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RESEARCH ARTICLE

CONSTRUCTION TECHNOLOGY AND NUMERICAL ANALYSIS OF RIVERBANK RETAINING WALLS USING PLAXIS 2D

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Abstract. *Ensuring reliable protection of riverbanks is particularly important in urbanised areas with complex engineering and geological conditions. This paper discusses construction technologies and performs a numerical analysis of the reliability of a retaining wall for coastal reinforcement on a pile foundation using the Plaxis 2D software package. The study is based on a combination of deterministic finite element modelling and probabilistic reliability assessment to analyse the stress-strain state of retaining walls under the combined action of soil and water loads. The numerical model takes into account the actual stages of construction, the layer-by-layer structure of the soil massif and the hydrostatic pressure of water, which allows the calculated conditions to be brought as close as possible to the operating conditions. According to engineering and geological surveys, layers of sandy loam and loam were identified, which are modelled using the Mohr–Coulomb elastic-plastic model. The simulation results showed that the maximum horizontal displacement of the retaining wall under combined loading does not exceed 2.0 cm, and the total deformations of the soil-structure system are within acceptable operational values. Probabilistic analysis using the Utkin method showed a reliability coefficient exceeding the recommended values for urban retaining structures. The results confirm that retaining walls on pile foundations, designed using modern numerical and probabilistic methods, are a technically reliable and cost-effective solution for strengthening riverbanks in conditions of weak soils and changing hydrological conditions.*

Keywords: *retaining wall, pile foundation, finite element method, Plaxis 2D, probabilistic reliability, soil-structure interaction, coastal reinforcement.*

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ҒЫЛЫМИ МАҚАЛА

PLAXIS 2D БАҒДАРЛАМАСЫН ПАЙДАЛАНА ОТЫРЫП ӨЗЕН ЖАҒАЛАУЫНДАҒЫ ТІРЕУ ҚАБЫРҒАЛАРЫНЫҢ САНДЫҚ ТАЛДАУЫ ЖӘНЕ ҚҰРЫЛЫС ТЕХНОЛОГИЯСЫ

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Аңдатпа. *Қалалық аумақтарда инженерлік-геологиялық жағдайлары күрделі болған кезде өзен жағалауларын сенімді қорғауды қамтамасыз ету аса маңызды болып табылады. Бұл мақалада қадалы іргетасқа орнатылған жағалауды бекітуге арналған тіреу қабырғаның құрылыс технологиялары қарастырылып, Plaxis 2D бағдарламалық кешенін қолдана отырып оның сенімділігіне сандық талдау жүргізіледі. Зерттеу тіреу қабырғаларының топырақ пен су жүктемелерінің бірлескен әсері жағдайындағы кернеу-деформациялық күйін талдау үшін детерминирленген ақырлы элементтер әдісімен модельдеу мен ықтималдық сенімділік бағалауын біріктіруге негізделген. Сандық модельде құрылыс жұмыстарының нақты кезеңдері, топырақ массивінің қабаттық құрылымы және судың гидростатикалық қысымы ескерілген, бұл есептік жағдайларды пайдалану жағдайларына барынша жақындатуға мүмкіндік береді. Инженерлік-геологиялық зерттеулер нәтижесінде құмбалшық және сазды топырақ қабаттары анықталып, олар Моор–Кулонның серпімді-пластикалық моделі арқылы модельденді. Модельдеу нәтижелері көрсеткендей, бірлескен жүктеме әсерінен тіреу қабырғаның максималды көлденең ығысуы 2,0 см-ден аспайды, ал «топырақ–құрылым» жүйесінің жалпы деформациялары рұқсат етілген пайдалану мәндері шегінде болады. Уткин әдісін қолдану арқылы жүргізілген ықтималдық талдау қалалық тіреу құрылымдары үшін ұсынылатын мәндерден асатын сенімділік коэффициентін көрсетті. Алынған нәтижелер қазіргі заманғы сандық және ықтималдық әдістерді қолдана отырып жобаланған қада іргетастағы тіреу қабырғалары әлсіз топырақтар мен өзгермелі гидрологиялық жағдайларда өзен жағалауларын нығайтудың техникалық тұрғыдан сенімді әрі экономикалық тиімді шешімі екенін растайды.*

Түйін сөздер: *тіреуші қабырға, қадалы іргетас, соңғы элемент әдісі, Plaxis 2D, ықтималдық сенімділік, топырақ – құрылым өзара әрекеттесуі, жағалауды нығайту.*

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НАУЧНАЯ СТАТЬЯ

ТЕХНОЛОГИЯ СТРОИТЕЛЬСТВА И ЧИСЛЕННЫЙ АНАЛИЗ ПОДПОРНЫХ СТЕН БЕРЕГОВОГО УКРЕПЛЕНИЯ С ИСПОЛЬЗОВАНИЕМ PLAXIS 2D

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Аннотация. *Обеспечение надёжной защиты речных берегов особенно важно в условиях урбанизированных территорий со сложными инженерно-геологическими условиями. В статье рассматриваются технологии строительства и выполняется численный анализ надёжности подпорной стены берегового укрепления на свайном фундаменте с использованием программного комплекса Plaxis 2D. Исследование основано на сочетании детерминированного моделирования методом конечных элементов и вероятностной оценки надёжности для анализа напряжённо-деформированного состояния подпорных стен при совместном воздействии грунтовых и водных нагрузок. В численной модели учтены реальные этапы строительства, послойное строение грунтового массива и гидростатическое давление воды, что позволяет максимально приблизить расчётные условия к эксплуатационным. По данным инженерно-геологических изысканий были выявлены слои супеси и суглинка, моделируемые с использованием упругопластической модели Моора–Кулона. Результаты моделирования показали, что максимальное горизонтальное перемещение подпорной стены при совместном нагружении не превышает 2,0 см, а суммарные деформации системы «грунт–сооружение» находятся в пределах допустимых эксплуатационных значений. Вероятностный анализ с применением метода Уткина показал коэффициент надёжности, превышающий рекомендуемые значения для подпорных сооружений в условиях городской застройки. Полученные результаты подтверждают, что подпорные стены на свайных фундаментах, запроектированные с использованием современных численных и вероятностных методов, являются технически надёжным и экономически эффективным решением для укрепления речных берегов в условиях слабых грунтов и изменяющихся гидрологических условий.*

Ключевые слова: *подпорная стена, свайный фундамент, метод конечных элементов, Plaxis 2D, вероятностная надёжность, взаимодействие грунта и сооружения, береговое укрепление.*

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CONFLICT OF INTEREST

The authors state that there is no conflict of interest.

During the preparation of this manuscript, the authors used artificial intelligence tools (ChatGPT) solely for editorial assistance, such as improving phrasing and checking grammar, spelling, and punctuation. All ideas, interpretations, and conclusions are the responsibility of the authors, who take full accountability for the content of the article.

АЛҒЫС / ҚАРЖЫЛАНДЫРУ КӨЗІ

Зерттеу жеке қаржыландыру көздерін пайдалана отырып жүргізілді.

МҮДДЕЛЕР ҚАҚТЫҒЫСЫ

Авторлар мүдделер қақтығысы жоқ деп мәлімдейді.

Мақаланы дайындау барысында авторлар жасанды интеллект құралдарын (ChatGPT) тек редакциялық көмек мақсатында пайдаланды: тұжырымдарды жетілдіру, грамматикалық, орфографиялық және тыныс белгілеріндегі қателерді тексеру үшін. Барлық идеялар, интерпретациялар мен қорытындылар авторларға тиесілі, және олар мақаланың мазмұнына толық жауапты.

БЛАГОДАРНОСТИ/ИСТОЧНИК ФИНАНСИРОВАНИЯ

Исследование проводилось с использованием частных источников финансирования.

КОНФЛИКТ ИНТЕРЕСОВ

Авторы заявляют, что конфликта интересов нет.

При подготовке рукописи авторы использовали инструменты искусственного интеллекта (ChatGPT) исключительно для редакторской поддержки: корректировки формулировок, проверки грамматических, орфографических и пунктуационных ошибок. Все идеи, интерпретации и выводы принадлежат авторам, которые несут полную ответственность за содержание статьи.

1 INTRODUCTION

The banks of urban rivers are subject to erosion, flooding and loss of slope stability, which poses significant risks to infrastructure and public safety. Retaining walls for bank reinforcement are widely used hydraulic structures designed to absorb lateral pressure from soil and water while ensuring slope stability. The effectiveness of such structures is largely determined by engineering and geological conditions, design solutions and the construction technology used.

The city of Astana (Kazakhstan) is characterized by complex engineering and geological conditions. The upper layers of the soil mass are dominated by weak sandy loam and loam, while dense bearing soils lie at a considerable depth. In such conditions, the use of traditional shallow foundations is often ineffective, making retaining walls on pile foundations the most rational solution. Piles transfer loads to more durable soils, reducing wall deformation and increasing the overall stability of the structure.

Modern research in the field of geotechnical engineering emphasises the importance of numerical modelling as a reliable tool for designing retaining structures. Software packages based on the finite element method, such as Plaxis 2D, allow detailed modelling of the interaction between the soil and the structure, taking into account the non-linear behaviour of soils, the phased nature of construction and the effects of hydrostatic water pressure.

This study is devoted to the analysis of construction technology and numerical modelling of a reinforced concrete retaining wall for coastal reinforcement on a pile foundation located along the Yesil River. The main objectives of the work are:

1. to describe the technology of retaining wall construction in the conditions of the city of Astana;
2. performing a numerical analysis using Plaxis 2D to assess deformations and stresses under soil and water loads;
3. assessing the reliability of the structure using probabilistic methods according to Utkin's methodology **(Utkin, V. S., & Solovyev, S. A., 2018)**.

Issues related to the calculation and design of retaining walls are widely covered in geotechnical literature. Classical approaches are based on Coulomb and Rankine theories, in which lateral soil pressure is determined using limit equilibrium methods. Despite their simplicity and widespread use, these methods do not fully account for the nonlinear nature of soil behavior, the phased nature of construction, and the interaction between the soil and the structure.

Retaining walls on pile foundations is particularly effective in weak soil conditions. Bowles (1996) noted that piles transfer loads to deeper and denser soil layers, thereby increasing the stability of structures and reducing settlement. **Das (2011)** emphasized that such structures are particularly important in urban development, where strict requirements are imposed on permissible deformations **(Das, B. M., & Sobhan, K., 2013)**.

Numerical modelling using the finite element method is now a standard tool in modern geotechnical design. The Plaxis 2D software package allows modelling of soil behavior using elastic-plastic models, considering the phased construction of structures and the effect of hydrostatic water pressure. Several studies, including those implementing the Hardening Soil Model (HSM), have shown that Plaxis 2D provides reliable predictions of retaining wall movements, stress distribution, and soil–structure interaction characteristics **(Schanz et al., 1999; Potts & Zdravković, 2001)**. While the present study performs calculations using the classical Coulomb–Mohr model, these HSM-based studies provide useful insights for future research and comparison.

Despite a significant amount of scientific research, applied data on the calculation of retaining walls for coastal reinforcement in the engineering-geological conditions of Central Kazakhstan remain limited. In addition, traditional deterministic calculation methods may underestimate the level of risk due to the uncertainty of soil characteristics. In this regard, Utkin proposed probabilistic methods for assessing reliability, which allow for the variability of soil strength characteristics and loads by determining reliability coefficients (β and K_n).

Recent studies **(Akbar et al., 2024; Zhao et al., 2025)** confirms the growing importance of finite element modelling and reliability-based approaches in geotechnical engineering. These works demonstrate that FEM-based methods provide accurate predictions of soil–structure interaction and deformation behaviour under complex soil and hydraulic conditions. They also show the practical effectiveness of pile-supported retaining walls under urban and weak soil conditions, consistent with the objectives of the present research **(Brinkgreve, R. B. J. et al., 2018)**.

In addition to local studies, numerous international investigations have focused on riverbank reinforcement using pile-supported retaining walls and numerical modelling. For example, **Won Pyo Hong et al., (2007)** studied the performance of pile-supported retaining walls in soft soil conditions, demonstrating the effectiveness of FEM in predicting wall behaviour. **Seo, H et al., (2022)** analysed the seismic performance of earth-retaining structures using reliability-based approaches. These international studies provide valuable insights into optimal design strategies, risk assessment, and numerical modelling techniques, which informed the methodology of the present research.

This study aims to integrate deterministic numerical modelling into Plaxis 2D with probabilistic reliability analysis for a comprehensive assessment of the performance and safety of coastal reinforcement retaining walls under real operating conditions.

2 MATERIALS AND METHODS

A retaining wall for coastal reinforcement was erected along the Yesil River in the engineering and geological conditions of the city of Astana. Due to the presence of weak soil in the upper layers of the foundation and the deep location of load-bearing soils, a reinforced concrete retaining wall on a pile foundation was chosen as the optimal design solution.

The retaining wall structure is a monolithic reinforced concrete wall 2.0 m high and 0.4 m thick. Precast reinforced concrete piles of type C60-30-8 with a square cross-section of 300 × 300 mm and a length of 6.0 m were used as the foundation. The main geometric and strength characteristics of the piles are given in **Table 1**.

Table 1
Properties of C60-30-8 Piles

№	Parameter	Unit	Value
1	Length	mm	6000
2	Width	mm	300
3	Height	mm	300
4	Concrete grade	-	200
5	Concrete volume	m^3	0.55
6	Weight	kg	1380

The piles were driven using the hammering method, which was chosen due to the relatively short length of the piles and the need to reduce construction time. The piles were installed with an axial pitch of 1.0 m, which corresponds to the recommended distance of approximately 3d and ensures effective joint operation of the piles in a group and load transfer. The pile driving process is shown in **Figure 1.**

The adopted design solution ensures reliable transfer of loads from the retaining wall to the deeper, more stable soil layers, by passing the weak upper strata. Special consideration was given to the interaction between the piles and the surrounding soil, which significantly affects the overall stability and deformation characteristics of the structure. The selected pile spacing and dimensions provide an optimal balance between structural safety and material efficiency. In addition, the construction method minimizes potential disturbances to the surrounding soil mass and reduces the risk of excessive settlements. Overall, the designed system meets the requirements for stability, durability, and serviceability under the given engineering and geological conditions.

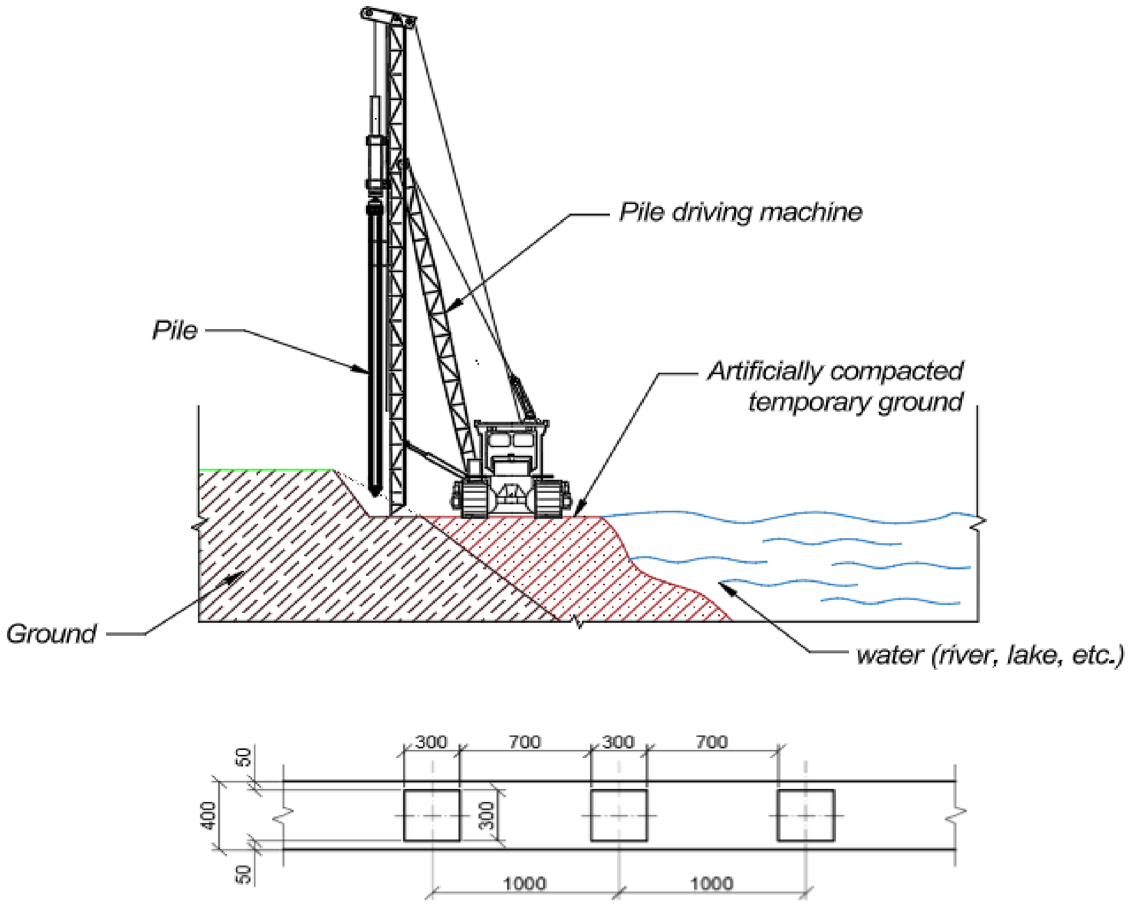

Figure 1 – Working process of a pile driving machine and location of pile foundations for a retaining wall (author's material)

After driving, the pile heads were cut and levelled to the mark using levelling instruments. The longitudinal reinforcement of the piles was exposed and connected to the reinforcement cage of the retaining wall, ensuring the monolithic operation of the 'pile-wall's system. Reinforcement work was carried out directly on the construction site. The reinforcement scheme of the retaining wall, including the spacing of the longitudinal and transverse reinforcement, as well as a 50 mm thick protective layer of concrete, is shown in **Figure 2.**

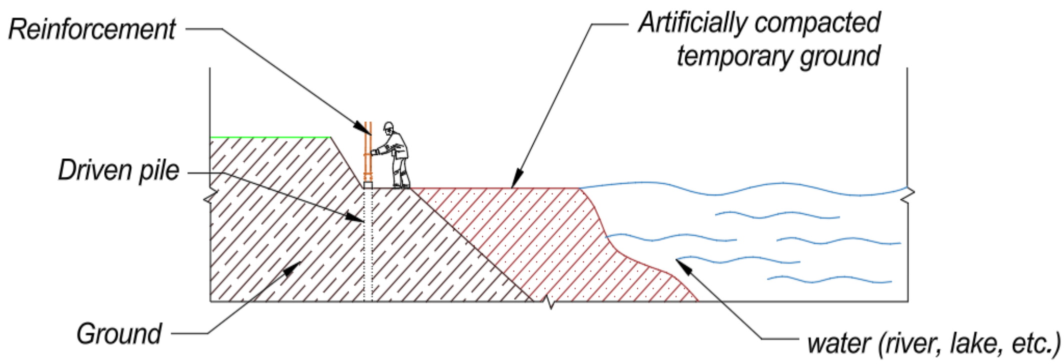

Figure 2 – Reinforcement of retaining wall (author's material)

The formwork was installed in stages along the length of the retaining wall, which allowed the formwork elements to be reused multiple times, reducing material costs and increasing the efficiency of the work. The concrete mix was delivered to the site by truck mixers and poured directly into the formwork. The concrete was compacted using deep vibrators to remove air voids and ensure uniform density. The concreting and vibration compaction processes are shown in **Figures 3 and 4.**

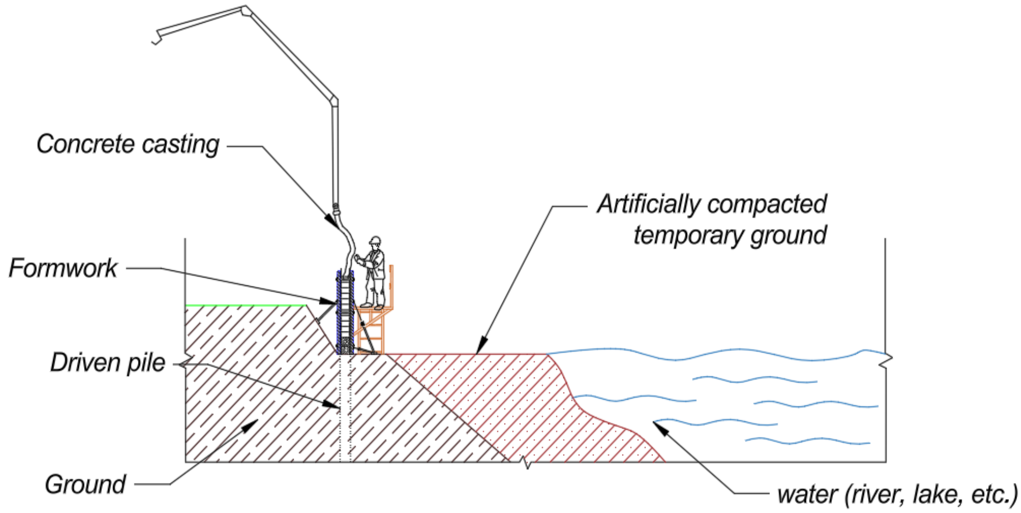

Figure 3 – Concrete work on the retaining wall (author's material)

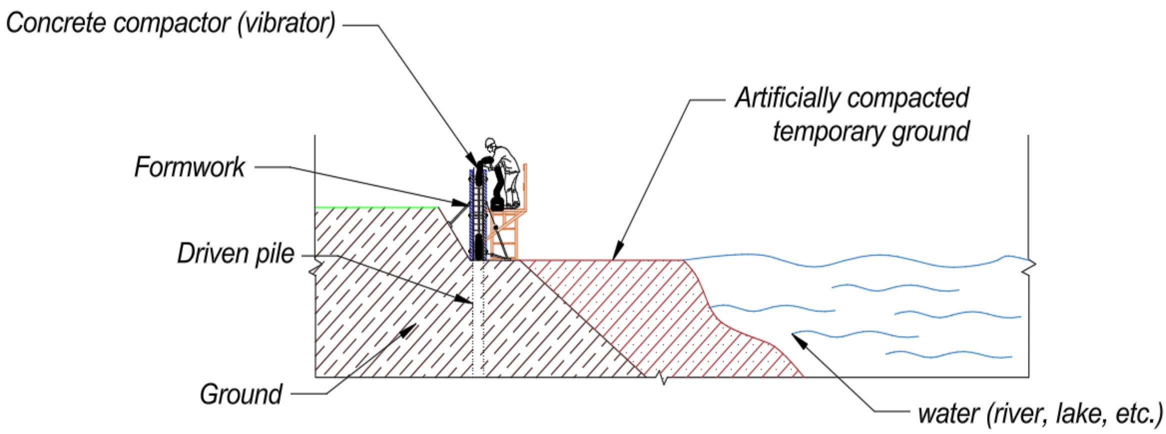

Figure 4 – Concrete compaction work (author's material)

To analyze the stress-strain state of the retaining wall of the coastal reinforcement on a pile foundation, a two-dimensional numerical calculation was performed using the Plaxis 2D software package. The calculation was performed using the finite element method under conditions of plane deformation, which is a reasonable assumption for long retaining structures with a constant cross-section. The calculated width of the model was taken to be 1.0 m.

The numerical model included the soil mass, reinforced concrete retaining wall, pile foundation, and water environment. The soil section consisted of three layers: an upper layer of sandy loam and two underlying layers of loam. The geological cross-sections are presented in Figures 5 and 7 of the Plaxis 2D model, while the physical and mechanical parameters of the soils are given in **Tables 2** and **Tables 3**. The geological conditions correspond to those typical of the city of Astana. The behaviour of the soils was described by the elastic-plastic constitutive model of Mohr–Coulomb **(Eurocode 7, SN RK 5.01-03-2013)**.

The selected soil model makes it possible to adequately describe the stress–strain behaviour of soils under loading conditions. Particular attention was paid to the assignment of boundary conditions to ensure the stability and convergence of the numerical solution. The groundwater level was taken into account in the model, as it significantly influences the effective stresses in the soil mass. In addition, the interaction between the retaining wall and the surrounding soil was simulated using appropriate interface elements. The adopted parameters were verified to ensure consistency with typical geotechnical conditions.

Table 2
Physical and Mechanical Properties of Soil Samples

№	Soil Type	I_l	I_p	ρ_s	ρ	ρ_d	γ_s	γ	γ_d	e	Sr
1	Sandy loam	0.2	0.15	2.7	1.99	1.75	26.46	19.5	17.2	0.54	0.66
2	Clay loam	0.3	0.18	2.72	2.01	1.79	26.6	19.69	17.5	0.52	0.64
3	Clay loam	0.3	0.18	2.6	2.0	1.8	25.48	19.6	17.64	0.52	0.64

Table 3
Physical Properties of Soil Samples

№	Soil Type	c' (kPa)	φ (°)	E (MPa)	R_0 (kPa)
1	Sandy loam	16	26	23	225
2	Clay loam	57	24	27	290
3	Clay loam	54	22	28	290

The retaining wall and piles were modelled as structural elements with linear elastic material properties corresponding to reinforced concrete. The interaction between the soil and structural elements was considered within the standard finite element formulation implemented in Plaxis 2D.

The geometry of the calculation area and boundary conditions were set to minimize the influence of edge effects. The lower boundary of the model was fixed horizontally and vertically, and the side boundaries were limited in horizontal displacement while maintaining the possibility of vertical deformation.

To account for the hydraulic impact, hydrostatic water pressure was applied to the retaining wall. The specific weight of water was taken to be 10 kN/m³, with the pressure distribution set linearly along the depth of the water column.

Numerical modelling was carried out in two consecutive stages to apply loads in stages and ensure the stability of the calculation model.

To account for the loads acting on the pile foundation, both axial and lateral forces were extracted from the Plaxis 2D model **(Eurocode 7, SN RK 5.01-03-2013, PLAXIS BV, 2020)**. The analysis showed that the maximum axial load on the piles reached approximately 235 kN, while the lateral loads varied between 15–25 kN depending on the pile location along the retaining wall. These results confirm that the pile foundation effectively transfers soil and hydrostatic loads to deeper, denser soil layers, thereby limiting wall displacements and ensuring overall structural stability. The distribution of loads along the wall also reflects the influence of local soil conditions and the phased construction process.

Stage 1: Soil load only

The first stage considered the weight of the soil and the lateral pressure on the retaining wall. This made it possible to assess the initial distribution of stresses, soil deformation and the mechanism of load transfer through the piles. The results are visualized through vector displacement fields and deformation isolines **(Figures 5 and 6)**. At this stage, moderate horizontal displacements of the wall towards the river are observed, with the piles effectively transferring the load to deeper soil layers.

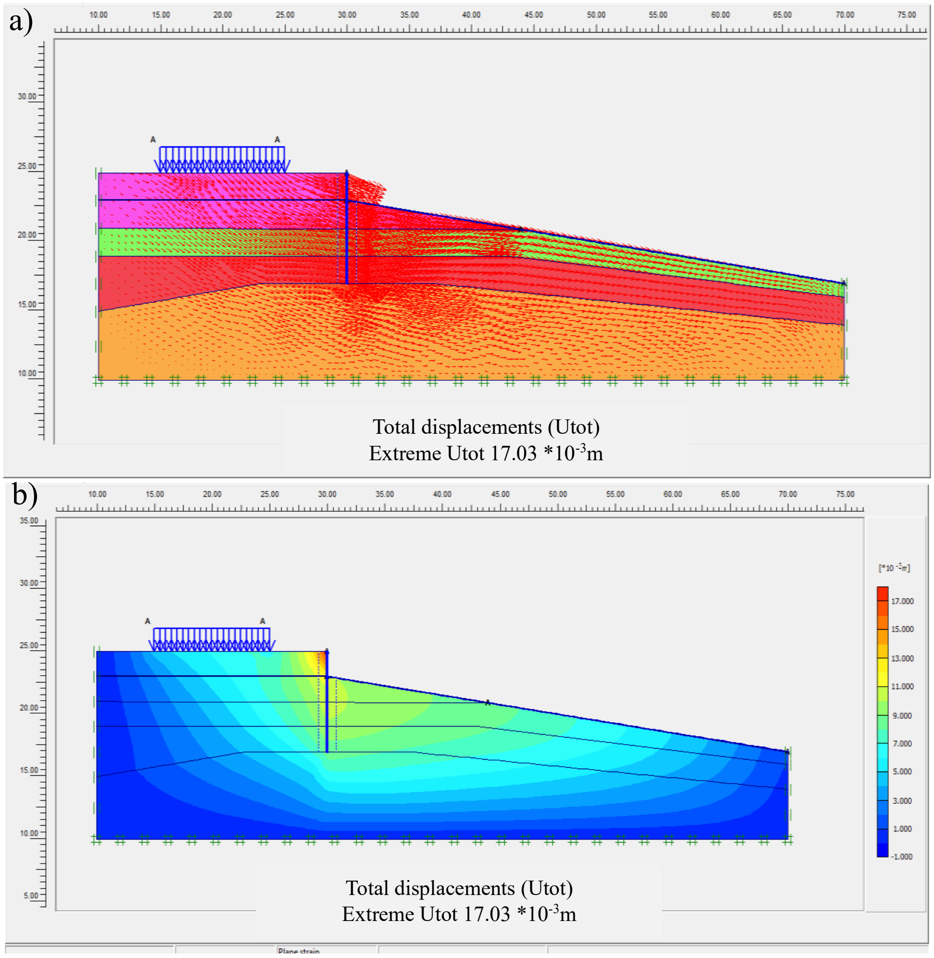

Figure 5 – Displacements of the retaining wall in the load zone. a - displacements shown as vectors; b - displacements shown using colour gradations (author's material)

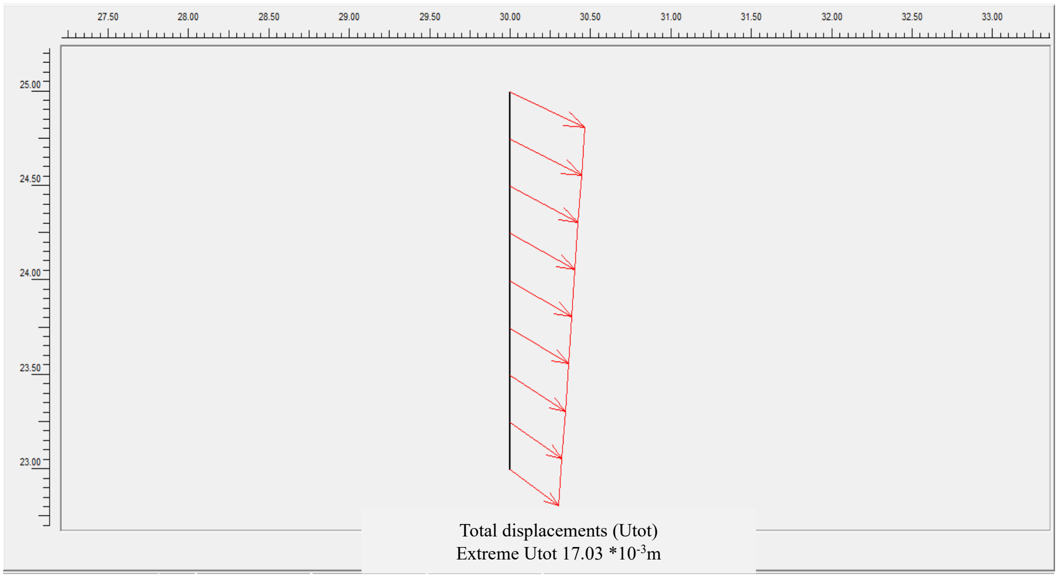

Figure 6 – Detailed illustration of retaining wall deformations from numerical modeling (author's material)

Stage 2: Soil and hydrostatic load

In the second stage, hydrostatic water pressure is added to the soil loads, simulating the most unfavorable loading conditions. The results are presented in the form of vector fields and color maps **(Figures 7 and 8)**. The soil-pile-wall system responds with increased deformations, especially in water-saturated areas, while the piles continue to provide stability and limit excessive displacements **(Abu, A. Z. et al., 2025)**.

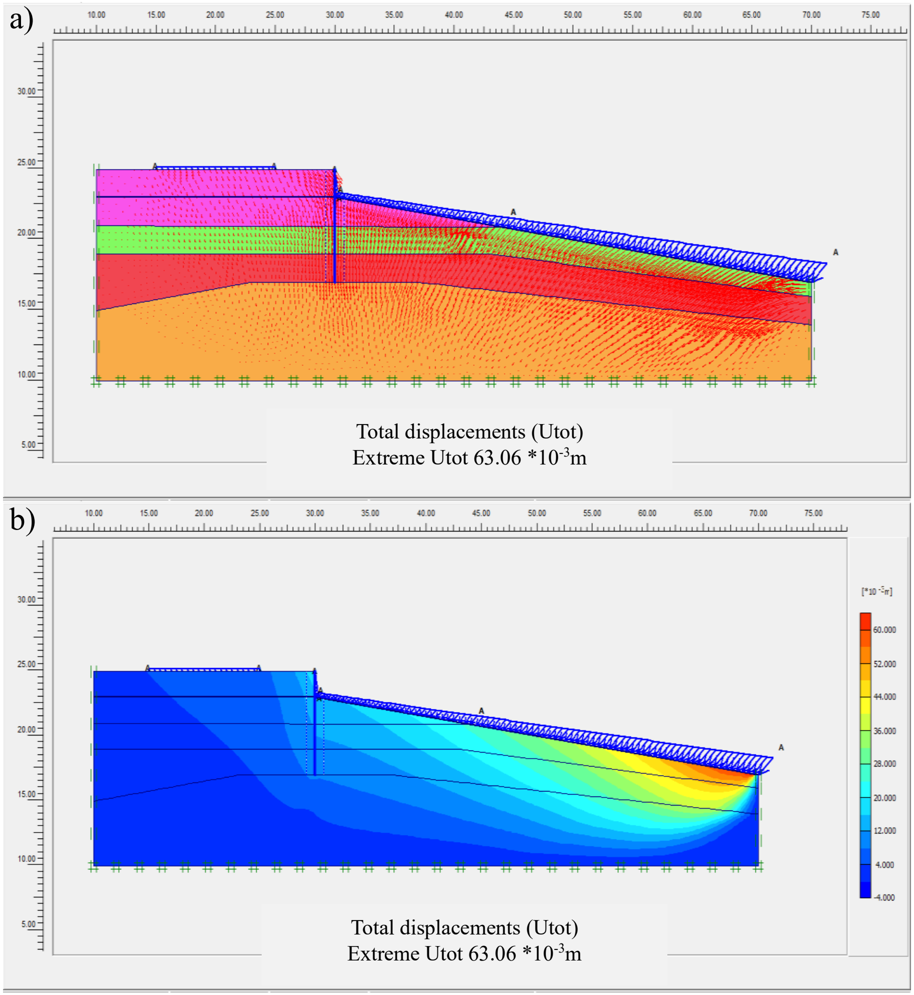

Figure 7 – Displacements of the retaining wall in the load zone. a - displacements shown as vectors; b - displacements shown using colour gradations (author's material)

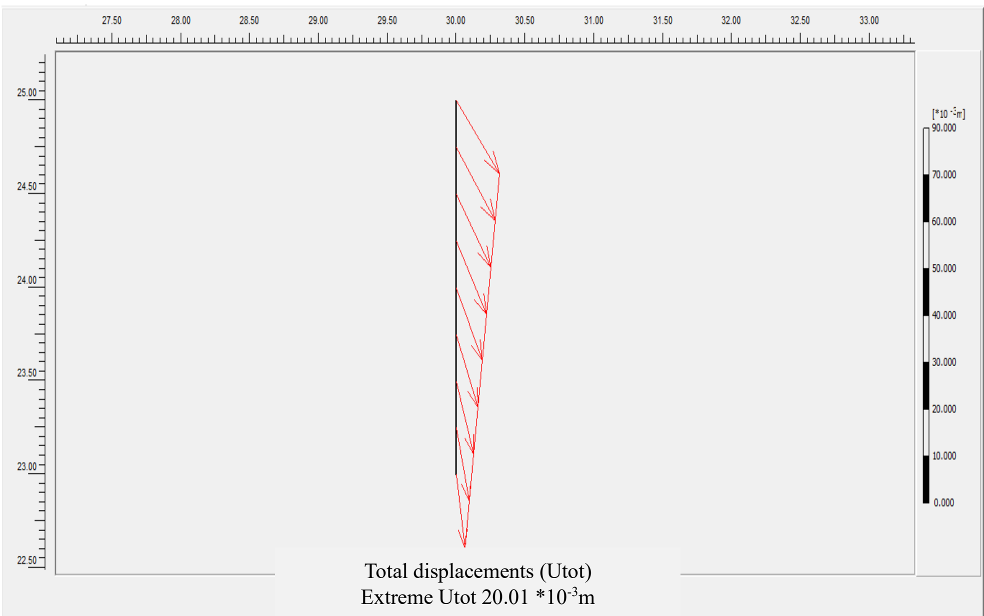

Figure 8 – Detailed illustration of retaining wall deformations from numerical modeling (author's material)

The adopted modelling strategy allows for the assessment of deformation and stress development in the retaining wall system under the combined action of soil and hydraulic loads and provides a consistent basis for subsequent reliability analysis **(Poulos, H. G., & Davis, E. H., 1980)**.

To account for the variability of soil properties and loads, a probabilistic approach based on Utkin's methodology was applied. Soil parameters - cohesion c, angle of internal friction ϕ, and specific weight γ - as well as hydrostatic water pressure were considered as random variables with known mean values and standard deviations **(Smith, I. M., & Griffiths, D. V., 2004)**.

The reliability coefficient was calculated using the following formula:

$$K_n = \frac{R-S}{Q_s} \tag{1}$$

where:
R - calculated resistance of the retaining wall–pile system;
S - applied load (soil + water);
Q_s - standard deviation of the load effect.
The variability of soil parameters was assumed to be as follows:
- coefficient of friction c: 0.15,
- angle of internal friction ϕ: 0.10,
- specific weight γ: 0.05,
- hydrostatic pressure of water: 0.05.

The results of the probabilistic analysis are shown in **Table 4**. The calculated values of the reliability coefficients K_n exceed the minimum recommended value of 2.5, which indicates sufficient reliability of the structure under variable soil and hydrological loads.

Table 4
Probabilistic soil parameters and reliability coefficients

№	Soil Type	Average φ (°)	σ_φ	Average c (kPa)	σ_c	β	F_s
1	Sandy loam	26	2	16	3	3.2	1.45
2	Clay loam	24	2.5	57	5	2.9	1.40
3	Clay loam	22	2.5	54	5	2.8	1.38

Thus, the proposed approach combines the results of deterministic finite element analysis with probabilistic assessment, which improves the accuracy of predicting the reliability of retaining walls under conditions of variability in soil and hydrological characteristics.

3 RESULTS AND DISCUSSION

Using the Plaxis 2D model described in section 3.2, displacements, stresses and soil-structure interaction were analyzed at all stages of construction.

The maximum wall displacements are observed in the middle part of the retaining wall height under full hydrostatic load. The displacements at each stage of construction were as follows:

Stage 1 (soil weight and lateral pressure): 1.703 cm

Stage 2 (combined effect of soil and hydrostatic pressure): 2 cm

Interpretation: the displacements remain within the permissible values for a reinforced concrete retaining wall with a height of 2.0 m, which confirms the adequacy of pile support to prevent excessive tilting of the structure.

As described in Section 3.3, the probabilistic approach takes into account uncertainties in soil properties and hydraulic loads.

The calculated reliability factor Kn=3.12 exceeds the recommended minimum of 2.5 for urban retaining walls, indicating a high probability of structural reliability under actual operating conditions (**Table 5)**.

Table 5
Comparison of deterministic and probabilistic results

№	Parameter	Deterministic (Plaxis)	Probabilistic	Notes
1	Maximum displacement	2 cm	2 ± 0.3 cm	Insignificant decrease due to variability
2	Maximum stress	235.62 kPa	228 ± 10 kPa	Insignificant decrease due to statistical averaging
3	Safety factor F_s	1.45	1.40 ± 0.05	Corresponds to the reliability index β

Combining deterministic FEM modelling with probabilistic reliability assessment allows for a more realistic assessment of structural safety, as it takes into account soil variability, hydrostatic pressure fluctuations and construction tolerances.

A sensitivity study was conducted to identify the factors that have the greatest impact on reliability:

- Soil friction (c): a change of ± 5% caused a change in K_n of 0.12
- Internal friction angle (φ): a change of ±10% caused a change in K_n of 0.08
- Specific weight (γ): a change of ±5% caused a change in K_n of 0.04
- Hydrostatic pressure: a change of ±5% caused a change in K_n of 0.05

The sensitivity of the reliability coefficient to soil parameters confirms that cohesion is the most critical parameter, which emphasizes the importance of accurate engineering geological testing for retaining walls on urban riverbanks.

Comparison with regulatory requirements:

The calculated stability reserve coefficients (Fs=1.40-1.45) comply with national and international standards for the design of retaining walls in urban environments (recommended value Fs ≥ 1.3).

The maximum displacement (≈2 cm) is below the permissible limit of 1/250 of the wall height, which ensures operational suitability.

The probabilistic approach confirms that even with variable soil properties, the wall remains structurally reliable, which is particularly important for areas with fluctuating groundwater levels.

The analysis demonstrates several key points:

1. Finite element modelling (FEM) provides a detailed understanding of the wall's performance by showing the distribution of stress and displacements, consistent with previous studies using Plaxis 2D **(Won Pyo Hong et al., 2007; Shegenbayeva et al., 2025)**.

2. Pile-supported retaining walls are effective in weak soil conditions, preventing excessive settlement and rotation of the structure, which agrees with local and international observations of similar urban riverbank reinforcement projects **(Akbar et al., 2024; Zhao et al., 2025; Useche-Infante, D., 2025).**

3. Probabilistic reliability analysis complements deterministic modelling by allowing for uncertainties in soil strength characteristics, water pressure, and material properties, as recommended by Utkin and supported by international geotechnical studies **(Seo, H et al., 2022; Useche-Infante, D., 2025)**.

4. Sensitivity analysis helps prioritise quality control of the most influential parameters, such as adhesion and internal friction angle, which directly affect wall safety.

This methodology - a combination of deterministic and probabilistic analysis - is a reliable approach to the design of retaining walls for urban riverbanks under variable hydrological conditions and aligns with findings reported in recent local and international literature.

4 CONCLUSIONS

This study examined the construction technology and numerical behavior of a pile retaining wall along the Yesil River in Astana. The use of a combined deterministic and probabilistic approach made it possible to comprehensively assess the stability of the wall and the soil-structure interaction. The following conclusions can be drawn:

1. Scientific novelty: The novelty of this research lies in the integrated approach combining deterministic finite element modelling with probabilistic reliability assessment, applied specifically to pile-supported retaining walls in the complex engineering-geological conditions of Astana. Unlike previous studies (Akbar et al., 2024), which focus either on numerical modelling or field performance, this study provides a comprehensive analysis of deformation, stress distribution, and reliability under variable soil and hydraulic conditions. The results demonstrate both methodological advancement and practical applicability for urban riverbank protection.

2. Construction technology efficiency: The selected reinforced concrete pile wall effectively transfers loads to deeper and stronger soil layers, reducing wall displacement and ensuring its stability in weak upper layers. Phased construction, careful reinforcement and correct installation of the piles were critical for even load distribution and maintaining the integrity of the structure.

3. Validation of numerical modelling: Full-scale analysis using Plaxis 2D reliably reproduced the stress-strain state of both the wall and the surrounding soil. The maximum displacement of the wall under the combined action of soil and water did not exceed 2.0 cm, while the total displacement of the soil-water profile reached 6.306 cm, which is within the acceptable limits for urban retaining walls.

4. Reliability and probability analysis: Probability assessment using the Utkin method showed a reliability coefficient K_n=3.12, which exceeds the recommended minimum of 2.5 for urban retaining walls. Sensitivity analysis showed that soil adhesion has the greatest impact on reliability, followed by the angle of internal friction, which emphasizes the importance of accurate geotechnical studies.

5. Practical significance: The combined deterministic-probabilistic method provides a reliable basis for the design of coastal retaining walls in urban environments with weak soils and changing hydrological conditions. The results obtained are applicable to similar hydraulic and geotechnical structures, contributing to safe and cost-effective coastal protection.

Prospects for further research may include three-dimensional modelling, long-term monitoring of wall behavior, and consideration of cyclic loads associated with seasonal water level changes to improve reliability and optimize design solutions.

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