International Journal of Advances in Engineering and Management (IJAEM)
Volume 5, Issue 8 Aug 2023, pp: 381-387 www.ijaem.net ISSN: 2395-5252

Study on the Buckling Stability of Pile Foundations for High Bridge Piers on Steep Slopes

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Date of Submission: 10-08-2023 Date of Acceptance: 20-08-2023

ABSTRACT: The current research on the buckling stability of high piers often considers the connection between the pile and the pier as a fixed end, and treats the pier cap as either free or elastically hinged, which makes it difficult to comprehensively and realistically reflect the boundary conditions of the pier. Moreover, the interaction between the soil and the pile on the stability of high piers is not taken into account. In this study, based on an actual engineering background, the ABAQUS finite element program is used as the analysis tool. Considering the force characteristics of high bridge piers with pile foundations on steep slopes and considering the pile-soil interaction, a linear buckling model is adopted to analyze the stability of the pile foundation on steep slopes. By solving the model, the critical buckling load of the bridge foundation piles on steep slope segments is obtained. Comparing the results with the calculation results from the specifications validates the reasonableness of the method proposed in this paper. Furthermore, the influencing factors of the buckling stability of the pile foundation on steep slope segments are further studied. The results show that the critical buckling load Pcr of the pile foundation increases nonlinearly with the pile diameter, increases slowly first and then decreases slowly with the increase of lateral force, and increases with the increase of the slope angle. The research findings can be used for the design and construction of pile foundations for high bridge piers on steep slopes.
KEYWORDS: Buckling, Finite element, High bridge pier, Stability, Steep slope

I. INTRODUCTION

The study of the buckling stability of bridge piers originated from Euler's theory of elastic columns. In the early stages, the research on buckling stability mainly focused on truss members. With the development of high-rise buildings, it gradually expanded to include reinforced concrete piers, and now it further encompasses bridge piers spanning deep mountain valleys. Many experts and scholars have gradually established a preliminary analytical system and achieved numerous theoretical and experimental results by improving classical theories to adapt to the complex boundary constraints, material nonlinearity, and geometric nonlinearity of high piers.

In 1910, Karman independently derived a formula for calculating the critical buckling load under small displacement conditions based on stress and strain theories developed by Engesser. He verified the practical value of this formula through experiments. In the years 1946-1947, Shanley analyzed the deformation limits of columns based on a series of field tests. In the 1970s, Wagner and Vlasov studied the buckling values of large slender members based on the theory of bending-torsional instability, and reasonably explained why the critical load values obtained were much smaller than those derived from Euler's theory. In the 1980s, Gillian et al. conducted relevant research on the buckling stability of thin-walled high piers. Taylor[1] and his research group poured 12 concrete thin-walled hollow piers with the same axial length but varying cross-sections and wall thicknesses. By applying vertical and moment loads, they obtained the variation law of buckling stability with aspect ratio and wall thickness.

Feng Zhongren[2] and Xu Yousheng[3] separately considered the stability of high piers under linear elastic and geometric nonlinear conditions, and concluded that the pier height has a certain influence on geometric nonlinearity. Gu Senhua[4]established a temperature gradient model for concrete

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thin-walled high piers based on field test data, and compared it with two recommended temperature gradient models in the code. The measured temperature gradient had a relatively small impact on the stability of high piers. He also studied the relationship between the amount of ordinary reinforcement and the stability factor. He Chang [5] et al. analyzed the nonlinear stability of high piers with initial defects. Yang Xiangzhan[6]used ANSYS to analyze the stability of high piers, considering geometric and material nonlinearity. They found that the stability factor under linear elastic conditions was much larger than that under nonlinear conditions, and the critical load and critical diameter in actual situations might be closer to the results under nonlinear conditions. Wang Yinhui [7]derived theoretical formulas for calculating critical loads of variable cross-section thin-walled hollow piles using the Timoshenko-Rayleigh-Ritz energy method with two common boundary constraints. Xi Guangheng[8]analyzed and studied the stability of double-arm thin-walled piers under lateral wind action using the principle of finite displacement virtual work. Cheng Jin[9] et al. studied the impact of static wind loads on the stability of high piers. Zheng Bing [10]used ANSYS to establish a solid model to analyze the influence of geometric parameters of transverse diaphragms on the local instability of hollow thin-walled high piers. LvYigang and YuQianhua[11] used the energy method to analyze the stability of high piers during the construction process of long-span continuous rigid-frame bridges, and proposed a calculation formula for the stability factor.

Although many researchers have made abundant achievements, the current research on the buckling stability of high piers usually considers the connection between the pile and the pier as a fixed end and treats the top of the pier as free or elastically hinged, which is difficult to comprehensively and realistically reflect the boundary conditions of the pier. It also does not consider the influence of the interaction between the rock-soil mass and the pile on the buckling stability of high piers. At the same time, there are few studies on the influence of downhill sliding force and lateral soil resistance on the buckling stability of high piers.

II. MODEL ESTABLISHMENT

No. 13 pier of Chishanxi Bridge on a certain expressway is a typical double-pile foundation for a high and steep slope section. Based on survey data and analysis of indoor experiments, a three-dimensional computational analysis model considering nonlinear contact and the elastic-plastic constitutive relationship of rock-soil mass was established for the double-pile foundation. In order to eliminate stress concentration and boundary effects as much as possible, the horizontal dimension of the model's rock-soil mass part is much larger than the geometric dimensions of the pile, as shown in Fig 1.

The length of this model is 143.92m, the total height of the slope is 80m, and the slope angle is 30°. The double-pile foundation consists of piles, columns, transverse beams, and cap beams. The diameter of the pile body is 2m, and the length is 25m. The diameter segment of the column is 2m, and the length is 10m. The height of the transverse beam is 2m, and the height of the cap beam is 2m. The center-to-center distance between the double piles is 9m. The material parameters of the pile body are determined according to actual engineering values. At the same time, the steep slope is simplified and divided into highly weathered granite layer and moderately weathered granite layer. The position of the rear pile is located in the highly weathered rock layer, with a thickness of 45.41m for highly weathered layer and 5m for moderately weathered layer. The position of the front pile is located in the highly weathered rock layer, with a thickness of 40.22m for highly weathered layer and 5m for moderately weathered layer.

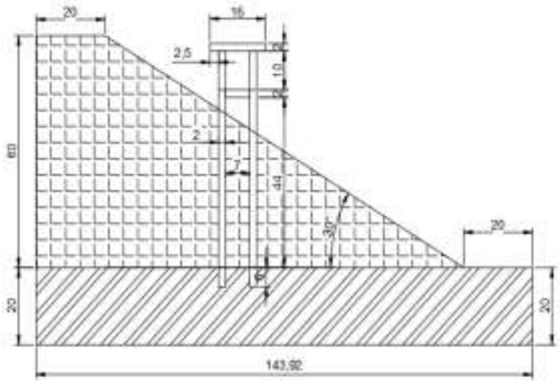

Figure 1: dimensions of the abaqus finite element model

III. MESH GENERATION AND CONTACT DEFINITION

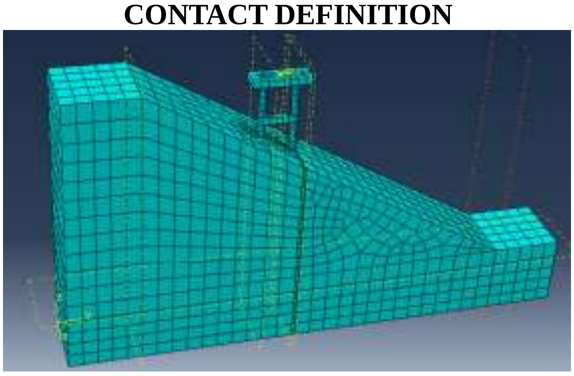

Figure 2: finite element mesh generation of double

pile foundations for high steep cross-slope section pylon bridges

The selection of elements directly affects the convergence of the model calculation. Choosing appropriate elements can not only reduce the computation time but also improve the accuracy of the solution. To ensure both computational efficiency and accuracy, a structured meshing method is used for the pile and steep slope rock-soil mass. Hexahedral twenty-node elements are employed, as shown in Fig 2.For the highly weathered rock layer, a total of 2,224 elements are used. For the moderately weathered rock layer, there are 1,327 elements. And for the pile body, there are 312 elements. By using a structured mesh and hexahedral twenty-node elements, the model can accurately represent the geometry and mechanical properties of the pile and slope, leading to reliable and efficient calculations. Fig 2 provides a visual representation of the selected element type.

Table 1: ABAQUS Finite Element Model Calculation Parameters

Materials	Cohesive Strength (kPa)	Internal friction angle (°)	Gravity (N/m³)	Elastic modulus (Pa)	Poisson's ratio
Weathered rock layer	120	21	19	470	0.32
Moderately weathered rock layer	80	25	23	30000	0.22
Concrete	——	——	22	28000	0.23

In this analysis, the materials for the pile body and the steep slope rock-soil mass are assumed to be isotropic and homogeneous. The double-pile body is modeled using a linear elastic constitutive relationship, while the moderately weathered rock layer and the highly weathered rock layer are modeled using the Mohr-Coulomb elastoplastic constitutive model. The material parameters are given in Table 1.

There are three methods available in ABAQUS for buckling analysis: linear buckling analysis, nonlinear buckling analysis (static-risk), and explicit dynamic analysis (dynamic-explicit). Linear buckling analysis is used to estimate the maximum critical load and buckling mode. It requires applying loads but cannot show the post-buckling state. It is typically used for calculations before introducing defects or for structures insensitive to defects. Nonlinear buckling analysis uses arc-length instead of time as the parameter and can show the post-buckling state. The buckling load is obtained by multiplying the load factor with the applied load. It is commonly used for defect-sensitive structures; however, convergence issues may arise when contact exists. Explicit dynamic analysis uses an explicit integration method and is suitable for contact separation problems. It can handle complex models and complex contact conditions with good convergence. The drawback is that it requires significant computational resources and long calculation times, and the reliability of the results needs to be assessed after computation. Considering the practical situation of this engineering project, linear buckling analysis is used for analyzing the pile foundation on the steep slope.

IV. POST-PROCESSING AND RESULTS OF MODEL ANALYSIS

The deformation of the pile's fourth-order buckling mode, as shown in Fig 3, is analyzed and visualized using the post-processing module (Visualization). To facilitate observation, ABAQUS has magnified the corresponding deformation effect by a factor of 13.1 for display. From the figure, we can determine the critical load factors for modes 1 to 4, which are 26.677, 237.42, 294.64, and 383.87, respectively.A concentrated load of 10,000 kN is applied on the surface of the double-pile cap beam. Typically, the critical load factor corresponding to the first-mode buckling is taken as the actual critical load factor, which is approximately 2.86773. This result is consistent with the calculation based on the specifications, indicating that the numerical model can effectively reflect the real situation.

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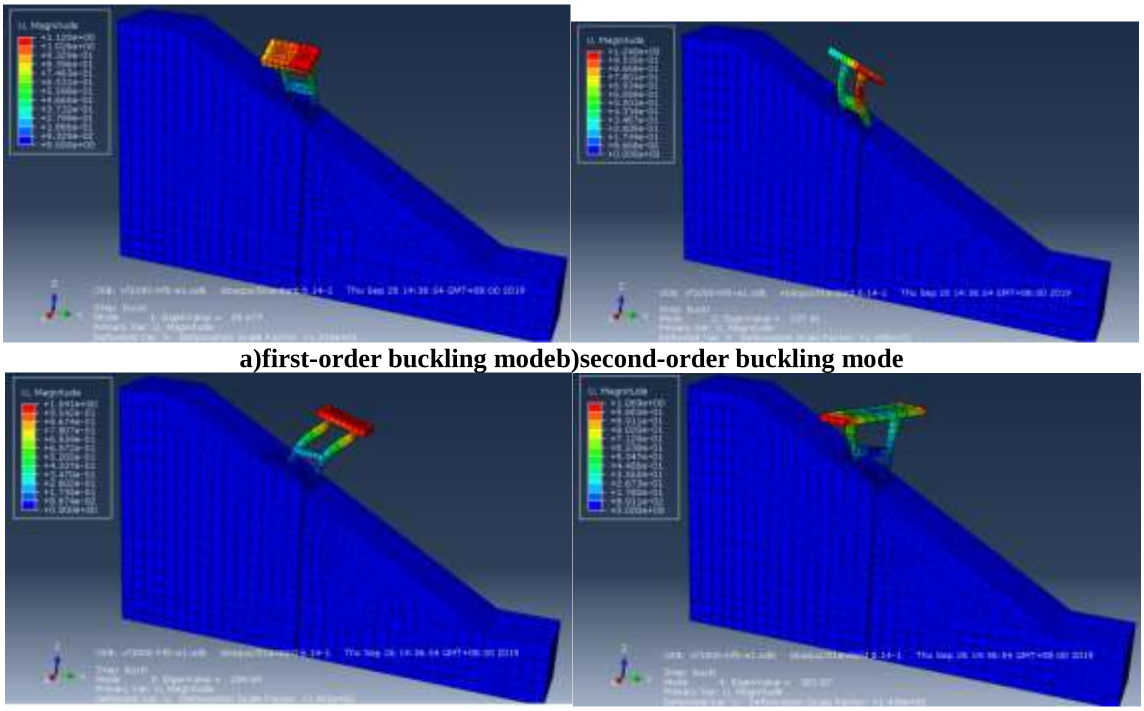

a)first-order buckling modeb)second-order buckling mode

c)three-order buckling moded)four-order buckling mode

Figure 3: buckling mode of the pile

V. ANALYSIS OF FACTORS INFLUENCING THE BUCKLING STABILITY OF STEEP SLOPE HIGH PIER PILE FOUNDATION

5.1Effect of pile diameter (d)

In order to investigate the influence of pile diameter on the buckling stability of pile foundations for high bridge piers in steep slope sections, we conducted a computational analysis using a finite element model while keeping other parameters constant. Pile diameters of 0.5E, 0.75E, 1.0E, 1.25E, and 1.5E were selected, where E represents the elastic modulus. The relationship curves between the critical buckling load(P_{cr})and pile diameter(d)for different elastic moduli are shown in Fig 4 and Fig 5.

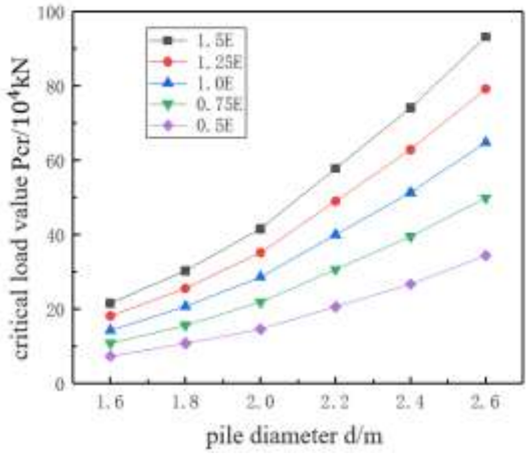

Figure 4: influence of pile diameter (d) on critical buckling load (P_{cr})

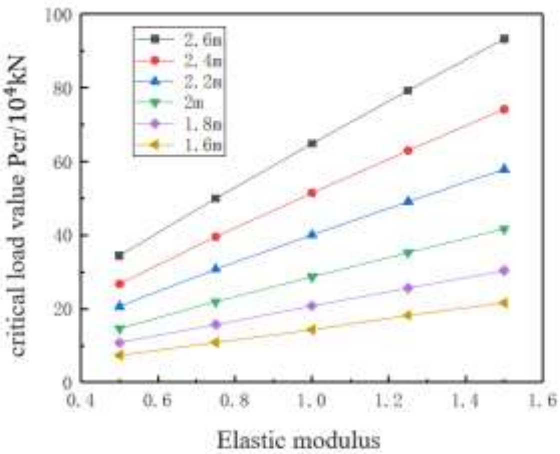

Figure 5: influence of elastic modulus (E) on critical buckling load (P_{cr})

Generally, pile diameter is an important parameter that controls the bearing capacity and deformation characteristics of pile foundations. From the analysis in Fig 4, it can be observed that as the pile diameter increases, the critical buckling load of the pile foundation tends to increase linearly. However, there are significant differences in the rate of increase under different elastic moduli (E) of the pile body. According to Fig 5, it can be noted that as the elastic modulus of the pile body (E) increases, the

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slope of the curve gradually becomes steeper. This trend becomes more pronounced for larger pile diameters. This indicates that the increase in pile diameter, resulting in a decrease in the calculated lengthfor stability, has a non-linear effect on the critical buckling load of the pile foundation. This effect is particularly significant for higher pile body elastic moduli.

5.2 Effect of lateral force (H)

In the normal operation of steep slope high-pier pile foundations, apart from vertical loads, they are also subjected to lateral forces from braking forces of vehicles and wind forces. The lateral force causes an increase in bending moment on the pile shaft, negatively affecting the buckling stability of the pile foundation. However, at the same time, the lateral force also induces displacement of the pile body away from the slope surface, reducing the sliding force acting on the slope. To study the comprehensive effect of lateral forces, lateral forces of H=200kN, 400kN, 600kN, 800kN, 1000kN, and 1200kN were applied to the upper surface of the pile cap beam. Different pile body elastic moduli were used, and the finite element analysis results are shown in Fig 6 and Fig 7.

From Fig 6 and Fig 7, it can be observed that with the increase in lateral force, the corresponding critical buckling load slowly increases, and the magnitude of this increase is positively correlated with the pile body elastic modulus (E). The critical buckling load for each pile body elastic modulus reaches its maximum value when the lateral force is H=600kN and then decreases with further increase in lateral force. This indicates that at lower lateral forces, the main effect is on unloading the pile behind the sliding slope. However, when the lateral force exceeds a certain critical value, it weakens the pile foundation. For this high-pier pile foundation, the critical value of the lateral force is around 600kN. Further research is needed to quantitatively establish the relationship between the critical value of the lateral force and the pile foundation and steep slope. Moreover, during the design of the steep slope high-pier pile foundation, lateral force factors should be considered to ensure that the maximum lateral force on the pile foundation is below its critical value and to avoid any negative effects.

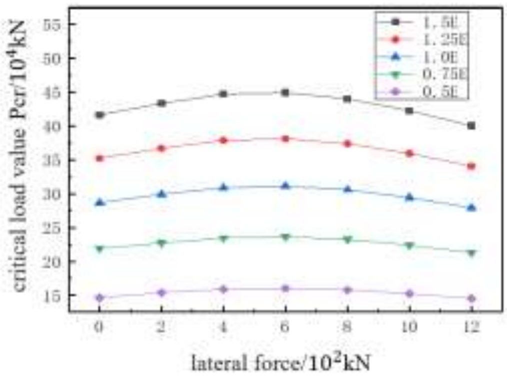

Figure 6: influence of lateral force (H) on critical buckling load (P_{cr})

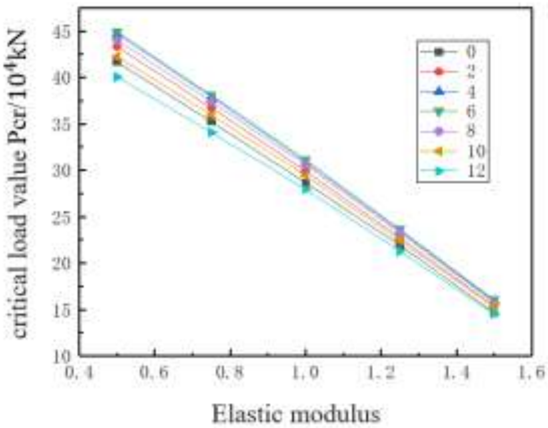

Figure 7: influence of elastic modulus (E) on critical buckling load (P_{cr})

5.3 Effect of embedment depth (h)

According to the literature research, existing studies have shown that there is a critical embedment depth for steep slope bridge pier foundations. When the embedment depth of the pile foundation reaches this value, further increasing the pile length has minimal effects on the internal forces and deformations of the pile, but further investigation is needed to determine its influence on the flexural stability of the foundation. Therefore, the influence of changes in embedment depth on the flexural stability of the pile foundation was analyzed for different elastic moduli of the pile body, and the results are shown in Fig 8 and Fig 9.

From Fig 8 and Fig 9, it can be observed that as the embedment depth increases, the calculated stable length gradually decreases, but the corresponding critical load remains relatively stable without significant changes. According to relevant research, when the embedment depth of the pile foundation is less than 4m, the flexural point of the

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pile foundation is located in the free segment above the slope surface, and the critical load for pile flexure is smaller. As the embedment segment length gradually increases, the flexural point of the pile foundation gradually moves down to the resistance-weakened segment below the slope surface. At this point, even if the embedment segment length increases further, both the critical load and the calculated stable length of the pile foundation tend to stabilize.

Thereason why the aforementioned characteristics may not apply to the high bridge pier pile foundation in question is possibly because the main part of the slope consists of highly weathered granite. The variation in embedment segment length did not cause the flexural point of the pile foundation to move down to the moderately weathered granite layer, hence the absence of a critical embedment depth. Further investigation is needed to confirm the specific circumstances.

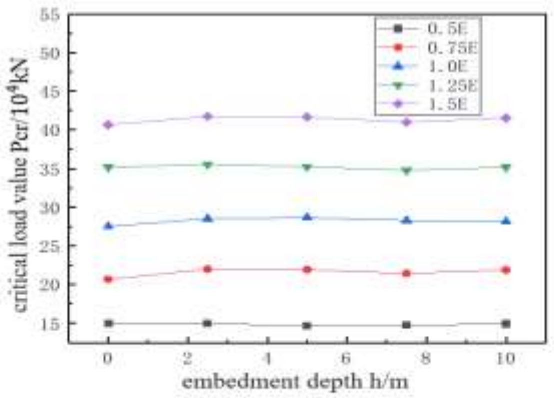

Figure 8: influence of embedment depth (h) on critical buckling load (P_{cr})

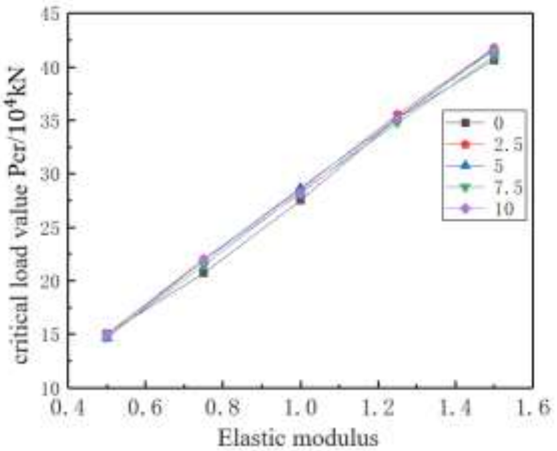

Figure 9: influence of elastic modulus (E) on critical buckling load (P_{cr})

5.4Effect of steep slope angle (α)

For steep slope bridge pier foundations, the asymmetry caused by the presence of the slope directly leads to the loss of soil in front of the pile foundation, forming a void face and reducing the lateral constraint of the soil on the pile foundation. The horizontal foundation resistance of the soil in front of the pile has been significantly weakened.

In design, it is common to reduce the resistance of the soil within a certain depth range. The depth is generally considered to be related to factors such as the load level carried by the pile foundation, the properties of the site soil, and the slope angle. It can be assumed that the pile diameter is proportional to the depth.

As for the specific values, many domestic and foreign scholars have provided relevant recommended values based on research analysis and engineering experience. However, there is relatively limited research on the relationship between steep slope angles and the flexural stability of the pile foundation. Therefore, while keeping other parameters constant, further investigation is needed, the flexural critical load Pcr was calculated for different pile body elastic moduli using slope angles $\alpha = 24°$、$27°$、$33°$ and $36°$,the results are shown in Fig 10 and Fig 11.

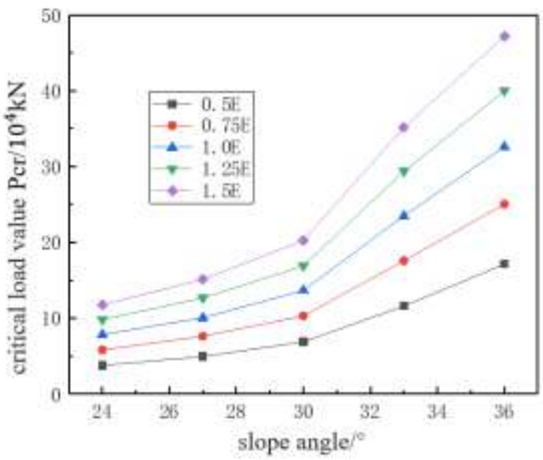

Figure 10: influence of slope angle (α) on critical buckling load (P_{cr})

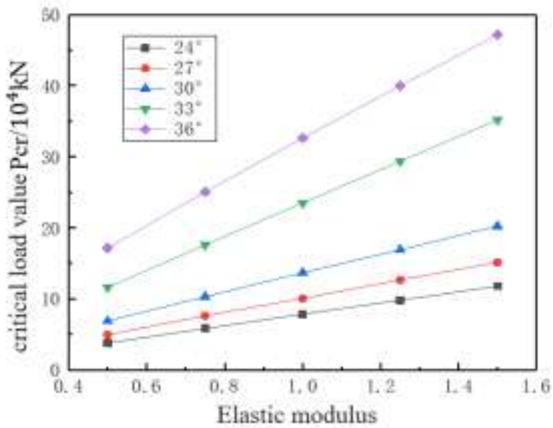

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Figure 11: influence of elastic modulus (E) on critical buckling load (P_{cr})

From Fig 10 and Fig 11, it can be seen that as the slope angle increases, the flexural stability load of the pile foundation also increases, and there is a clear inflection point for each curve when the slope angle is 30°. When the pile body elastic modulus is 1.0E and the slope angles α = 24°、27°、30°、33° and 36° respectively, the critical loads are increased by 22.03%, 36.05%, 71.86%, and 36.86% compared to the previous case. This indicates a non-linear increasing trend. It suggests that the increase in slope angle leads to a decrease in effective thickness, a decrease in the effective stable calculation length, and an increase in the resistance provided by the soil in front of the pile.

VI. CONCLUSION

(1) Taking actual engineering as an example, the ABAQUS finite element program is used as the analysis tool to establish a two-dimensional numerical calculation model for the buckling stability analysis of high bridge pier piles on steep slope sections, considering the pile-soil interaction. By solving the model, the corresponding critical buckling load of the steep slope bridge pier piles is obtained. The calculation results are validated by comparing them with the results from codes, indicating the rationality of the numerical method used in this paper.

(2) Using the numerical calculation method proposed in this paper, the influencing factors of the buckling stability of bridge pier piles on steep slope sections are analyzed. The results show that there is an inherent connection between the critical buckling load Pcr and the pile diameter, and the critical buckling load Pcr increases nonlinearly with the pile diameter. The embedded depth effect of the high bridge pier piles on steep slope sections is related to the properties of the soil layer and the depth of pile embedding. For piles with long embedding depth in weakly weathered rock layers and short rock embedding depth, there is no significant effect of rock embedding depth. The change in slope gradient has a significant influence on the buckling stability of the pile foundation, and the larger the slope gradient value, the more pronounced the effect on the critical buckling load Pcr. When the pile body is inclined, the deformation will continue to increase due to the effect of the "P-Δ" effect, which may cause buckling failure of the pile body due to insufficient strength of the cross-sectional material. Soil stratification has an important influence on the buckling stability of the pile foundation. Different stratification conditions will result in different buckling stability of the pile foundation.

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