Study on the Impact of Bridge Pile Excavation on the Stability of Deep Loose Deposits Slope

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Abstract. This paper takes the deep deposit slope of Longwangxi as a case study. Using the method of strength reduction, the stability of pre-disturbance and post-disturbance conditions is calculated separately to investigate the influence of human-induced disturbances during bridge pile construction on slope stability. The research results indicate that excavation operations lead to a decrease in the safety factor of slope stability by 7.1% to 11.7%. It is recommended to provide slope support before bridge pile construction. Plastic zones and areas with significant displacements are mainly observed in the upper and lower portions of steep slopes, while the middle section with gentler slopes remains in a stable state. It is advisable to implement slope support measures separately for the upper and lower parts of the slope. Additionally, human-induced disturbances may result in significant displacement zones in the root zone of isolated boulders above the slope, leading to instability. Therefore, it is suggested to focus on stabilizing the root soil of isolated boulders when addressing their instability and to implement targeted measures before commencing bridge pile construction.

Keywords: Slope; Artificial Disturbance; Numerical Simulation

1 Introduction

Human-induced disturbance is one of the triggering factors for slope instability. Such disturbances can be broadly categorized into two classes: those occurring during the construction process and those occurring after the bridge is put into use. Construction disturbance has been a focal point of research both domestically and internationally. Hanazato and Colaço et al. [1~3] proposed a numerical method that combines nonlinear one-dimensional pile analysis with three-dimensional elastic finite element and layering techniques to predict construction disturbances caused by impact piling. Sun et al. [4] investigated intelligent prediction and control methods for slope deformation induced by construction disturbances during various engineering activities in urban settings, conducting a systematic study on the influencing factors of construction disturbances. Li and Yu [5] used numerical simulation to analyze the influence of surrounding embankment loading during construction on the stability of pile-supported excavation systems. Li [6] conducted numerical simulations to analyze the stability of slopes under

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the coupled effects of rainfall and construction disturbances. Wu et al. [7] employed theoretical analysis, numerical simulation, laboratory model tests, and on-site monitoring to study the impact of tunnel shield construction disturbances on the performance of existing pile foundations. Han et al. [8] proposed an assessment framework for the impact of nearby construction disturbances on existing underground engineering structures. Fan et al. [9] studied construction disturbances of closely spaced overlapping shield tunnels through finite element numerical simulations. These studies predominantly focus on dynamic disturbances during construction, particularly addressing the effects of pile driving, vibration, and tunnel construction disturbances. Research on the impact of construction disturbances on slope stability is relatively scarce, with little consideration given to static disturbances during the construction process.

During construction, slopes are mainly influenced by soil excavation disturbances. For instance, a high slope at the inlet and outlet of the Fengning Pumped Storage Power Station reservoir experienced local instability due to excavation [10], and significant deformation occurred in the right bank of the Tongzilin Hydropower Station during the reconstruction process due to delayed support after excavation [11]. Additionally, poorly managed, improper embankment loading during construction can lead to overall slope instability [12]. However, excavation disturbances often only consider the large-volume unloading at the slope angle. While many scholars have studied the impact of pile foundations on slope stability or dynamic characteristics after piling [13], suggesting a positive effect on slope stability, few have considered the effects of excavation disturbances during the piling process.

To explore the influence of static disturbances on slope stability during construction, this study takes the deep deposit slope of Longwang Creek in practical engineering as an example. Using Flac 3D, the slope stability is analyzed under natural conditions and the most unfavorable conditions during pile foundation excavation. The study investigates the impact of slope foot pile foundation excavation on slope stability and explores feasible preventive measures introduced by construction disturbances caused by bridges crossing deep deposit slopes.

2 Basic geological characteristics of the slope

The bridge location area of Longwangxi belongs to a region characterized by tectonic denudation hills and river erosion topography. The topography on both sides of the Longwangxi River exhibits asymmetric distribution. The western bank, where the slope under study is located, has steeper terrain. The deposit width ranges from approximately 250 to 280 meters, with a length along the bridge axis of about 640 meters and a thickness ranging from 4 to 35 meters. The elevations vary between 185 and 320 meters. The slope exhibits a terraced terrain with steep lower and upper sections, while the middle section has gentler slopes. Along the bridge axis, the slope angles range from 4 to 10 degrees, and transverse terrain slopes range from 20 to 49 degrees. Large, upright, and unstable cliffs, reaching heights of up to 12.0 meters, are present in some areas, primarily near the bridge piers or the higher western side. The slope is rich in vegetation, and the bottom terrain is relatively flat, with slopes ranging from 3 to 10 degrees.

The lowest elevation of the Longwangxi riverbed floor is approximately 180.0 to 186.0 meters. Utilize two sets of geological cross-sectional profiles along the transverse section of the bridge, as illustrated in Figures 1 and 2. The Three Gorges Reservoir operation maintains a constant water level between 145 and 175 meters. During normal water levels, Longwangxi is approximately 20 meters above the Three Gorges Reservoir water level, and in cases of upstream reservoir discharge, the highest flood level reaches 183.5 meters.

The surface soil consists of Quaternary colluvium and residual debris layers ($Q^{4col+dl}$) and primarily comprises fine-grained clay and fragmented shale blocks with a minor presence of shale. The block content is approximately 50%, with particle sizes ranging from 30 to 2000 mm and the largest exposed particle diameter reaching 8000 mm in drilling. In some areas, the block content is lower, and the soil mainly consists of fine-grained clay in a plastic state. The block content gradually decreases from the slope's crest to the slope's base, while the clay content increases. The top layer has a thickness of about 3 meters, the middle layer reaches a thickness of 30 to 40 meters, and the lower edge measures around 5 meters. The soil structure is loose, with a measured permeability coefficient of 8.28 m/d, indicating moderate permeability.

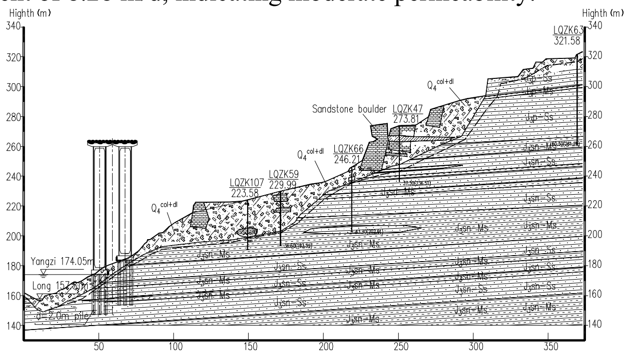


Fig. 1. Geological profile of pier 16.

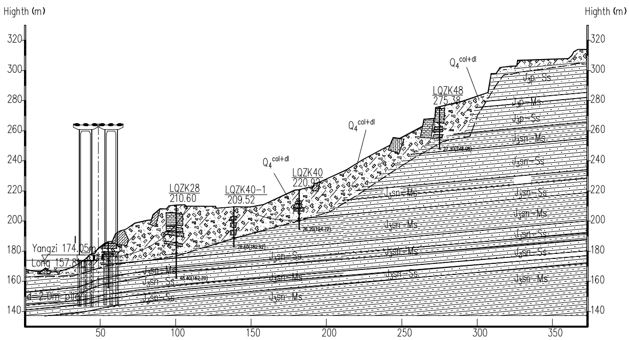


Fig. 2. Geological profile of pier 17.

The geological interface in the rock and soil boundary is relatively steep, typically ranging from 0 to 40 degrees, with the rear portion steepening to 68 degrees or more.

According to drilling profiles, it consists of purple-red mudstone debris and fragments. The slope mass may experience sliding failures along the rock-soil interface.

The underlying bedrock comprises mudstone and sandstone layers from the Upper Jurassic Suining Formation (J_{3sn}) and the Penglai Formation (J_{3p}). These formations are characterized by thin to medium thickness and exhibit a layered structure. The bedding orientations range from 120 to 151 degrees with dips of 8 to 13 degrees. Two sets of fractures have been identified within the bedrock:

1. Set 1: Orientation of 2 to 5 degrees with dips of 80 to 85 degrees. These fractures feature relatively smooth and flat surfaces with an aperture of 4 to 10 mm. They extend for 2 to 3 meters and are spaced at intervals of 3 to 5 meters per fracture. Some of these fractures contain minor mud infill, and their cohesion is relatively poor. They are considered as rigid structural planes.

2. Set 2: Orientation of 283 to 295 degrees with dips of 70 to 78 degrees. These fractures also have smooth and flat surfaces with an aperture ranging from 5 to 100 mm. They extend for distances between 1.5 to 5.5 meters and are spaced at intervals of 2 to 3 meters per fracture. These fractures are filled with mud material, and their cohesion is weak. They are also classified as rigid structural planes.

In summary, the Longwangxi deep deposit slope exhibits steep terrain at both the deposit-soil interface and the slope itself. The deposit structure is loose, with moderate permeability. The upper portion of the deposit is thinner, while the middle and lower portions are thicker, resulting in an overall higher center of gravity. In its natural state, the deposit slope does not show obvious signs of deformation. However, the construction of the Longwangxi Bridge, which cuts through the slope at its base, introduces adverse disturbances to the slope. These disturbances, including potential landslides or instability of isolated boulders, can significantly impact bridge construction. Therefore, it is necessary to study the stability of the deposit slope under both natural conditions and during bridge pile excavation at typical cross-sections.

3 Numerical analysis model and calculation conditions

3.1 Computational Model, Parameters, and Boundary Conditions

The Longwangxi Bridge passes through the lower edge of the deep deposit slope of the Longwangxi. Its overall orientation is nearly parallel to the Longwangxi River, and the bridge piers are positioned at locations where the slope steepens in the lower part of the slope. Specifically, the pile foundation of Pier 16 is located in the lower-middle part of the slope, while the pile foundation of Pier 17 is positioned at the base of the slope. Two cross-sections corresponding to the above descriptions were selected to establish two-dimensional models. In the models, the calculation profile is oriented perpendicular to the Longwangxi River, with the horizontal plane defined as the x-axis and directed from the riverbed toward the mountains. The vertical direction is defined as the z-axis, with positive values indicating upward. The length along the x-axis for the two models is 390 meters and 493 meters, respectively, while the depth along the z-axis extends from the ground surface to an elevation of 50 meters. The specific models are shown in Figures 3 and 4. The material's constitutive model adopts the Mohr-Coulomb elastoplastic model, and the thickness of the weathering zone is considered at the deposit-soil interface, with finer grids applied in local areas within the deposit-soil interface and bedrock. The mechanical parameters of the deposit, deposit-soil interface, and bedrock are listed in Table 1. The stress boundary conditions include horizontal constraints on the left and right sides and bidirectional constraints on the bottom. Under the artificial disturbance condition, the most critical scenario occurs when the excavation of the first row of piles is completed but the reinforced concrete has not been poured. The pile hole diameter is set at 1 meter, and the lengths of the first and second rows of piles are 30 meters and 40 meters, respectively.

Table 1. Geomechanical parameters.

Stratigraphic Rock Types	γ/kN.m^{-1}	E/MPa	μ	c/MPa	φ/(°)	R_t/MPa	$k/10^{-6}$m.s^{-1}
Natural Deposit	22	2.78	0.4	0.008	27	0	9.58
Saturated Deposit	23	2.0	0.45	0.005	24	0	
Natural Weathered Zone	20	13	0.35	/	32	0.08	4.0
Saturated Weathered Zone	21	10	0.38	/	30	0.05	
Moderately Weathered Mudstone	26.5	27.8	0.35	0.0625	22.1	0.5	0.4
Moderately Weathered Sandstone	26.1	47.8	0.3	0.468	29.75	0.8	0.6

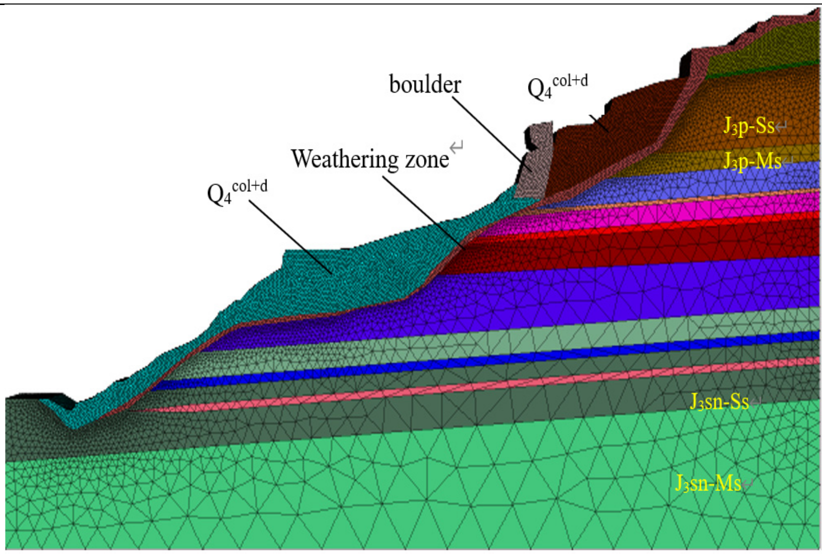


Fig. 3. Model of the deposit slope(pier 16)

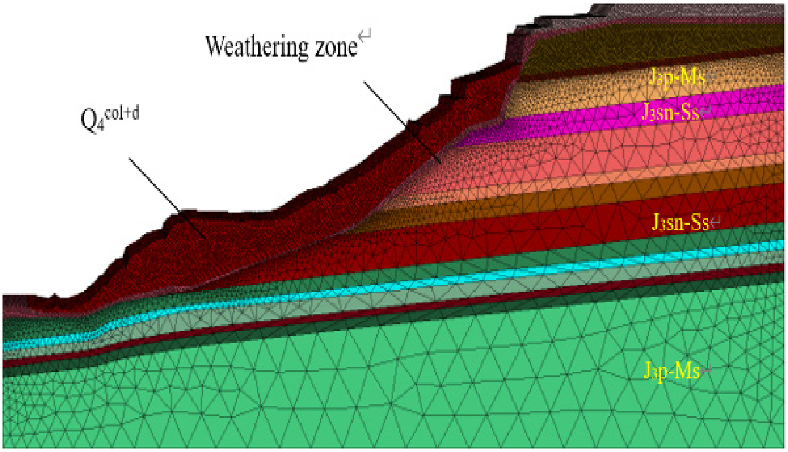


Fig. 4. Model of the deposit slope(pier 17)

3.2 Calculation Scenarios

Considering the characteristics of bridge construction, the maximum disturbance to the deposit slope occurs when pile excavation is carried out within the abutment pit after it has been prepared. To mitigate the risk of instability, construction sequences generally involve excavating the abutment pit after pile construction is completed. Pile construction, when completed, provides the slope with a certain overall resistance to sliding. Therefore, in this paper, the maximum disturbance to the deposit slope is assumed to occur during pile excavation. Based on the condition of the deposit slope in its natural state (Condition 1), a second model (Condition 2) is established to assess the impact of artificial disturbance during pile excavation on the stability of the deposit slope.

4 Analysis of numerical simulation results

Numerical simulations were conducted for different cross-sections and scenarios, and the safety factors of the deposit slope under natural conditions and artificial disturbance are presented in Table 2. Due to the artificial disturbance, the safety factors are reduced to varying degrees, indicating that the deposit slope tends to approach the critical point of instability. The reduction in safety factor exceeds 10% in some cases.

Figure 5 illustrates the distribution of plastic zones for the cross-section of Pier 16 under both natural and disturbance conditions. Plastic zones concentrate at the upper and lower edges of the slope, which have steeper gradients. In the case of natural conditions, the isolated boulder in the upper-middle part of the slope remains relatively stable, with no plastic zones detected inside it. However, under the artificial disturbance condition, plastic zones appear within the isolated boulder, and signs of collapse in the concave rock cavity are observed. Additionally, under artificial disturbance, deep bedrock around the pile hole also exhibits plastic zones, which may lead to displacement in deeper rock layers.

Table 2. Comparison of safety factors for the deposit slope under different conditions.

Cross-Section	Natural Condition	Artificial Disturbance	Reduction Ratio
Pier 16	1.8	1.59	11.7%
Pier 17	1.41	1.36	7.1%

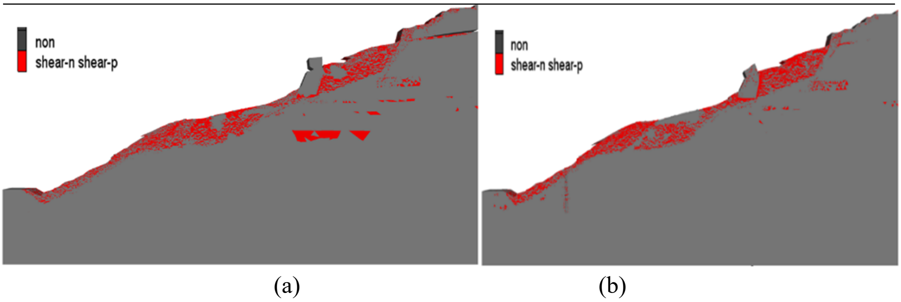


Fig. 5. Distribution of plasticzones in the profile of the slope at pier 16. (a)Natural Condition, (b)Artificial Disturbance

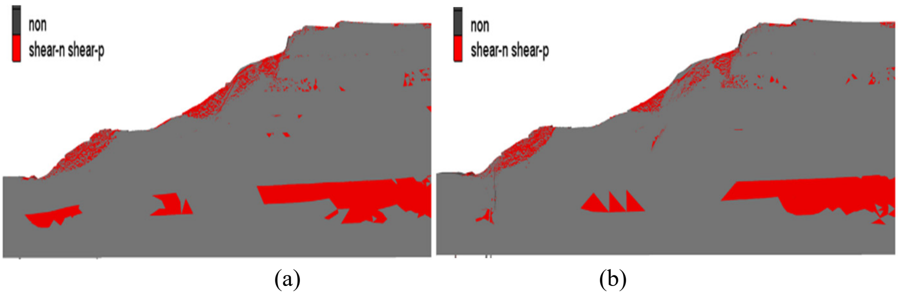


Fig. 6. Distribution of plasticzones in the profile of the slope at pier 17. (a)Natural Condition, (b)Artificial Disturbance

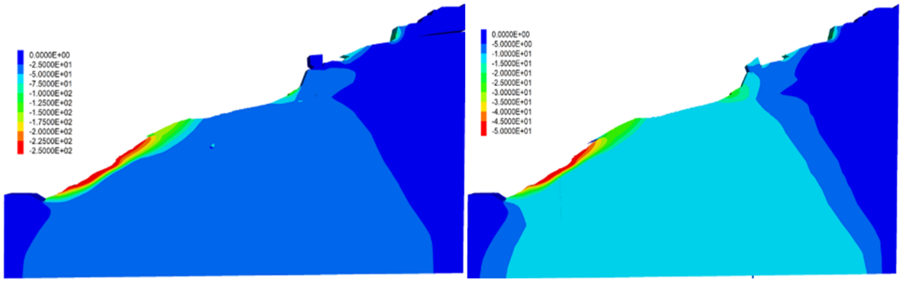
The distribution of plastic zones for the cross-section of Pier 17, as shown in Figure 6, is similar to that of Pier 16. Therefore, when providing support for the slope, it is advisable to consider separate support for the upper and lower parts with steeper gradients to prevent localized instability in the upper or lower sections, which could trigger overall landslides.

Figures 7 and 8 respectively provide displacement contour maps in the X-direction for two cross-sections of the slope under natural and artificial disturbance conditions.

For the cross-section of Pier 16 in its natural state, significant displacement is observed in the lower part of the surface deposit, while the middle portion with a gentler slope experiences minimal displacement. In the upper-middle section, where the isolated boulder interfaces with the slope's surface, larger areas of displacement are evident, whereas the upper part of the slope exhibits less noticeable displacement. Under artificial disturbance conditions, the maximum displacement in the slope occurs near the pile hole surface. Additionally, the X-direction displacement below the isolated boulder and in the surrounding area increases, raising the possibility of isolated boulder instability.

From the simulation analysis, it is evident that before the isolated boulder becomes unstable, significant displacement occurs in its lower part. Therefore, reinforcing the isolated boulder can be approached by enhancing the stability of the deposit below its base.

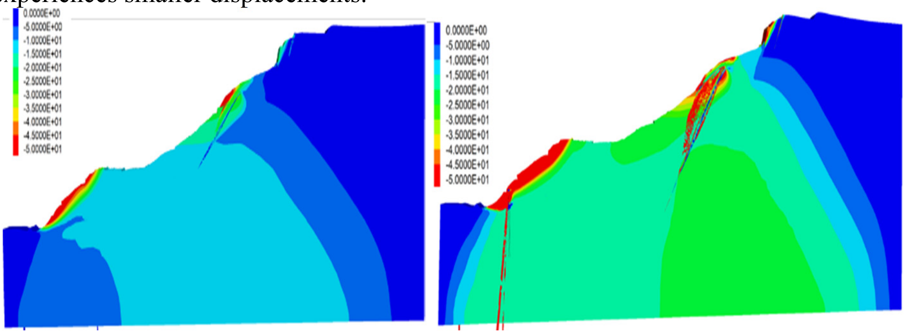
The excavation of the pile hole for Pier 17, which is located at the base of the slope, leads to an increase in the displacement area in the lower part of the slope. Furthermore, larger areas of displacement appear in the middle-upper section of the slope, and the displacement extends towards the deeper bedrock. This could potentially result in slope instability due to sliding within the bedrock. Comparing the displacement contour maps for the pile hole excavation at Pier 16 and Pier 17, it becomes evident that when the pile foundation excavation is located at the slope's base, it causes larger displacement disturbances.



(a) (b)

Fig. 7. Displacement contour map in the profile of the slope at pier 16. (a)Natural Condition, (b)Artificial Disturbance

The displacement contour maps for both Pier 16 and Pier 17 show that the displacement areas in both cases are divided into two separate regions, with no continuous connection between them. These regions correspond to the upper and lower parts of the slope, where the slope has steeper gradients, while the middle part with gentler slopes experiences smaller displacements.



(a) (b)

Fig. 8. Displacement contour map in the profile of the slope at pier 17. (a)Natural Condition, (b)Artificial Disturbance

The excavation of the pile hole for Pier 17, which is located at the base of the slope, leads to an increase in the displacement area in the lower part of the slope. Furthermore, larger areas of displacement appear in the middle-upper section of the slope, and the displacement extends towards the deeper bedrock. This could potentially result in slope instability due to sliding within the bedrock. Comparing the displacement contour maps for the pile hole excavation at Pier 16 and Pier 17, it becomes evident that when the pile foundation excavation is located at the slope's base, it causes larger displacement disturbances.

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5 Conclusion

In this study, the Longwangxi deep deposit slope was examined as a case study. Two-dimensional geological models were established using Flac 3D for different cross-sections under both natural and artificial disturbance conditions. The stability of the conditions before and after disturbance was evaluated using the strength reduction method. The research findings indicate:

(1) Excavation work during the construction of bridge piles leads to a decrease in the safety factor of the slope by approximately 7.1% to 11.7%. It is recommended to provide support to the slope before commencing bridge pile construction.

(2) Plastic zones and areas of significant displacement primarily occur in the upper and lower portions of the slope, which have steeper gradients. The middle portion of the slope, with gentler slopes, remains in a stable condition. It is advisable to provide separate support to the upper and lower sections of the slope.

(3) Artificial disturbance can lead to significant displacement in the lower part of the slope above isolated boulders, increasing the risk of isolated boulder instability. Therefore, when addressing isolated boulder instability, it is recommended to focus on securing the base rock and soil beneath the isolated boulders. Additionally, targeted support measures should be implemented for the slope before bridge pile construction.

(4) Pile hole excavation results in stress concentration around the pile hole, and this phenomenon increases with the depth of the pile hole.

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