HOSTED BY

ELSEVIER

Available online at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/jtte

Journal of Traffic and Transportation Engineering (English Edition)

Original Research Paper

Influence of earthquake input angle on seismic response of curved girder bridge

Yongjun Ni [a,b,*], Jiayu Chen [b,c], Hualiang Teng [a], Hui Jiang [b]

[a] Department of Civil and Environmental Engineering, University of Nevada-Las Vegas, Las Vegas 89119, USA
[b] School of Civil Engineering, Beijing Jiaotong University, Beijing 100044, China
[c] Central Research Institute of Building and Construction Co., Ltd., Beijing 100088, China

ARTICLE INFO

Article history:
Available online 3 June 2015

Keywords:
Curved girder bridge
Earthquake input
Seismic response
Unfavorable angle

ABSTRACT

The maximum seismic response of curved bridge is significantly related to the input angle of designated earthquake. Owing to structure irregularities, bridge reactions result from the interaction between the moment and torsion forces. Based on the solving of the seismic response of structure excited by a one-way earthquake input, a uniform expression of the unfavorable angle of the earthquake input was derived, and the corresponding maximum response of structure was determined. Considering the orthotropic and skewed dual-directional earthquake input manners, the most unfavorable angles for the two cases were also derived, respectively. Furthermore, a series finite element models were built to analyze the multi-component seismic responses by examining an example of curved girder bridge considering the variation of curvature radius and the bearings arrangement. The seismic responses of the case bridges, were excited by earthquakes at different input angles, and were calculated and analyzed using a response spectrum method. The input angles of earthquake excitation were progressively increased. From the analysis and comparison based on the calculation results mentioned above, the most unfavorable angle of earthquake excitation corresponding to the maximum seismic response of the curved bridge could be determined. It was shown that the most unfavorable angles of earthquake input resulted from the different response combination methods were essentially coherent.

1. Introduction

Curved bridges have been extensively applied to the construction of roads and railways. As an important variation of the girder bridge, the curved bridge is playing a significant role in bridge engineering. Since the 1970s, engineers have observed numerous devastating earthquakes globally that have severely impacted a large number of curved bridges. One of the most destructive cases known by engineering

* *Corresponding author*. School of Civil Engineering, Beijing Jiaotong University, Beijing 100044, China. Tel.: +86 10 51687252; fax: +86 10 51683764.
E-mail address: yjni@bjtu.edu.cn (Y. Ni).

Peer review under responsibility of Periodical Offices of Chang'an University.
http://dx.doi.org/10.1016/j.jtte.2015.05.003

researchers was the San Fernando earthquake in 1971, which caused serious damage to a multi-span girder bridge spanning between two large grade-separated interchanges projects. Since then, the research on the seismic responses of curved bridges has been given increased attention in the field of bridge engineering. Tseng and Penzien (1975a, 1975b) published two articles on the analysis results of the nonlinear seismic response of continuous curved bridges under severe earthquake. Williams and Godden (1979) published their experimental results derived from shake table model of curved girder bridge that had collapsed in the San Fernando earthquake and the corresponding theoretical results of their finite element analysis. Kawashimak and Penzien (1979) established the mechanical model of expansion joints by considering collision and yielding phenomena, and studied the influences of expansion joints on the seismic response of curved bridges. Wilson and Button (1982) discussed the stress direction of the structure response excited by the multi-directional earthquake input, but their results proved to be in the later documents applied only to the situation of single-degree-of-freedom (SDOF) structure as of one-way input. Li et al. (1984) developed a curved coordinate system to study the seismic response of the curved bridge. Yuan et al. (1996) analyzed the linear and nonlinear response of a 9-span continuous curved bridge considering the wave passage effect. Based on the analysis of two curved bridge newly constructed, Qin et al. (1996) discussed the seismic performance respecting on the yielding and deformation of piers and the sliding and collision of the expansion joints. Zhu et al. (2000, 2002) discussed the principle input angle of the irregular bridges based on the SRSS combination method, pointed out that the maximum response of irregular bridge could be obtained by using response spectrum analysis inputted along the arbitrary two directions in plane. The factors such as the curvature and the type of the connecting of the pier and the beam were also analyzed. Zhang et al. (1999) and Fan et al. (2003) determined the most unfavorable input direction based on the yielding surface function theory. Applying the fiber element in piers, the sliding elements to simulate the bearings and the contacting elements to simulate the collision of the adjacent upper structures, Nie et al. (2004) evaluated the seismic performance of a curved bridge. Based on the detailed comparison analysis of the multiple calculating methods on the curved bridge, Gao and Zhou (2005) verified that the CQC3 (complete quadratic combination 3) method was the proper method for obtaining the maximum seismic response under the multiple-direction earthquake inputs. Relying on the multiple shaking table array tests of small scale curved girder bridge, Saad et al. (2012) and Wieser et al. (2012) analyzed the influence of indices such as beam curvatures, seat types, foundation areas, and isolation measures on the curved girder bridges, it was shown that the seismic response of curved bridges was significantly affected by the parameters mentioned above.

The newly issued *Caltrans Seismic Design Criteria* (2013) presents two methods to calculate the elastic earthquake response of curved bridges, namely that the maximum of the two cases is used for the bridge design; the response combination of the longitudinal direction and the transverse direction by CQC3 method. Whether the Caltrans method is suitable for the curved girder bridge is still a question worthy of verification because of the detailed construction difference in California, USA and China.

Owing to the difference in determining the most unfavorable input direction of curved bridge by different methods, the unfavorable input angle of earthquake ground motion is much needed in order to evaluate the seismic behavior of curved bridge more coherently.

2. Theory of computation

2.1. *Single-direction earthquake acceleration input along a random direction in plane*

Suppose an $x-y$ coordinate system is to be adopted by the structure, as shown in Fig. 1(a). The single-direction earthquake acceleration $\ddot{a}_{1(t)}$ is inputted along a random direction ($0^\circ < \alpha < 180^\circ$) in the $x-y$ plane.

The dynamic equilibrium equation of the structure is given as Eq. (1)

$$M\ddot{v}_{(t)} + C\dot{v}_{(t)} + Kv_{(t)} = -M\left[I_x\cos(\alpha) + I_y\sin(\alpha)\right]\ddot{a}_{1(t)} \tag{1}$$

where M, C and K are the mass matrix, damping matrix and stiffness matrix of the system, respectively, I_x and I_y are the unit column vectors along the coordinates x and y, respectively, $-MI_x\ddot{a}_{1(t)}$ and $-MI_y\ddot{a}_{1(t)}$ are the earthquake inertia forces excited by the single-direction earthquake acceleration $\ddot{a}_{1(t)}$ inputted along the x axis and y axis, respectively, α is the input angle anticlockwise from the x axis. Solving Eq. (1), we can get

$$v_{ij}^{\alpha} = \gamma_j^{\alpha} S_d(T_i, \xi_i)\phi_{ij} \tag{2}$$

where ϕ_{ij} is the element of the vibration mode vector for the j-th mode of the i-th mass point of the system, $S_d(T_i, \xi_i)$ is the displacement response spectrum calculated by Duhamel integral method for the period T_i and the damping ratio of the structure ξ_i, γ_j^{α} is the modal participation coefficient of the j-th modal mass of the system excited by the single-direction earthquake along angle α. It can be then calculated using Eq. (3)

$$\gamma_j^{\alpha} = \frac{\Phi_j^{T} M\left[I_x\cos(\alpha) + I_y\sin(\alpha)\right]}{\Phi_j^{T} M \Phi_j} = \gamma_j^{x}\cos(\alpha) + \gamma_j^{y}\sin(\alpha) \tag{3}$$

where Φ_j is the vibration mode matrix, and Φ_j^{T} is its transport matrix, γ_j^{x} and γ_j^{y} are the modal participation coefficients of the j-th modal mass of the system along the global coordinate of x and y axes, respectively.

Substituting the Eq. (3) into Eq. (2), we can get

$$v_{ij}^{\alpha} = \left[\gamma_j^{x}\cos(\alpha) + \gamma_j^{y}\sin(\alpha)\right] S_d(T_j, \xi_j)\phi_{ij} = v_{ij}^{x}\cos(\alpha) + v_{ij}^{y}\sin(\alpha) \tag{4}$$

where v_{ij}^{x} and v_{ij}^{y} are the relative displacements for the j-th mode and the i-th mass point of the system under the single-direction earthquake acceleration $\ddot{a}_{1(t)}$ along the global coordinate of x and y axes, respectively. Similarly, we can get

$$R_{ij}^{\alpha} = R_{ij}^{x}\cos(\alpha) + R_{ij}^{y}\sin(\alpha) \tag{5}$$