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Study Buckling Stability of High Pier Pile Foundation on A Steep Slope

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ABSTRACT

At present, the research on the buckling stability of high pier usually regards the connection of pile and pier as fixed end and the top of pier as free or elastic hinge, which is difficult to fully and truly reflect the boundary conditions of pier, and does not consider the influence of the interaction between rock and soil and pile on the buckling stability of high pier. Based on the research background of practical engineering, ABAQUS finite element program is selected as the analysis tool, combined with the mechanical characteristics of high pier pile foundation in steep slope section, considering the pile-soil interaction, the linear buckling model is used to analyze the stability of steep slope pile foundation. By solving the model, the corresponding critical buckling load of bridge foundation pile in steep slope section is obtained. The rationality of this method can be seen by comparing the calculation results in this paper with those in the code. The results show that the critical buckling load PCR increases nonlinearly with the pile diameter, increases first and then decreases slowly with the increase of lateral force, and increases with the increase of slope angle. The research results can serve the design and construction of high pier pile foundation on steep slope.

Keywords: *Steep Slope; High Bridge Pier; Flexion; Finite Element Method; Stability*

I. INTRODUCTION

The research on buckling stability of high bridge piers originated from Euler's theory of elastic compression rods. The early buckling stability research objects were mostly truss rods. With the development of high-rise buildings, it gradually expanded to reinforced concrete piers and columns, and now it further includes the spanning of deep mountains high piers of bridges in the canyon.By improving the classical theory to adapt to the complex boundary constraints, material nonlinearity and geometric nonlinearity of high piers, many experts and scholars have gradually established a preliminary analysis system and achieved many theoretical and experimental results at home and abroad.

In 1910, Based on Engesser's stress and strain theory, Kowalsky independently derived a formula for calculating the critical load of nonlinear stability under the condition of small displacement, and verified the general practical value of this formula through experiments.Based on a series of field tests[1] .During 1946-1947,Mirza analyzed the deformation limit of the compression bar through data In the 1970s,Wagner and Vlasov[2] studied the buckling values of large slender members based on the bend-torsional instability theory, and rationally explained why the critical load values were much smaller than those derived from Eule theory. Taylor's research group [3] poured 12 thin-walled concrete hollow piers with the same length in the weak axis direction, but the cross-section and wall thickness are constantly changing along the height. By applying vertical and moment loads, the variation law of buckling stability with slenderness ratio and wall thickness is obtained.

Feng Zhongren [4] and Xu Yousheng [5] considered the stability of high piers under linear elastic and geometric nonlinear conditions, respectively, and concluded that pier height has a certain influence on geometric nonlinearity. Gu Senhua [6] established a temperature gradient model for thin-walled high piers based on field test data. Compared with the two recommended temperature gradient models in the norm, the measured temperature gradient has less influence on the stability of high piers. The relationship between the amount of ordinary steel bars and the stability coefficient is analyzed.He Chang [7] et al. analyzed the nonlinear stability of high piers with initial defects. Yang Xiangzhan [8] used ANSYS to analyze the stability of high piers, and considered geometric and material nonlinearity, and found that the stability coefficient under linear elastic conditions is much larger than that under nonlinear conditions, and the critical load and critical diameter in actual conditions may be closer to the results under nonlinear conditions.Zheng Bing [9] used ANSYS to establish a solid model to analyze the influence of the geometric parameters of the diaphragm on the local instability of the hollow thin-walled high pier.

Although many researchers have made abundant achievements, the current research on the buckling stability of high piers usually regards the pier connection as a fixed end, and the pier top is free or elastically hinged, which is difficult to fully and truly reflect the pier's buckling stability, also do not take into account the influence of the interaction between the rock and soil mass and the pile on the buckling stability of the high pier. At the same time, there are few reports on the effects of the sliding force and lateral soil resistance of steep slopes on the buckling stability of high piers.

II. RESEARCH METHOD

(1) Model building

The No. 13 pier on the left side of the Chishanxi Bridge of a highway is a typical double-piled foundation of a pile-type bridge in the cross-slope section of the high-steep slope. According to the analysis of survey data and laboratory experiments, a three-dimensional calculation and analysis model of double piles considering nonlinear contact and elastoplastic constitutive relationship of rock and soil mass is established. The size is much larger than the geometric size of the pile body, as shown in figure 1.

The model is 143.92m long, the total slope height is 80m, and the slope angle is 30°. The double pile foundation consists of piles, columns, transverse beams and cover beams. The diameter of the pile body is 2m and the length is 25m. The diameter of the pier column is 2m and the length is 10m, the height of the horizontal tie beam is 2m, the height of the cover beam is 2m, and the center distance of the double pile is 9m The material parameters of the pile body are determined according to the actual engineering values, and the steep slope is simplified at the same time. It is divided into strong weathered granite layer and moderately weathered granite layer. The strong weathered rock layer is 45.41m at the rear pile position, and the medium weathered rock layer is 5m, strong wind at the front pile position the chemical rock layer is 40.22m, and the medium weathered rock layer is 5m.

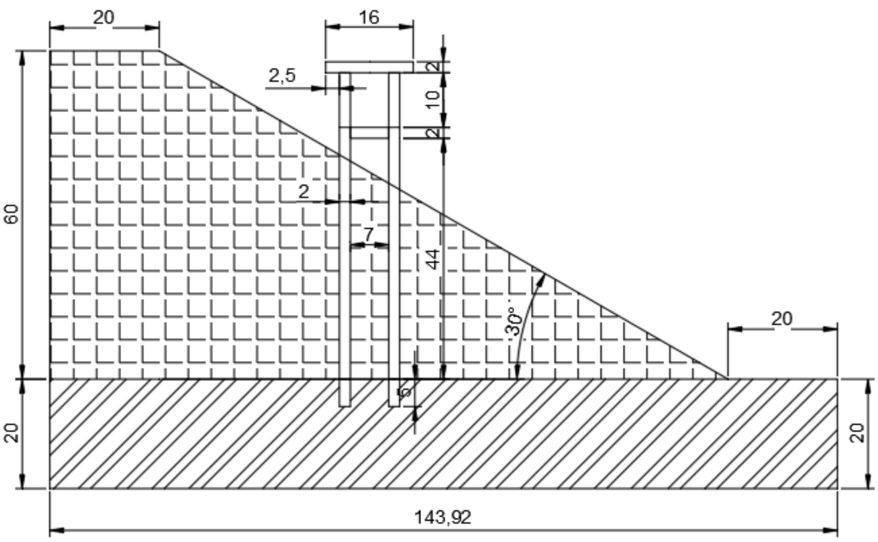


Figure 1 Dimensions of ABAQUS finite element model

(2) Meshing and Contact Definition

The selection of elements directly affects whether the model calculation converges, and selecting appropriate elements can not only reduce the time spent in the calculation, but also improve the accuracy of the solution. In order to ensure the calculation efficiency and calculation accuracy requirements, the pile body and the rock and soil mass of the steep slope adopt a structured division method, and a hexahedral twenty-node element is used, as shown in Figure 2. There are 2224 units of strongly weathered rock layers, 1327 units of moderately weathered rock layers, and 312 units of pile bodies.

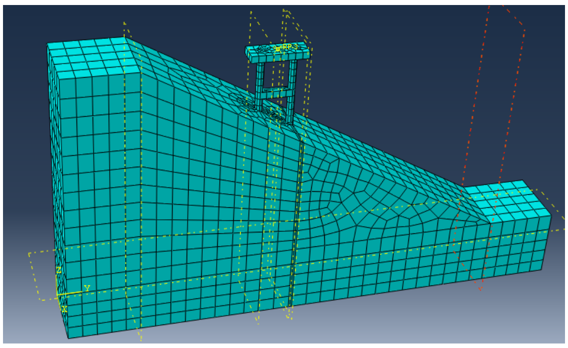


Fig. 2 Finite element mesh division of double-pile foundation of pile-type bridges in high and steep cross-slope sections

Table 1 Calculation parameters of ABAQUS finite element model

Material	Cohesion (kPa)	internal friction angle（°）	Severe (kN/m3)	Modulus of elasticity(Mpa)	Poison's ratio
Strongly Weathered Rock Stratum	120	21	19	470	0.32
Moderately Weathered Rock Stratum	80	25	23	30000	0.22
Concrete	——	——	22	28000	0.23

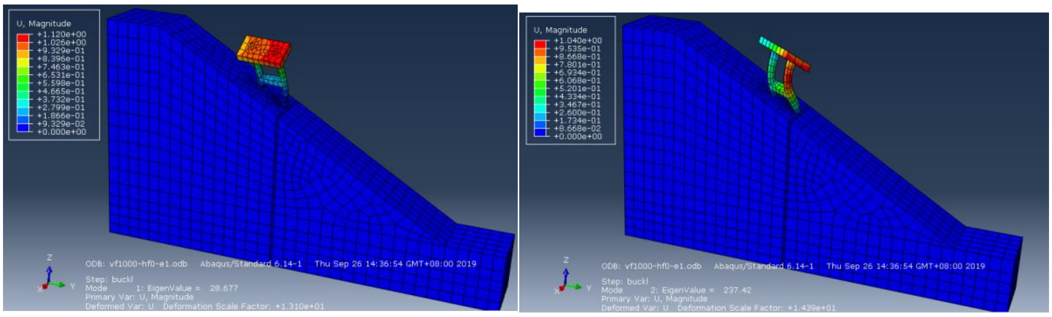
In this analysis, the material of the pile body and the rock and soil material of the steep slope are set as isotropic homogeneous materials, the double pile body is simulated by linear elastic constitutive relation, and the Mohr-Coulomb elastic bomb is used for the moderately weathered and strongly weathered rock layer for the plastic constitutive model, the material parameters are shown in Table 6-4.

Abaqus has three methods for buckling analysis: linear buckling analysis (buckle), nonlinear buckling analysis (static-risk), and explicit dynamic analysis (dynamic-explicit). Among them, linear buckling analysis is used to estimate the maximum critical load and buckling mode, and it needs to apply loads. The disadvantage is that the post-buckling state cannot be viewed, and it is usually used in the calculation and analysis steps before the introduction of defects or for defect-insensitive structures;The nonlinear buckling analysis uses the arc length instead of the time. The post-buckling state can be viewed, and the load scale factor multiplied by the load is the buckling load. It is usually used for defect-sensitive structures, but the structure has contact and is prone to convergence problems; display dynamic analysis Using the explicit integration method is suitable for the problem of contact disengagement, and can adapt to complex models and complex contact pairs, and the convergence effect is better. The disadvantage is that the calculation amount is large and the calculation time is long. After the calculation, it is necessary to evaluate whether the calculation result is reliable.Considering the actual situation of the project, linear buckling analysis is used to analyze the steep slope pile foundation.

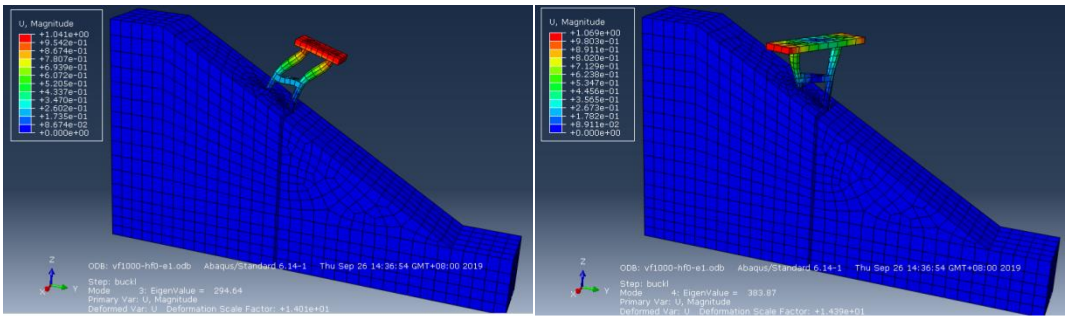
III. DISCUSSION

3.1 Model analysis post-processing and results

In the post-processing module (Visualization), the buckling stability analysis results of the pile-slope system are read, and the deformation of the fourth-order buckling mode of the pile is shown in Figure 3. In order to facilitate observation, ABAQUS has enlarged the corresponding deformation effect by 13.1 times for display. From the figure, it can be concluded that the critical load factors of orders 1 to 4 are: 26.677, 237.42, 294.64 and 383.87, respectively.The concentrated load applied to the upper surface of the double pile cap beam is 10000kN. Generally, the critical load factor corresponding to the first-order buckling mode is taken as the actual critical load factor, that is, the critical buckling load is about 2.86773, which is in line with the results calculated according to the code, indicating that the numerical model can better reflect the real situation.



a) First order buckling mode **b) Second order buckling mode**



c)Third-order buckling mode **d) Fourth-order buckling mode**

Figure 3 Buckling modes of piles

3.2 Analysis of Influencing Factors on Buckling Stability of Pile Foundation of High Bridge Pier with Steep Slope

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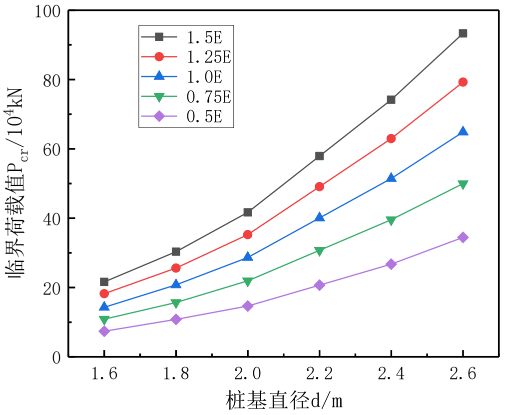
3.2.1 Influence of pile diameter d

In order to explore the influence of pile diameter on the buckling stability of high bridge piers in the steep slope section, and keep other parameters unchanged, 0.5E, 0.75E, 1.0E, 1.25E and 1.5E were selected for calculation and analysis using the finite element model, and different elastic modes were obtained. The relationship curve between the pile foundation buckling critical load P_{cr} and the pile diameter d is shown in Figure 4 and Figure 5.



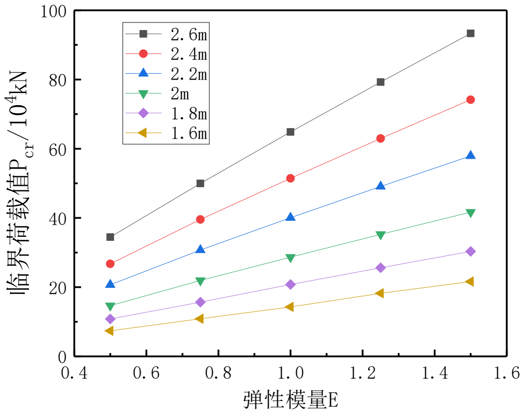


FIG. 4 Influence of pile diameter D on Pcr of buckling critical load

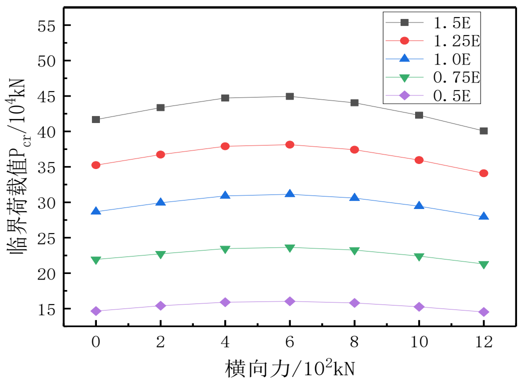
FIG. 5 Influence of elastic modulus E on Pcr of buckling critical load

Usually, the pile diameter is an important index to control the acceptance and deformation characteristics of the pile foundation. From the analysis of Fig. 4, it can be found that with the increase of the pile diameter, the buckling critical load of the pile foundation basically increases linearly, but different elastic modulus of the pile body There is a big difference in the growth rate under E.It can be seen from Fig. 5 that with the increase of the elastic modulus E of the pile body, the slope of the curve gradually increases, and this trend is more obvious when the pile diameter is larger, which shows that the increase of the pile diameter causes the decrease of the stable calculation length The effect on the buckling critical load of the pile foundation is non-linear and is more pronounced at high elastic modulus of the pile body.

3.2.2 Influence of transverse force H

In normal use, the pile foundation of steep-slope high bridge piers will be subjected to the lateral force of vehicle braking force and wind force in addition to the vertical load. However, at the same time, the lateral force also causes the displacement of the pile body away from the slope surface, thus reducing the effect of the sliding force on the slope body.In order to study the comprehensive effect of the lateral force, the lateral forces H=200kN, 400kN, 600kN, 800kN, 1000kN and 1200kN were applied to the upper surface of the pile top cover beam respectively, and different elastic moduli of the pile body were used， whcih obtained finite element calculation results are shown in the figure 6 and figure 7.

It can be seen from Fig. 6 and Fig. 7 that with the increase of the lateral force, the corresponding buckling critical load value also increases slowly, and the increase rate is positively correlated with the magnitude of the elastic modulus E of the pile body.The buckling critical loads under each elastic modulus of the piles all reach the maximum value when the lateral force H=600kN, and then decrease with the increase of the lateral force, which indicates that when the lateral force is small, its effect on the landslide body behind the pile is small which unloading plays a major role, and when it exceeds a certain critical value, the existence of lateral force plays a role in weakening the pile foundation.For this high pier pile foundation, the critical value of lateral force is around 600kN. The quantitative relationship between the critical value of lateral force and pile foundation and steep slope needs to be further studied in the future. In addition, the lateral force factor should be considered in the design of the pile foundation of the steep-slope high bridge pier, so that the maximum lateral force on the pile foundation is less than its critical value to avoid its negative influence.



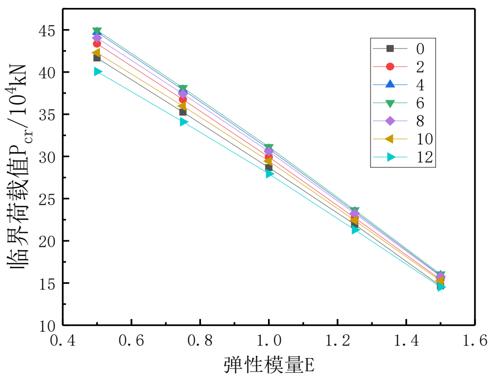


FIG 6 Influence of transverse force H on Pcr of buckling critical load

Fig 7 Influence of elastic modulus E on buckling critical load Pcr

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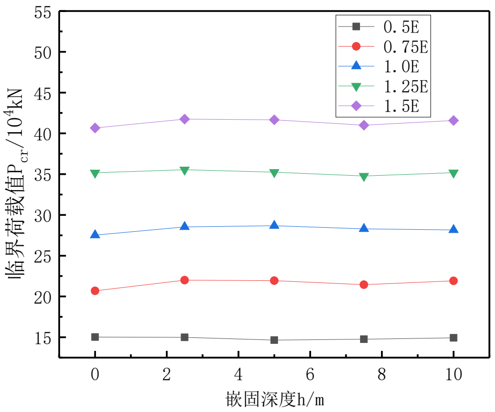
3.2.3 Influence of embedded depth h

According to the literature survey, the existing research shows that there is a critical embedding depth in the pile foundation of the steep-slope high bridge pier. When the embedded depth of the pile reaches this value, the length of the pile continues to increase, and the impact on the internal force and deformation of the pile body is minimal, but the impact on the buckling stability of the pile needs to be further studied. For this reason, the influence of the change of the embedded depth on the buckling stability of the foundation pile under different elastic moduli of the pile body is analyzed, and the results are shown in Figures 8 and 9.

It can be seen from Figures 8 and 9 that with the increase of the embedding depth, the stable calculation length gradually decreases, but the corresponding critical load is basically stable and has no obvious change. According to relevant research, when the depth of the embedded section is less than 4m, the buckling point of the pile is located in the free section above the slope surface, and the critical load of pile buckling is small. As the length of the embedded section increases, the buckling point of the pile gradually decreases moving to the weakened section below the slope, even if the length of the embedded section increases again, the critical load value and the calculation length of the pile foundation tend to be stable.

The pile foundation of this high bridge pier does not have the above characteristics, which may be because the main part of the slope body is mainly composed of strongly weathered granite, and the change of the length of the embedded section cannot make the buckling point of the pile foundation move down to the moderately weathered granite stratum, so it does not appear critical embedment depth.



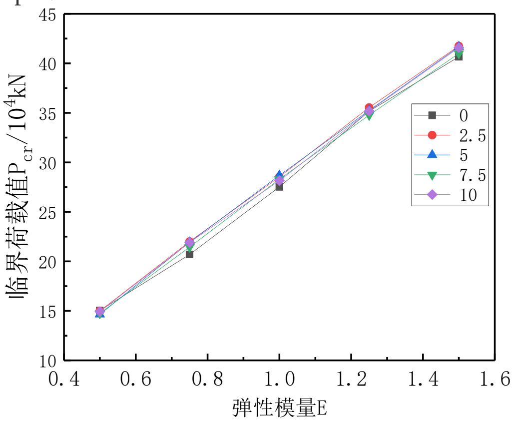


Fig.8 Influence of embedding depth h on buckling critical load Pcr

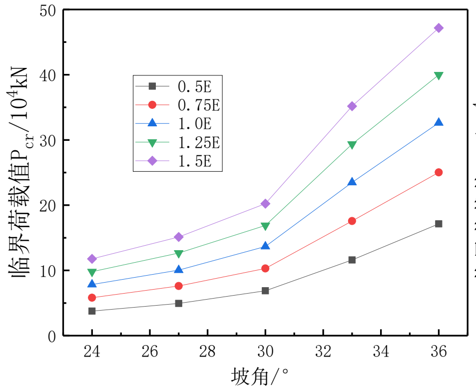
Fig.9 Influence of elastic modulus E on buckling critical load Pcr

3.2.4 Influence of steep slope angle α

For the pile foundation of high bridge piers on steep slopes, since the front and rear of the pile foundation are no longer symmetrical, the existence of the slope body directly leads to the lack of rock and soil in front of the pile and forms a free surface, which reduces the constraining effect of the soil on the side of the pile on the pile foundation, the horizontal foundation resistance of the soil has been weakened to a considerable extent.

In the design, the resistance of the rock and soil mass within the depth and thickness range is usually reduced. It is generally believed that the depth is related to the load level of the pile foundation, the properties of the site soil, the slope angle and other factors, and it can be assumed that the pile diameter is proportional.

For the value of , many scholars at home and abroad give relevant suggestions based on research and analysis combined with engineering experience. However, there are relatively few studies on the slope angle of the steep slope and the buckling stability of the pile foundation. Therefore, keeping other parameters unchanged, select the slope angl $\alpha=24°, 27°, 30°, 33°$ and $36°$, and calculate the critical buckling load Pcr under different elastic moduli of the pile body. The results are shown in Figure 10 and figure 11.



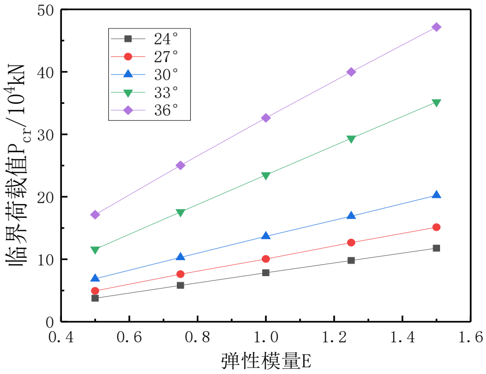


Fig.10 Influence of slope angle α on buckling critical load Pcr

Fig.11 Influence of elastic modulus E on buckling critical load Pcr

It can be seen from Figures 10 and 11 that with the increase of the slope angle, the buckling stable load of the pile foundation also increases, and each curve has obvious turning points when the slope angle is 30°. When the elastic modulus of the pile body is 1.0E and the slope angles α are $24°$, $27°$, $30°$, $33°$ and $36°$, respectively, the critical load increases by 22.03%, 36.05%, 71.86%, and 36.86%, showing a nonlinear increasing trend. This shows that the increase of the slope angle reduces the effective thickness, the effective stability calculation length, and the resistance provided by the soil in front of the pile increases.

IV. CONCLUSION

1. Taking the actual project as an example, using the ABAQUS finite element program as an analysis tool, combined with the stress characteristics of the pile foundation of the high bridge pier in the steep slope section, and considering the pile-soil interaction, a two-dimensional analysis of the buckling stability of the bridge foundation pile in the steep slope section is established numerical Computational Model. By solving the model, the corresponding critical buckling load of bridge foundation piles in the steep slope section is obtained. The numerical method used is reasonable by verifying the calculation results in this paper and the code calculation results.
2. Using the numerical calculation method proposed in this paper, the influencing factors of the buckling stability of the bridge foundation piles in the steep slope section are mainly analyzed. The results show that there is an inherent relationship between the critical buckling load Pcr of the pile foundation and the pile diameter, and the critical buckling load Pcr increases nonlinearly with the diameter of the pile;The embedded depth effect of the pile foundation buckling stability of high bridge piers in the steep slope section is related to the properties of the soil layer and the buried depth of the pile. There is no obvious rock-socketed depth effect in the pile foundation; the change of the steep slope has a great influence on the buckling stability of the pile foundation, and the larger the value, the more obvious the influence on the buckling critical load Pcr;When the pile body is inclined, the deformation will continue to increase due to the influence of the "P-Δ" effect, which may lead to the buckling failure of the pile body due to insufficient cross-section material strength; soil stratification plays an important role in the buckling stability of the foundation pile the buckling stability of the piles will also be different depending on the delamination conditions.

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