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Nonlinear seismic response of a base isolated single pylon cable-stayed bridge

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ABSTRACT

The vulnerability of single pylon cable-stayed bridges under strong ground motions are of great concern to both researchers and engineers. This paper investigates the seismic performance of reinforced concrete (RC) single pylon cable-stayed bridge equipped with friction sliding bearings under bi-directional earthquake excitations. Three-dimensional numerical models, consisting of the dynamic *p-y* elements, the fiber elements and the multi-layer shell elements, were developed in this study based on the prototype of a single pylon cable-stayed bridge in Guizhou Province, China, to investigate its seismic response. Three different types of friction sliding bearings were implemented between the base of the RC pier and the pile foundation to mitigate the dynamic response of the bridge superstructure under strong ground motions. The results of the nonlinear time history analyses indicate that friction sliding bearings can effectively reduce the base shear and the bending moment of the RC pier, as well as the seismic responses of substructure, at the cost of increasing the absolute displacement of the deck. To reduce the deck displacement, viscous dampers were implemented in parallel to the friction sliding bearings. Parametric studies and optimization analyses were performed on the critical parameters of the viscous dampers with the target of minimizing the absolute displacement of the deck and reducing the base shear of the RC pier to an acceptable level. The numerical results show that implementation of friction sliding bearings together with the viscous dampers is an effective seismic control approach to mitigate the seismic damage of the single pylon cable-stayed bridge.

1. Introduction

In the last few decades, the single pylon cable-stayed bridge has become one of the most popular types of the bridges in engineering practice due to their aesthetic appeal, excellent spanning capacity, being able to rapidly and easily constructed, and efficient utilization of structural materials [1–3]. Since cable-stayed bridges play an important role in the modern transport networks, the main structural components in the bridge should remain elastic under the design earthquake motions [4]. The current practice in the design of single pylon cable-stayed bridges with short to medium span is to integrally construct the pylon, the deck, and the pier, in order to reduce the deformation of the bridge superstructure under regular loads and wind actions [5]. However, during the ChiChi Earthquake, severe earthquake damage was reported in the Chi-Lu Bridge, one of the typical single pylon cable-stayed bridges with the aforementioned configurations. It was reported that flexural plastic hinges formed at the pylon above the bridge deck in the transverse direction and vertical cracks in the concrete pylon extended upward to the height of the lowest cables. In addition, one of the stay-cables was pulled out from its top and bottom anchorages [6]. Based on the post-earthquake damage investigation and numerical studies, it was found that although rigid connections at the junction of the deck, the pier and the pylon could reduce the deck displacement, it also significantly increased the shear force and the bending moment in the pylon under seismic loading, which could lead to bridge damage under strong earthquake shakings. One possible solution to this problem in the seismic design of bridge structures is to introduce energy dissipation devices and base isolation systems to the bridge to mitigate the dynamic response of the bridge. The seismic isolation strategy, widely used in seismic active regions to protect the structures from earthquake damage for nearly three decades, has been proven as an effective and economical method for seismic control of structures. For the cable-stayed bridge, the seismic isolation devices could decouple the dynamic response of the deck-pylon system from that of the substructure to reduce the seismic inertia forces transmitted to the substructure, and thus effectively reduce the inelastic deformation in the superstructure.

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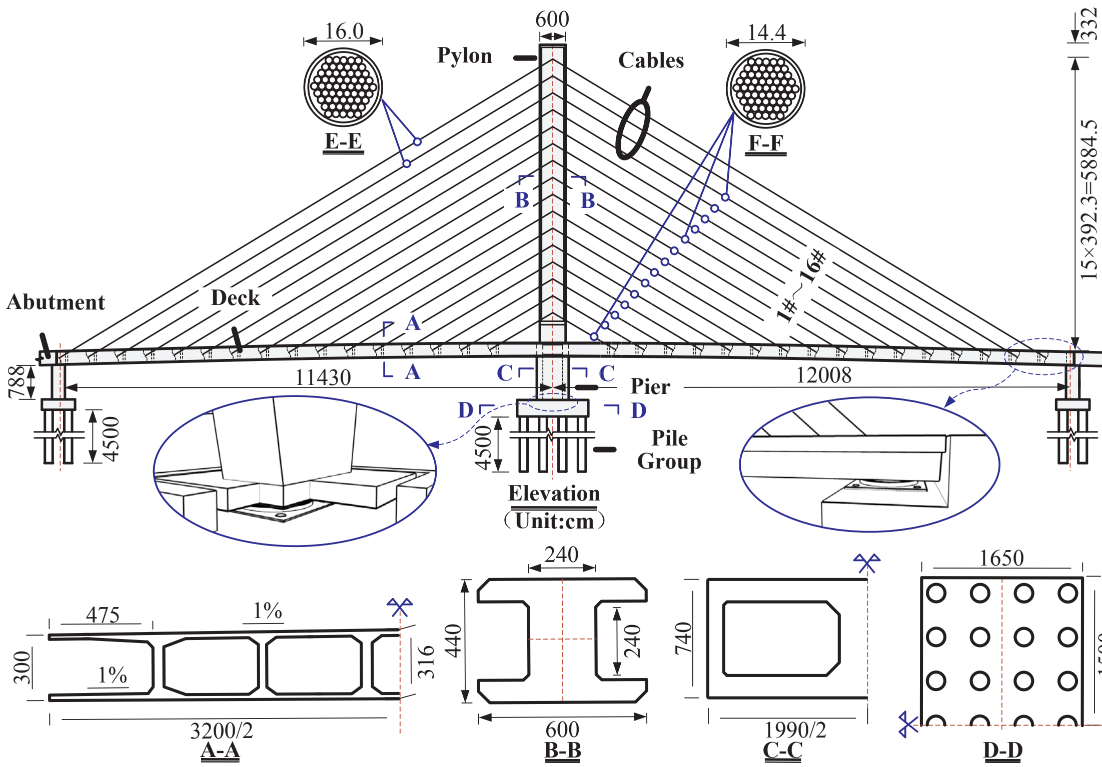

Fig. 1. General view of the example cable-stayed bridge.

Therefore, seismic isolation could be a promising strategy to improve the seismic performance of the single pylon cable-stayed bridges. However, there is few work on the use of base isolation techniques on cable-stayed bridges.

In the last two decades, numerical studies have been performed to investigate the effects of different types of isolators with different installation locations, such as between the deck and the top of the bridge pier [7–12] or between the pylon base and the foundation connection. Chadwell [13] conducted a series of numerical studies to examine the effectiveness of the isolation system for protecting the Chi-Lu single pylon cable-stayed bridge. Nonlinear time history analyses were performed by Atmaca et al. [14] to study the seismic performance of the Manavgat cable-stayed bridge isolated by friction pendulum bearings (FPB), which were applied between the pylon base and foundation. Javanmardi et al. [15] investigated the bi-directional seismic responses of an existing steel cable-stayed bridge isolated by lead rubber bearing (LRB) at the base of the pylon. The elastic 3D beam elements were used to model the box girder and pylon, and the nonlinearity of the cable elements were taken into account in their numerical analyses. Soneji et al. [16,17] considered to place different isolation devices between the pylon and the deck to protect the superstructure from the seismic damages during earthquakes. The soil-structure interaction were also considered in the numerical analyses. Wesolowsky et al. [18] examined three cable-stayed bridges equipped with LRBs under near field ground motions. These studies have demonstrated that isolations in the single pylon cable-stayed bridge could substantially reduce the bending moment and shear force in the pylon, but slightly increase the displacements of the superstructure.

The previous numerical studies mainly concentrated on the seismic performance of the cable-stayed bridge isolated by elastomeric bearings and FPB bearings. The behaviors of the cable-stayed bridge isolated by the double concave friction pendulum (DCFP) and the triple friction pendulum bearing (TFPB) have not been well investigated. DCFP and TFPB usually have larger displacement capacity and better adaptable ability and therefore can be more effective for the seismic isolation of the cable-stayed bridge. Moreover, most of the previous finite element (FE) models used lumped springs or linear elastic soil model to account for the soil-pile interaction (SPI), which do not necessarily lead to accurate estimate of the effects of SPI on the dynamic response of the bridge. Soneji et al. [17] pointed out that, in the dynamic analyses of the bridge, it is essential to properly consider the nonlinear SPI, which significantly affects the seismic response of bridge structures. Additionally, as addressed by Priestley et al. [19], special cares are also needed to be taken during the numerical modeling of the bridges with short piers suffering from typical shear failure under seismic loading, because the traditional fiber beam element is unable to capture the shear or flexure-shear mechanisms of these short piers [20].

The present study is aimed at investigating the seismic performance of a single pylon cable-stayed bridge before and after the implementation of friction sliding bearings under bi-directional excitations. The specific objectives of the paper include: (1) to assess the effectiveness of three different types of friction sliding bearings (FPB, DCFP and TFPB) for the seismic performance of a typical single pylon cable-stayed bridge; (2) to investigate the effects of the critical design parameters of the base isolation systems on the dynamic response of the bridge superstructures and substructures; (3) to examine the influence of SPI on the seismic response of the cable-stayed bridge; and (4) to evaluate the effectiveness of the viscous dampers implemented in parallel to the base isolation systems on mitigating the large displacement responses of superstructure of the cable-stayed bridge.

2. Prototype of cable-stayed bridge

The prototype of the bridge model used in this study is the Longwan Bridge crossing the Jian River in Guizhou Province, China. The bridge is a semi-harp type cable-stayed bridge with two unequal spans of 120 m and 114 m, as shown in Fig. 1. The single RC pylon is approximately 62 m tall above the deck and sustains the superstructure with 16 pairs of steel stay cables. The deck is rigidly connected to the pylon to limit the displacement of the deck under regular loads. Each end of the