Analysis of the stability of the construction phase of rigidly constructed bridge based on pile-earth effect

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Abstract. In the rapidly emerging Yunnan-Guizhou-Sichuan region, high-pier and long-span bridges are mostly high-pier and long-span continuous rigid-frame bridges over 100 meters, and the stability of their high-piers becomes more and more important. In order to study the stability of the structure under the action of pile-soil, the Wugong Bridge in Guizhou was used as a supporting project, and a large-scale finite element software was used to establish a construction model considering the effect of pile-soil. The influence of this type of bridge on the linear elastic stability of the structure under the action of pile-soil and the geometric nonlinear stability after considering the deflection of the structure is compared and analyzed.

1. Introduction

Continuous rigid frame bridges have good economic efficiency, and therefore become the preferred bridge type when crossing valleys, rivers or under-bridge clearance is restricted. However, continuous rigid frame bridges with high piers in mountainous areas are subject to unbalanced forces during construction and the inevitable nonlinear effects of the high piers themselves, resulting in outstanding stability problems. Aiming at the stability problem of rigid frame bridges[1], Li Kaiyan, Chen Zhengqing, and Han Yan deduced the static stability coefficient expression of high-pier rigid frame bridges from the energy point of view. Wang Junli and He Shuanshui analyzed the stability of the main pier under different design parameters[2]. Bai Hao considered the structural stability under different nonlinear mechanical characteristics[3]. However, the research on the stability of rigid frame bridges in literature [1]~[3] ignores the effect of pile-soil.

The interaction among structure, pile foundation, and soil is a complicated one. In fact, it is unreasonable in most cases to ignore the effect of pile and soil in high-pier rigid frame bridges. Li Yaoyu deduced the stability coefficient expression of the stability of high piers under the action of pile-soil by the energy method[4]. Xin Yanfu analyzed the response of the geometric nonlinear effect of the bridge to the structure under the action of pile-soil[5].

Literature [4]~[5] analyze the stability of rigid frame bridges considering the effect of pile-soil, and provide a theoretical basis for the effect of pile-soil. Literature [5] considered the coupling problem of pile-soil action and geometric nonlinearity, and concluded that considering the effect of pile-soil action on high-pier and long-span structures, the effect of geometric nonlinearity was considered. However, the analysis of the stability parameters of the bridge cantilever construction under the action of pile-soil is less involved. Based on the literature [6], this paper uses Midas/civil software to analyze the stability of a high-pier rigid frame bridge considering the effect of pile-soil, discusses the influence of related parameters on the stability of the structure considering the effect of pile-soil, and provides references to similar engineering stability problems.
2. Project Overview
Guizhou Wugong Bridge is a multi-span prestressed continuous rigid frame bridge with a main span of 150m. The plane of the main bridge lies on a circular curve R=1505m. The layout of the span and pier height of the bridge is shown in Figure 1. The main girder is cantilevered with C55 concrete, the bridge pier is C40 concrete hollow pier, the net spacing between the two limbs is 5m; the thickness of the concrete cap is 4.5m, and the pile foundation uses eight 2m diameter cast-in-place piles.

![Figure 1 Elevation layout drawing of Wu-gong Bridge (cm)](image)

3. High pier stability theory and finite element model establishment
The first type of instability is the instability of the branch point, which is the phenomenon of ideal component stability. Under the condition of satisfying the small displacement, the geometric stiffness matrix and the rod end force are proportional to \( \{F\} \), which satisfies the following relationship (1)

\[
([K_0] + \lambda[K_G])\{\sigma\} = \lambda[\{F\}]
\]

(1)

The buckling load can be obtained through the eigenvalue analysis. Because the eigenvalue analysis is relatively simple, it can provide a basis for the stability of the bridge, but because the analysis belongs to the elastic range, only buckling is provided for the solution of high piers such as high nonlinear instability problems. Upper limit [6].

The second type of instability is extreme point instability, which is the phenomenon of structural stability with material and geometric nonlinearity. The research is actually to explore the law of the load-displacement curve when the structure is under load, and analyze the structure's response under the load. The method of solving the load-displacement curve mainly adopts the incremental method. The instability problem can be expressed by the updated Lagrangian matrix [7].

\[
[K]_0 = \int [B_0]^T[D]e[B_0] \, dv
\]

(2)

\[
[K]_{\sigma}d(\delta) = \int [B_n]^T[\sigma] \, dv
\]

(3)

\[
[K]_e = \int [B_0]^T[D]_e[B_0] + [B_n]^T[D]_e[B_0] \, dv
\]

(4)

\[
([K]_0 + [K]_e + [K]_p)[\Delta \phi] = [K]_p[\Delta \phi]
\]

(5)

This paper uses the finite element software Midas 2018 to establish the 135.9m model of the highest pier of the Wugong Bridge (see Figures 2 and 3). One set of simulated piers is directly consolidated as the B model, and the other set of simulated piers is considered as the B1 model considering the effect of pile-soil. Considering that the pile foundation is an end-bearing pile, the vertical freedom of the pile end is constrained during modeling, and the soil spring stiffness acting on the pile and soil along the bridge and across the bridge is calculated by the “m” method[8].
4. Stability analysis of maximum cantilever stage

When the construction progresses to the maximum cantilever stage, the bridge structure is most prone to high pier instability under the dead weight load and external load. However, in the stability analysis of conventional high piers, the pile-soil interaction is often ignored. This deviates from the actual structural boundary conditions of the bridge. Based on this situation, this paper discusses the influence of pile-soil action on the stability of high piers.

4.1. Linear stability analysis

Considering the load received during the construction of the bridge, the most unfavorable arrangement of the load during cantilever construction is listed. The most unfavorable load conditions are as follows: bridge deadweight load + hanging basket load + partial load + transverse and longitudinal wind load.

a) The self-weight of the bridge and the concrete self-weight are calculated according to 26kN/m.

b) Under normal conditions (not counting the falling of the hanging basket) the load of the hanging basket is 896kN.

c) Uniform load on one side of the cantilever, and at the end of The part acts with a concentration of 200 kN.

e) Cross-bridge wind load

f) Longitudinal bridge wind load

| Model | B | B1 | Rate of change |
|-------|---|----|---------------|
| Stability factor | 5.401 | 4.279 | 21.64% |
| Buckling mode | Lateral buckling | Lateral buckling | - |

The calculation results are shown in Table 1. The analysis results show that the first-order eigenvalue of model B is 5.401, and the first-order eigenvalue of model B1 is 4.279 when the pile-soil effect is considered. After taking into account the pile-soil effect, the first-order linear elastic stability safety factor is reduced by 21.64%. Due to the changes in the structural forces after considering the pile-soil interaction, the stability of the structure is significantly reduced.

4.2. Geometric nonlinear stability calculation under zero defect

Regarding the material as a linear elastic material, using finite element software to establish a spatial beam element, the geometrically nonlinear stability of the maximum cantilever stage is calculated.
Table 2. Stable safety factor table under geometric nonlinearity

| Model B Stability factor | Model B Rate of change | Model B1 Stability factor | Model B1 Rate of change |
|--------------------------|------------------------|---------------------------|-------------------------|
| 4.727                    | 12.48%                 | 3.495                     | 17.41%                  |

From the calculation results in Table 2, it can be seen that after taking into account the geometric nonlinear effects, the stability coefficients of the pier bottom consolidation model and the model considering the foundation stiffness have decreased by 12.48% and 17.41%, respectively. In this section, the material is regarded as an elastic material, and the structural rigidity will be too large, resulting in a small change in the stability safety factor.

4.3. Geometric nonlinear stability analysis considering initial imperfections

For flexible piers, the actual position and theoretical position of the structure will inevitably produce errors during the pouring process. In addition, under the influence of the uneven temperature field, the pier will also be deformed. Therefore, the initial defect of the structure is inevitable[9]. The eigenvector buckling mode provides an effective basis for the buckling of the structure. Therefore, this paper adopts the method based on the eigenvector to impose initial defects on the structure, and simulates l/1500, l/1000 and l/500 defects respectively.

Table 3. Consider the geometric nonlinear characteristic value table of initial defects

| Initial defect | B Stability factor | Rate of change | B1 Stability factor | Rate of change |
|----------------|-------------------|----------------|---------------------|----------------|
| l/1500         | 4.633             | 14.22%         | 3.472               | 17.96%         |
| l/1000         | 4.521             | 16.29%         | 3.418               | 19.23%         |
| l/500          | 4.464             | 17.35%         | 3.302               | 21.98%         |

The calculation results are shown in Table 3 below. From the calculation results, it can be seen that after considering the initial defects, the geometric nonlinear stability coefficients of the two groups of models have decreased in different ranges.

4.4. Double nonlinear stability analysis

In this paper, the nonlinear constitutive relationship of concrete is adopted as Hognestad, and the specific expression is as follows:

\[
\sigma_c = \begin{cases} 
\sigma_0 \left( 2 \frac{\xi}{\xi_0} - \left( \frac{\xi}{\xi_0} \right)^2 \right) & \xi > \xi_0 \\
\sigma_0 \left( 1 - \left( \frac{\xi - \xi_0}{\xi_u - \xi_0} \right)^2 \right) & \xi_0 \leq \xi \leq \xi_u 
\end{cases}
\]  (6)

In the formula: the peak stress is the compressive strength of the cylinder; the peak strain is 0.002; the ultimate strain is 0.0038. The simplified calculation of the constitutive relationship is treated as a broken line, as shown in the figure.
The Midas-FEA spatial entity unit is used to check the stability of the maximum cantilever stage of the Wugong Bridge. The iterative method adopts the modified Newton-Raphson method, and the displacement is the convergence criterion. Since the first type of stability characteristic value is the upper limit of the second type of stable critical load, it can be used as a dual nonlinear given load, so 15 times the most unfavorable load of the first type of stability is selected in this section. The convergence coefficients of the Wugong Bridge pier consolidation model and the model considering the pile-soil interaction are 0.168 and 0.136, respectively. The stability and safety factors of Wugong Bridge are 2.52 and 2.03 respectively. However, the stability safety factor of both is greater than 1.58, and both meet the minimum permitted stability safety factor according to the specification.

5. Conclusion
Under the most unfavorable distribution, this paper analyze the pier bottom consolidation and consider the stability of the pile-soil interaction model. After taking into account the pile-soil effect, the linear elastic stability safety factor is reduced by 21.64%. Considering the geometric nonlinear state of the initial defect, the geometric nonlinear stability coefficients of the two models have different degrees of decline, but the decline is not large. After considering the double nonlinearity, the stability of the bridge is greatly reduced. In order to obtain the true bearing capacity of the structure, the double nonlinearity of the structure needs to be considered.

References
[1] Li Kaiyan, Chen Zhengqing, Han Yan. A fast algorithm for stability analysis of double-limbed thin-walled high piers during construction [J]. Journal of the China Railway Society. 2004,26(5): 86-90.
[2] Wang Junli, He Shuanhai. Design and stability of high piers of long-span continuous rigid frame bridges[J]. Journal of Chang'an University Natural Science Edition. 2006,26(5):35-39.
[3] Bai Hao, Yang Yun, Zhao Xiaoxing. Three dimension stability and non-linear analysis of long span curve continuous rigid frame bridge with high pier[J]. Journal of Highway and Transportation Research and Development, 2005, 22(5): 111–113.
[4] Li Yaoyu. Stability analysis of continuous rigid frame bridges with variable cross-section high piers[D]. Central South University, 2007.
[5] Xin Yanfu, Wang Xueji, Hou Wei, et al. Analysis of geometric nonlinear effects of high piers and long-span continuous structures considering the effect of pile-soil[J]. Highway Traffic Technology.2017,34(11):84-90.
[6] Tang Feng, Li Dejian. Analysis of stability and parameter influence of high-pier long-span continuous rigid frame bridge in mountainous area[J]. Journal of Railway Science and Engineering, 2016, 13(3) 506-511.
[7] Wang Zongwei. *Research on nonlinear stability of high-pier long-span continuous rigid frame bridges in mountainous areas during construction* [D]. Chongqing: Chongqing Jiaotong University, 2019.

[8] Lv Yigang. *Finite element analysis of geometric nonlinearity and stability of high-pier and long-span bridges* [D]. Changsha: Changsha University of Science and Technology, 2004.

[9] Tie Huaimin, Jiang Xinyu. *The influence of pier construction deviation on the performance of high-pier bridges* [J]. Transportation Science and Engineering, 2017, 33(2): 31–36.