Journal of World Architecture, 2024, Volume 8, Issue 5
https://ojs.bbwpublisher.com/index.php/JWA
Online ISSN: 2208-3499
Print ISSN: 2208-3480

Seismic Performance of Prefabricated Continuous Girder Bridge

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Abstract: Bearings are the weak link in the seismic design of bridges. Using a continuous girder bridge as an example, it is demonstrated that bearing damage should be considered under large earthquake conditions. The bearing, acting as a fuse-type unit, can be designed to be preferentially damaged to effectively control the displacement of the beam and the response at the base of the pier during an earthquake.

Keywords: Cable-stayed bridge; Seismic analysis; Dynamic performance; Structural design

1. Introduction

In recent years, there have been many strong earthquakes around the world, which not only caused heavy casualties but also damaged urban infrastructure, especially bridge structures, resulting in huge property losses. The research work on the problems related to the seismic resistance of bridge structures has become particularly urgent.

2. Project overview

Using a five-span prestressed concrete continuous girder bridge as the engineering background, the span configuration is 96 + 3 × 160 + 90 m. The superstructure consists of a prestressed concrete variable-height straight web continuous girder with a single-box, single-cell section. The top plate of the box girder is 13.50 m wide, the bottom plate is 7 m wide, and the cantilever is 3.25 m wide. The beam height varies from 8.5 m at the main pier to 3.5 m at the mid-span and the ends of the side span. The substructure's main pier is a cylindrical solid pier with a cap beam, with a diameter of 5 m. The upper box girder uses C55 concrete, while the pier cap and pier body use C40 concrete.

The bridge's seismic performance was analyzed using the finite element program MIDAS Civil, which was used to create a 3D model of the entire bridge. The analysis focused on the effects of bearing damage and the nonlinearity of the limit device on the elastic-plastic seismic response. A comprehensive element hysteresis curve model, considering bearing damage, contact with the limit device, and material nonlinearity, was proposed. It was found that when the movable support loses its sliding capacity (due to damage and contact with the limiting device), it not only restricts the displacement of the beam but also effectively reduces the seismic response at the fixed pier.

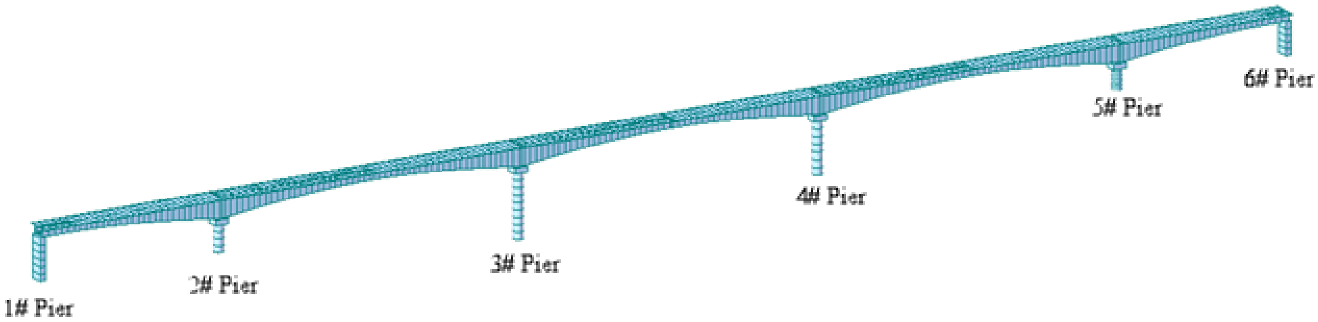

Figure 1. Structural calculation finite element model

3. Structural finite element modeling

In the calculation and analysis, the interaction between the foundation, the pile foundation, and the pile-soil structure is not considered. The pier base is assumed to be fixed to the ground, and a limit device is applied to simulate the bearing damage (see **Table 1**) [1]. The piers are modeled using nonlinear elastic-plastic elements, and the nonlinear deformation behavior follows the Modified Takeda model (Modified Takeda Type). The piers have a circular cross-sectional design. To simplify the analysis, the effects of collision forces are omitted in the finite element model. The limit devices are arranged along the transverse direction of the bridge, and the study focuses solely on the seismic response in this direction.

Table 1. Bridge model boundary conditions

Location	DX	DY	DZ	RX	RY	RZ
Pier 1#	1	1	1	1	1	1
Pier 2#	1	1	1	1	1	1
Pier 3#	1	1	1	1	1	1
Pier 4#	1	1	1	1	1	1
Left end of beam	0	1	1	1	0	1
Right end of beam	0	1	1	1	0	1

Note: "0" represents free, "1" represents a constraint

Following the establishment of the finite element model for the continuous girder bridge, various seismic analysis cases are considered to assess the bridge's response under different assumptions. These cases explore the influence of support friction, limit device behavior, and nonlinear effects, as outlined below:

(1) Case 1: Pier elastoplastic scheme – In this scenario, friction at the support is ignored, and the analysis focuses on the elastoplastic behavior of the piers, which is a standard approach for continuous girder bridges in elastoplastic seismic analysis [2].

(2) Case 2: Support friction scheme – This case considers the friction of the active support, but the limit device's role is not included. The support is modeled as an ideal elastoplastic element, with a friction coefficient of μd = 0.02, a yield displacement of xy = 0.005, and zero stiffness after the support slides.

(3) Case 3: Elastic limit device scheme – In this case, after the support slides a certain distance, the limit device restricts further sliding, assuming no failure of the limit device (elastic behavior). The initial displacement of the support's limit device is set at 0.1 m.

(4) Case 4: Nonlinear limit device scheme – This scenario accounts for the limit device entering a plastic state or the support undergoing shear failure. The nonlinear behavior is introduced by adjusting the critical yield force and stiffness of the limit device in the model.

4. Model of the movable support unit of the finite device

Under seismic action, the movement range of the support with the limit device is restricted. When the longitudinal deformation of the girder bridge becomes significant, it may lead to collision contact issues. This can cause connecting components, such as the support and limit device between the main girder and the substructure pier, to enter a nonlinear state. This process can be described in the following five points:

(1) The movable support does not begin to slide; it remains in an elastic state, and the bridge pier is elastically connected to the main beam [3].

(2) The movable support starts to slide, but its stiffness is negligible, leading to only friction acting between the pier and the main beam.

(3) When the displacement reaches a certain threshold, the movable support continues to slide, activating the limit device. At this point, the bridge pier and the main beam are connected through the limit device, and the transmitted force is the sum of the friction force from the movable support and the force exerted by the limit device.

(4) As the movable support slides further, the limit device enters a nonlinear state, and the transmitted force remains the sum of the friction force of the movable support and the force of the limit device.

(5) The main beam shifts in the opposite direction, resulting in unloading.

A sliding friction element (ideal elastic-plastic model) simulates the movable support. Additionally, a bearing element is established to consider both the friction of the bearing and the dual nonlinear effects of the limit device, in accordance with the characteristics of the sliding friction and collision contact elements [4].

5. Dynamic characteristics calculation and analysis

Select the El Centro wave (peak acceleration 0.3569 g, duration 53.72 s) and apply a factor of two to simulate large earthquake conditions. Input the combination of horizontal + vertical (2/3) and vertical + vertical (2/3) combinations of the earthquake. By calculating the dynamic characteristics of the bridge, as shown in **Figure 2** and **Figure 3**:

(1) When Scheme 1 is adopted, the bending moment and curvature at the bottom of each bridge pier are the largest, entering a fully plastic state, which significantly increases the likelihood of damage. In contrast,

when Scheme 2 is adopted, the bending moment and curvature at each pier bottom are the smallest.

(2) In Scheme 3, when considering the friction of movable supports and the elastic effect of the limit device, the bending moment and curvature at each pier bottom are compared with Schemes 2 and 4, revealing significant changes in the internal forces of movable piers 2# and 5#.

(3) In Scheme 4, while considering the friction of movable supports and the nonlinear effect of the limit device, the section bending moment and curvature at the bottom of each pier are reduced compared to Scheme 3. However, the curvature of the plastic middle movable pier bottom hardly changes, while the curvature of the fixed pier bottom decreases by 22.8%, indicating a significant reduction. This demonstrates that when the limit device enters a nonlinear state, more ground motion energy is dissipated, effectively reducing the seismic response at the fixed pier bottom.

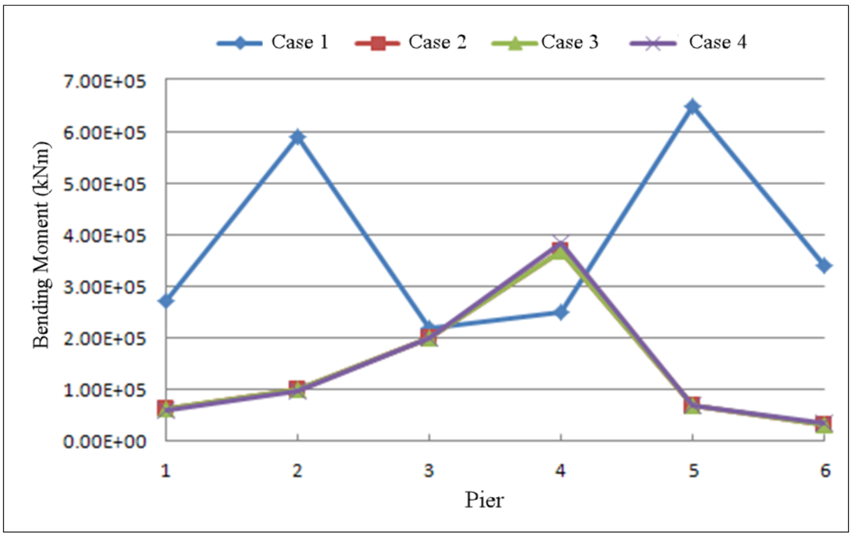

Figure 2. The bending moment at the pier bottom in longitudinal and vertical ground motion

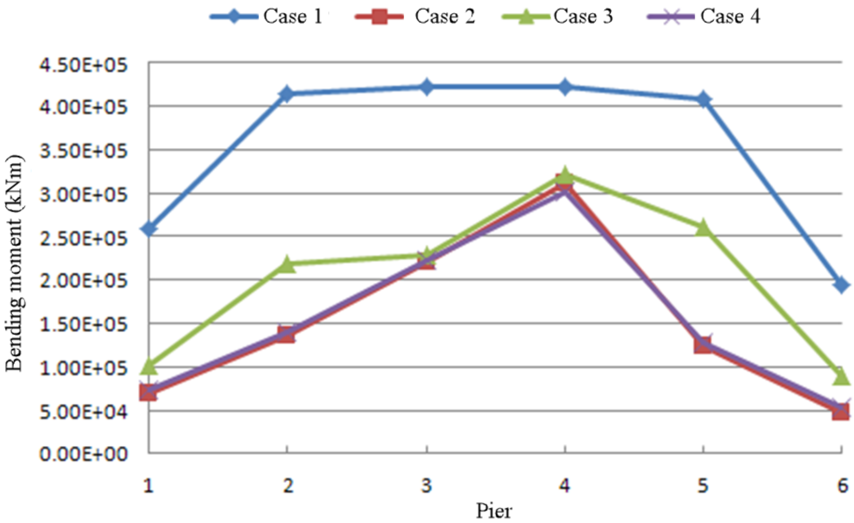

Figure 3. The bending moment at the pier bottom in horizontal and vertical ground motion

6. Conclusion

In this paper, a finite element model is established for the overall calculation of the bridge, considering the elastoplasticity of the bearing, the limit device, and the pier body, and a seismic response analysis is carried out. The results show that:

(1) Under large earthquake conditions, when the movable bearing loses its sliding performance, it is highly likely to cause damage to the bridge pier. Therefore, it is necessary to configure a certain amount of steel reinforcement in the bridge pier to ensure its ductility.

(2) The use of limit devices can effectively limit the displacement of the beam body, reduce the seismic response of the fixed piers, and simultaneously balance the distributed seismic force among the piers.

(3) When the movable support loses its sliding performance and comes into contact with the limit device, it can not only limit the displacement of the beam body but also effectively reduce the seismic response of the fixed pier.

(4) For different bridge structures, by adjusting the initial distance between the limit device and the movable support, as well as modifying the stiffness and yield strength of the limit device, and the friction coefficient and stiffness of the support, it is possible to effectively prevent excessive structural displacement. This approach aims to reduce the seismic response of the fixed piers and achieve a balanced distribution of the input energy from ground motion among the piers.

Disclosure statement

The author declares no conflict of interest.

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