Transportation Infrastructure Geotechnology (2025) 12:76
https://doi.org/10.1007/s40515-025-00534-7

TECHNICAL PAPER

A Novel Approach to Predicting Horizontal Displacement of Riverbank Retaining Walls

Phuong Tuan Nguyen[1] · Truong Xuan Dang[2] · Tuan Anh Nguyen[3] · Luan Nhat Vo[4] · Hoa Van Vu Tran[5]

Accepted: 5 January 2025 / Published online: 14 January 2025

Abstract

This study introduces a novel method for predicting horizontal displacement in riverbank retaining walls, with a specific focus on the riverbank in Ho Chi Minh City, Vietnam. Employing finite element analysis (FEA) in conjunction with linear regression, the research establishes a predictive formula tailored to the unique geological conditions of the region. The analysis encompasses a variety of 160 scenarios involving differing pile lengths, diameters, spacings, and weather conditions to understand their impact on horizontal displacement. Based on the depth of the piles (24 m, 30 m, 36 m, 42 m, and 48 m), results demonstrate that a pile length of 36 m optimally minimizes horizontal displacement. The investigation reveals that variations in pile spacing and diameter do not consistently lead to reduced displacements, reflecting the complex interactions between soil and structure. This innovative approach merges the detailed modeling capabilities of FEA with the statistical rigor of linear regression; the study detected the extent to which various factors (number of piles, pile diameter, pile spacing, pile type, and weather conditions) influence horizontal displacement, providing a practical tool for engineers to estimate displacement values efficiently. The findings emphasize the need for appropriate design solutions based on factors influencing horizontal displacement to improve the reliability and cost-effectiveness of retaining wall designs. This research contributes valuable insights into the design of stable retaining wall foundations, ensuring their safety and durability against the dynamic forces encountered in riverbank environments.

Keywords Finite element analysis · Retaining wall foundations · Linear regression · Soil-structure interactions

Extended author information available on the last page of the article

1 Introduction

In Ho Chi Minh City, the Saigon River plays a crucial role not only in the transportation system but also as an environmental and infrastructure protection factor. With its strategic location and socio-economic significance, maintaining the stability of retaining wall structures with densely spaced pile foundations along the riverbanks is an essential task. These retaining walls are responsible for preventing soil erosion and have been constructed with retaining walls featuring densely spaced pile foundations, protecting adjacent infrastructure, and ensuring the safety of residents and surrounding economic activities. However, the dynamic geological and hydrological conditions of the Saigon River pose significant challenges to the stability of these structures. Despite this, many current studies have indicated that traditional methods often employ simplified formulas or experience-based approaches to evaluate the displacement of retaining walls, while these methods fail to fully capture complex factors such as soil-structure interaction, the impact of weather conditions, or changes in the retaining wall structure (Shangyu, et al. 2016; Ren et al. 2022; Sianturi 2024; Derghoum and Meksaouine 2019; Mangraviti et al. 2023).

One of the biggest drawbacks of current methods is the lack of accuracy and reliability when applied to the specific geological and hydrological conditions of the Saigon River. These methods often cannot handle the complexity of soil-structure interactions, leading to inaccurate assessments of retaining wall displacement. In particular, changes in weather conditions, such as heavy rains causing erosion, can significantly alter the displacement of retaining walls, but these factors are often overlooked or inadequately assessed. Moreover, current studies have not provided a specific and reliable predictive formula for the geological and hydrological conditions of the Saigon River area. Although many studies on riverbank retaining walls have been conducted, most focus on other areas or use models that are not suitable for the specific conditions of the Saigon River (Morelli et al. 2020; Papageorgiou et al. 2020; Heydari and Diplas 2020; Nakazawa et al. 2018; Hosseinzadeh Asl and Yasi 2023; Sotiropoulos and Diplas 2017; Udomchai et al. 2018). This gap makes the design and maintenance of retaining walls challenging and inefficient, highlighting the need for a new analytical approach that can fully integrate all influencing factors to provide more accurate predictions.

The aim of this study is to combine finite element analysis (FEA) and linear regression to develop a predictive model for wall displacement (Ahmadabadi et al. 2016; Jia et al. 2018; Ebeling 1990; Ling and Leshchinsky 2003; Popa and Batali 2010; Ereiz et al. 2022; Ruiz de Galarreta et al. 2020; Liu et al. 2021; Korumaz et al. 2017; Cremonesi et al. 2020; Vahedifard and Meehan 2011). By varying the stiffness of the piles, this research explores their individual and combined impacts on the displacement of retaining walls. With the objective of developing a horizontal displacement prediction model for retaining walls, the study uses FEA and linear regression to build a predictive formula based on key parameters such as pile type, pile spacing, pile diameter, number of piles, and weather conditions.

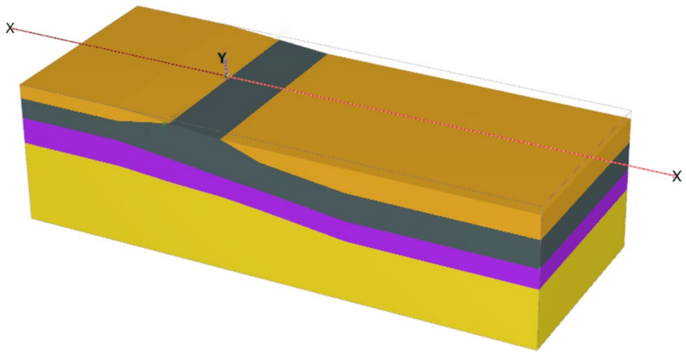


Fig. 1 Geological section

Table 1 Soil description parameters

Hardening soil	Fill layer	Mud layer	Clay layer	Sand layer
Drainage type	D	U.D	U.D	U.D
γ_{unsat}	18.63	14.25	18.02	20
γ_{sat}	19.4	15.03	18.24	20.4
e_{int}	0.6	1.8	0.7	0.606
k_x	8.64	$1.20E^{-04}$	$8.64E^{-06}$	$1.38E^{-03}$
k_y	8.64	$1.20E^{-04}$	$8.64E^{-06}$	$1.38E^{-03}$
k_z	8.64	$6.00E^{-05}$	$4.32E^{-06}$	$6.91E^{-04}$
P^{ref}	100	100	200	400
$E^{ref}{}_{50}$	8000	4600	24000	36000
$E^{ref}{}_{oed}$	8000	4600	24000	36000
$E^{ref}{}_{ur}$	24000	13800	72000	108000
m	0.55	0.85	0.8	0.55
φ’	26.6	18.5	23.5	30
c’	4.5	17.8	32	5.4
Ψ	0	0	0	0

2 Material and Methods

The research region has terrain and geology along the Saigon Riverbank, situated in Ho Chi Minh City, Vietnam. The geological composition of the site comprises four separate layers: fill, mud, clay, and sand. Within this geological profile, the fill layer is 2 m thick, followed by a 20-m thick mud layer, a 32-m thick clay layer, and finally, a 70-m thick sand layer, as shown in Fig. 1. The strata in this area are characteristic and provide a representative sample of the underground conditions, which are crucial for the finite element analysis.

The parameters describing the soil layers are detailed in Table 1. The retaining wall has a thickness of 300 mm (Dhamdhere et al. 2018) and a height of 2.5 m and is supported by a foundation with a thickness of 400 mm and a length of 3 m,

Table 2 Description parameters of soil retaining wall material

Parameter		Foundations	Soil retaining wall
Material type	-	Elastic	Elastic
EA1	kN/m	12E06	9E06
EA2	kN/m	12E06	9E06
EI	kN m^2/m	160E3	67.5E3
d	m	0.4	0.3
w	kN/m/m	10	7.5
υ	-	0.2	0.2

Table 3 Description parameters of piles material

Parameter		Square piles	Round piles
Material type	-	Elastic	Elastic
E	kN/m^2	30E6	30E6
Y	kN/m^3	10	10
Width/diameter	m	0.35; 0.4; 0.45	0.35; 0.4; 0.45
Thickness	m	-	0.08
Lspacing	m	0.5; 1; 1.5; 2; 2.5	0.5; 1; 1.5; 2; 2.5

along with an underlying system of driven piles using concrete B25 and line load – 3 kN/m/m with 20 m characteristic of the load used. Parameters describing soil retaining wall materials and piles are shown in Tables 2 and 3. By employing finite element analysis (FEA), this study investigates how variations in pile length affect the displacement of retaining wall foundations in riverbank geological settings. Through a series of simulations, we modeled different scenarios of pile length adjustments to observe their impact on the displacement. The goal was to identify the optimal pile length that would ensure minimal and stable displacement of the retaining wall foundation. The simulations were conducted using a detailed FEA model that accurately represents the physical and mechanical properties of the riverbank soil and the retaining structure. The analysis involved systematically varying the pile lengths and recording the resulting displacements to determine the relationship between pile length and foundation displacement. Pile lengths are changed to 24 m, 30 m, 36 m, 42 m, and 48 m respectively.

This approach allowed for a comprehensive assessment of the pile length required to achieve stable displacement conditions for the retaining wall foundation and provided the optimal pile length value for further analysis. To determine the optimal pile depth, a configuration of five square piles with a width of 350 mm was arranged. This arrangement was chosen to effectively distribute the load and analyze the impact of varying pile depths on the displacement of the retaining wall foundation. The selected configuration allowed for a comprehensive examination of how different pile depths influence the interaction between the soil and the retaining structure, providing a robust basis for identifying the most effective pile depth for ensuring minimal and stable displacement.

After determining the optimal pile depth, the study proceeded with finite element analysis (FEA) under various scenarios involving changes in the number of piles (5, 4, and 3) as shown in Fig. 2, pile types (round or square), pile diameters (350 mm, 400 mm, and 450 m), and spacing between piles (2.5 m, 2 m, 1.5 m, 1 m, and 0.5 m), as well as different weather conditions (rain-induced erosion and no rain). The weather variable was considered under two distinct conditions. The no-rain scenario included only the applied load used (− 3 kN/m/m) without additional environmental factors. The spacing and inclination of the piles in configurations with 3, 4, and 5 piles are as follows: for 3 piles, the spacing is 1 m each with an inclination of 9°; for 4 piles, the spacing is 0.5 m, 1 m, and 0.5 m with an inclination of 9°; and for 5 piles, the spacing is 0.5 m between each pile with an inclination of 9°. Conversely, the rain-induced erosion scenario was described by heavy rainfall leading to water runoff down to the base of the retaining wall, occurring when the river water level is at its lowest during the rainfall event. A total of 160 scenarios were analyzed (Brooks 2010).

The results from all simulation scenarios were aggregated and statistically analyzed using regression analysis in the OLS (ordinary least squares) method. This included tests of significance (Sig values) in ANOVA, R-squared values, and Student's *t*-tests, as shown in Fig. 3 (Guide 1998).

Besides, the VIF index evaluates multicollinearity, and regression coefficients are also considered. From these analyses, the study derived Beta coefficients from developing a linear regression formula aimed at predicting the displacement of the retaining wall foundation system. The multicollinear regression equation has the form in Eq. (1).

$$Y = B_0 + B_1X_1 + B_2X_2 + \cdots + B_nX_n + \varepsilon \quad (1)$$

where Y is the dependent variable (horizontal displacement); X_1, X_2, X_n: independent variables (pile type, spacing between piles, number of piles, and weather conditions); B_0 is regression constant; B_1, B_2, B_n, regression coefficients; ε, residual.

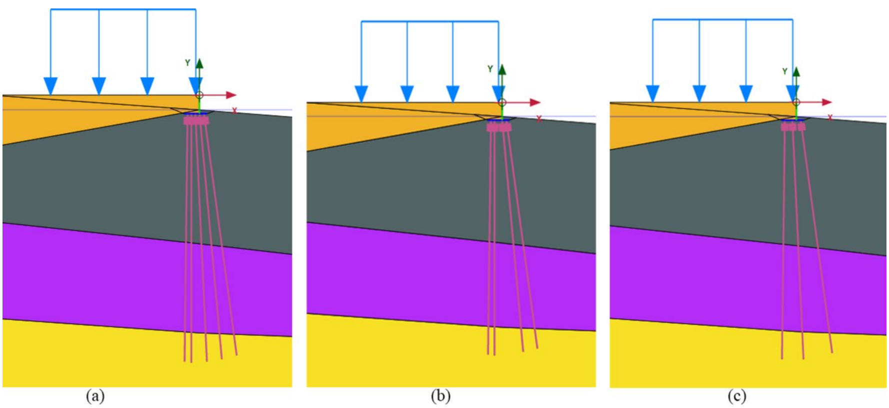


Fig. 2 Structure of the foundation system of the soil retaining wall with 5 piles (**a**), 4 piles (**b**), and 3 piles (**c**)

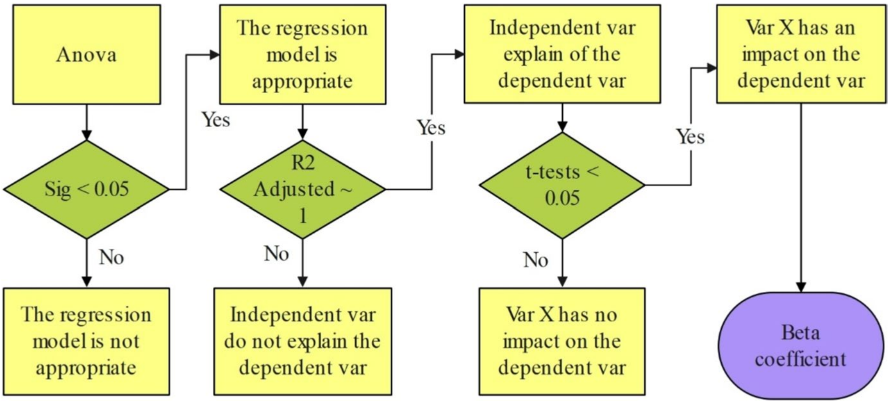


Fig. 3 Regression analysis process

The regression assumptions were evaluated using three key plots: the histogram of standardized residuals to assess their frequency distribution and the normal P-P plot of standardized residuals to check for normality to verify the linear relationship assumption. In this study, the independent variables are pile type, spacing between piles, number of piles, and weather conditions. The dependent variables under consideration are Ux.

3 Results

The finite element analysis of different pile depths yielded the results shown in Fig. 4. From the analysis of the Ux and Uy displacement of the foundation block under different pile lengths, it was observed that a pile length of 36 m is optimal,

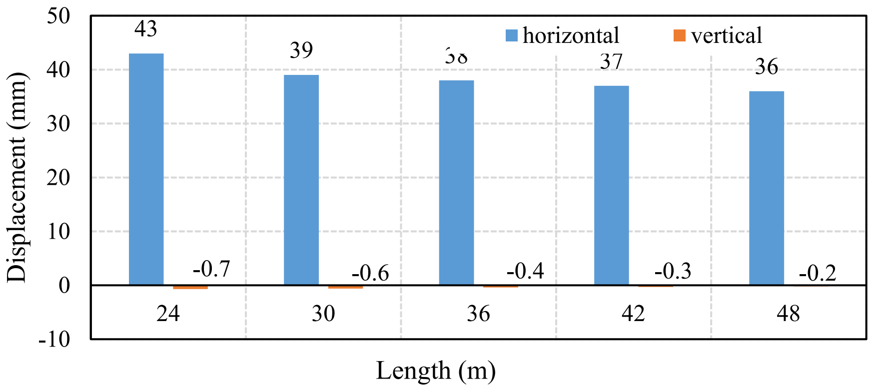


Fig. 4 Compare the displacement in the case of pile lengths

with a Ux displacement of 0.038 m and Uy displacement of − 0.002 m. Increasing the pile length to 48 m did not result in significant changes in this displacement.

The analysis encompassed 160 different scenarios, each varying in terms of pile type, spacing, number of piles, and weather conditions. The results provide a comprehensive understanding of how these variables influence the displacement of the retaining wall foundation, specifically in the Ux direction. This extensive dataset allows for a detailed examination of the interplay between the independent variables and their impact on the displacement of the structure.

The descriptive statistics for different scenarios are presented in Table 4, and the analysis results for the three-pile, four-pile, and five-pile scenarios are illustrated in Figs. 5, 6, and 7, respectively. The maximum and minimum values of horizontal displacement are summarized in Table 5.

Following the analysis of 160 different scenarios, a linear regression analysis was conducted. The independent variables are pile type, spacing between piles, number of piles, and weather conditions. The dependent variables under consideration are Ux, with the Sig value result in the ANOVA table close to $0 < 0.05$ (Table 6), which determined that the regression model was suitable (Table 7).

A Sig value less than 0.05 indicates that the regression coefficient of the independent variable has a significant impact on the dependent variable. The standardized coefficients beta values reveal that the variables with the greatest influence on Ux are, in order, weather, pile diameter, pile spacing, pile type, and number of piles (a negative sign indicates that the relationship is in the opposite direction to the

Table 4 The descriptive statistics for different scenarios

Number of piles	Value	*N*	Min	Max	Mean	Std. dev
3	Pile space	54	500	2500	1583.333	718.6859
	Pile diameter	54	350	450	403.7037	41.03823
	Weather	54	1	2	1.5	0.504694
	Pile type	54	1	2	1.518518	0.504348
	Ux	54	3.44	16.8	9.236851	4.491248
4	Pile space	54	500	2500	1555.55	731.1574
	Pile diameter	54	350	450	400	41.20817
	Weather	54	1	2	1.5	0.504695
	Pile type	54	1	2	1.44444	0.50157
	Displacement (Ux)	54	3.24	16.2	8.74481	4.284997
5	Pile space	52	500	2500	1519.231	720.5767
	Pile diameter	52	350	450	401.9231	40.77862
	Weather	52	1	2	1.5	0.504878
	Pile type	52	1	2	1.461538	0.503382
	Displacement Ux	52	3.1	15.8	8.388269	4.136077

Note: The values 1 and 2 in the weather variable correspond to no rain and rain-induced erosion, respectively. Similarly, the values 1 and 2 in the pile type variable represent square and round piles, respectively

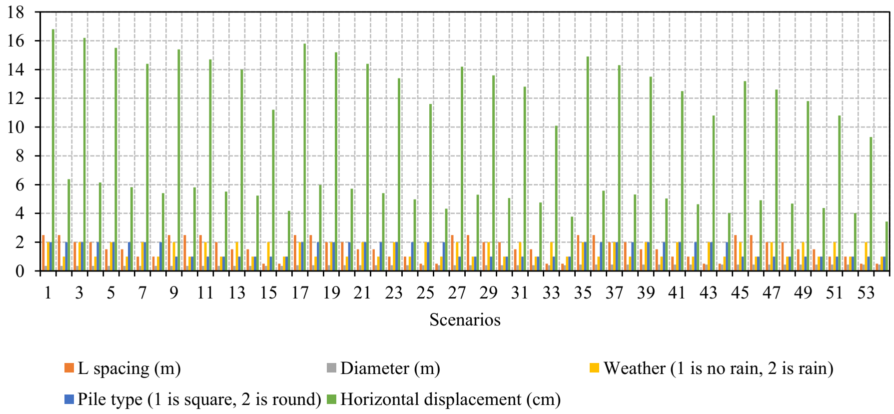


Fig. 5 Displacement Ux in the 3-pile scenario

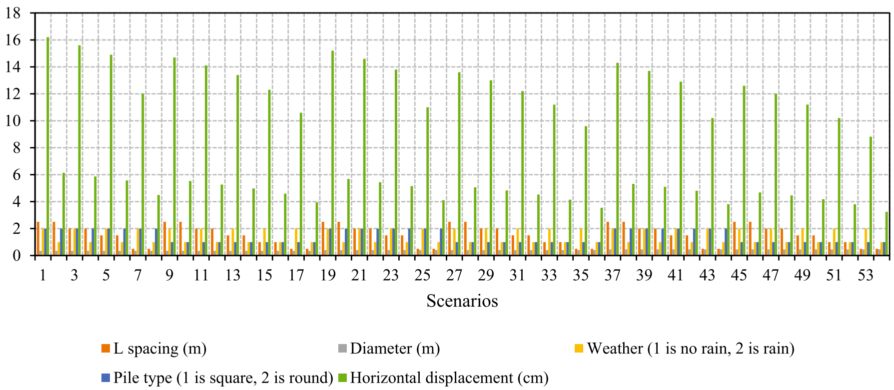


Fig. 6 Displacement Ux in the 4-pile scenario

increase in the Ux variable), VIF coefficient < 2 so multicollinearity does not occur causing bias in regression estimates, as shown in Table 8.

The importance of various factors influencing the dependent variable, displacement (Uy), in descending order, is as follows: Weather has the greatest impact, followed by pile diameter, pile space, pile type, and number of piles as shown in Fig. 8.

In Table 9, the residual value ε is 7.956208. To verify this value, use a histogram of standardized residuals and a normal P-P plot as shown in Figs. 9 and 10.

The residual value columns are bell-shaped, confirming that the distribution is approximately normal and that the assumption of normal distribution of residuals is not violated. Specifically, as shown in Fig. 9, the mean is 6.18E-16, which is close to 0, and the standard deviation is 0.984, which is close to 1.

In Fig. 10, the residual data points are closely aligned with the diagonal line, indicating that the residuals are approximately normally distributed. Thus, the assumption of normal distribution of residuals is not violated.

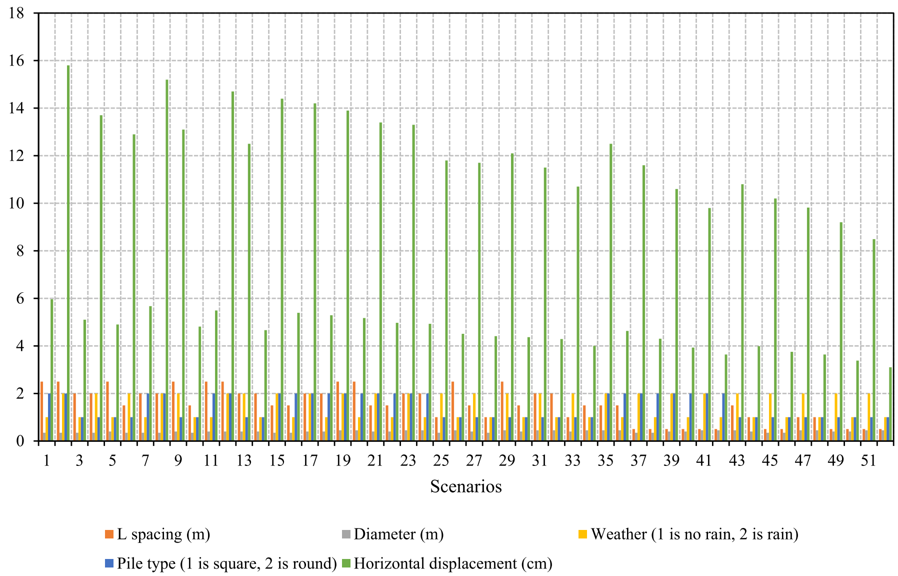


Fig. 7 Displacement Ux in the 5-pile scenario

From the test results and residual values, the predictive formula for Ux displacement is established as follows:

$$U_x = -3.76508X_1 + 0.010187X_2 - 0.1804X_3 - 80.24383X_4 + 11.10982X_5 + 30.8413 \quad (2)$$

where U_x is the displacement with direct X (mm); X_1 is the number of piles (mm); X_2 is the Pile space (mm); X_3 is the pile diameter (mm); X_4 is the weather (with 1 when no rain, 2 when rain-induced erosion); X_5 is the pile type (with 1 for square pile, 2 for round pile).

4 Discussion

The analysis of the impact of different factors on the horizontal displacement of retaining walls, based on the results from 160 simulation scenarios, shows that factors such as weather conditions, pile type, pile diameter, pile spacing, and the number of piles all have significant effects on the horizontal displacement Ux of the retaining walls. Among these, weather conditions were identified as having the most substantial impact, with a regression coefficient of – 80.24383, indicating that rain-induced erosion can significantly increase horizontal displacement. This is an important finding, as it underscores the need for designs that can withstand harsh weather conditions, particularly in areas frequently affected by heavy rainfall.

Table 5 Comparison of Ux displacements under different conditions

Piles	Condition	Max Ux (cm)	Min Ux (cm)	Pile spacing for max (mm)	Pile diameter for max (mm)	Pile spacing for min (mm)	Pile diameter for min (mm)
3	Square piles, no rain	5.8	3.44	2500	350	500	450
	Round piles, no rain	6.38	4.02	2500	350	500	450
	Square piles, rain	15.4	9.3	2500	350	500	450
	Round piles, rain	16.8	10.8	2500	350	500	450
4	Square piles, no rain	5.53	3.24	2500	350	500	450
	Round piles, no rain	6.14	3.81	2500	350	500	450
	Square piles, rain	14.7	8.82	2500	350	500	450
	Round piles, rain	16.2	10.2	2500	350	500	450
5	Square piles, no rain	5.1	3.1	2000	350	500	450
	Round piles, no rain	5.96	3.64	2500	350	500	450
	Square piles, rain	13.7	8.49	2000	350	500	450
	Round piles, rain	15.8	9.8	2500	350	500	450

Table 6 ANOVA

Model	Sum of squares	df	Mean square	*F*	Sig
Regression	283,331.86	5	56,666.37	867.04	0.000
Residual	10,064.899	154	65.35648		
Total	293,396.76	159			

Table 7 Model summary

Mo	*R*	R^2	Adjusted *R* square	Std. error of the estimate	Durbin-Watson
1	0.983	0.965695	0.964581	8.084336	2.297236

Table 8 Coefficients

Value	Unstandardized coefficients beta	Std. error	Standardized coefficients beta	*t*	Sig	Collinearity statistics, tolerance	VIF
(Constant)	22.88535	7.826399		2.924123	0.003976		
Number of piles	−3.76508	0.786761	−0.07156	−4.78555	3.96E-06	0.996322	1.003691
Pile space	0.010187	0.000894	0.170621	11.39595	3.34E-22	0.993732	1.006307
Pile diameter	−0.1804	0.015728	−0.17126	−11.4697	2.11E-22	0.999103	1.000897
Weather	80.24383	1.278258	0.936945	62.77593	1.3E-111	0.999981	1.000019
Pile type	11.10982	1.284293	0.129559	8.650533	6.32E-15	0.993087	1.006961

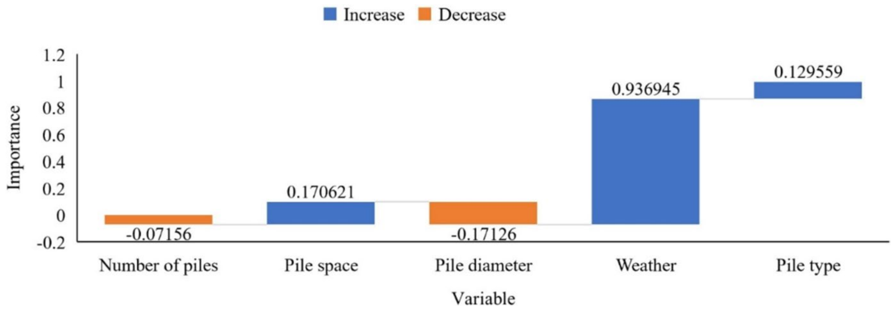


Fig. 8 The influence of independent variables

Table 9 Residuals statistics (Ux)

Value	Min	Max	Mean	Std. dev	*N*
Predicted value	19.32853	156.6269	87.95	42.21328	160
Residual	−16.3573	29.27809	5.15E-15	7.956208	160
Std. predicted value	−1.62559	1.626903	1.57E-16	1	160
Std. residual	−2.02333	3.621583	5.93E-16	0.984151	160

In addition, other factors were also noted to have significant impacts. Pile diameter, with a regression coefficient of −0.1804, indicates that increasing the pile diameter helps reduce horizontal displacement, as larger piles generally have better load-bearing capacity and enhance the stability of the foundation system. Conversely, pile spacing, with a positive regression coefficient of 0.010187, suggests that increasing the spacing between piles may lead to a slight increase in horizontal displacement. Furthermore, pile type also has a notable influence,

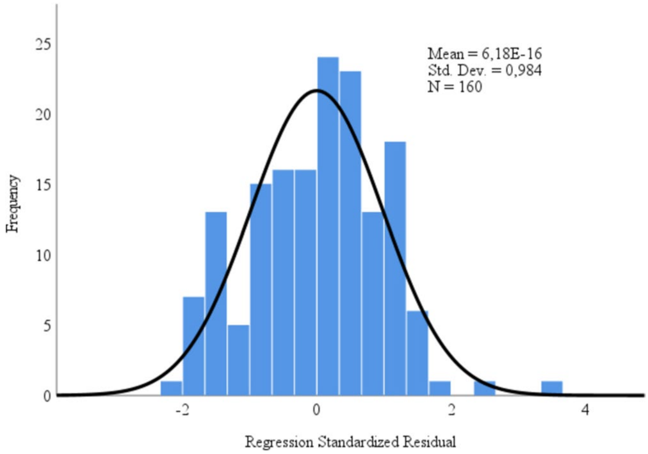
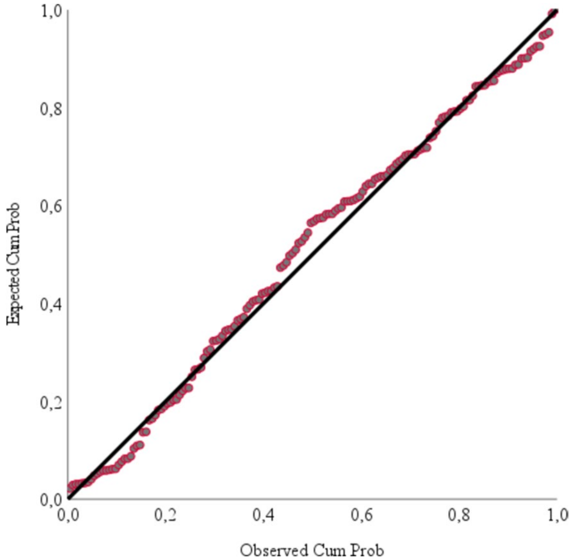


Fig. 9 Histogram normalized residuals (Ux)

Fig. 10 Normal P-P Plot (Ux)



with a regression coefficient of 11.10982, indicating that round piles may lead to greater displacement compared to square piles, likely due to differences in load distribution and resistance characteristics of each pile type. The number of piles, with a regression coefficient of – 3.76508, suggests that increasing the number of piles tends to reduce horizontal displacement, as the foundation system becomes more robust when multiple piles share the load.

Compared to previous studies, these results expand the understanding of how geological and hydrological factors impact the displacement of retaining walls. For instance, the study by Shangyu et al. (2016) indicated that changes in water levels and backfill materials can significantly affect the deformation of retaining walls, with the greatest horizontal displacement occurring when the subsoil is clay. This finding aligns with our results. Similarly, the study by Ren et al. (2022) demonstrated that fluctuations in groundwater levels can greatly affect the seismic displacement of geosynthetic-reinforced soil retaining walls, which is further supported by our findings that rain-induced erosion is the most significant factor affecting horizontal displacement. Despite achieving several important results, this study still has certain limitations. The focus of the research was limited to analyzing the horizontal displacement of retaining walls without considering other factors such as overall structural stability, tilt, or lateral pressure, which can significantly impact the integrity and safety of the structure. These factors will be examined in greater detail in future studies to provide a more comprehensive understanding of retaining wall stability under complex geological conditions.

To further improve the predictive capability and applicability of the research models, future simulations should focus on assessing the impact of load variations on the top of the embankment layer. These load changes will help better understand the effects of dynamic factors on the deformation of retaining walls, particularly under sudden changes due to natural disasters or human activities. Additionally, incorporating other variables such as soil type, geological structure, and environmental conditions will enhance the accuracy and efficiency of predictive models, thereby optimizing design and ensuring safety for infrastructure projects.

5 Conclusions

The findings highlight that a pile length of 36 m is optimal for achieving minimal Ux displacement, a crucial insight for engineers aiming to design stable and cost-effective retaining wall systems. The study further reveals that increasing the pile length to 48 m does not significantly reduce displacement, emphasizing the importance of tailoring pile lengths to specific site conditions rather than relying on overly conservative designs.

Contrary to common assumptions, the analysis indicates that shorter pile spacing and larger pile diameters do not invariably lead to reduced displacements. In some cases, these configurations can actually increase displacement due to the complex interactions between soil and structure. This counterintuitive result underscores the necessity of precise modeling and careful consideration of all influencing factors to avoid oversimplified design choices that may not perform as expected in real-world conditions.

The linear regression models developed in this study provide a practical tool for predicting Ux displacements. The significant predictors identified include pile type, spacing, diameter, number of piles, and weather conditions. The regression formulas derived from the analysis allow for quick estimation of displacement values, thereby facilitating the optimization of design parameters to achieve cost efficiency. For Ux displacement, the regression formula is:

$$U_x = -3.76508X_1 + 0.010187X_2 - 0.1804X_3 - 80.24383X_4 + 11.10982X_5 + 30.8413 \quad (3)$$

These formulas enable engineers to tailor their designs based on specific site conditions and expected weather patterns, significantly improving the reliability and efficiency of retaining wall projects. The study confirms that weather conditions, particularly rain-induced erosion, have the most substantial impact on displacement, highlighting the need for designs that can withstand severe environmental stresses.

Author Contribution Conceptualization: Phuong Tuan Nguyen, Tuan Anh Nguyen; methodology: Truong Xuan Dang, Tuan Anh Nguyen, Luan Nhat Vo; formal analysis and investigation: Tuan Anh Nguyen, Hoa Van Vu Tran; writing—original draft preparation: Phuong Tuan Nguyen, Hoa Van Vu Tran, Luan Nhat Vo; writing—review, and editing: Phuong Tuan Nguyen, Tuan Anh Nguyen, Truong Xuan Dang. All authors read and approved the final manuscript.

Data Availability The data used in this work are available on request from the corresponding author.

Declarations

Ethics Approval and Consent to Participate Not applicable.

Consent for Publication Not applicable.

Competing Interests The authors declare no competing interests.

References

Ahmadabadi, M., Hosseini, S., Rezai, M.: Investigation of the effect of soil and wall interaction on the displacement of retaining walls using finite element method. Bull. Soc. Roy. Sci. Liège **85**, 1–7 (2016)

Brooks, H.: Basics of retaining wall design. HBA Publ **11**, 220 (2010)

Cremonesi, M., et al.: A state of the art review of the Particle Finite Element Method (PFEM). Arch. Comput. Methods Eng. **27**, 1709–1735 (2020)

Derghoum, R., Meksaouine, M.: Coupled finite element modelling of geosynthetic reinforced embankment slope on soft soils considering small and large displacement analyses. Arab. J. Sci. Eng. **44**, 4555–4573 (2019)

Dhamdhere, D., Rathi, V., Kolase, P.: Design and analysis of retaining wall. Int. J. Manag. Technol. Eng. **8**, 1246–1263 (2018)

Ebeling, R.M.: Review of finite element procedures for earth retaining structures. Final Report Army Engineer Waterways Experiment Station (1990)

Ereiz, S., Duvnjak, I., Jiménez-Alonso, J.F.: Review of finite element model updating methods for structural applications. Structures **41**, 684–723 (2022)

Guide, U.: SPSS for Windows. Adv. Stat. Release **10**, 285–310 (1998)

Heydari, N., Diplas, P.: Flow dynamics in the vicinity of a gravel embedded vertical retaining wall: conditions corresponding to the initial stages of local erosion. Environ. Fluid Mech. **20**, 203–225 (2020)

HosseinzadehAsl, R., Yasi, M.: Numerical comparison of performance and stability of concrete and gabion retaining walls in riverbanks protection. J. Hydraul. **18**, 21–37 (2023)

Jia, X., Xu, J., Sun, Y.: Deformation analysis of reinforced retaining wall using separate finite element. Discret. Dyn. Nat. Soc. **2018**, 6946492 (2018)

Korumaz, M., et al.: An integrated Terrestrial Laser Scanner (TLS), Deviation Analysis (DA) and Finite Element (FE) approach for health assessment of historical structures. A Minaret Case Study. Eng. Struct. **153**, 224–238 (2017)

Ling, H.I., Leshchinsky, D.: Finite element parametric study of the behavior of segmental block reinforced-soil retaining walls. Geosynth. Int. **10**, 77–94 (2003)
Liu, C., et al.: The role of TBM asymmetric tail-grouting on surface settlement in coarse-grained soils of urban area: field tests and FEA modelling. Tunn. Undergr. Space Technol. **111**, 103857 (2021)
Mangraviti, V., Flessati, L., di Prisco, C.: Mathematical modelling of the mechanical response of geosynthetic-reinforced and pile-supported embankments. Int. J. Numer. Anal. Meth. Geomech. **47**, 2438–2466 (2023)
Morelli, S., et al.: Characterization and geotechnical investigations of a riverbank failure in Florence, Italy, UNESCO World Heritage Site. Journal of Geotechnical and Geoenvironmental Engineering **146**, 05020009 (2020)
Nakazawa, H., et al.: Experimental evaluation on earthquake-resistance of road retaining wall using gabion. J. Disaster Res. **13**, 897–916 (2018)
Papageorgiou, G., Alamanis, N., Xafoulis, N.: Acceptable movements of road embankments. Electron. J. Struct. Eng. **20**, 30–32 (2020)
Popa, H., Batali, L.: Using finite element method in geotechnical design. Soil constitutive laws and calibration of the parameters. Retaining wall case study. WSEAS Trans. Appl. Theor. Mech **5**, 177–186 (2010)
Ren, F.-F., et al.: Influence of groundwater level changes on the seismic response of geosynthetic-reinforced soil retaining walls. J. Zhejiang Univ.-Sci. A **23**, 850–862 (2022)
Ruiz de Galarreta, S., J.R.T. Jeffers, and S. Ghouse: A validated finite element analysis procedure for porous structures. Materials & Design 189, 108546 (2020)
Shangyu, H., et al.: Influence of water level change on deformation and stability of retaining walls with different back materials. Proceedings of the 2016 5th International Conference on Sustainable Energy and Environment Engineering (ICSEEE 2016), 296–300 (2016)
Sianturi, N.M.: Protection of Bah Bolon River Cliffs with geosynthetic reinforcement on segmental concrete blocks–a comprehensive analysis. Power System Technology **48**, 67–90 (2024)
Sotiropoulos, F., Diplas, P.: Scour at the base of retaining walls and other longitudinal structures. National Academies of Science, Washington (2017)
Udomchai, A., et al.: Failure of riverbank protection structure and remedial approach: a case study in Suraburi province Thailand. Eng. Fail. Anal. **91**, 243–254 (2018)
Vahedifard, F., Meehan, C.L.: A multi-parameter correlation for predicting the seismic displacement of an earth dam or embankment. Geotech. Geol. Eng. **29**, 1023–1034 (2011)

Authors and Affiliations

Phuong Tuan Nguyen[1] · Truong Xuan Dang[2] · Tuan Anh Nguyen[3] · Luan Nhat Vo[4] · Hoa Van Vu Tran[5]

✉ Tuan Anh Nguyen
tuanna@ut.edu.vn

Phuong Tuan Nguyen
tuanphuongvk@gmail.com

Truong Xuan Dang
dxtruong@hcmunre.edu.vn

Luan Nhat Vo
luanvn@vhu.edu.vn

Hoa Van Vu Tran
hoa.tranvu.htgroup@gmail.com

1 Mien Tay Construction University, Vinh Long Province, Vietnam

2 Ho Chi Minh University of Natural Resources and Environment, Ho Chi Minh City, Vietnam

3 University of Transport Ho Chi Minh City, Ho Chi Minh City, Vietnam

4 Faculty of Engineering and Technology, Van Hien University, Ho Chi Minh City, Vietnam

5 The SDCT Research Group, University of Transport Ho Chi Minh City, Ho Chi Minh City, Vietnam