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Comparative analysis of an anchored retaining wall system in a deep foundation excavation: A case study of Sivas Cultural Center Building in Türkiye

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Abstract
Modeling the surface element and support system in deep excavation pits and investigating the deformation mechanism is an important issue. In this study, alternative solution methods for an anchored bored pile model are compared and discussed, and it is aimed to contribute to the studies to be carried out in the deep excavation area. A numerical analysis of retaining wall design is examined in the case of the Sivas cultural center building's deep excavation using Plaxis 2D and GGU-Retain software. Measured field data and simulated results are discussed. As a result, the bending moment and lateral deformation reach a maximum when the foundation pit is excavated to the bottom. It can be said that the lateral deformation value found with Plaxis 2D is within the allowable limits, closer to the field data, and provides sufficient quality. The research results will provide theoretical and practical knowledge for designing and constructing similar deep excavation pits for the optimal strategy.

1. Introduction

The recent increase in demand for the urban area and intensive construction have led to increased high-rise buildings and deep foundation excavations. It can be dangerous for the buildings around the excavation area and the people working in the excavation pit due to the horizontal displacement of the retaining wall during deep excavation and may cause significant damage. A retaining wall and a supporting system are needed to prevent such possible damage in deep pits. Retaining walls can support steeply, near-vertically, or vertical sloped soils [1].

In this study, bored piles are used as the retaining wall, and anchors are preferred to support them. Prestressed anchors balance the soil pressure and control the wall's lateral deformation. Since the ground conditions in each region differ and vary according to the depth, it is impossible to design a retaining wall in a deep excavation pit with the instructions. In contrast, retaining wall design and construction require extensive engineering effort.

Plaxis 2D [2] and GGU-Retain [3] software have been widely used to simulate and consider variable soil conditions and are well-known calculation methods in deep excavations walls. Today, an anchored bored pile retaining wall system is increasingly used in geotechnical engineering due to its convenient structure that does not cause significant vibration or shakes to surrounding structures and its successful support capability. Maleki et al. [4] analyzed the hardening soil (HS) constitutive model for deep excavations supported by an anchored retaining wall system in various dry or unsaturated soils using Plaxis 2D [5]. They proposed a single practical relationship that predicts the maximum horizontal displacement of the pile top with high accuracy for deep excavations.

In another study, deformation problems related to the interaction between excavation pit and adjacent buildings are examined. They stated that it is impossible to accurately determine a structure's response to excavation-related deformation due to the variability of many factors affecting horizontal and vertical deformations in structures. The article analyzed the

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various risk factors that cause deformations by monitoring the historic building [6]. Consequently, the structure's deformations must be estimated based on continuous monitoring and approximate calculations.

Wang et al. [7] studied the stress and deformation characteristics of composite soil nailing wall and anchored soldier pile wall combined retaining system during excavating 31.4 m deep. They analyzed the construction process of foundation excavation using simulation software and monitoring data. The research proved that the lateral displacement of retaining piles increases with excavation depth. Chen et al. [8] researched the pile anchor support system for a deep foundation in a congested area of Changchun by monitoring and calculating lateral deformation with Plaxis 2D [5]. The results showed that the maximum horizontal displacement in the pit could be reduced by over 50%, 40%, and 30%, respectively, using the combination of soil nailing wall and pile anchor compared with a single support solution. Yang et al. [9] showed that when using a single prestressed anchor in foundation pit engineering, the closer the anchor rope's position is to the foundation pit's center, the greater the anchor stress. Through the field inspection, Shen et al. [10] investigated the performance of a deep foundation pit supported by suspended piles in soil and rock strata for a subway station in Qingdao Metro Line 3 in China. Many site-measured data are analyzed to investigate the horizontal displacement of piles at different depths under different construction stages. The maximum horizontal displacement of the ground is found to be 6 mm. They also proved that early application of prestressed anchor cables during construction increases the project cost, while the excessive late application may destroy the foundation pit.

Raddatz and Taiba [11] compared the horizontal deformations of the piles obtained from the GGU-Retain and Plaxis 2D software in gravelly soil with the deformations obtained from the field. As a result, they found that the model performed with Plaxis 2D provides the most closer deformation values with the results measured at the site in the final phase. Oróstegui and Villalobos [12] conducted a situation analysis to design a steel-profile wooden shoring (solder pile wall) on silty clay soil with no groundwater. The research showed that the GGU-Retain program could successfully model multi-story underground car parks with deformation control. Bilgehan and Kiliç [13] investigated the landslide problem affecting 30 buildings in the Taşova and Alparslan regions of Amasya province using GGU software. As a result, the total amount of slip is calculated according to the type of soil layers, and comparisons are made by taking field deformation measurements. Ruiz et al. [14] analyzed using GGU software and Plaxis 2D for a 2.3 m high road fill project sitting on 8 m deep soft clay soil. These programs calculate a sufficient safety factor for overall stability, and the analysis results are compared with deformation values measured after the landslides. They proved that the deformation results obtained from both programs are close to each other, and both are on the safe side according to the field deformation data.

Although current research results have revealed various aspects of deep foundation pit support engineering, there is a lack of professional research on lateral displacement in anchored bored pile walls and the impact of different software on design. Therefore, this study explores ways to achieve quality engineering design and construction of anchored wall systems.

2. Description of case study

The project is located close to İstasyon Street, one of the most heavily used streets of the Sivas province in T (Fig 1). The location map shows that the project is 100 meters from the Sivas State Hospital.

Figure 1. Sivas Cultural Center Building Location

Sivas Cultural Center building project consists of 3 basement floors, one ground floor, and two normal floors. The architectural view of this 6-story project is shown in Figure 2. The total closed construction area of the project is 22127 m^2, the base floor area is 6060 m^2, and the excavation pit depth is 12.5 m.

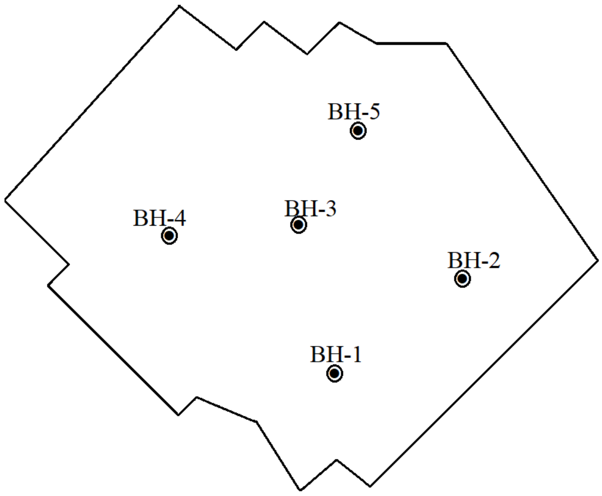
a) South Site view b) North Site view

Figure 2. Outside views of the project

2.1. The soil profile and field exploration studies

Brown and light grey clays are encountered in the study area and its surroundings. Five boreholes are drilled during soil exploration to determine the soil properties, and the location plan of the drillings in the field is shown in Figure 3.

The soil exploration area has a flat topography, consisting of various fillings at 0.50 m from the surface, brown clay at 0.50-7.00 m, a 10-15 cm pebbly band at about 6 m levels, and CH clay at 7.00-22.00 m. There is no water or stream around the building site. The groundwater level is about 15 m. The geotechnical parameters obtained from the field and laboratory test results and used in the model are given in Table 1.



BH-1 39°44'42.7'' N; 37°00'33.3''E
BH-2 39°44'22.9'' N; 37°00'33.9''E
BH-3 39°44'43'' N; 37°00'33'' E
BH-4 39°44'44'' N; 37°00'30'' E
BH-5 39°44'45'' N; 37°00'32'' E

Figure 3. Bore Hole Layout Plan

According to the Unified Soil Classification System, the soil class is CH, stiff clay (Table 1). As a result of the tests performed at 5 boreholes, the SPT-N impact values are observed as 6 cm for 50 impacts. For the average soil parameters, the SPT-N 50, internal friction angle 7 degrees, cohesion c, 150 kPa, unit weight 19 kN/m^3, elasticity modulus 50 MPa, modulus of subgrade reaction coefficient 40000 kN/m^3 are calculated.

3. Numerical Simulation Analysis

First, one anchor point is used vertically, and then it is started to determine the horizontal anchor spacing. Each anchor point consists of 4 anchor cables. The safe working load of each selected rope is 625 kN. The ropes' root length Lk is 9 m, each with a 1.524 cm (0.6 inches) diameter. The pre-tensioned rope's total length is found to be L=17m. These values are for anchor horizontal spacing s=2m. The breaking value for four ropes with a diameter of 1.524 cm is 1043kN. The safe working load is 626 kN, 0.6 times the breaking value. In the project, since the total load on an anchor point is 520 kN, the rope is on the safe side below the breaking value. The safety factor for the ropes against pulling is 2.3, i.e., greater than 2.0 and safe. Numerical analyzes are carried out in phases with Plaxis 2D and GGU-Retain computer programs for the deep excavation model. Static pressure analysis is performed at each stage, except for the addition of the seismic increase between the second and fourth phases.

3.1. Modeling with the GGU Retain

Geometry was created as in Fig. 4 by entering the slope information in the 'Active berms' menu of the GGU Retain program. There is no construction around the excavation area, but the surcharge load effect of 10 kN/m^2 has been considered since there may be live loads. Since a single row anchor is used in the model, the anchor information and the bored pile starting elevation are entered. For this reason, a single row of anchors is defined at the 3.80m elevation from the anchor's menu. Thus, the geometry and dimensioning of the model are completed using the GGU-Retain program (Fig 4).

Tablo 1. Soil parameters obtained from boreholes

SAMPLE			Water Content (%)	Unit Weight (kN/m3)	Dry Unit Weight (Mg/m3)	Specific Gravity (Gs)	Atterberg Limits			Sieve Analysis (Percent Passing)		Hydrometer	USCS	TRIAXIAL COMPRESSION TEST				
Boring/Pit Hole No	Sample No	Depth (m)					LL	PL	PI	No.4 Remaning %	No.200 Passing %			C_U (kPa)	ϕ_U (Deg)	C' (kPa)	ϕ' (Deg)	Type
BH-1	UD	12.00	17.3	19.8	1.59	2.67	75.2	27	78.2	20.9	67.7		CH	151	7			
BH-1	SPT	12.45					76.2	25	51.3		93.2		CH					
BH-2	UD	4.50	26.3	20	1.4		52.9	24	29		81.3		CH	160	7			
BH-2	SPT	10.50					64.1	25	39.1		90.4		CH					
BH-3	UD	7.50	23.3	19.4	1.42	2.7	57.7	24.4	31.7		92.3		CH	158	8			
BH-3	SPT	13.50					56.1	24.3	31.7		93.8		CH					
BH-4	UD	12.00					57.8	26.7	31.1		94.9		CH					
BH-4	SPT	15.00					58	21.3	36.7		94.7		CH					
BH-5	UD	4.50	29.3	18.6	1.24	2.65	76.3	26.4	49.9	1.5	95.3		CH	166	6			
BH-5	SPT	12.00					104.6	31.4	73.2		95.4		CH					

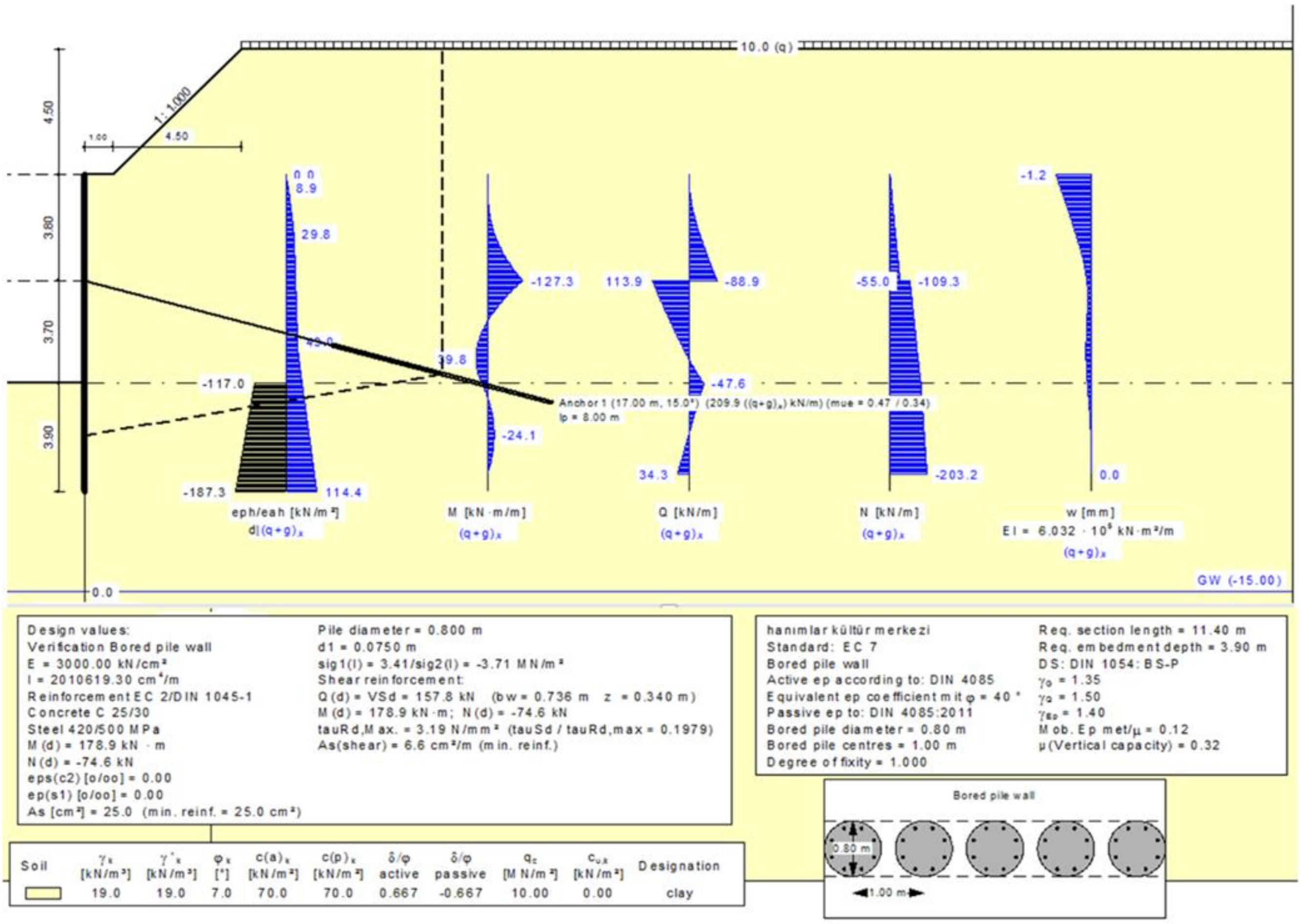


Figure 4. GGU-Retain analysis results of the model

3.2. Modeling with the Plaxis 2D

The set of model parameters is presented in Table 2. After the excavation geometry is determined, the excavation and manufacturing phases of the project are created using the 'Initial conditions' command of the Plaxis 2D program. In Phase1, the initial conditions and then the slope excavation is defined. Fig. 5 is the data entry window of the Plaxis program. Fig 6 is the slope (berm) excavation construction view in the field.

In Fig 7, bored piles are manufactured in the deep excavation of the Sivas Cultural Center building, and in Fig 8, bored piles are connected to the cap beam.

Table 2. Soil parameters used for HS model in Plaxis 2D

Soil Parameters/Units	Symbol	Values
Soil type	CH	Clay
Unit weight (kN/m3)	γ	19
Cohesion (kPa)	C	150
Friction Angle (Degree)	ϕ	7
Dilation Angle (Degree)	ψ	0
Secant stiffness (kPa)	E_{Ref}^{50}	50000
Tangent stiffness (kP)a	E_{Oed}^{Ref}	50000
Unloading/Reloading stiffness (KPa)	E_{UR}^{Ref}	150000
Power for stress level dependency of stiffness	m	1
Interface reduction factor	R_{int}	0.9
Earth pressure coeff. at rest	K_0^{nc}	0.38

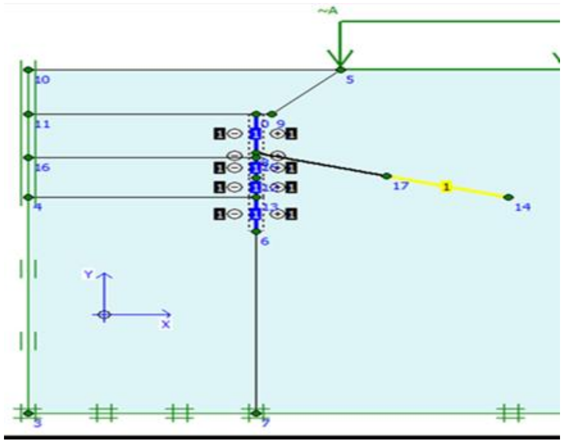


Figure 5. Phase1- Model with Plaxis 2D

Figure 6. Phase1-Slope excavation in the field

Figure 7. Phase 1 Bored pile construction

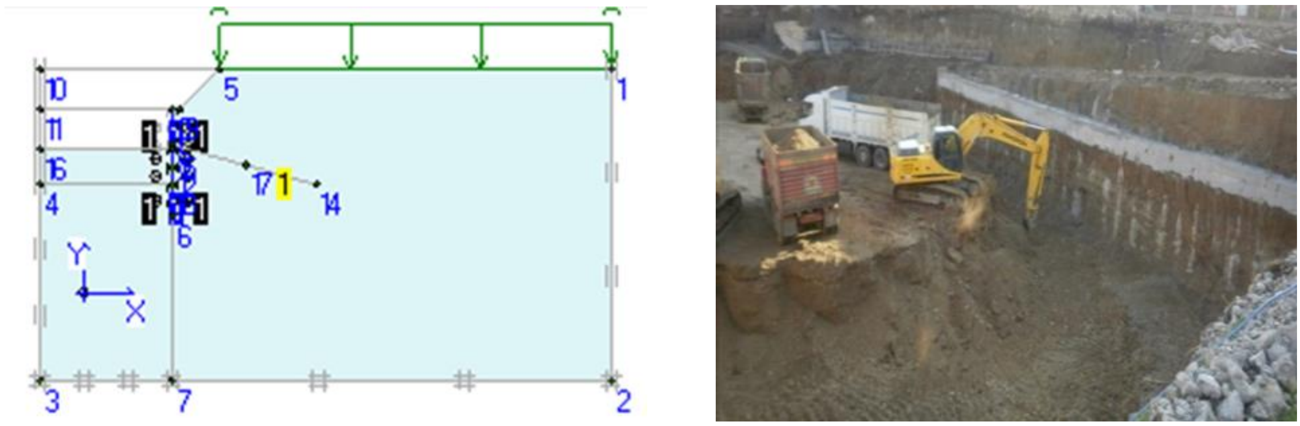
Figure 8. Phase1 Capping beam construction

In Phase 2, the model is created, and the bored pile is activated. Next, the soil layer is excavated up to the anchor level. Phase 2 is shown in Fig 9(a). In this 2nd phase of the project, the anchor holes are drilled, and the anchor ropes are inserted into the drilled holes with the protection cover (Fig 9(b).

In Phase 3, cement mortar is injected into the anchor root zone (bonded length), breast beam reinforcements are connected, and concrete is poured. Fig.10 shows these production steps in the field.

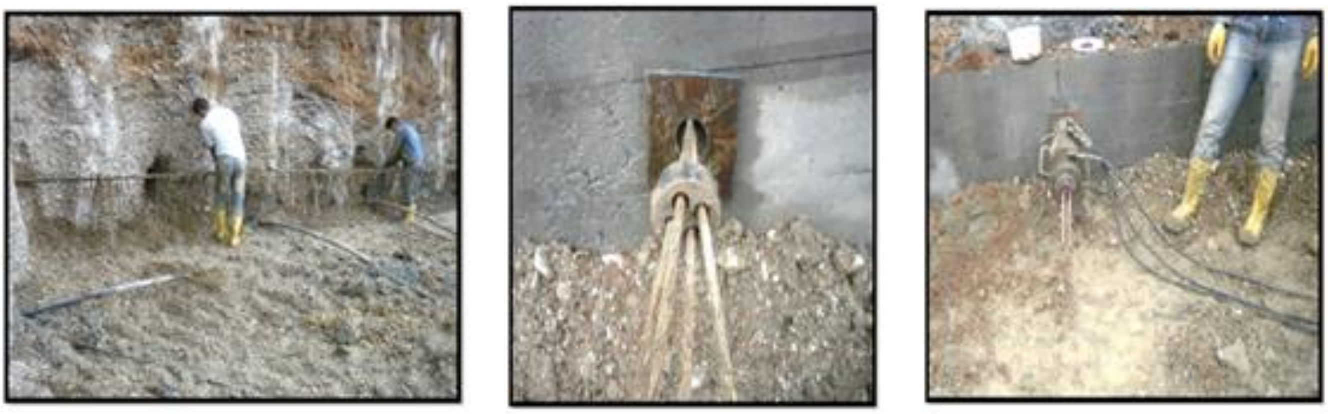
After the production of the breast beam is completed, the anchor heads are placed, and the pre-tensioning process is applied. The stages are defined in phase 3 in the Plaxis 2D program. The pre-tensioned anchor application to the ground model is included in the calculations in phase 3 (Fig 10).

Phase 4 includes excavation from the anchor level to the excavation floor level. Phase 4 can be seen in Fig 11. The excavation process is completed, and the analysis phase begins. Figure 12 shows the completed excavation area.



a) Phase 2-Plaxis 2D Model **b)** Phase2-Excavation up to the anchor level at the site

Figure 9. Phase 2-Excavation up to anchor level and activation of bored piles



a) Phase3-Anchor and breast beam **b)** Phase3-Anchor Head **c)** Phase3-Prestressing

Figure 10 Phase 3-Breast beam construction, placement of anchor heads, and prestressing at the site

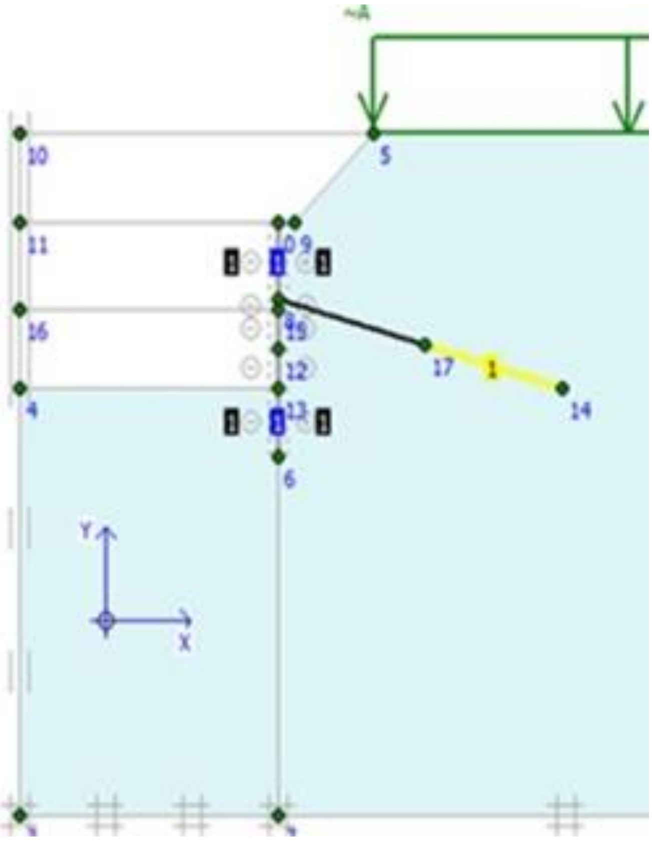


Figure 11. Phase 4-Reaching the excavation base level

Figure 12. Phase4-Excavation completed

4. Results and Discussion

The model of the anchored wall system is designed with Plaxis 2D software with the hardening soil (HS) method and GGU-Retain software with the subgrade reaction modulus method (SRM). The results of the research are discussed in detail.

4.1. Analysis Results with Plaxis 2D

The maximum bending moment in the vertical elements of the shoring system is 155,48 kNm/m, as given in Fig 13. This value is multiplied by the pile spacing, S=1.00 m, and the bending moment affecting the bored pile is included in the calculations. According to this bending moment, the piles are equipped with 80 cm diameter and 16 BC III class longitudinal reinforcements with 20 mm diameter.

The shear force value used in bored pile reinforcement calculations, 164.39 kN/m, is taken from the bored pile shear force diagram shown in Fig. 14.

In phi-c reduction analysis, the system's number of safety factors (Msf) is determined. The Msf value of this design is around 1.7 and remains on the safe side as this value is above 1.5.

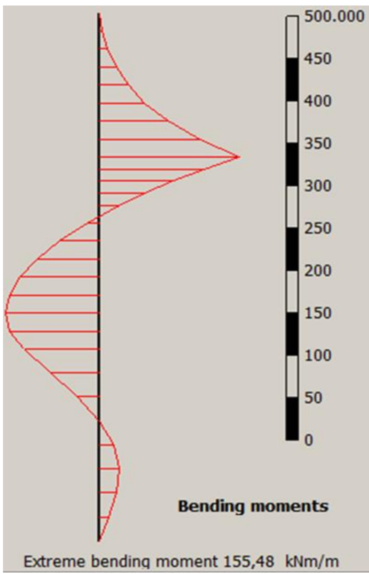


Figure 13. Maximum bending moment

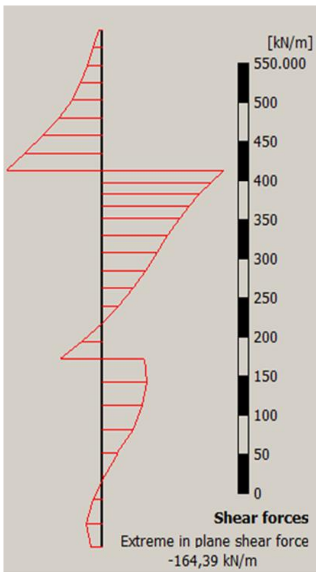


Figure 14. Maximum plane shear force

4.2. Analysis Results with GGU-Retain

A bored pile system with 80 cm diameter and 100 cm spacing is used in the GGU-Retain model. Since there is no construction near the excavation area, a 4.5m-4.5m slope (berm) was made around the excavation to save cost and manufacturing time before the piles were driven.

In the system, which is solved with a single row of anchors, the excavation depth is 12 m, including the sloped part (berm). Anchor intervals are determined as 2 m horizontally. The safe maximum moment capacity of the pile section is calculated as 178.9 kN.m, whereas the maximum moment value acting on the cross-section is 127 kN.m. The pile length is 11.40 m in total, 3.90 m of which is buried under the excavation pit depth.

The stability analysis of slopes is checked with the GGU-Slope [15] program. The circles are tightened where slip may occur, and the most critical slip surface is found. Slope stability analysis is performed with utilization factor. The µmax (Utilization Factor) parameter used in the calculations shows the risk of global failure. FS (Factor of safety) can be examined using GGU-Slope [15] software, but here µmax is the inverse of FS, i.e., equal to 1 over FS. It is found that the model is safe in terms of slope stability, with the µmax value being the highest at 0.76, which is less than 1. There is no global failure problem (Fig.?)

Soil	φ_k [°]	c_k [kN/m²]	γ_k [kN/m³]	max ψ_A [°]	Designation
(yellow)	7.00	150.00	19.00	80.00	clay

Example 21 Schulze/Simmer 94 Grundbau 1
Initial calculation data
Unfavourable slip circle:
μ_{max} = 0.76
x_m = -0.31 m y_m = 7.17 m
R = 18.09 m
Partial factors:
- γ(φ') = 7.00
- γ(c') = 1.50
- γ(c_u) = 1.50
- γ(Unit weights) = 1.90
- γ(Permanent actions) = 1.00
- γ(Variable actions) = 1.30

Maßstabsfaktor Porenwasserdruck = 0.050

Fig. 15 Slope stability analysis

4.3. Discussion and comparison of numerical simulation results with field data

Field maximum horizontal deformation monitoring data are compared with numerical simulation results. After completing the anchored wall system, the maximum horizontal displacement (dhmax) at the top of the pile in the field is measured as 9 mm.

The maximum allowable lateral displacement of the top of the anchored pile is calculated using different approaches in the literature [16-19]. Generally accepted in the literature, in anchored wall applications, for stiff clay soils (i.e., undrained cohesion is more than 50 kPa), the allowable dhmax over H ratio varies between 0.2% and 0.9% for clays ranging from stiff to soft (H is the excavation depth.). The maximum allowable lateral deformation is calculated as 15 mm using the FHWA (1999) [16] criterion. The maximum lateral deformation value at the top of the pile is measured as 9mm in the field, which is below the allowable limit (15 mm).

The Plaxis 2D using HS theory is a finite element method. This method allows us to consider the soil-structure interaction, including anchors, and determine the soil's stresses and strains throughout the excavation. This method models the plastic volumetric strain in soil compression quite successfully. With Plaxis 2D, the maximum horizontal deformation value allowed at the top of the wall is calculated as 12.41 mm. (Figure 16.). This result shows acceptable consistency with the FHWA [16] criteria of 15mm and closer to the field value of 9mm. During the installation of this anchor, the soil mass is subjected to unloading and loading with increasing excavation depth, and the actual behavior of the soil becomes elastoplastic. It can be said that the Hardened Soil model in Plaxis 2D accurately reflects this elastoplastic behavior of the soil considering lateral deformations.

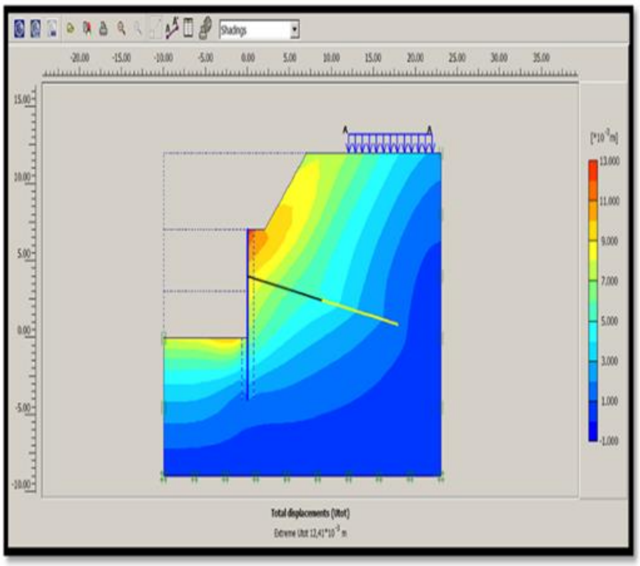


Figure 16. Total Lateral displacement

GGU-Retain uses a calculation method based on SRM (also called the Winkler method). The cohesion value of the stiff clay soil is given as 150 kPa in the geotechnical report. The maximum lateral deformation value at the top of the retaining wall is calculated as 1.2mm, even when the cohesion value is accepted as 70 kPa with applying the safety factor. The GGU-Retain program underestimates the maximum lateral deformation from the field value and Plaxis 2D. GGU-Retain creates a balance between the sliding and holding forces acting on the excavation wall, considering the density of the soil, the internal friction angle, the cohesion, and the concrete-soil friction. For example, calculating the required embedment depth of anchored bored piles takes an initial embedment length value and then iteratively calculates the optimal depth. According to the authors, the inaccuracy of the subsoil reaction method is that it is challenging to choose the appropriate value of the subsoil reaction coefficient accepted throughout the calculations, and it is also assumed to be constant. In reality, there is a non-linear relationship between soil pressure and displacement.

5. Conclusion and Recommendations

In this research, a comprehensive numerical study is carried out to analyze the anchored bored pile retaining wall design in the case of the Sivas cultural center building's deep excavation. The proposed anchored wall system model is designed with two different programs: Plaxis 2D with HS and GGU-Retain with SRM. Retaining wall design in deep excavations, one of the essential branches of geotechnical engineering, is a very diverse, complex, and comprehensive engineering task. The quality of the project mainly depends on whether the maximum lateral deformation caused by the foundation pit excavation is within a permissible limit. After the retaining wall was completed, the maximum dhmax was measured at 9 mm at the top of the pile. This deformation value is calculated with Plaxis 2D and GGU-Retain programs as 12.45mm and 1.2mm, respectively.

The maximum lateral deformation value found with both GGU-Retain and Plaxis 2D was within the allowable limits, and both programs' solutions remained on the safe side. However, in GGU calculations, it was observed that the maximum lateral deformations were much smaller than PLAXIS 2D. In addition, with PLAXIS 2D, the deformation value is much closer to the field data and provides sufficient quality. Considering that this low deformation value is due to the high cohesion value of the stiff clay, the authors used an undrained cohesion value of 70 kN/m2 instead of 150 kN/m2 in the GGU-Retain program, and even in this case, the lateral deformation was calculated as 1.2 mm. As a result, Plaxis 2D solution method was preferred instead of GGU-Retain for the wall design.

This anchored wall project is implemented in a foundation pit with a relatively shallow excavation depth. To better understand the differences in the GGU-Retain and Plaxis 2D programs, it needs to be confirmed by further studies that take into account the actual effective parameters of the soil and the deformation behavior of the wall with increasing excavation depth. In addition, another critical point is that the construction of a safe and economic retaining wall will be possible with a comprehensive subsoil investigation. The proposed HS method for designing an anchored pile retaining wall is based on soil parameters obtained from a geotechnical report. Therefore, the accuracy of the determined parameters depends on the subsoil investigation that reveals the actual ground behavior in the field.

Finally, it can be concluded that Plaxis 2D, using the Hardening Soil theory, can be used with high accuracy for deep excavation pits in hard clay soil.

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Author contributions

Mehmet Cemal Acar: Conceptualization, Methodology, Software, Data curation, Writing-Original draft preparation. **Abdullah Kekül:** Visualization, Investigation, Software, Validation. Writing-Reviewing and Editing.

Conflicts of interest

The authors declare no conflicts of interest.

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