Shake Table Test on the Seismic Bearing Uplift of Long-Span Cable-Stayed Bridges Considering Wave Passage effects

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Abstract

1. Introduction

The span capacity of cable-stayed bridges has advanced remarkably with the development of high-performance materials, refined structural analysis and design methods, and modern construction technologies. From the world's first modern cable-stayed bridge, Strömsund Bridge, built in Sweden in 1956, to the recently opened Changtai Yangtze River Bridge in China, it can be seen that the span capacity of cable-stayed bridges has exceeded the hundred-meter level and reached the kilometer level. Owing to their favorable balance between structural efficiency, stiffness, constructability, and economy, cable-stayed bridges have become one of the most competitive bridge forms in the range of 200 to 1200 m.

For long-span cable-stayed bridges located in regions of strong seismicity, the spatial variability of earthquake ground motions may exert a non-negligible influence on structural seismic responses. Because of the substantial span length and the wide separation of support locations, seismic-wave propagation may introduce appreciable arrival-time lags among different supports, such that the support excitation can no longer be idealized as synchronous. Therefore, among the various components of spatially varying ground motions, the wave passage effect is of particular importance for long-span cable-stayed bridges. Previous studies have shown that wave passage may significantly alter the seismic response of cable-stayed bridges, and that its influence may be either favorable or unfavorable depending on the structural system, input motion characteristics, and apparent wave velocity.

It should be noted, however, that the existing literature has focused predominantly on the global response of primary structural components, such as the deck, towers, stay cables, and seismic control devices, with emphasis on displacement and force demand, and vibration mitigation performance. By contrast, much less attention has *been paid to the local seismic response of bridge bearings. Under uniform longitudinal excitation, the bearing responses at nominally symmetric support locations are expected to be precisely symmetric. Under traveling-wave excitation, this phenomenon may be broken. However, this side-dependent influence of wave passage on bearing response has not yet been sufficiently clarified by experimental evidence.*

The present study employs the results of a shaking table test from a 1/35-scale long-span cable-stayed bridge model to investigate the wave passage effect on the seismic response of auxiliary-pier bearings under longitudinal earthquake excitation, with particular emphasis on the bearing response and uplift behavior between the two sides of the bridge.

2. Test model and loading cases

The study is based on a 1/35-scale shaking table model of a long-span double-tower cable-stayed bridge. The prototype bridge has a main span of 1088 m and two 400 m side spans, giving a total bridge length of 2088 m. It is a steel-box-girder cable-stayed bridge with two inverted Y-shaped reinforced-concrete towers and a longitudinal floating system, in which the deck is longitudinally free at the pier locations. To satisfy the geometric and payload limitations of the shaking-table facility, the prototype bridge was simplified while preserving the essential structural characteristics governing the longitudinal seismic response. The resulting test model had a geometric scale factor of 1/35, a total length of about 59.6 m, and a tower height of about 9.1 m, as shown in Figure 1. Micro-concrete was adopted for the towers and piers, and additional lumped masses were attached to the deck and towers to satisfy the similitude requirements of mass.

Figure 1. Photo of test model

Particular attention in the present study is paid to the bearings at auxiliary-piers. Sliding bearings were arranged at the pier locations to reproduce the longitudinal floating system of the prototype bridge. At the auxiliary piers, the bearings were intentionally designed without vertical restraint so that possible bearing uplift under seismic motions could be captured. Tri-axial force transducers were installed *beneath the bearings to directly measure the seismic bearing forces, while the displacement responses of the deck and towers were recorded by displacement transducers and accelerometers.*

Three representative longitudinal ground motions were considered in the present study, namely HWA014, SWVC, and SAGM. These motions were selected to cover different spectral characteristics relevant to long-span cable-stayed bridges. HWA014, recorded during the 1999 Chi-Chi earthquake, contains rich long-period components. SWVC, recorded during the 1989 Loma Prieta earthquake, is characterized by a distinct velocity pulse. SAGM denotes a site-specific artificial ground motion with relatively rich long-period components, a long characteristic period, and a relatively large displacement demand.

Two categories of excitation cases, both with a PGA of 0.3 g, were considered. The first consists of the uniform-excitation cases, in which the four shaking tables were driven synchronously. Under this condition, the bearing responses at the two auxiliary piers were expected to be symmetric because of the symmetric bridge configuration. The second consists of the wave-passage cases with different apparent wave velocities. The scaled apparent wave velocities were 42.25, 84.5, 126.75, and 169 m/s, corresponding to prototype values of 250, 500, 750, and 1000 m/s, respectively. In the present study, the comparison focuses on the seismic responses of the north-side and south-side auxiliary-pier bearings under the corresponding uniform-excitation and wave-passage cases.

3. Test results

Under the uniform-excitation reference cases, possible bearing uplift of the north-side auxiliary-pier bearings was first identified. On this basis, the present subsection focuses on the vertical response of the north-side auxiliary-pier bearings in the floating system when the wave passage effect is considered. The results show that the influence of the wave passage effect is highly dependent on the input motion and apparent wave velocity, and no monotonic trend can be identified. For the auxiliary-pier bearing, the maximum and minimum vertical bearing forces may either increase or decrease as the apparent wave velocity changes. Although no uplift was observed in the considered wave-passage cases, the response does not simply become less unfavorable. Under the SAGM motion at an apparent wave velocity of 84.5 m/s, for example, the maximum compressive force decreased, but the minimum compressive force also decreased and approached zero, indicating an increased risk of bearing uplift. This result suggests that the wave passage effect may either alleviate or aggravate the local bearing demand in a non-uniform manner.

The variation amplitude of vertical bearing force further highlights this complexity. At the same apparent wave velocity, the largest variation amplitude is generally observed under SAGM, followed by HWA014, while SWVC gives the smallest value under uniform excitation. When the wave passage effect is considered, the variation amplitude decreases under SAGM and HWA014, but may increase under SWVC. The *corresponding influence ratio reaches −36.1% under SAGM and −25.8% under HWA014, whereas under SWVC the variation amplitude increases by as much as 25.7% at 84.5 m/s. These results indicate that the wave passage effect does not simply amplify or reduce the bearing response as a whole, but may redistribute the local demand and modify the uplift tendency depending on the ground-motion characteristics and apparent wave velocity.*

4. Numerical analysis

Due to the limited number of data-acquisition channels in the shaking table tests, the vertical bearing-force response of the south-side auxiliary-pier bearing was not recorded in the wave-passage cases. Therefore, a finite-element model previously validated against the shaking table model was adopted to further investigate the vertical seismic-force responses of the north-side and south-side auxiliary-pier bearings under the wave passage effect. The same three ground motions, namely HWA014, SWVC, and SAGM, were used in the numerical analysis. To better activate bearing uplift, the PGA was increased from 0.3 g in the tests to 0.4 g in the numerical analysis, while the input direction and the apparent wave velocities remained unchanged.

The numerical results under the SAGM motion further confirm the side-dependent influence of the wave passage effect. Under uniform excitation, short-duration bearing uplift occurs at both sides, and the vertical bearing-force histories of the two bearings are nearly opposite in phase. Once the wave passage effect is considered, however, the response pattern changes markedly. For the south-side auxiliary-pier bearing, the response becomes noticeably smaller at an apparent wave velocity of 42.25 m/s, whereas one uplift event occurs at the other apparent wave velocities. For the north-side bearing, the uplift occurrence is reduced to one at 84.5 m/s, but increases to three at 126.75 m/s and 169 m/s. These results indicate that the wave passage effect may either reduce or aggravate bearing uplift depending on the apparent wave velocity, and that the north-side auxiliary-pier bearing is more sensitive to this effect than the south-side bearing.

5. Conclusions

1. *The shaking table results show that the wave passage effect significantly modifies the vertical response of the auxiliary-pier bearing in the floating system, and its influence depends strongly on the input-motion characteristics and apparent wave velocity.*
2. *For the tested bearings, the wave passage effect does not simply amplify or reduce the vertical bearing force in a uniform manner. Instead, it may either alleviate or aggravate the seismic demand of local bearings, and may drive the minimum compressive force closer to zero even when the maximum compressive force is reduced.*

3. *The numerical analysis further confirms that the wave passage effect breaks the nearly symmetric response pattern observed under uniform excitation and leads to evident differences in uplift behavior between the two sides of the bridge.*
4. *The results indicate that the wave passage effect may redistribute the unfavorable local support demand between the north-side and south-side auxiliary-pier bearings. Therefore, the critical bearing location under longitudinal earthquake excitation cannot always be identified from uniform-excitation analysis alone, and wave passage effects should be explicitly considered in the seismic assessment of uplift-vulnerable bearings in long-span cable-stayed bridges.*