankrajın kök enjeksiyonunun yapılmasına engel olmaktadır. Ayrıca, kaya ortamındaki sert birimlerin veya magmatik sokulumların varlığı ankraj delgisinin istenilen uzunlukta yapılmasına mani olmaktadır. İstenilen uzunlukta delinememiş veya istenilen kalitede kök enjeksiyonuna sahip olamayacağı düşünülen ankrajların uygulaması iptal edilmektedir ve genellikle boş bir delgi çukuru olarak bırakılmaktadır. Bu çalışmada, ilk kademede bulunan iptal edilmiş kaya ankrajlarının en azından kısa köklü ankrajlar olarak kullanılabilirliği incelenmiştir. Ayrışmış kaya ortamında oluşturulacak 5.0 metre'lik bir kazı çukurunu desteklemek üzere tasarlanmış, 500 kN öngerme yüküne ve 6.0 metre kök uzunluğuna sahip bir kaya ankrajının, daha kısa kök uzunluklarına sahip olduğu durumlar Plaxis 3D yazılımı ile analiz edilmiştir. Buna göre, ilgili kaya ankrajının işlevi, 4.0 metre kök uzunluğuna sahip ankraj tarafından da karşılanabilmektedir. Kök uzunluğunun 4.0 metre olduğu durumda ankraj kökünün tamamı tam verimle çalışmaktadır. 4.0 metreden daha kısa kök boyuna sahip ankrajlarda, 500 kN'luk öngerme yükü sıyrılma

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yenilmesine sebep olmaktadır. Fakat, örneğin, 2.0 metre kök uzunluğuna sahip bir ankraj, 250 kN'luk öngerme yükü ile iksa sisteminin toptan göçme güvenlik katsayısını arttırarak, iksa sistemine katkı vermeyi sürdürmüştür.

Anahtar kelimeler: *İksa perdesi, Kaya ankrajı, Ankraj kök boyu, Verim, Plaxis 3D, Toptan göçme.*

1. Introduction

Inclined ground/rock anchors are one of the lateral support elements used for the safe continuation of deep excavations. Ground/rock anchors operate on the principle of transferring the prestressing load (T_w) applied to them to the supporting ground behind the sliding surface. These horizontal support elements are designed to minimize the movement of vertical support walls located at the excavation boundary. A ground/rock anchor consists primarily of three main parts: 1) the anchor prestressing zone where the prestressing load is applied to the cables in the anchor; 2) the anchor unbonded zone, which is the part without injection where the anchor load is transferred to the back of the anchor with steel cables; 3) the anchor bond zone, where the anchor cables are bonded with cement injection, producing frictional resistance with the surrounding ground [1].

Ground/rock anchors provide their resistance from the anchor bond zone. The bond body, consisting of cement grout and steel cables, generates frictional stress (p_b) by friction with the surrounding ground. The development of this stress is as follows from the initial application of T_w load on the anchor: In the initial moments of the applied T_w load, this load is resisted by the upper bond zone, increasing the p_b value in this region. With an increase in the applied T_w load, the stress in the upper bond zone reaches its maximum value (peak), then yielding and dropping to a residual value. After this point, the resistance of the anchor bond zone gradually shifts downward (Figure 1). As indicated, the stress distribution in the anchor bond zone is at residual in some regions and peak in others [1].

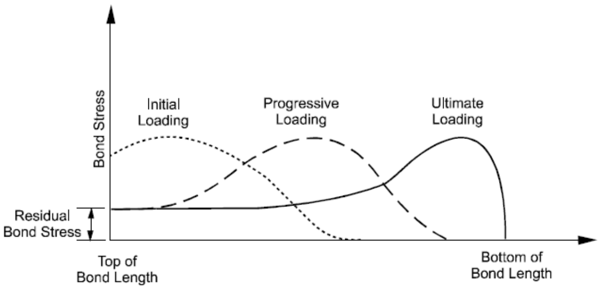


Figure 1. *Mobilization of bond stress for ground/rock anchors [1]*

The widely used standard for the design of ground/rock anchors worldwide is FHWA-IF-99-015 (1999). According to this standard, the bond length (L_b) of anchors to be installed in rock media should be a minimum of 3.0 meters and a maximum of 10.0 meters. Since the recommended minimum L_b value is limited to 3.0 meters, the production of anchors with a shorter bond length is not common. Therefore, there is a lack of sufficient studies on anchors with short bond length in the literature.

As the L_b of the ground/rock anchors increases, the load carrying capacity does not show a linear increase. When the L_b value of the anchor is long, the stress distribution along the bond zone remains at residual over a wide region, as shown in Figure 1. Consequently, as the L_b value increases, the efficiency of the anchor decreases (Figure 2) [2,3]. This phenomenon is also observed in the p_b value between the anchor and the soil [4].

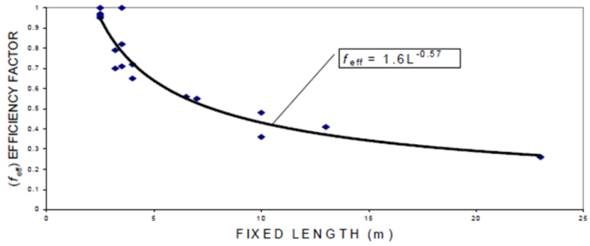


Figure 2. *The relationship between the load carrying efficiency of ground/rock anchors and the bond length (L_b) [2]*

In excavations for deep foundation pits, some of the ground/rock anchors, which serve as horizontal support elements, may not be manufactured in the dimensions specified in the project. This situation may arise due to encountering hard rock formations during anchor drilling, inability to form the anchor pit at the desired depth, or failure to achieve the desired performance of grouting in weak rock formations. As a result of such unforeseen circumstances, many anchors in excavation stages are canceled. The cancellation of anchors necessitates the revision of the excavation support project, adding additional time and cost to the project. The canceled anchors are usually left behind as abandoned boreholes (Figure 3) [5]. In this study, the load-bearing capacity and behavior of ground/rock anchors in shallow zones were investigated. The effects of using anchors with shorter L_b values under the existing anchor design load (T_{des}) on the excavation system were analyzed using Plaxis 3D software. Thus, the feasibility of using anchors with shorter L_b values in necessary cases has been examined.

Figure 3. *The canceled first row of anchors [5]*

2. Materials and Methods

2.1. Materials

In this study, five models were generated in Plaxis 3D software to investigate the effects of L_b on the behavior of the first row of anchors. Since the focus of the study is on the behavior of anchors in rock media, the soil type defined in the models simulates a moderately weathered greywacke unit. The soil parameters defined in the models are the values used by Yıldız and Berilgen (2020) for a moderately weathered greywacke unit. The rock unit, defined with the Mohr-Coulomb material model, had a dry unit weight ($\gamma_d=\gamma_{unsat}$) of 24 kN/m³, an internal friction angle ($\varnothing$) of 32°, a dilation angle (ψ) of 0°, a cohesion value (c) of 68 kPa, and an elastic modulus ($E=E_{ref}$) of 90 MPa [6]. It was assumed that there was no water effect in the soil, and analyses were conducted under dry and drained conditions (Table 1).

Table 1 Material properties of the rock

Parameter	Symbol	Value	Unit
Soil type		Moderately weathered greywacke	
Material model		Mohr-Coulomb	
Drainage condition		Drained	
Unsat. unit weight	γ_{unsat}	24	kN/m^3
Saturated unit weight	γ_{sat}	25	kN/m^3
Modulus of elasticity	E_{ref}	90000	kPa
Poisson's ratio	v	0,2	
Initial stress ratio	K_0	0,47	
Cohesion	c	68	kPa
Internal friction angle	$\varnothing$	32	°
Dilation angle	Ψ	0	°
Strength reduction fac.	R_{inter}	1	

A reinforced concrete diaphragm wall has been chosen as the retaining wall, and this element has been modeled as a plate element in Plaxis 3D. The height (h) of the wall is 7.0 meters, the thickness (d) is 1.0 meter, and the depth (l) is 3.0 meters. Interface elements have been assigned on the surfaces where the wall contacts the soil on both sides. A negative interface is defined on the surface facing the excavation pit, and a positive interface is defined on the surface facing the anchor (Table 2).

Table 2 Properties of the diaphragm wall

Parameter	Symbol	Value	Unit
Element type		Plate	
Material type		Elastic	
Unit weight	γ	24	kN/m^3
Mod. of elasticity	E	30	GPa
Poisson's ratio	v	0,15	
Section type		Rectangular prism	
Height	h	7	m
Thickness	d	1	m
Depth	l	3	m

The anchor bond zone was modeled as an embedded beam element in Plaxis 3D software. The anchor bond's unit weight (γ) is defined as 24 kN/m³, elastic modulus (E) is 30 GPa, and diameter (D) is 0.127 meters (Table 3). The unbonded zone of the anchor is modeled as a node-to-node element in Plaxis 3D software. The axial stiffness (EA) of the anchor's unbonded zone is defined as 320×10^3 kN (Table 4).

Table 3 Material properties of the anchor bond zone

Parameter	Symbol	Value	Unit
Element type		Embedded beam	
Material type		Elastic	
Unit weight	γ	24	kN/m^3
Modulus of elasticity	E	30000	MPa
Section type		Circular	
Diameter	D	0,127	m
Axial surface resistance		Linear	
$T_{skin,\ start,\ max}$		280	kN/m
$T_{skin,\ end,\ max}$		0	kN/m
Tip resistance	F_{max}	0	kN

Table 4 Material properties of the anchor unbonded zone

Parameter	Symbol	Value	Unit
Element type		Node-to-node	
Material type		Elastic	
Axial stiffness	EA	320000	kN

2.2. Method

The model created in Plaxis 3D software was simulated to have a final excavation depth (H) of 5.0 meters to reflect near-surface (shallow) anchors. Upon reaching the final excavation level, all lateral loads will be resisted by the retaining wall and a single rock anchor. The retaining wall was dimensioned to accommodate all lateral loads as a cantilever. The additional contributions of the rock anchor to the existing stable condition were examined. In the first stage of the study, the pre-dimensioning of the retaining wall and anchor components was designed according to the criteria specified in the FHWA-IF-99-015 (1999) standard. According to this standard: The L_b of rock anchors should be in the range of 3.0-10.0 meters; the unbonded length of the anchor (L_{unb}) should be a minimum of 4.5 meters and should be offset from the sliding surface by a minimum of 1.5 meters or a distance equivalent to 1/5 of the wall height (h); The embedded length of the retaining wall should be selected to withstand lateral loads as a cantilever element until the anchors are mobilized. Pre-dimensioning calculations were made based on the active soil pressure condition. The potential inclination angle (α) of the sliding surface was calculated as 61° using Equation (1) suggested by Rankine (1857) to determine the sliding surface in the active state [7].

$$\alpha = 45 + \frac{\varnothing'}{2} \quad (1)$$

Here: $\emptyset'$, the effective internal friction angle, was used as 32° in the model (Table 1). A surcharge load (p_v) of 25 kPa was applied to the top surface of the model. This load can be considered as a light external load or as an additional overburden load of 1.0 meter. The coefficient of active earth pressure (K_a) was determined as 0.307 using Equation (2) [7].

$$K_a = tan^2\left(45 - \frac{\emptyset'}{2}\right) \tag{2}$$

At the final excavation level, the active earth pressure (p_{soil}) acting on the retaining wall was determined using Equation (3), which provides the uniform stress distribution envelope suggested by Terzaghi and Peck (1967) and Peck (1969) for sands [8,9].

$$p_{soil} = 0.65 \times K_a \times \gamma \times H \tag{3}$$

Here, K_a represents the coefficient of active earth pressure, γ indicates the unit weight of the soil, and H denotes the excavation depth. Accordingly, the value of p_{soil} acting on the retaining wall was determined as 23.9 kPa for the values K_a = 0.307, γ = 24 kN/m³, and H = 5.0 meters. The lateral surcharge pressure (p_{sur}) created by the vertical surcharge load (p_v) of 25 kPa on the retaining wall was calculated as 7.7 kPa using Equation (4).

$$p_{sur} = p_v \times K_a \tag{4}$$

The total lateral pressure (p_{sum}) acting on the retaining wall is calculated as 31.6 kPa using Equation (5).

$$p_{sum} = p_{soil} + p_{sur} \tag{5}$$

In the Plaxis 3D model, the depth (l) of the soil was created as 3.0 meters. Therefore, the horizontal distance (S_h) that the anchor is responsible for carrying is equal to this value. The total lateral force acting on the surface by the excavation depth (H) of 5.0 meters and the horizontal distance (S_h) of 3.0 meters is determined using Equation (6) and this value is employed in determining the anchor load.

$$T = p_{sum} \times H \times S_h \tag{6}$$

Accordingly, the anchor load (T) was determined to be 474.0 kN for the values of p_{sum} = 31.6 kPa, H = 5.0 meters, and S_h = 3.0 meters. Since the anchor is inclined at a given angle (i), Equation (7), which gives the component of the anchor load (T) along the direction of the anchor, defines the anchor design load (T_{des}) value.

$$T_{des} = \frac{T}{\cos\ (i)} \tag{7}$$

For an anchor with i = 15° and T = 474.0 kN, the T_{des} value was determined to be 490.7 kN. The anchor will resist this load with the frictional resistance between the outer surface of the bond zone and the soil. The L_b of the anchor is determined to provide this resistance. The p_b value between the weathered sandstones and the anchor bond zone is recommended to be in the range of 700-800 kPa according to FHWA-IF-99-015 (1999). The L_b of the anchor is determined as the value that satisfies Equation (8).

$$T_{des} \times FS = \pi \times D \times L_b \times p_b \tag{8}$$

Here, T_{des} represents the anchor design load, FS is the factor of safety, D is the diameter of the anchor bond, L_b is the bond length of the anchor, and p_b is the frictional stress between the anchor bond and the soil. Accordingly, the L_b of the anchor was determined to be 5.3 meters for the values of T_{des} = 490.7 kN, FS = 3, D = 0.127 m, and p_b = 700 kPa.

Based on the calculations provided above, in the main model (M1) in Plaxis 3D, an anchor prestressing load (T_w) of 500 kN was selected to be compatible with the T_{des} load, with the L_b as 6.0 meters, and the L_{unb} as 5.0 meters (Figure 4). In models M2 and M3, the L_b was reduced to 5.0 and 4.0 meters, respectively. In model M4, the L_b was reduced to 3.0 meters, and the T_w was reduced to 400 kN. In model M5, L_b was reduced to 2.0 meters, and the T_w was reduced to 250 kN (Table 5). In this way, the effects of the changes in the L_b were examined.

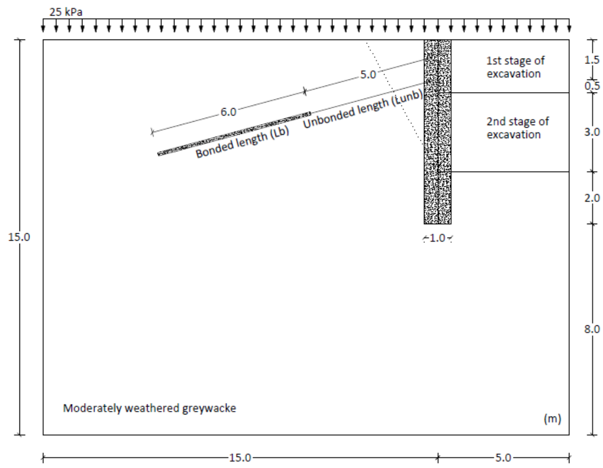
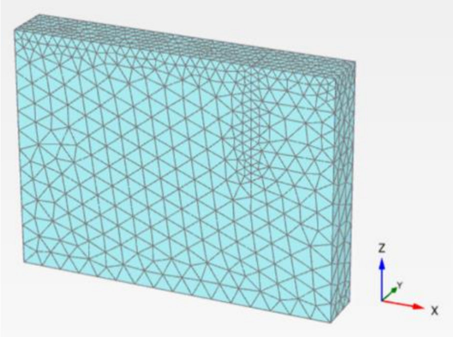


Figure 4. *Main model (M1) geometry*

Table 5 Properties of the anchors

Model name		M1	M2	M3	M4	M5
Anchor bond length	L_b (m)	6	5	4	3	2
Anchor unbonded length	L_{unb} (m)	5	5	5	5	5
Anchor prestress. load	T_w (kN)	500	500	500	400	250

The model created in Plaxis 3D was meshed with a medium element distribution. The mesh for the initial state of the M1 main model is shown in Figure 5a, while the mesh for the final excavation level is given in Figure 5b.



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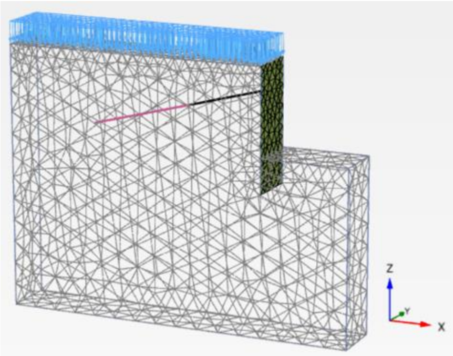


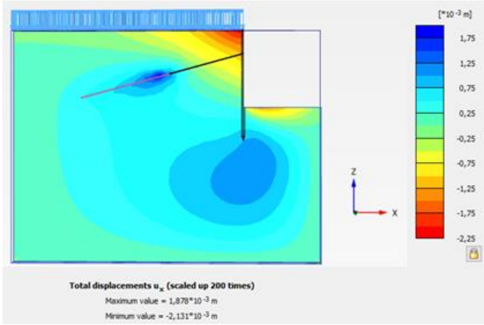
(b)

Figure 5. *Finite element mesh of the Plaxis 3D model. (a) Initial state, (b) Final excavation level*

3. Model Analysis Results

3.1. Displacements around the anchor bond zone (x-dir.)

In the M1 model consisting of a rock anchor with L_b = 6.0 meters and $T_w \approx T_{des}$ = 500.0 kN, as determined by the FHWA-IF-99-015 standard, it was found that the displacements (in x-direction) around the anchor bond zone concentrate in the first 4.0 meters of the bond zone, with the maximum displacement value in this zone being 1.88 mm (Figure 6a). Accordingly, the friction resistance developed between the soil and the outer surface of the bond body has evolved in the first 4.0 meters of the bond. The behavior that mobilizes the frictional resistance is provided by the relative displacement between the soil and the anchor bond zone. At the point where this displacement becomes excessive, the frictional resistance will be overcome. Therefore, it is understood that friction is not mobilized in the last 2.0 meters of the M1 model. Hence, in the second model (M2), the L_b of the anchor was reduced to 5.0 meters. Even in this case, it was found that approximately the first 4.0 meters of the anchor bond zone are mobilized, with the maximum displacement in this area being 1.97 mm (Figure 6b). In the M3 model, the L_b of the anchor was 4.0 meters. In this case, displacement development was achieved throughout the anchor bond zone, and the maximum displacement value was determined to be 1.90 mm. With the applied T_w of 500.0 kN in this model, it was observed that the entire anchor bond zone was mobilized, reflecting full efficiency (Figure 6c). In the M4 model, an attempt was made to reduce L_b of the anchor to 3.0 meters. However, the applied T_w of 500.0 kN resulted in anchor pullout failure. Therefore, the T_w value was reduced in this model. As a result, the anchor worked stably under a T_w of 400.0 kN. In this model as well, full-efficiency displacement development continued in the anchor bond zone, with the maximum displacement in the bond zone being determined as 1.72 mm (Figure 6d). In the M5 model, the L_b of the anchor was 2.0 meters. The T_w that stabilized this length was 250 kN. In this model too, the L_b worked at full efficiency, and the maximum displacement around bond was obtained to be 1.77 mm (Figure 6e).



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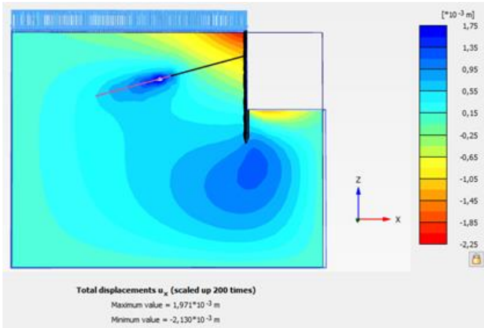

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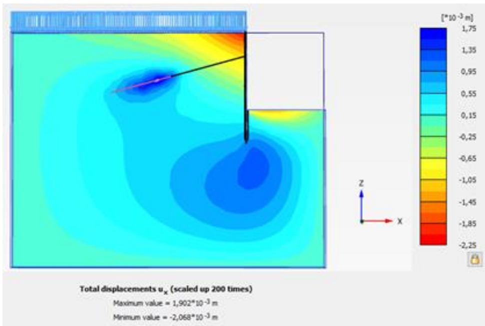

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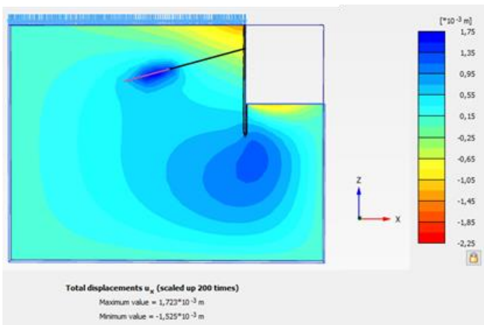

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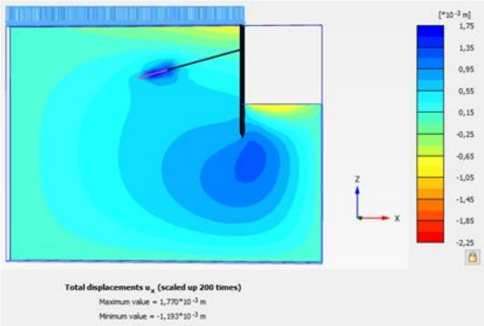
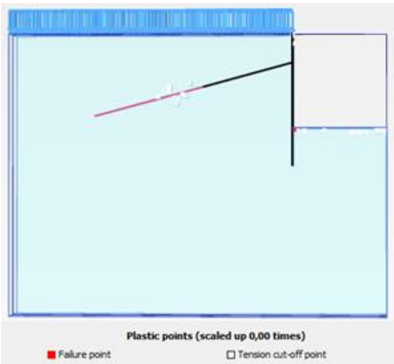


(e)

Figure 6. *Displacements around the anchor bond zone in Plaxis 3D models (in the x-direction).*
(a) M1 model, (b) M2 model, (c) M3 model, (d) M4 model, (e) M5 model

3.2. Plastic points around the anchor bond zone

In the models, plastic points formed around the anchor bond zone were identified as "tension cut-off plastic points" indicating points of failure due to tensile stresses. In regions along the bond zone where displacement accumulations have occurred, as in Figure 6, plastic points have become concentrated. In models M1 and M2, plastic points did not develop up to the lower end of the bond and clustered in the upper regions (Figure 7a, b). However, in models M3, M4, and M5, plastic points spread throughout the entire anchor bond zone (Figure 7c, d, e).



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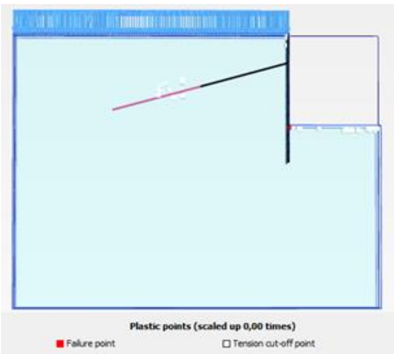

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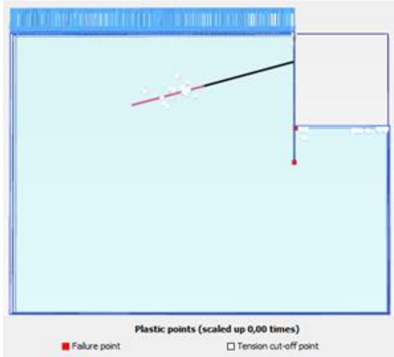

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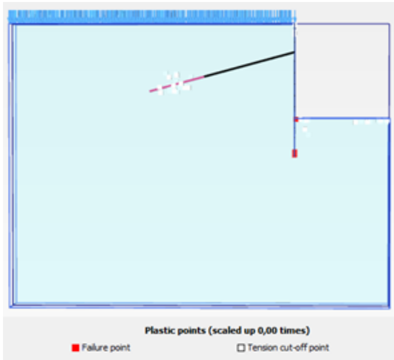

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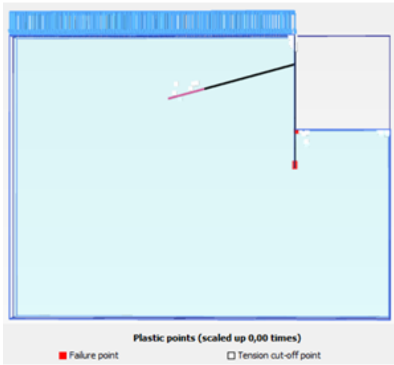
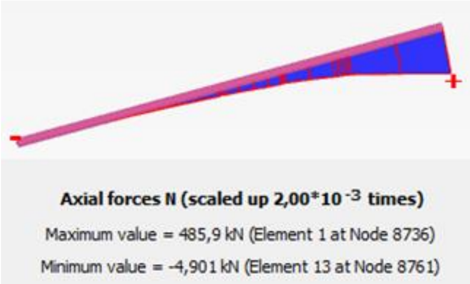


(e)

Figure 7. *Plastic points around the anchor bond zone in Plaxis 3D models.*
(a) M1 model, (b) M2 model, (c) M3 model, (d) M4 model, (e) M5 model

3.3. Axial forces along the bond zone

In the models, axial load *(N)* values corresponding to the T_w load applied to the anchor were determined along the anchor bond. Due to the effect of displacement changes on the axial load occurring in the bond zone, a difference between these two values can be observed [10]. In the M1 model, in response to the T_w of 500.0 kN applied to the anchor, a maximum axial load (N_{max}) of 485.9 kN has developed at the anchor bond zone. The proximity of these two values ($T_w \approx N_{max}$) indicates the accuracy of the assumed frictional stress (p_b) value between the soil and the bond body, chosen as 700 kPa in the preliminary calculation (Figure 8a). The ratio of the N_{max} value developed at the anchor bond zone to the T_w value was obtained as 0.95-0.97 (close to 1.00) in the M1, M2, M3, and M4 models, and as 0.78 in the M5 model (Figure 8) (Table 6).



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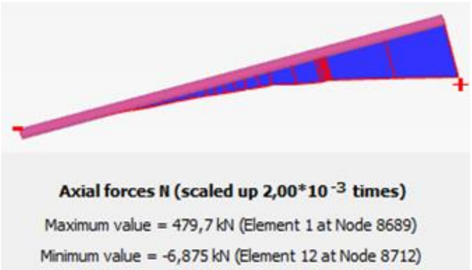

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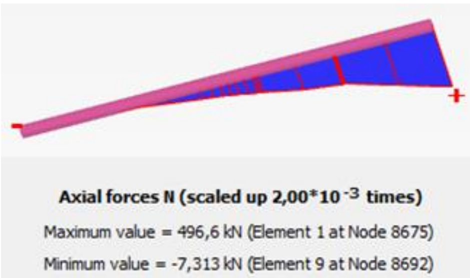

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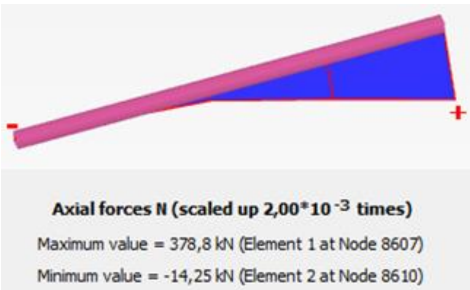
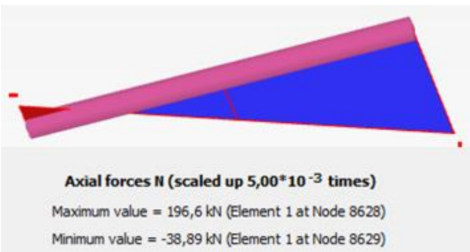


(d)



(e)

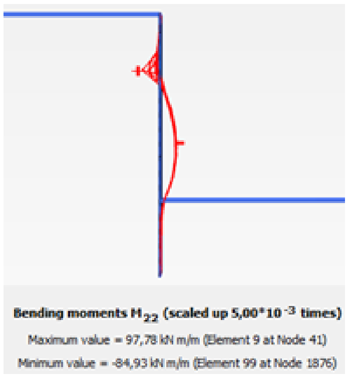
Figure 8. *Axial forces along the anchor bond zone in Plaxis 3D models.*
(a) M1 model, (b) M2 model, (c) M3 model, (d) M4 model, (e) M5 model

Table 6 Anchor axial forces obtained in the models

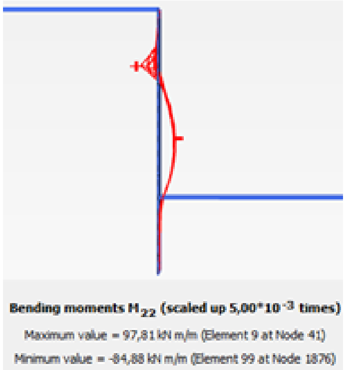
Model name		M1	M2	M3	M4	M5
Anchor prestress. load	T_w (kN)	500,0	500,0	500,0	400,0	250,0
Max axial load	N_{max} (kN)	485,9	479,7	496,6	378,8	196,6
	N_{max} / T_w	0,97	0,96	0,99	0,95	0,79

3.4. Moments generated in the retaining wall

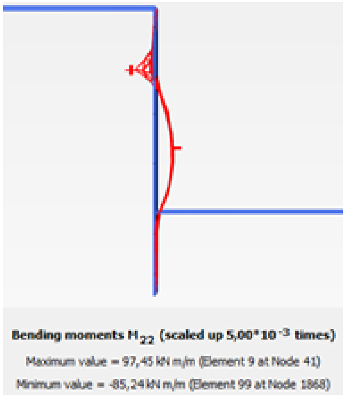
In the models, it was determined that the positive moment generated in the retaining wall decreases with the decrease in the T_w value, while it was not affected by the change in the L_b value. The maximum positive moment in the models occurred in the region where the anchor is located, while the maximum negative moment occurred in the region between the anchor and the final excavation level. For the applied T_w value of 500 kN in the M1, M2, and M3 models, the maximum positive moment generated in the retaining wall was determined to be 97.5-97.8 kN.m/m, while the maximum negative moment was 84.9-85.2 kN.m/m (Figure 9a, b, c). For the M4 model, with an applied T_w value of 400 kN, the maximum positive moment generated in the retaining wall was 71.6 kN.m/m, while the maximum negative moment was 79.8 kN.m/m (Figure 9d). The highest absolute moment among the models was obtained for the M5 model, which had the shortest L_b and the lowest T_w values. Accordingly, for the applied T_w value of 250 kN in the M5 model, the maximum positive moment generated in the retaining wall was determined to be 31.8 kN.m/m, while the maximum negative moment was 154.1 kN.m/m (Figure 9e) (Table 7).



(a)



(b)



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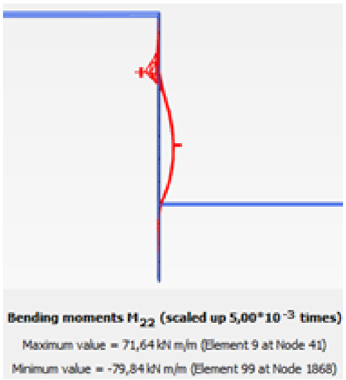

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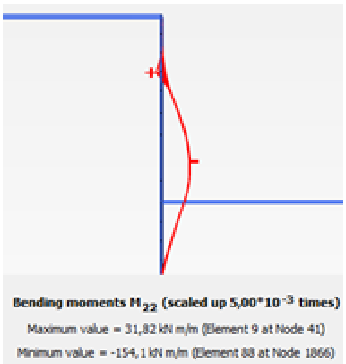


(e)

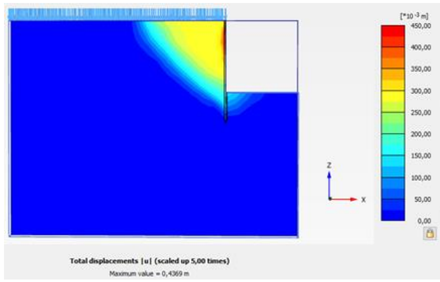
Figure 9. *Moment distribution in the retaining wall in Plaxis 3D models.*
(a) M1 model, (b) M2 model, (c) M3 model, (d) M4 model, (e) M5 model

Table 7 Moments generated in the retaining wall

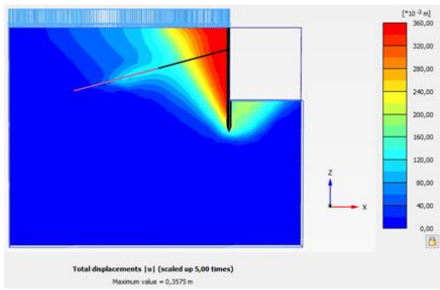
Model name		M1	M2	M3	M4	M5
Positive moment	*M+ (kN.m/m)*	97,8	97,8	97,5	71,6	31,8
Negative moment	*M- (kN.m/m)*	84,9	84,9	85,2	79,8	154,1

3.5. Factor of safety against overall stability

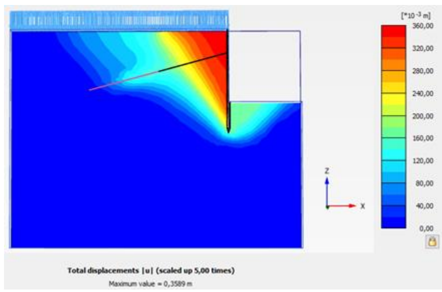
In deep excavations, a minimum *FS* of 1.20-1.30 is targeted against overall stability [1]. Since the first stage excavation will be cantilevered, the *FS* against overall stability at this level of excavation is expected to be high. Owing to the fact that there may be a problem during the installation of the first stage anchors, it is recommended to design the second excavation stage in such a way that the retaining wall can be cantilevered as well. Therefore, in the model studies, the *FS* against overall stability was initially determined for the case where there were no anchors in the retaining wall. Accordingly, the *FS* against overall stability at the final excavation level for the excavation without anchors was determined to be 2.75 (Figure 10a). This value reached 3.71 for the M1 model, the main model with anchors (Figure 10b). Generally, *FS* against overall stability decreased with the decrease in the T_w and the L_b values. The *FS* against overall stability values for M2, M3, M4, and M5 were determined to be 3.64, 3.51, 3.36, and 3.18, respectively (Figure 10c, d, e, f) (Table 8).



(a)



(b)



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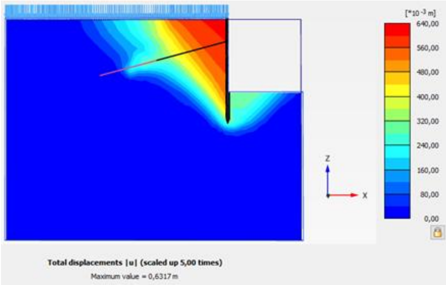
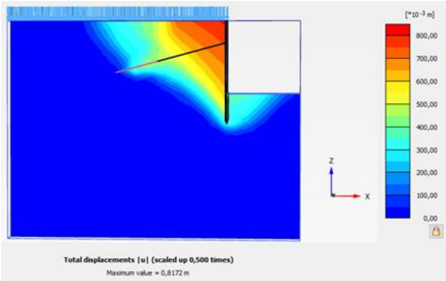
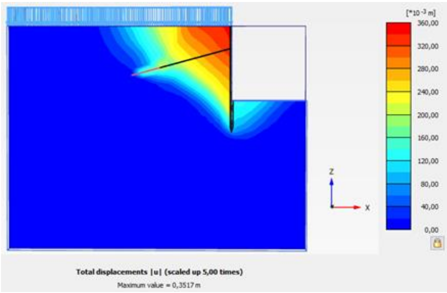


(d)



(e)



(f)

Figure 10. *Overall stability analysis in Plaxis 3D models.*
(a) Model without anchor, (b) M1 model, (c) M2 model, (d) M3 model, (e) M4 model, (f) M5 model

Table 8 *FS* against overall stability

Model name	Without anchor	M1	M2	M3	M4	M5
Factor of safety, *FS*	2,75	3,71	3,64	3,51	3,36	3,18

4. Results

In construction site practices, due to the reliance on the cantilever capacity of the retaining wall during the first excavation phases, due importance is not given to the first row of anchors. As a result of the difficulties encountered during the installation of these anchors, they are often disregarded and canceled. In this study, based on the results of the finite element analyses performed by Plaxis 3D for fractured rock formations, it was determined that an anchor with L_b = 4.0-meter can provide a contribution similar to that of an anchor with L_b = 6.0-meter in the excavation system. In both cases, the anchors were able to support a T_w value of 500 kN, and achieve a *FS* against overall stability of 3.50-3.71 for the excavation system. It was observed that the first 4.0 meters of the anchor with L_b = 6.0-meter mobilized, and plastic zones developed in this section. In the model studies, although an anchor with L_b = 2.0-meter was unable to carry the desired T_w value, it still contributed to the excavation system by increasing the *FS* against overall stability to 3.18 with a lower T_w value. As a result of this study, instead of canceling anchors that cannot be manufactured in the specified dimensions in the project, it is recommended to produce these anchors with the achievable L_b, and incorporate them into the excavation system.

Conflict of Interest Statement

The authors declare no conflict of interest regarding the investigation, authorship, and/or publication of this article.

Acknowledgement

This work was supported by Research Fund of the Istanbul Technical University. Project Number: MGA-2024-45704.

References

[1] FHWA-IF-99-015 (1999). Geotechnical engineering circular no.4: ground anchors and anchored systems. *U.S. Department of Transportation, Federal Highway Administration*. Washington DC.

[2] Barley, A.D. (1995). Anchors in theory and practice. *International Symposium on Anchors in Theory and Practice*. -Saltzburg, October 1995.

[3] Woods, R.I., & Barkhordari, K. (1997). The influence of bond stress distribution on ground anchor design. *ICE Conference and Anchored Structures*. London, March 1997.

[4] Ostermayer, H. (1974). Construction carrying behaviour and creep characteristics of ground anchors. *ICE Conference on Diaphragm Walls and Anchorages*. London.

[5] Sefi, F. (2014). Yarı-top-down inşaat yönteminin çok sıra ankrajlı iksa üzerine etkisi. *Yüksek Lisans Tezi*, İstanbul Teknik Üniversitesi, İstanbul.

[6] Yıldız, Ö., & Berilgen, M.M. (2020). Artificial neural network model to predict anchored pile-wall displacements on İstanbul greywackes. *Teknik Dergi*, 584, 10147-10166.

[7] Rankine, W.J.M. (1857). On the Stability of Loose Earth. *Philosophical Transactions of the Royal Society of London*, 147:9–27, 1776-1886.

[8] Terzaghi, K., & Peck, R.G. (1967). *Soil Mechanics in Engineering Practice*. John Wiley & Sons, Inc., New York.

[9] Peck, R.B. (1969). Deep Excavations and Tunneling in Soft Ground, State of Art Report. *Proceedings of the 7th International Conference on Soil Mechanics and Foundation Engineering*, 225-290. Mexico City, Mexico.

[10] Çınar, A. (2010). Trakya formasyonunda yapılan öngermeli ankrajlı derin kazıların sonlu elemanlar ile modellenmesi. *Yüksek Lisans Tezi*, İstanbul Teknik Üniversitesi, İstanbul.