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STABILITY ANALYSIS OF RIVERBANK RETAINING STRUCTURES USING PLAXIS 2D

PLAXIS 2D БАҒДАРЛАМАСЫН ҚОЛДАНА ОТЫРЫП ЖАҒАЛАУ ТІРЕУ ҚҰРЫЛЫМДАРЫНЫҢ ТҰРАҚТЫЛЫҒЫН ТАЛДАУ

АНАЛИЗ УСТОЙЧИВОСТИ БЕРЕГОВЫХ ПОДПОРНЫХ КОНСТРУКЦИЙ С ИСПОЛЬЗОВАНИЕМ PLAXIS 2D

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Keywords:
Plaxis 2D, retaining wall, hydrostatic pressure, geotechnical modeling, finite element analysis, urban load, anchor.

ABSTRACT
The relevance of this study lies in the fact that rapid urbanization along the Yesil River has led to increased loading on riverbank retaining walls, posing significant challenges to their structural stability. The objective of this study is to apply advanced numerical modeling techniques using Plaxis 2D to analyze the deformation behavior of retaining walls under complex loading conditions and to evaluate their performance both with and without anchoring systems. The novelty of this study lies in its consideration of real-world loading scenarios, including hydrostatic pressure and urban-induced surcharges, alongside a comparative analysis of retaining wall configurations with and without anchoring systems. The simulation results demonstrated that the horizontal displacement of the retaining wall was only 2 cm, indicating a high level of structural stability even in the absence of an anchoring system. Under the given conditions, the implementation of a non-anchored design proved to be both technically sound and economically efficient. These findings underscore the importance of a comprehensive approach to the design of coastal protection structures, taking into account both natural factors and anthropogenic impacts.

Түйінді сөздер:
Plaxis 2D, тіреу қабырғасы, гидростатикалық қысым, геотехникалық модельдеу, соңғы элементтер әдісі, қалалық жүктеме, анкер.

ТҮЙІНДЕМЕ
Бұл зерттеудің өзектілігі Есіл өзені бойындағы жылдам урбанизация өзен жағалауындағы тіреу қабырғаларына түсетін жүктеменің артуына алып келіп, олардың құрылымдық тұрақтылығына айтарлықтай қиындықтар туғызуымен байланысты. Зерттеудің мақсаты – Plaxis 2D бағдарламалық кешенін пайдалана отырып, күрделі жүктеме жағдайларындағы тіреу қабырғаларының деформациялық мінез-құлқын талдау және анкерлік және анкерсіз қабырға құрылымдарының тиімділігін бағалау. Зерттеудің жаңалығы – гидростатикалық қысым мен қала құрылысының әсерінен туындайтын антропогендік жүктемелерді қоса алғанда, нақты жүктеме жағдайларын ескеруімен, сондай-ақ анкерлік және анкерсіз тіреу қабырға құрылымдарын салыстырмалы талдаумен ерекшеленеді. Модельдеу нәтижелері тіреу қабырғасының көлденең орын ауыстыруы небәрі 2 см екенін көрсетті, бұл конструкцияның тіпті анкерлік жүйе қолда-

данылмаған жағдайда да жоғары тұрақтылыққа ие екенін білдіреді. Қарастырылып отырған жағдайларда анкерсіз құрылым нұсқасы тиімділігімен және үнемділігімен ерекшеленді. Бұл деректер табиғи және антропогендік факторларды ескере отырып, жағалауды қорғау құрылыстарын жобалауда кешенді тәсілдің маңыздылығын көрсетеді.

Ключевые слова:
Plaxis 2D, подпорная стена, гидростатическое давление, геотехническое моделирование, метод конечных элементов, городская нагрузка, анке

АННОТАЦИЯ

Актуальность данного исследования обусловлена тем, что быстрая урбанизация вдоль реки Есиль привела к увеличению нагрузок на подпорные стены береговой линии, создавая серьезные проблемы для их структурной устойчивости. Цель данного исследования — применение передовых методов численного моделирования с использованием Plaxis 2D для анализа деформационного поведения подпорных стен в условиях сложного нагружения и оценка их эффективности конструкций как с анкерными системами, так и без них. Новизна исследования заключается в учете реальных сценариев нагружения, включая гидростатическое давление и антропогенные нагрузки, вызванные городской застройкой, а также в сравнительном анализе конструкций подпорных стен с анкерными системами и без них. Результаты моделирования показали, что горизонтальное перемещение подпорной стены составляет всего 2 см, что свидетельствует о высокой устойчивости конструкции даже без применения анкерной системы. В рассматриваемых условиях решение с неанкерной конструкцией продемонстрировало рациональность и экономическую эффективность. Эти данные подчёркивают важность комплексного подхода к проектированию берегозащитных сооружений с учётом как природных факторов, так и антропогенных нагрузок.

INTRODUCTION

The stability of riverbank retaining walls has represented a critical challenge in geotechnical and hydraulic engineering, especially in the context of rapid urbanization. In recent decades, cities such as Astana, Kazakhstan, have undergone significant expansion along riverbanks, including the Yessil River. Urban development has included the construction of parks, pedestrian areas, cycling paths, and public facilities in close proximity to the water. As a result, surface usage has intensified, increasing the loads acting on retaining structures.

This increase in loading conditions has created complex stress environments that must be properly understood to ensure the long-term performance and safety of riverbank protection systems. The influence of surcharge loading on the mechanical behavior and strength improvement of soft soils has been demonstrated in previous studies (Horpibulsuk et al., 2018), where it was shown that external loads significantly affect soil stiffness, settlement behavior, and overall structural stability.

In past studies, researchers have calculated the effects of earth pressure and hydrostatic loads on retaining walls under various boundary conditions. Additionally, several projects have monitored wall deformations and failure mechanisms under urban loading scenarios. Advanced finite element software, such as Plaxis 2D, has been widely used to simulate soil-structure interaction, seepage, consolidation, and staged construction effects (Pereira, A.B & Porto, T.B., 2020).

Numerous authors have analyzed soil behavior using models like Mohr-Coulomb and Hardening Soil to better understand the influence of hydraulic and structural parameters. These contributions have improved the predictive capacity of numerical simulations in geotechnical design (Imran, H et al., 2023).

However, while the individual effects of natural forces and anthropogenic loading have been studied separately, there is still a lack of comprehensive analyses that integrate both within real-world urban environments like the Yessil River in Astana.

Although many models have been developed for idealized conditions, fewer studies have considered site-specific data and infrastructure-related surcharges. There remains a critical need to evaluate how combined loading conditions affect wall displacements, stress distribution, and overall stability in urban riverbank systems.

This gap limits the ability of engineers to make fully informed design decisions for safe and resilient waterfront infrastructure.

Previous studies have examined earth pressure and hydrostatic loading under simplified conditions, using finite element methods to analyze soil–structure interaction and compare constitutive models (Pereira, A. B & Porto, T. B., 2020; Imran, H et al., 2023). However, these studies generally relied on idealized geometries and generalized soil parameters. In contrast, the present research integrates site-specific geotechnical data, real river geometry, and urban surcharge loading within a unified numerical framework.

The present study investigates the structural performance and deformation behavior of a riverbank retaining wall along the Yessil River using Plaxis 2D. The numerical model incorporates site-specific data, including borehole-derived soil profiles, groundwater conditions, and external loading from adjacent infrastructure.

Earth pressure, hydrostatic river forces, and urban surcharges are modeled under staged construction to simulate real behavior. Special attention is given to displacement patterns, internal stress distributions, and overall wall stability under varying load scenarios.

This research aims to offer practical recommendations for engineers and planners engaged in riverbank design, highlighting the importance of accounting for both natural and anthropogenic influences in numerical modeling. By addressing current limitations, the study contributes to the development of more reliable and cost-effective retaining wall solutions in urban environments.

MATERIALS AND METHODS

The program enables modeling and analysis by building a profile and performing calculations accordingly. A cross-section of the terrain in the area under investigation is created within the software. This cross-section includes representations of the soil layers, retaining wall, piles, and other essential elements. The section is constructed directly in the program, allowing for a clear visual display of soil stratigraphy, retaining walls, piles, and groundwater levels.

Once the required elements are placed in the cross-section, their corresponding geotechnical parameters must be input. The process begins with the characterization of soil layers. Soil samples are collected from the construction site and classified based on their mechanical and physical properties.

The next input parameter in the model is the pile. The use of a piled retaining wall is dictated by structural requirements. The selected pile type is designated as C60-30-8, classified as a suspended pile based on its working behavior. The characteristics of the pile are provided in Table 1.

Table 1. Parameters of Pile Type C60-30-8

Parameter	Value	Unit of measurement
Length	6000	mm
Width	300	mm
Height	300	mm
Concrete grade	200	-
Concrete volume	0.55	m^3
Weight	1350	kg
Note – compiled by the author		

The retaining wall is constructed at the project site. It is designed with a height of 2 m and a thickness of 0.4 m, and modeled as a simple structural element. Its structural behavior can be approximated to that of a basement wall.

Following the input of all geotechnical and structural parameters, external loads are applied. The specific weight of water is assumed to be 10 kN/m³.

The analysis is carried out in Plaxis 2D, where the profile is defined and analyzed with a unit width of 1 meter. The software automatically processes all input parameters along this one-meter section. Within the profile view, the cross-section and computational domain are both clearly represented.

The user defines the extent of the computational domain, which can be larger than the modeled profile if required. All work is performed within this profile window. The lateral boundaries are fixed to prevent any influence from beyond the computational domain. All deformation and flow changes occur strictly within the defined limits.

The geotechnical and hydraulic parameters used in this analysis are based on data from the Yesil River, obtained from official environmental sources. The modeled half-width of the river is approximately 40 meters, and the river depth is assumed to be 8 meters, within the reported range of 8–10 meters.

The external load is applied at a horizontal distance of 5 meters from the wall. This configuration represents a typical simplified case of a riverbank retaining wall. All parameters described above have been implemented in Plaxis 2D.

Geotechnical parameters for soil layers are entered into the software as illustrated in Figures 1, 2, and 3.

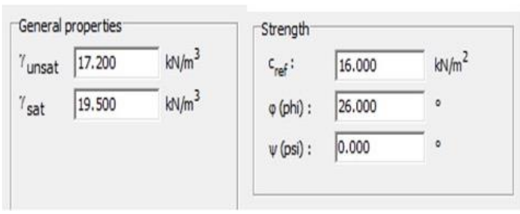


Figure 1. Input Parameters for Sandy Loam Soil in Plaxis 2D

Note – compiled by the authors

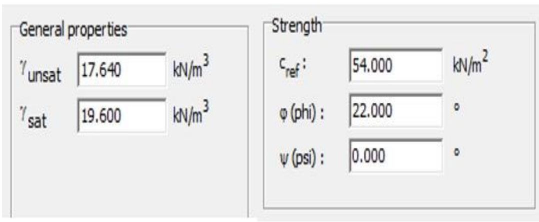


Figure 2. Input Parameters for Loam Soil in Plaxis 2D

Note – compiled by the authors

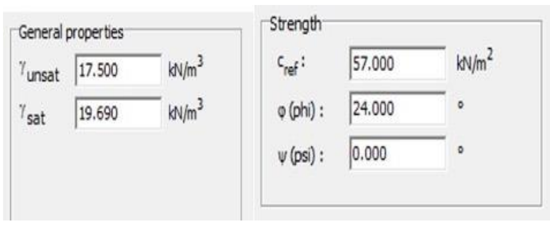


Figure 3. Deep-Layer Loam Soil Properties in the Model

Note – compiled by the authors

The numerical analysis is conducted in two phases. In the first phase, the model simulates deformations and changes resulting from external forces acting on the retaining wall. This phase accounts for several key factors, including the protective function of the retaining structure, the load imposed by the surrounding soil mass, and additional external loads applied to the system.

The outcomes of the analysis for this phase are visually presented in the figures below (Figures 4 and 5).

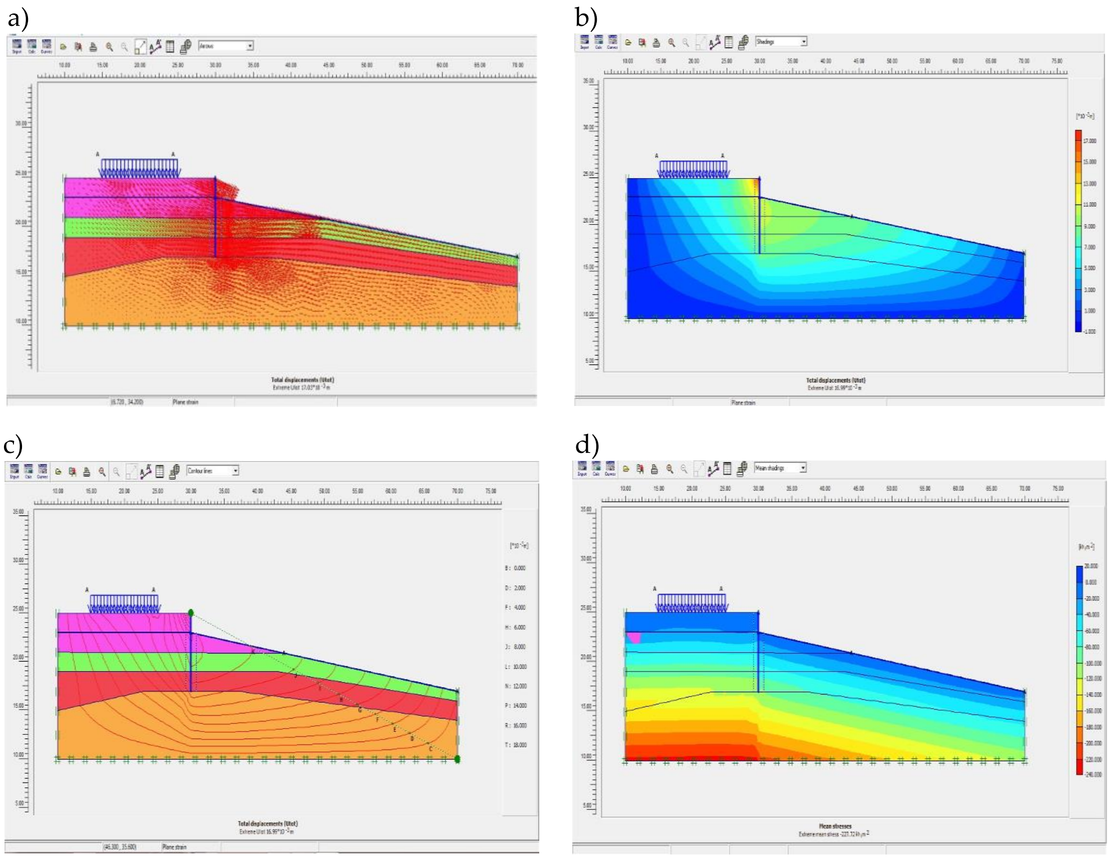


Figure 4. Displacement of the retaining wall in the iso zone:
(a) displacement represented by vectors; (b)displacement shown through color shading;
(c) iso-lines of displacement; (d) pressure distribution visualized with color gradients

Note – compiled by the authors

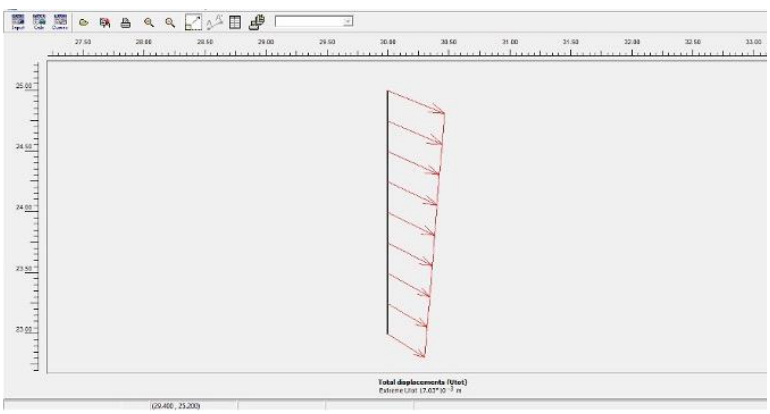


Figure 5. Isolated Visualization of the Retaining Wall Displacement

Note – compiled by the authors

The displacement vectors indicate the direction of movement of the retaining wall. The color shading highlights the zones where displacement occurs. The iso-lines represent the magnitude of settlement across different areas. According to the pressure distribution results, the maximum pressure observed is 227.72 kN/m².

Based on the results of the first phase, a displacement of 1.703 cm was observed.

The second phase represents the final stage of the analysis. In this phase, all conditions and parameters from the first stage are preserved, with the addition of the hydrostatic water load. This enables a comprehensive evaluation of the final response of the structure. The results of this phase are presented in Figures 6 and 7.

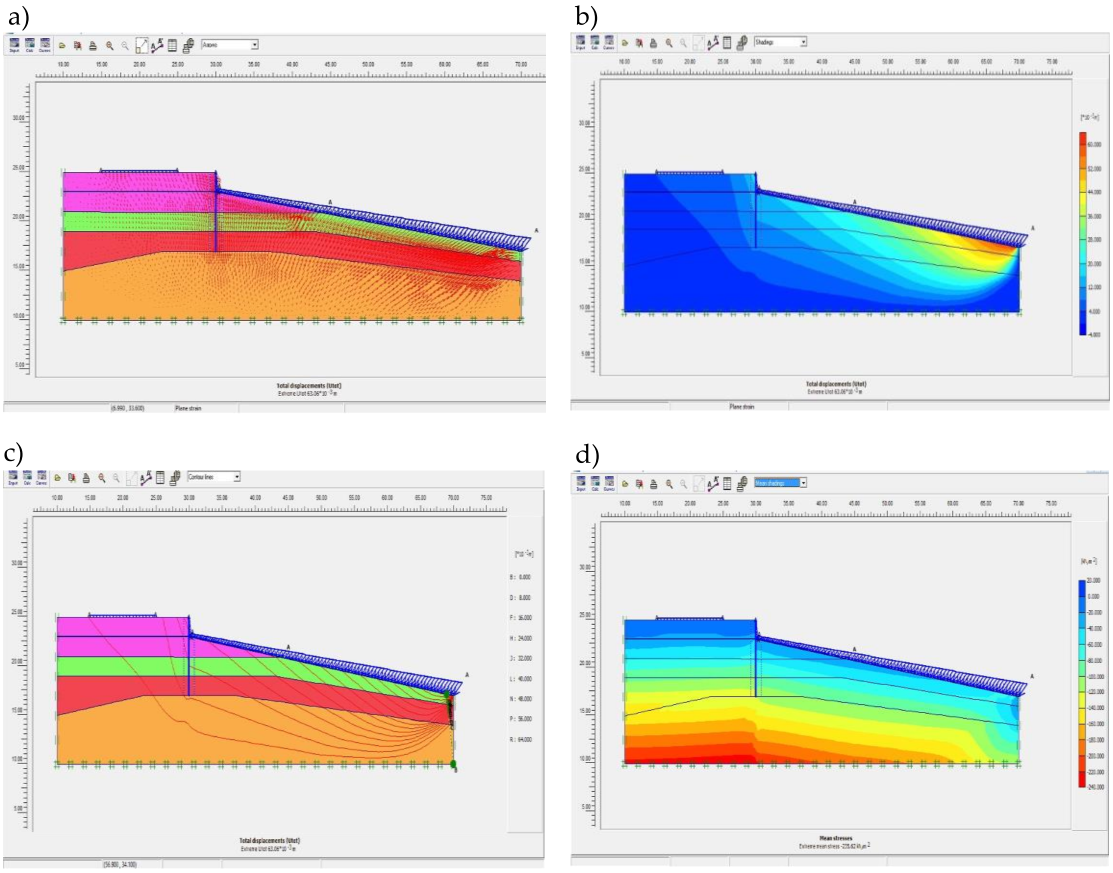


Figure 6. Displacement of the retaining wall in the iso zone:
(a) displacement represented by vectors; (b)displacement shown through color shading;
(c) iso-lines of displacement; (d) pressure distribution visualized with color gradients

Note – compiled by the authors

In the second phase, the maximum pressure recorded was 235.62 kN/m².

According to the results of the analysis, the total displacement amounts to 6.306 cm. However, this displacement occurs across the entire profile and is primarily concentrated in the lower section, where water pressure dominates. With regard to the displacement of the retaining (shoreline protection) wall itself, it is 2 cm.

The problem can also be considered from another perspective. To do this, certain modifications must be made in the computational model. One such modification involves the inclusion of an anchor, which provides additional stability. The anchor is installed at a height of 1 meter from the base of the wall, corresponding to its midpoint, and contributes to structural reinforcement.

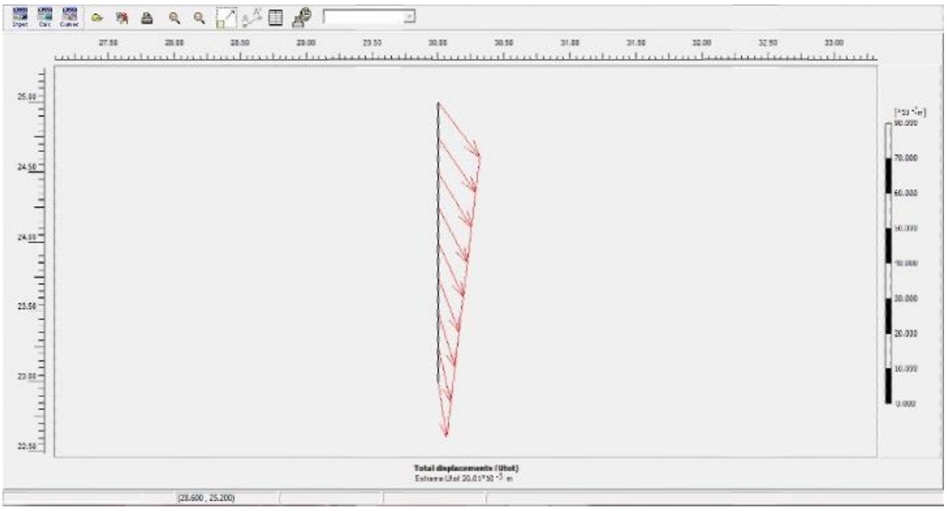


Figure 7. Displacement profile of the retaining wall

Note – compiled by the authors

However, in this case, it is possible to evaluate whether the installation of the anchor is necessary. This can be assessed by comparing two indicators. The characteristics of the anchors are provided in Table 2.

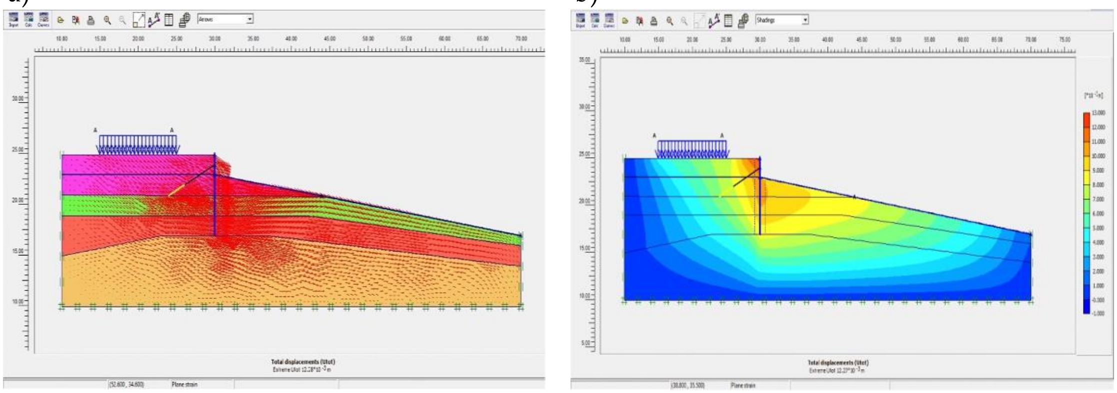
Table 2. Anchor reinforcement applied to the retaining wall

Parameter	Description	Value	Unit of measurement
Axial stiffness	EA	2×10^6	kN
Anchor spacing	Ls	2.5	m
Maximum compressive force	$F_{max,\ comp}$	1×10^{15}	kN
Maximum tensile force	$F_{max,\ tens}$	1×10^{15}	kN
Note – compiled by the author			

In this case as well, the analysis can be conducted under two different scenarios within the software. Two stages are introduced into the computational model. All conditions are modeled according to the previously described example. The only modification involves the inclusion of an anchor, and the calculation is repeated from the beginning (Figures 8 and 9).

a)

b)



c) d)

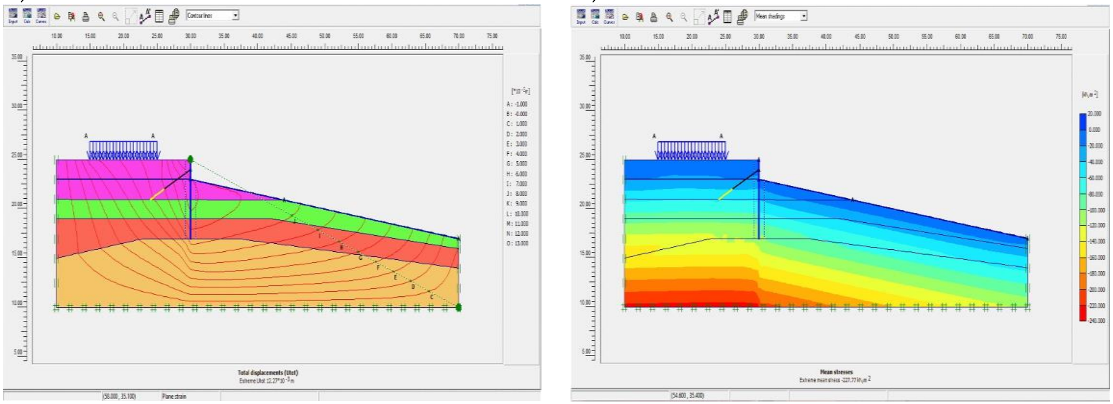


Figure 8. Displacement of the retaining wall in the iso zone:
(a) displacement represented by vectors; (b)displacement shown through color shading;
(c) iso-lines of displacement; (d) pressure distribution visualized with color gradients

Note – compiled by the authors

The maximum pressure force on the second type of retaining wall during the first stage is -227.77 kN/m².

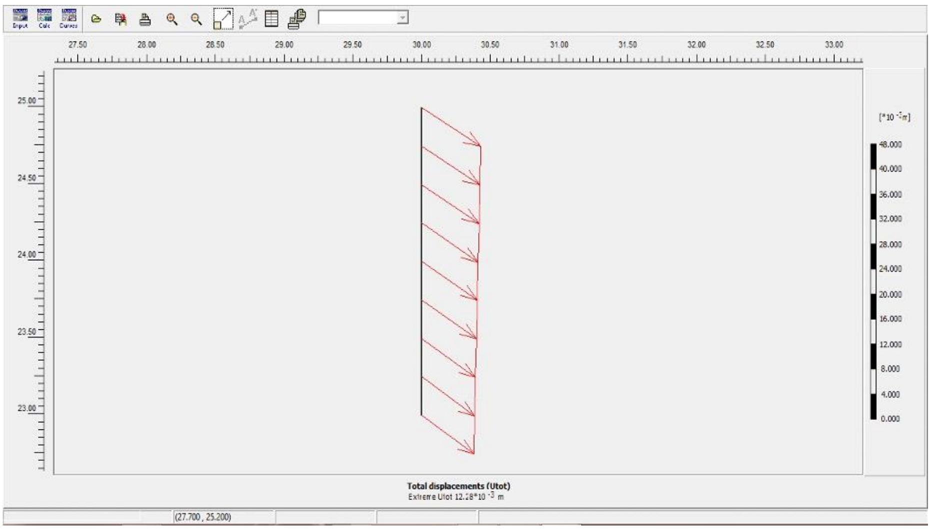


Figure 9. Detailed displacement profile of the retaining wall

Note – compiled by the authors

According to the analysis results, the displacement value is 1.228 cm. This value is an improvement compared to the result from the first stage of the analysis, which was 1.703 cm. Naturally, the smaller displacement from the first scenario is preferable. However, when considering the overall situation, it becomes apparent that this difference is not significant. The discrepancy between the two results is only 0.5 cm, which is not substantial when compared to practical realities.

Nevertheless, the analysis should be completed thoroughly to evaluate the final extent of the change. The second stage is considered the final stage and is conducted as described above, meaning the software simulates the entire loading conditions combined. The difference from the first stage is that the wall is anchored in this final analysis (Figures 10 and 11).

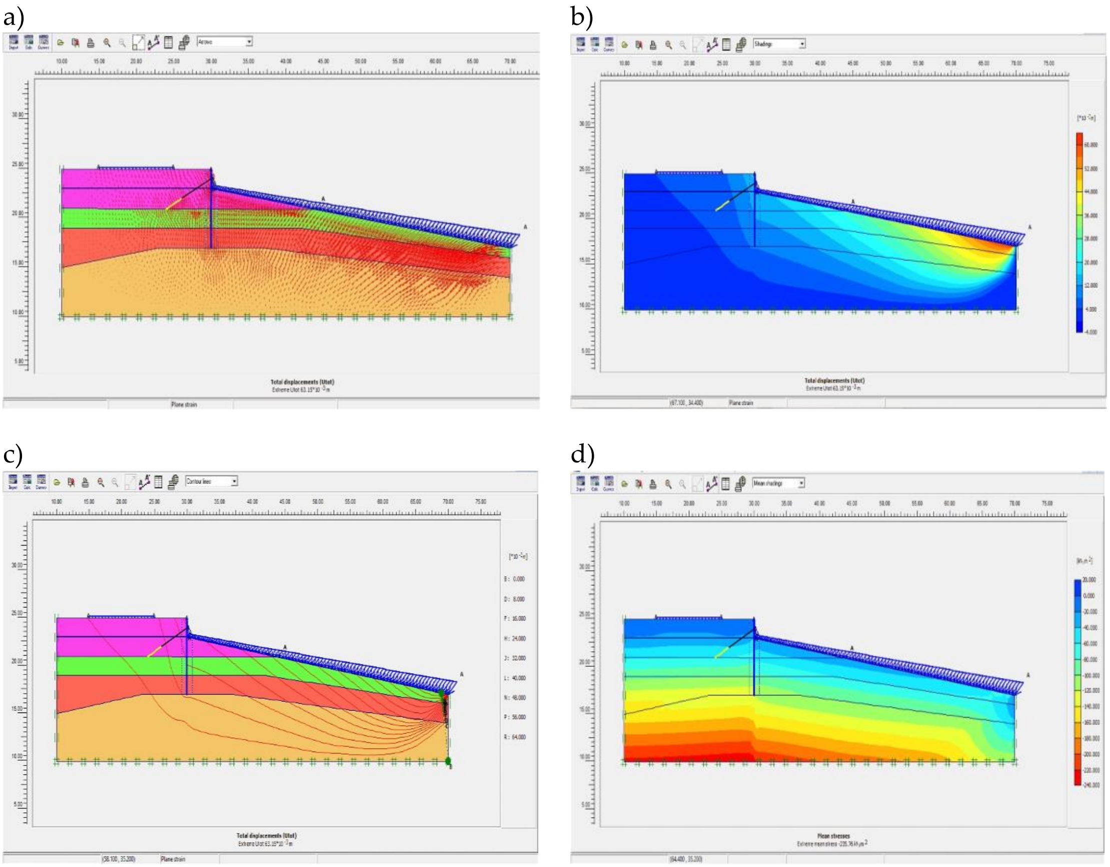


Figure 10. Displacement of the retaining wall in the iso zone:
(a) displacement represented by vectors; (b)displacement shown through color shading;
(c) iso-lines of displacement; (d) pressure distribution visualized with color gradients

Note – compiled by the authors

The maximum pressure force on the second type of retaining wall during the second stage is -235.76 kN/m².

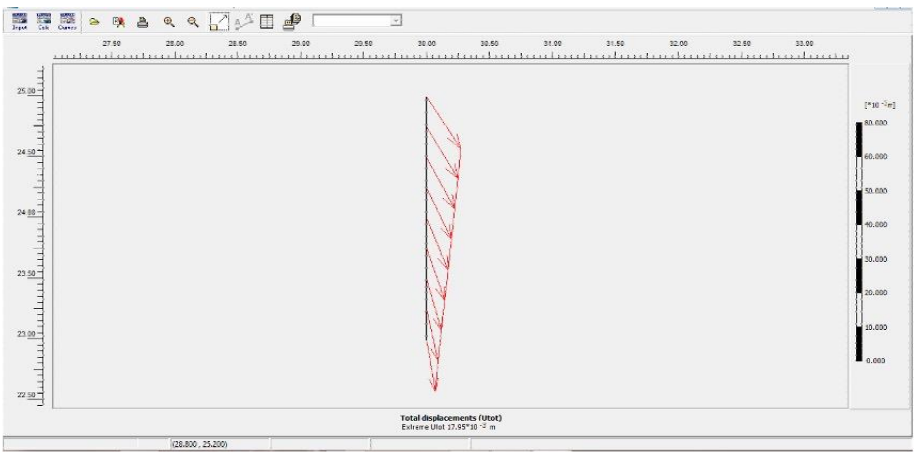


Figure 11. Detailed displacement profile of the retaining wall

Note – compiled by the authors

Regarding the final analysis, the displacement value obtained was 1.795 cm.

RESULTS AND DISCUSSION

According to the Plaxis analysis for the first type of retaining wall, the displacement was 1.795 cm. This result should be compared with the displacement value obtained for the first type of shoreline protection wall, which was 2.0 cm. The difference between the two structural designs is therefore only 0.205 cm, which is not significant. Moreover, the additional work required to install the anchor is considerable. Despite this extra effort, the displacement improvement is merely 0.205 cm.

The costs associated with the additional work are much higher than the small gain in displacement. These costs include purchasing the anchors, installing them into the wall, the labor intensity, and the time required for installation. Furthermore, the machinery needed to place the anchors incurs separate expenses.

Therefore, considering all scenarios, the first structural design of the shoreline protection wall is the more cost-effective and practical solution. Of course, the effectiveness depends on the applied loads. Under the current loading conditions, the initially considered wall design proves to be very efficient.

This section should present the main findings obtained in the course of the study. The data should be clearly structured and, if necessary, supplemented with tables, graphs, or figures. Excessive descriptions should be avoided — focus on interpreting key observations, measurements, or calculations. If needed, the results can be divided into subsections or thematic blocks. Table 3 presents a comparison between the two different types of retaining walls.

Table 3. Calculated displacement values of two types of retaining walls

Stage	Retaining wall without anchor	Retaining wall with anchor	Difference
First stage	1.703 cm	1.228 cm	0.475 cm
Second stage	2.000 cm	1.795 cm	0.205 cm
Note – compiled by the author			

- Retaining Wall without Anchor:

In the first simulation phase, considering only earth pressure and urban surface loads, the maximum horizontal displacement of the retaining wall reached 1.703 cm. In the second phase, which included hydrostatic water pressure, the total deformation across the profile was 6.306 cm, but the localized wall displacement was approximately 2.0 cm. The maximum recorded earth pressure acting on the wall was 235.62 kN/m^2.

- Retaining Wall with Anchor:

When the anchoring system was introduced at the wall's midpoint (1 m above the base), the maximum displacement in the first simulation phase was reduced to 1.228 cm. In the second phase, the total wall displacement was 1.795 cm, showing an overall reduction of 0.205 cm compared to the unanchored wall. The pressure distribution remained relatively similar, with a slightly higher peak pressure of 235.76 kN/m^2.

Comparative Analysis:

The reduction in horizontal displacement due to the anchoring system ranged from 0.475 cm (Phase 1) to 0.205 cm (Phase 2). While this reduction is technically measurable, it is not significant from a practical or structural perspective.

CONCLUSION

This study employed finite element modeling using Plaxis 2D to evaluate the structural behavior of riverbank retaining walls along the Yesil River under combined natural and urban loading conditions. Based on the simulations, the following conclusions are drawn:

1. The introduction of an anchoring system led to only a 0.205 cm reduction in wall displacement under full loading conditions, a marginal improvement compared to the cost and effort involved.

2. The retaining wall structure without anchors, under the conditions of this project, demonstrated adequate structural strength, satisfying safety and deformation criteria under realistic urban and hydrostatic loading conditions.

3. The results underscore the importance of performing cost-benefit analyses during the design phase, especially in urban environments where budget and construction logistics are major constraints.

4. Future studies should investigate:

- Varying anchor configurations (spacing, depth, stiffness)
- Dynamic and extreme environmental conditions (floods, earthquakes)
- Long-term effects (consolidation, erosion, seasonal water level changes)
- Validation of numerical models against field data or physical tests

Overall, the findings support a cost-effective, rational design approach for urban riverbank infrastructure, where non-anchored retaining walls may offer optimal performance without unnecessary structural complexity.

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