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Seismic response of long span continuous rigid-frame arch bridge

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Abstract: This paper investigates the spatial variability effects of ground motion on the seismic response of long-span continuous rigid-frame arch bridge. The analyses are performed on the Xinguang bridge in Guangzhou, which is the worldwide first 3-span continuous rigid-frame and steel-truss arch bridge with reinforced concrete V-shaped rigid frame. Its spans of the main bridge are as long as (177 + 428 + 177) m. The spatial variability of ground motions between pivots of the bridge is taken into account with multi-support excitation and traveling wave effect by exciting the bridge in both transverse and longitudinal directions of the bridge. New study shows the characteristics of seismic response of the critical bridge members are varied with different seismic excitations. The spatially varying ground motion has a considerable influence on the seismic responses of the ribs of the main arch and V-shaped rigid frame, whereas the influence on the side arch ribs is insignificantly predominant. As the shear wave velocity increases the peak longitudinal displacement of the crown of the main arch relative to the arch springing decreases, while, the effect of shear wave velocity on the longitudinal displacement of the ribs of the side arch can be neglected.

Key words: arch bridge; continuous rigid-frame arch bridge; seismic response; spatially varying ground motion; multi-support excitation; traveling wave effect; finite element method

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In current seismic design code, it is assumed that all pivots of a bridge structure have the same type of seismic ground wave effect, which indicates that the propagation velocity of a seismic wave is infinite and all pivots of the structure share the synchronous seismic excitation. This assumption is reasonable for small-span bridge, but would lead to grave error for large-span bridge because of the influence of spatial variability of ground motion. Multi-support ground motion can induce seismic responses significantly different from that calculated by using synchronous ground motion at each pivot. Since an earthquake excitation consists of superposition of a large number of waves with various characteristics, at different positions along a long-span bridge the input motion would be different. During an earthquake, the difference in reflection and refraction of the wave at different locations along propagation direction results in the loss of partial components of the wave. Hence the movement of each point on the ground is usually different. If the propagation of the same seismic wave along the longitude of the bridge has hysteretic phenomenon, i. e., the input of pivot seismic wave has different phase angle, the effect of traveling wave needs to be considered[1,2]. Although long-span bridges subjected to spatially varying ground motion has been widely studied by various researchers, it has not been found from any publication about the study of the influences of spatial variability of ground motions on seismic response of long-span continuous rigid-frame arch bridge with reinforced concrete V-shaped rigid frame[1-5]. In this paper, Xinguang bridge is used as an example in which the spatial variability of ground motion among pivots of this bridge is taken into account with multi-support excitation and traveling wave effect. The long-span continuous rigid-frame arch bridge is assumed to be excited by earth-

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quakes in both the transverse and longitudinal directions of the bridge.

1 A brief description of Xinguang bridge

Xinguang bridge, which is located at Xinguang express way of Guangzhou city in China, is the first 3-span continuous rigid-frame steel-truss arch bridge with reinforced concrete V-shaped rigid frame in the world. The spans of the main bridge are (177 + 428 + 177) m, as shown in Fig. 1. Among the bridges of the same type, the length of the main bridge is the longest in the world. The style of the bridge is unique and modern. It differs from the traditional style of "flying bird" 3-span arch bridge, and exalts two side arch ribs over the deck of the bridge. The Xinguang bridge utilizes the superior crossing capability of the truss arch bridge, and takes fully advantage of large stiffness and good seismic performance of a continuous rigid frame bridge[6]. In order to effectively reduce the horizontal thrust of arch springing, the arch ribs of the Xinguang bridge are completely made of steel truss, and the deck system of mid-span is a reinforced concrete combined system. The use of steel truss arch in structure design can reduce the self-weight of the bridge structure remarkably, and consequently reduce the horizontal thrust of the arch springing. However, the connection between the steel truss arch and reinforced concrete structure of arch springing becomes an important factor to the global stability of the structure. The usage of V-shaped triangular rigid frame solves the transition problem of steel and concrete, which makes the connection of the transition zones simple and efficient.

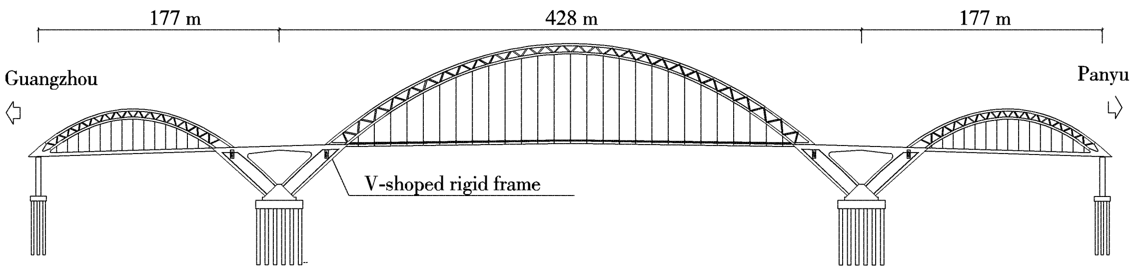

Fig. 1 Elevator of Xinguang bridge

图 1 新光大桥立面图

2 Numerical model

In evaluating the seismic performance of the bridge, a three-dimensional nonlinear finite element model is established by using commercial program ANSYS[7]. The upper chords, lower chords, web members of arch rib, stiffening girder, cross beam, V-shaped rigid frame, and lateral bracing are modeled by 3D beam elements based on actual cross sectional properties. Link element is employed to model the suspenders and the tie of the main arch rib. The stiffness and self-weight of the floor system are taken into account in the girders.

Considering the importance of the Xinguang bridge in the entire transportation network of Guangzhou, a two-level, two-stage aseismic design procedure is adopted in the study of the main bridge structure. The dynamic nonlinear analysis of the bridge is performed based on earthquakes with probability of non-exceedance of 2% in 100 years. In this study, it is assumed that when the ground motion is propagating across the bridge, it propagates from Panyu to Guangzhou with a finite wave velocity of 196 m/s. The peak acceleration of artificial earthquake time history of Panyu site and Guangzhou site is 2.381 m/s^2, and 2.472 m/s^2, respectively. The duration of the input motion is 43 s[8].

3 Characteristics of seismic response

3.1 Characteristics of internal force response

As earthquake-induced internal forces in the lower chords of arch ribs of the bridge are almost the same as those in the upper chords, only the internal forces of upper chords are presented in this paper.

When the bridge is subjected to a ground motion in the longitudinal direction, the absolute maximum axial forces are compared in Fig. 2 (a). The plot shows that the peak axial forces of the upper chords at the main arch crown under synchronous excitation, multi-support excitation and traveling wave effect, are 10.5 kN, 12.1 MN and 29.9 MN, respectively. The ratio of force is 1∶115∶285. The reason is that a horizontal ground motion appears anti-symmetrical under synchronous seismic excitation. Only anti-symmetry modal shapes participate in the superposition of dynamic modes. The factors of modal contribution of all other symmetry modes equal to zero. However, in the cases of multi-support excitation and traveling wave excitation, anti-symmetry and symmetry modes work together. Their quantities of

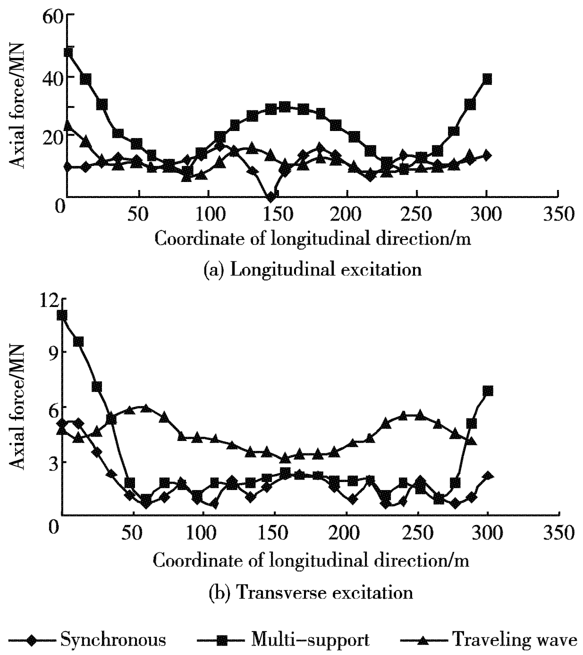

Fig. 2 Maximum axial force of the upper chord of the main arch rib

图2 主拱上弦杆最大轴力

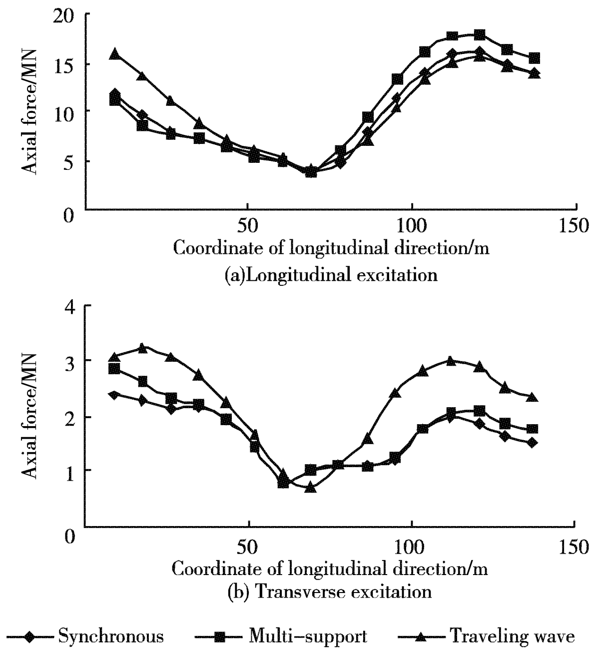

Fig. 3 Maximum axial force of the upper chord of side arch rib

图3 边拱上弦杆最大轴力

response are split into dynamic and pseudo-static components. The axial force of the main arch crown is drastically underestimated since anti-symmetric modes are not excited by synchronous excitations. Thus, the axial forces considering multi-support excitation or traveling wave effect are greater than those under synchronous excitation. It is necessary to consider the influence of the multi-support excitation and traveling wave effect for large-span continuous rigid-frame steel-truss arch bridge. It can be observed from Fig. 2 (b) that for the transverse multi-support and synchronous excitations, the axial force due to multi-support excitation is 110% larger than that for synchronous excitation, although the maximum axial forces in both cases occur at the springing of the main arch rib.

In comparing seismic responses of the upper chord of side arch rib under different excitations, it is shown that the axial force due to traveling wave is greater than those corresponding to multi-support and synchronous excitations. The maximum increment of the axial forces is about 50% as shown in Fig. 3 (a). This trend is also shown in the comparison of axial forces of the upper chords subjected to the out-of-plane excitation, as shown in Fig. 3 (b).

Fig. 4 (b) reveals that under transverse excitation, the axial force of the slant leg of the main arch rib due to synchronous excitation is close to those due to multi-support excitation. In considering traveling wave, the axial force of the slant leg of the main arch rib is by far the smallest whereas the in-plane bending moment of the main arch slant leg is the largest as shown in Fig. 5 (b).

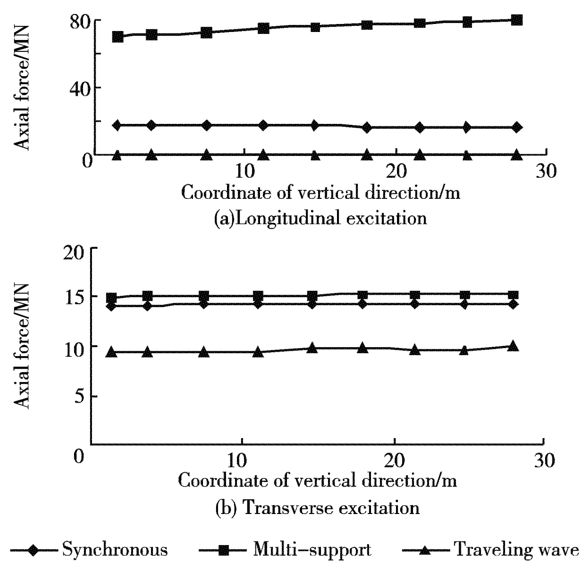

Fig. 4 Maximum axial force of the slant leg of the main arch ribs

图4 主拱斜腿最大轴力

The maximum axial force and in-plane bending moment of the slant leg of the main arch rib are compared in Fig. 5 (a) and Fig. 6 (a), respectively. The results indicate that the axial forces and bending moments of the slant leg of the main arch rib caused by the longitudinal multi-support excitation and traveling wave effect are quite close to each other, but are much higher

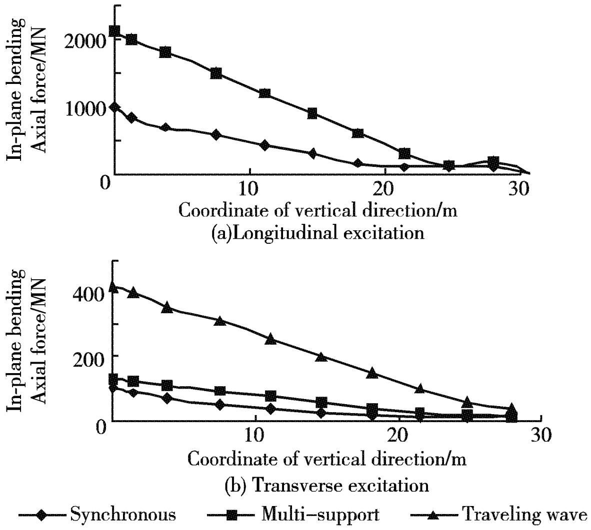

Fig. 5　Maximum in-plane bending moment of the slant leg of the main arch

图 5　主拱斜腿面内最大弯矩

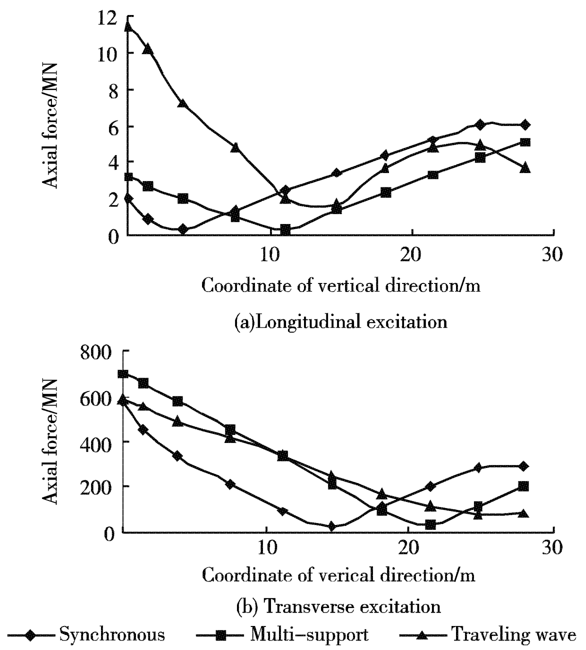

Fig. 6　Maximum out-of-plane bending moment of the slant leg of the main arch

图 6　主拱斜腿面外最大弯矩

than those caused by the synchronous excitation.

Fig. 6 (a) and Fig. 6 (b) demonstrate that the calculated out-of-plane bending moment of the slant leg of the main arch under synchronous excitation is much larger than those under multi-support excitation and traveling excitation at certain locations. These results indicate that the synchronous excitation may result in higher responses than the multi-support excitation and traveling wave effect, which means that the use of synchronous excitations may greatly overestimate the responses at some locations and meanwhile underestimate the responses at other locations.

It can be observed in Fig. 2 to Fig. 6 that the axial forces of the chord of the arch rib and the slant leg of the main arch rib under longitudinal excitation are more predominant than those under transverse excitation. When the bridge is subjected to earthquake in the out-of-plane excitation, the in-plane bending moments of the slant leg are smaller than those subjected to earthquake in the in-plane excitation. By comparison, when the bridge is subjected to earthquake in the in-plane excitation, the out-of-plane bending moments of slant legs are smaller than those subjected to earthquake in the out-of-plane excitation. In despite of longitudinal excitation and transverse excitation, the seismic responses of the main arch rib are more predominant than those of the side arch rib.

3.2　Seismic response characteristics of displacements

Fig. 7 (a) and Fig. 7 (b) show the longitudinal displacement time history of the main arch crown related to springing at the shear wave velocity of 196 m/s, 2×196 m/s, 3×196 m/s, 6×196 m/s, 8×196 m/s and infinite (as synchronous excitation), respectively.

It can be observed in Fig. 7 to Fig. 8 that the shear wave velocity has a substantial effect on the waveform curve and peak value of longitudinal displacement of the main arch crown. As the

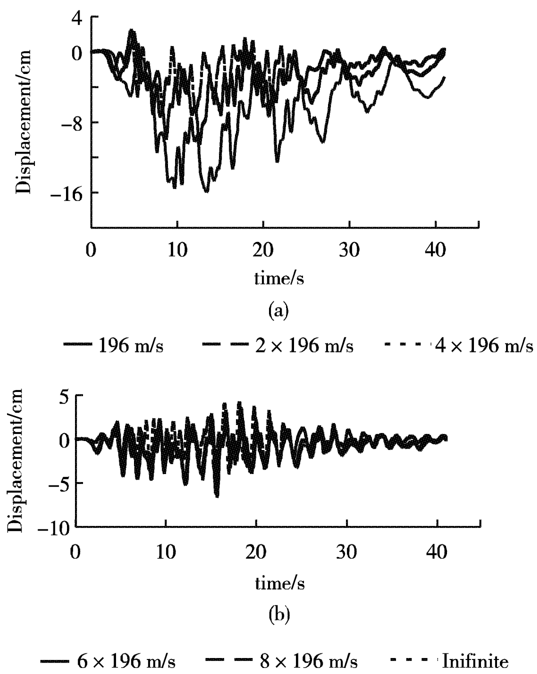

Fig. 7　Longitudinal displacement time-history curves of relative displacement between the main arch crown and arch springing at different shear wave velocity

图 7　不同剪切波速下主拱拱顶相对拱脚的纵向位移时程曲线

increase in shear wave velocity from 196 m/s to infinite, the longitudinal displacement of the main arch crown is 15.7 cm, 10.4 cm, 6.54 cm, 6.62 cm, 6.23 cm and 4.12 cm, respectively. The time history of displacement are quite different when the shear wave velocity is changed from 196 m/s to 4 × 196 m/s. For lower shear wave velocity, the longitudinal displacement time history shows globally longitudinal vibration, and the main arch crown appears to deviate from the equilibrium location. The displacement is the sum of the dynamical displacement and the pseudo-static displacement, in which the longitudinal pseudo-static displacement of arch crown is much larger. When the shear wave velocity is much higher, the longitudinal time history of displacement of the arch crown shows symmetrical vibrating from the main arch crown. And the approximate static displacement is relatively small. If the shear wave velocity tends to be infinite, the pseudo-static displacement is close to zero. However, the wave velocity has no obvious influence on the relative displacement between the crown and the springing of side arch rib.

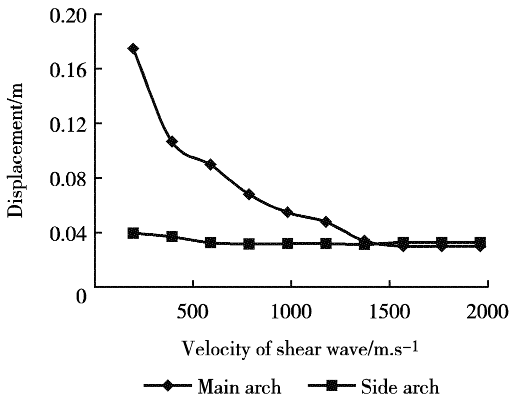

Fig. 8 Maximum longitudinal relative displacements between the main arch crown and the arch springing
图 8 主拱顶和拱脚之间的纵向最大相对位移

Conclusion

The present investigation can lead to the following conclusions:

① Multi-support excitation and traveling wave effect analysis lead to different results from that caused by synchronous excitation, which implying that spatial variability of ground motions has an important effect on the internal forces of most bridge members, especially on the axial forces and moments of the upper and lower chord of the main arch rib and V-shaped rigid frame. The multi-support excitation and traveling wave effect are the control factor to the seismic design of the long-span rigid-frame arch bridge.

② In carrying out the traveling wave analysis, the shear wave velocity has considerable influence on the wave shape and magnitude of the longitudinal displacement time-history at the main arch crown of the bridge. It shows that as the shear wave velocity is reduced, the pseudo-static displacement has significant influence on the time-history of displacement. However, the shear wave velocity does not affect the longitudinal displacement of the side arch crowns.

③ The influences of multi-support excitation and traveling wave effect on the main arch rib are more predominant than those on the side arch rib.

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大跨度连续刚架拱桥的地震响应研究

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摘　要：广州新光大桥是世界上第一座三跨连续钢桁拱与钢筋混凝土 V 型刚构结合的钢－混凝土组合体系桥梁，主桥跨度为（177＋428＋177）m．以广州新光大桥为例，研究地震动空间变化对大跨度连续刚架-拱组合体系桥梁地震响应的影响．地震空间效应变化考虑了桥梁支点间横桥向和顺桥向多点激励和行波效应，研究结果表明：在不同的地震激励下桥梁的地震响应特征截然不同，地震动的空间变化对主拱肋、V 型刚架的影响很大，而对边拱肋的影响相对较小；且随着剪切波速增加，主拱顶相对拱脚的纵桥向位移逐渐减小，而边拱拱顶的纵桥向位移基本不受剪切波速的影响．

关键词：拱桥；连续刚架拱桥；地震响应；地面空间变化；多点激励；行波效应；有限元

中图分类号：U 443. 15；U 442. 55　　　　**文献标识码：**A

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·简　讯·

2007 年中国嵌入式技术研讨会暨展示会在京、深两地举行

围绕嵌入式技术的创新和提速开发应用，由中国计算机学会、中国半导体行业协会与北京大学及《电子产品世界》联合举办的中国嵌入式技术研讨会暨展示会，今年决定在北京和深圳两地巡回举行．其中深圳会议与中国半导体行业协会主办的 IC China 同期举行，定于 2007－08－28～29 日，在深圳北京大学研究生院召开，主题是芯片与系统联动及片上系统；北京会议是 2007 年中国计算机学会嵌入式系统专业委员会年会的会场，定于 2007－09－13～14 日，在北京国际贸易中心召开，主题是嵌入式系统与 SOC．我们预祝这次强强联手，合作共赢的盛会圆满成功．　　（春　华）