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## Numerical Analysis of Single Piles Adjacent to Claytones Slope Under Lateral Load

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### ABSTRACT

The behavior of a pile adjacent to a slope differs from that of a pile on level ground when subjected to lateral loads. As the distance from the slope increases, its behavior progressively resembles that of a pile on level ground. This study aims to analyze this behavior using the Midas GTS NX finite element software, employing two modeling approaches: the Hardening Soil model and the Mohr-Coulomb model. The soil types analyzed consisted of a silty clay layer from 0 to 3 m depth and a claystone layer extending to 40 m depth; meanwhile, the piles were modeled as beam elements. Furthermore, this study investigated the critical edge distance at which the pile behavior begins to closely resemble that of a pile on level ground. This was done by testing variations in slope ratio and pile distance from the slope crest, then comprehensively analyzing the response of both the pile and the surrounding soil. Additionally, the study examined the distribution of deflection and bending moment in foundation piles subjected to lateral loads. The results indicate that as the slope steepens, the behavior of the foundation deviates further from that on level ground, and the influence of the slope becomes negligible when the foundation is located at a distance greater than 6D.

**Keywords:** Lateral Load; slope; single pile; critical edge distance; hardening soil; mohr-coulomb; Midas GTS NX.

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### INTRODUCTION

The construction of structures and infrastructures requires foundations capable of withstanding not only axial but also lateral loads. The impact of lateral loads becomes particularly significant when structures are situated close to slopes, as the presence of a slope reduces the lateral resistance of the soil (Hatami et al., 2018; Ma'ruf et al., 2023; Wang & Shao, 2024; Zhang et al., 2021). The slope ratio influences the pile response to lateral loads, making it crucial to determine the extent to which a pile's lateral capacity is diminished by the slope. There are limited measures available to mitigate these adverse effects other than increasing the distance between the pile and the slope crest. Both the pile's distance from the slope edge and the slope ratio significantly impact the pile's lateral resistance.

The behavior of piles near slopes has been studied by several scholars. Liu et al. (2021) investigated the behavior of a single pile adjacent to slopes and concluded that when the distance between the pile and the slope exceeds 5D, the slope effects on pile behavior become negligible. Building upon this work, Liu and Jiang (2023) advanced the study of soil-structure interaction by modifying the p-y curve to account for slope surface displacement, demonstrating that the actual soil resistance displacement is smaller than the displacement of

the pile. Georgiadis and Georgiadis (2012), in their study on single piles adjacent to slopes, explained that the critical depth increases with greater distance between the pile and the slope, and that the presence of the slope significantly influences the distribution of lateral loads along the pile. Kranthikumar and Jakka (2020) stated that the lateral load-bearing capacity of a pile increases with larger pile diameter, higher soil unit weight, greater internal friction angle, and higher soil modulus of elasticity, with the modulus of elasticity exerting a more significant influence on the critical edge distance than the internal friction angle. Beyond a certain distance, the foundation exhibits behavior similar to that of a pile on level ground; in this study, this distance is referred to as the critical edge distance, which is influenced by the slope ratio. Therefore, this study analyzes several slope conditions, specifically 1V:1H, 1V:2H, and 1V:3H.

Due to the asymmetry of soil conditions in front of and behind the pile, the loading direction significantly influences its behavior. Lateral load applied toward the slope results in greater deflection compared to lateral load applied away from the slope (Jiang et al., 2018; Muthukkumaran, 2014; Nandhagopal & Muthukkumaran, 2021; Raja & Muthukkumaran, 2021). This finding serves as a reference for the present study in selecting the load direction, prioritizing loading toward the slope due to its greater impact. This research employs the finite element method with two variations of soil modeling: the Mohr-Coulomb model, which assumes constant soil stiffness, and the Hardening Soil model, which accounts for non-linear soil behavior and follows a hyperbolic stress-strain curve, providing a more representative approach to actual soil conditions. The foundation is situated on silty clay and claystone layers, which remain underrepresented in existing research.

To summarize, this study presents the response of piles located near a slope under lateral loading using the *Hardening Soil* model and *Mohr-Coulomb* model, and determines the critical edge distance of the pile group from the slope's edge. The effect of slope ratio on the lateral resistance of the pile group is also examined in detail. The primary objectives of this study are to analyze the lateral behavior of single piles adjacent to slopes using finite element modeling in *MIDAS GTS NX*, incorporating both *Hardening Soil* and *Mohr-Coulomb* models; to determine the critical edge distance for piles near slopes of varying heights and ratios; and to evaluate the influence of slope steepness and height on pile deflection and bending moment under lateral loads. This research holds significant practical value for geotechnical engineers and designers by offering empirical data and validated models to predict pile behavior near slopes, thereby improving the accuracy of foundation designs in sloping terrains. By establishing clear guidelines for critical edge distances, it enables cost-effective and safe foundation placement near slopes. Additionally, it demonstrates the superiority of the *Hardening Soil* model in capturing real-world soil behavior, supporting its adoption in similar geotechnical analyses. Through these contributions, the study addresses gaps in existing knowledge and supports safer, more efficient infrastructure development in challenging terrains.

## METHOD

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This research uses a computer simulation-based numerical method with the Finite Element Method (FEM) approach to analyze the behavior of a single pole near the slope of claystone that receives lateral load.

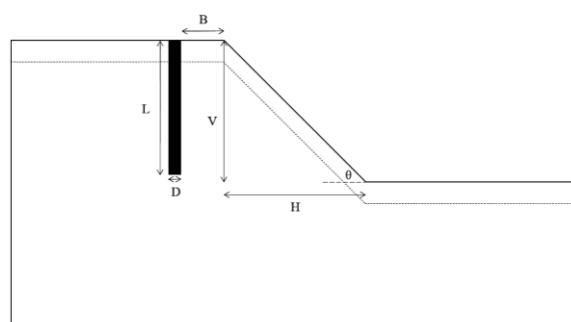
The present research uses MIDAS GTS NX 3D software to analyze pile with a diameter of 0.8 m and a length of 19 m, being positioned at varied distances from the slope to the crest and considering two slope heights,  $V = 10$  m and  $V = 20$  m, defined as  $B = \text{distance} \times \text{diameter}$ . Soil Model are carried out using Hardening Soil model and Mohr-Coulomb model. For hardening soil model parameter, the moduli refers to Lim et al., (2010) and Calvello and Finno

(2004), tangent stiffness for primary oedometer loading ( $E_{oedref}$ ) is obtained from  $0.7 E_{50ref}$  and Unload / reloading stiffness ( $E_{ur}$ ) is obtained from  $3 \times E_{50ref}$ . The soil types analyzed consisted of silty clay layer on 0 to 3 m of depth and clay stone layer extending up to 40 m depth. The model illustrations are presented in Figure 1. The pile is modeled as a 1D beam element and linear elastic pile with pile surrounded by soil meanwhile the soil is assumed to be isotropic (their properties on Table 1.), be represented using the Hardening Soil model and Mohr-Coulomb model. The soil domain is discretized using the Tetra Mesher technique which employs tetrahedral elements (triangular pyramids) for meshing. Figure 2 shows finite element model of meshing and pile – soil interaction, then described as shear stiffness. The soil boundary conditions are defined such that displacement in the y-direction is constrained on the positive and negative sides, while displacement in the x-direction is restricted on the positive and negative sides. Additionally, displacement in the z-direction is fixed at the bottom of the model and the pile boundary condition is set to prevent rotation in the z-direction. In order to minimize the influence of size effects on the calculation results, the total model height is set to twice the length of the bored pile, while the model width is defined as 30 times the pile diameter.

**Table 1. Soil and Pile Properties for Analysis**

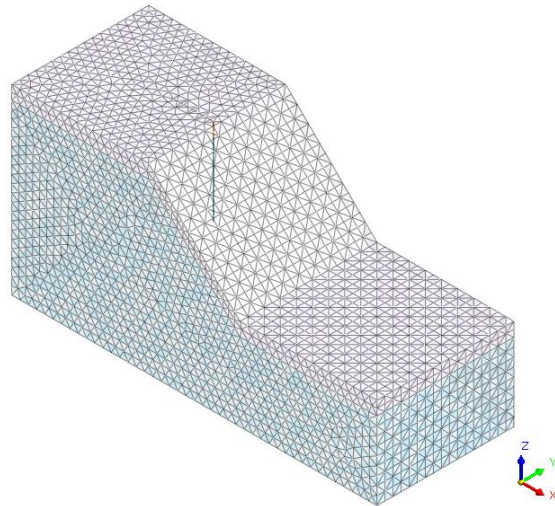
Hardening Soil Model Parameters											
Depth	Type	$\gamma$	$E_{50}^{ref}$	$E_{oed}^{ref}$	$E_{ur}^{ref}$	C	$\varphi$	$\mu$	Rf	Pref	$K_0$
m	-	kN/m <sup>3</sup>	kPa	kPa	kPa	kPa	°	-	-	kPa	-
0.0 - 3.0	Silty Clay	16	41,250	28,875	123,750	67.5	17	0.35	0.9	60	0.702
3.0 -30.0	Claystone	21	275,000	192,500	825,000	200.0	32	0.45	0.9	100	0.476
Mohr Coulomb Model Parameters											
0.0 - 3.0	Silty Clay	16	41,250	-	-	67.5	17	0.35	-	-	0.702
3.0 -30.0	Claystone	21	275,000	-	-	200.0	32	0.45	-	-	0.476
Pile Parameters											
19	Bored Pile	25	27,805,575	-	-	-	-	0.10	-	-	-

Source: Calibration of data by Lim et al., (2010) and Calvello & Finno, (2004)



**Figure 1. Illustration of Analysis Model**

Source: This research document



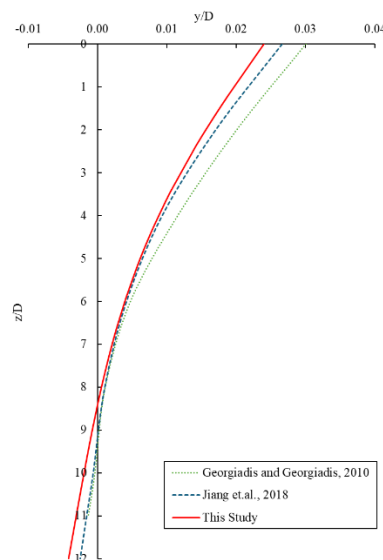
**Figure 2. Mesh of Model Analysis with V = 20m and Slope Ratio 1V 1H**  
 Source: MIDAS GTS N Simulation

The validation of the numerical model with Mohr-Coulomb model is conducted by referencing previous studies to verify the accuracy of the proposed modeling approach. Jiang et al., (2018) first performed validation modeling using data from Georgiadis and Georgiadis (2010) that is also utilized on this study accordingly. Georgiadis and Georgiadis (2010) conducted a three-dimensional finite element analysis to examine the behavior of a foundation pile adjacent to a slope under lateral loading. The analyzed foundation pile has a length  $L = 12$  m, a diameter  $D = 1$  m, and slope angle =  $30^\circ$ . The soil and pile properties used in the analysis are presented in Table 2 and the results in Figure 3.

**Table 2. Soil and Pile Properties for Validation (Georgiadis and Georgiadis, 2010)**

Properties	E (kPa)	$\gamma$ (kN/m <sup>3</sup> )	$\mu$	c (kPa)	$\varphi$ ( $^\circ$ )	$\psi$ ( $^\circ$ )
Pile	$2.9 \times 10^7$	25	0.10	-	-	-
Soil	$1 \times 10^4$	18	0.49	50	0	0

Source: Georgiadis & Georgiadis, (2010)



**Figure 3. Displacement Curve for Validation using Georgiadis and Georgiadis, 2010 Model**  
 Source: Georgiadis & Georgiadis, (2010)

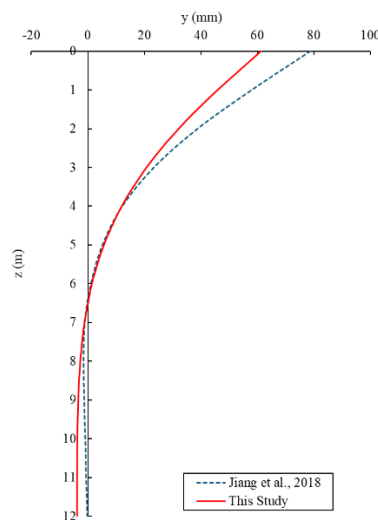
Meanwhile Jiang et al., (2018) performed three-dimensional finite element analyses with the length  $L = 12$  m, diameter  $D = 0.6$  m, and slope angle =  $45^\circ$ . The validation of the numerical model with Mohr-Coulomb model with soil and pile properties used in the analysis are presented in Table 3 and the results in Figure 4.

**Table 3. Soil and Pile Properties for Validation (Jiang et al., 2018)**

Properties	E (kPa)	$\gamma$ (kN/m <sup>3</sup> )	$\mu$	c (kPa)	$\varphi$ ( $^\circ$ )	$\psi$ ( $^\circ$ )
Pile	$3 \times 10^7$	25	0.10	-	-	-
Soil	$1.2 \times 10^4$	18	0.40	30	35	5

Source: Jiang et al., (2018)

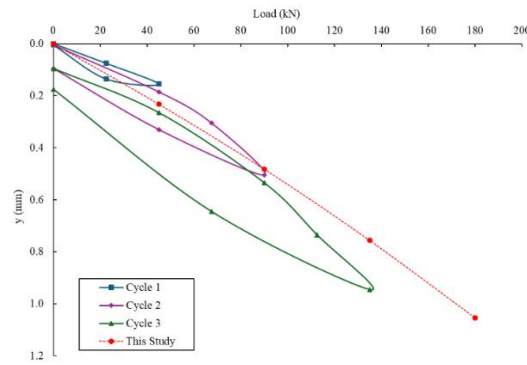
The referenced papers used as a three-dimensional (3D) solid elements to represent pile. This paper used a one-dimensional (1D) beam element in MIDAS GTS NX. This difference in element types affect the interaction between the pile and the soil. However, the graph indicates that the trends observed in both the Georgiadis and Georgiadis (2010) and Jiang et al., (2018) models are closely aligned. The consistency validates the accuracy of the modeling approach.



**Figure 4. Displacement Curve for Validation using Jiang et al., 2018 Model**

Source: Jiang et al., (2018)

The soil in this study consists of a layer of silty clay overlying clay stone. Based on the results of the lateral load test, a pile with a diameter of 0.8 m, a length of 19 m, and subjected to a lateral load of 90 kN exhibited a lateral deflection of 0.51 mm. As a reference for this study, a numerical analysis was conducted using the Hardening Soil model behavior. The analysis considered a single pile with a diameter of 0.8 meters and a length of 19 meters, consistent with the dimensions used in the lateral load test. Under an applied lateral load of 90 kN, the pile exhibited a maximum lateral deflection of 0.48 meters, results in 6% discrepancy which falls within an acceptable range, further confirming the accuracy of the modeling approach. The result of lateral test and validation model are presented in Figure 5.



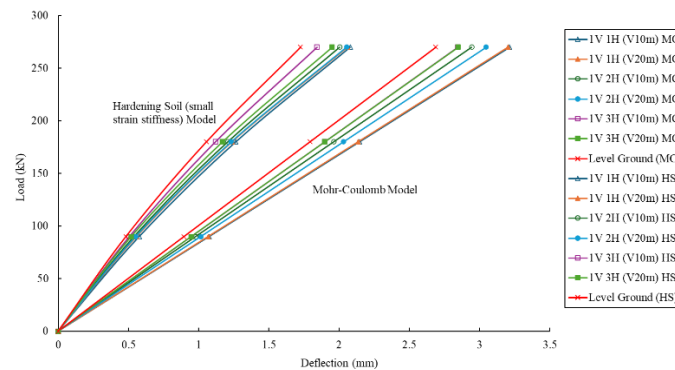
**Figure 5. Displacement Curve for Validation using Lateral Test Result**

Source: Data of this research experiment

## RESULT AND DISCUSSION

### Effect of Soil Model

By using the same data, it can be obtained that the displacement value from Mohr-Coulomb model is greater than Hardening Soil model. The deflection results from the analysis using the Hardening Soil model closely align with the lateral load test results due to the fact that the Hardening Soil model effectively captures the non-linear and stress-dependent behavior of soil stiffness. Pile deflection for both soil modeling approaches at a pile position of  $B/D=1$ , is presented in Figure 6. Based on these results, this paper employed further the Hardening soil model.

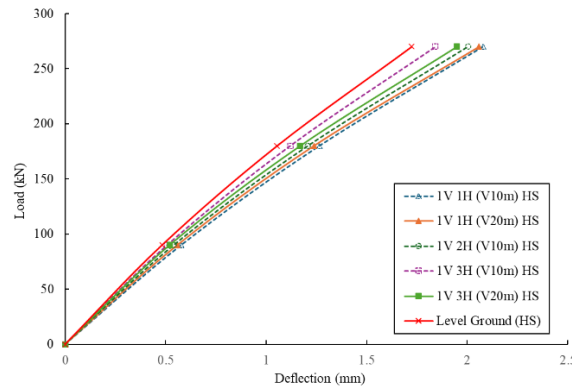


**Figure 6. Deflection Comparison of Mohr-Coulomb Model and Hardening Soil Model**

Source: Numerical analysis of this study

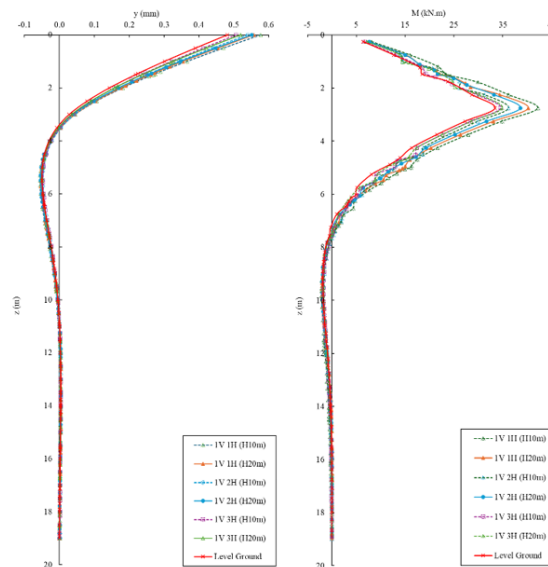
### Effect of Slope Height (V) and Slope Ratio

The analysis of two slope heights, 10 m and 20 m, on pile lateral capacity successfully identified that the pile deflection at a slope height of 20 m is greater than of 10 m due to a pronounced reduction in passive soil resistance and lateral confinement. The deflection for both slope heights approaching at pile position of  $B/D = 1$  is presented in Figure 7 and Figure 8 presented deflection and moment of pile with lateral load 90 kN at a pile position of  $B/D = 1$  with 20 m slope height. The maximum bending moment is observed at a depth of 3 m, corresponding to a stratigraphic interface characterized by a significant discontinuity in the soil's modulus of elasticity. This variation in stiffness induces localized changes in the pile-soil interaction mechanism, which in turn affects the bending moment distribution as influenced by slope height.



**Figure 7. Deflection Comparison of Slope Height of 10 m and 20 m for Hardening Soil Model**

Source: MIDAS GTS NX Simulation



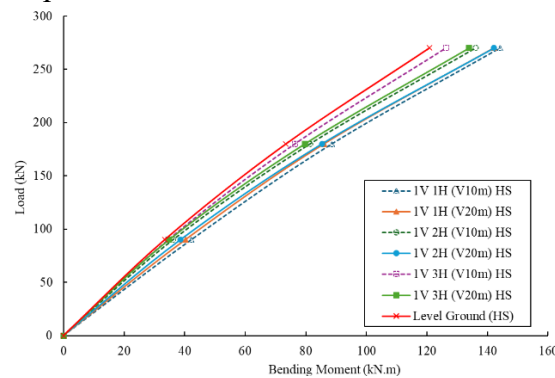
**Figure 8. Deflection and Moment for Hardening Soil Model with Lateral Load 90 kN**

Source: Research data processing results)

The effect of slope ratio on the pile under various lateral loads: 90 kN, 180 kN, and 270 kN, with a pile-to-slope crest distance of  $B/D = 1$ , is presented in Figure 7 for deflection and Figure 9 for bending moment. Three types of slope ratios were also analyzed: 1V 1H, 1V 2H, and 1V 3H. For a slope height of 10 m, the maximum percentage increases in pile deflection relative to level ground were found to be 17.04%, 13.93%, and 6.41%, respectively. At a greater slope height of 20 m, these increases were 16.27%, 15.98%, and 11.54%, respectively. The results reveal that pile deflection systematically decreases as the slope ratio is reduced. In steeper slopes, the potential for passive wedge failure limits the mobilization of passive soil resistance, reducing the effectiveness of lateral load transfer. As the slope becomes shallower, improved stress arching and lateral confinement around the pile enhance the mobilized resistance, causing the pile response to converge toward that observed under level ground conditions.

The applied load plays a critical role in governing soil-structure interaction behavior; an increase in load value results in greater pile deflections and the surrounding soil experiences nonlinear deformation behavior, leading to an expanded interaction zone and stress

distribution. The distribution of bending moments along the pile was found to be influenced by the magnitude of the applied load, particularly at a pile-to-slope crest distance of  $B/D = 1$ . For slope ratios of 1V 1H, 1V 2H, and 1V 3H, the maximum percentage increases in pile bending moments relative to level ground were 16.17%, 11.24%, and 4.35%, respectively, for a slope height of 10 m. For a slope height of 20 m, the corresponding increases were 14.99%, 15.05%, and 9.78%, respectively. The results show the steeper slopes generating substantially larger bending moments. This behavior indicates that both load value and slope steepness play critical roles in influencing the pile bending moment. These results are consistent with the findings reported by Jiang et al. (2018), who highlighted the significant interaction between load intensity and slope angle in pile behavior.



**Figure 9. Moment under Various Slope Ratios for  $B/D = 1$  Using the Hardening Soil Model**

Source: Analysis of the variability parameters of the study

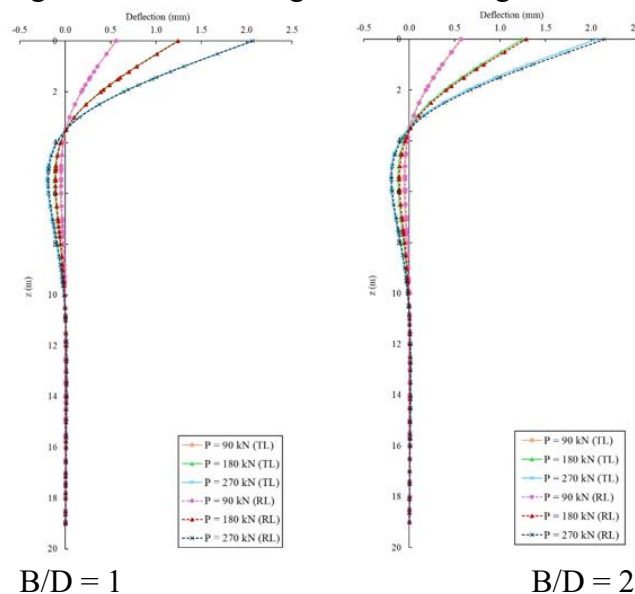
### Effect of Edge Distance

The influence of the distance between the pile and the edge of the slope varies depending on the slope ratio and slope height. The direction of applied loading, toward loading or reverse loading, further affects the pile's response and overall bearing mechanism. Due to the absence of sufficient soil mass on the slope side, the bearing capacity of the pile is reduced. As a result, the direction of loading, whether toward or away from the slope has a significant impact on the pile's bearing behavior. Under forward loading, where the pile is pushed toward the slope, the lack of lateral confinement on the slope side leads to reduced soil resistance, thereby decreasing the pile's lateral bearing capacity. In contrast, under reverse loading, when the pile moves away from the slope, the pile's lateral bearing capacity is increased. This study uses TL for toward loading and RL for reverse loading to simplify the results interpretation. The results of this study demonstrate that as the slope becomes steeper and higher, a greater distance is required between the pile and the slope's edge in order to eliminate the influence of the slope. The numerical results (Figure 10) indicate that pile deflection remains relatively unaffected by variations in the distance from the edge of the slope.

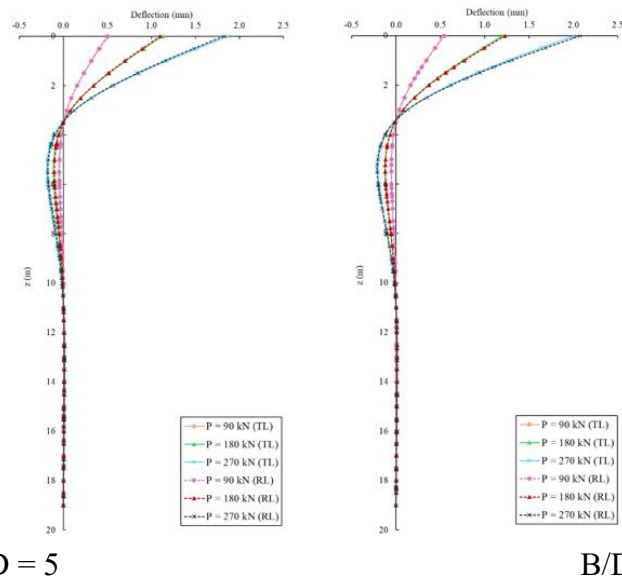
The bending moment distribution exhibits a more significant response to changes in pile location. This suggests that the influence of the pile's proximity to the slope is more effectively captured through the bending moment behavior rather than through deflection measurements alone. These findings highlight the importance of considering bending moment as a critical parameter in assessing the structural performance of pile near slopes. These findings are illustrated in Figure 11.

## Numerical Analysis of Single Piles Adjacent to Claytones Slope Under Lateral Load

- a) For a slope with an inclination of 1V 1H, numerical analysis indicates that a vertical height of  $V = 10$  m requires a normalized distance ratio of  $B/D = 5$  to effectively mitigate the influence of the slope, where the ratio of bending moment under toward loading to that under reverse loading is 0.4% - 1.6%. In contrast, for an increased slope height of  $V=20$  m, a greater ratio of  $B/D = 6$  is required to achieve comparable isolation from slope effects. This behavior is illustrated in Figure 10.b, which presents the relationship between distance and bending moment response for a slope height of  $V = 20$ m under a 1V 1H configuration. At this condition, the ratio of bending moment under toward loading to that under reverse loading (RL) is 2.85% - 2.9%, indicating a minimal discrepancy between loading directions. This level of variation is considered acceptable for design purposes, confirming the adequacy of the  $B/D = 6$  threshold for neglecting slope influence in this scenario.
- b) For a slope inclined at 1V 2H, numerical analysis demonstrates that a vertical slope height of  $V = 10$  requires a minimum normalized edge distance of  $B/D = 4$  to sufficiently reduce the influence of the slope on the lateral response of the embedded pile. At this distance, the ratio of bending moments under toward loading and reverse loading conditions ranges between 0.25% and 2.4%, suggesting negligible directional dependency. When the slope height is increased to  $V = 20$  m, the critical edge distance increases to  $B/D = 5$ , which the effect of the slope becomes negligible. Under this configuration, the TL-to-RL bending moment ratio varies between 0.93% and 5.6% and these values fall within an acceptable range
- c) For a slope ratio of 1V 3H, both heights  $V = 10$ m and  $V = 20$ m require a consistent distance ratio of  $B/D = 2$  to ignore the slope's effect. At this distance, the ratio of bending moments under toward loading and reverse loading conditions ranges between 0.5 – 4.7.

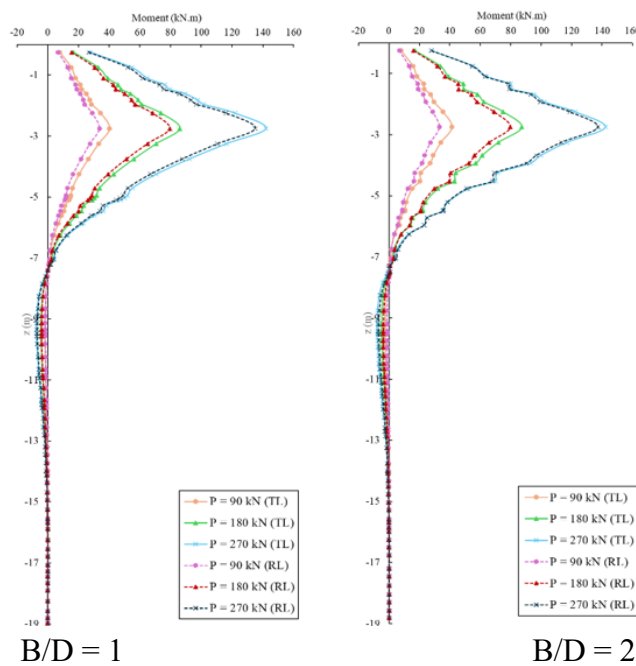


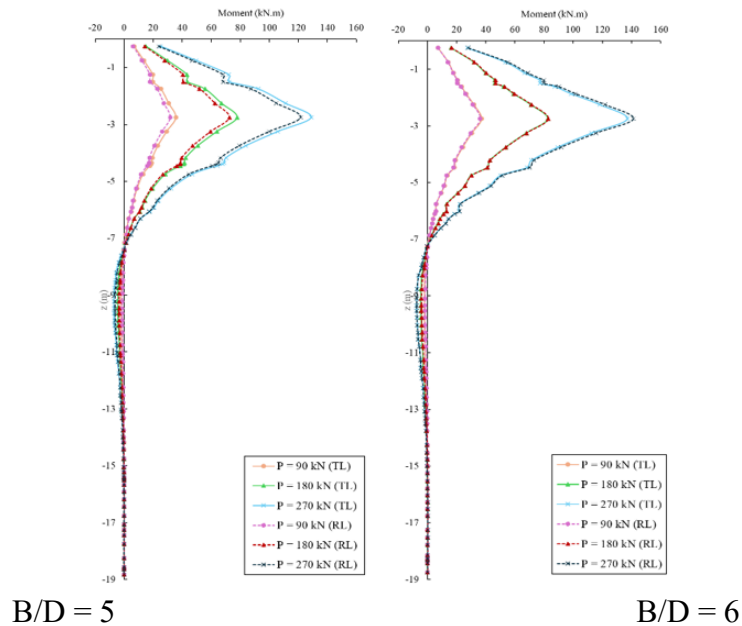
# Numerical Analysis of Single Piles Adjacent to Claytones Slope Under Lateral Load



**Figure 10. Effect of Distance on Pile Deflection for Slope Ratio 1V 1H with Slope Height,  $V = 20\text{m}$**

Source: Simulation data processing





b. Bending Moments of Pile

**Figure 11. Effect of Distance on Bending Moments for Slope Ratio 1V 1H with Slope Height, V = 20m**

Source: Simulation data processing

## CONCLUSIONS

This research investigates the lateral behavior of piles adjacent to slopes with slope ratios of 1V:1H, 1V:2H, and 1V:3H using three-dimensional finite element analysis, employing both the *Hardening Soil* and *Mohr-Coulomb* models. The pile is modeled as a one-dimensional linear elastic beam surrounded by isotropic soil. Model verification against prior studies by Jiang (2018) and Georgiadis and Georgiadis (2010) confirmed the accuracy of the approach. Results show that the *Mohr-Coulomb* model predicts higher pile deflections and bending moments than the *Hardening Soil* model, with greater values observed for taller slopes (20 m vs. 10 m) and steeper gradients. Gentler slopes improve lateral pile performance by reducing deflection and bending moments, while steeper and higher slopes require greater setback distances between the pile and slope crest to mitigate slope effects. For future research, it is suggested to explore the impact of non-isotropic soil conditions and pile group interactions on lateral pile behavior near slopes to enhance model realism and practical applications.

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