Seismic Analysis of the Pounding on the Expansion Joints of Long-Span Cable-Stayed Bridge

Fangwen WU *, Binglong FENG, Qingkai ZHANG, Caofang YANG

School of Highways, Chang'an University, Xi'an, Shaanxi,710064, China

Abstract **— It has been the focus of recent research to control the relative displacement between the approach bridge and main bridge, to prevent collision damage, even fall beam under seismic action. The expansion joint of one bridge plays an important role in the connection affecting the bridge structure seismic performance. This study develops one-sided and two-sided pounding models using the nonlinear dynamic time history analysis of pounding on the expansion joint in a long-span cable-stayed bridge during an earthquake. The effect of pounding on this expansion joint under seismic action is analyzed. Parameter analysis of the approach bridge and main bridge is performed. Moreover, the effect of one-sided pounding and that of two-sided pounding on the displacement of the structure and the bending moment at the bottom of the tower are analyzed and compared. Results show that the pounding response of the bridge structure to the one-sided pounding of the two-sided approach bridge is greatly different. This difference is related to the input direction of the earthquake wave. Two-sided pounding has little effect on bridge displacement. However, pounding has a small effect on a cable-stayed bridge with an adjacent cycle ratio of more than 0.6 and approach bridge.**

Keywords - Cable-stayed bridge; Approach bridge; Period ratio; Two-sided pounding; Seismic wave

I. INTRODUCTION

In recent decades, earthquakes have frequently occurred across the world, causing huge losses. Infrastructures in earthquake zones have been severely damaged, and the damage to bridges is particularly serious. The pounding a bridge structure during an earthquake is deemed to be an important factor that influences the seismic response and earthquake resistance of the structure.[1–2] All previous damages caused by earthquakes on the a bridge structure show that the pounding on the connecting structure of the bridge during an earthquake and the damage caused by falling beams are the main causes of structural earthquake damage.

For a cable-stayed bridge with a floating system, the beam end undergoes a large displacement during an earthquake. The excessive displacement of this beam end in turn causes pounding on the main bridge and the adjacent approach bridge, thereby resulting in the loss of structural integrity. For example, the cause of the falling beam of the approach bridge of the Nishinomiya Harbor Bridge during the large earthquakes in Osaka and Kobe in Japan in 1995 was the excessive relative displacement between the main and approach bridges, which resulted in pounding; the bearing surface of the bridge pier was too narrow, given the failure of the connection limit component of the bearing.[3] In the case of the Loma Prieta Earthquake of the United States in 1989, the underestimation of the relative displacement between the adjacent beams also caused the beam of the approach bridge of the San Francisco–Oakland Bay Bridge to fall.[4] Therefore, the effect of pounding on the joint between a cable-stayed bridge and an approach bridge during an earthquake should be further investigated.

At present, many researchers at home and abroad have conducted in-depth studies on the effect of pounding on the expansion joint between adjacent beams. For example, Deng Yulin et al.[5] studied the effect of pounding on the expansion joint of a long-span cable-stayed bridge during a strong earthquake and concluded that a strong earthquake easily causes pounding on the main and approach bridges. Moreover, pounding not only results in a huge attack but also increases the demand of the approach bridge for seismic force, the displacement of the beam end of the approach bridge, and the demand of the beam end of the approach bridge for splice length. Zhou Guangwei et al.[6] studied the effect of pounding on the relative displacement between the pier and beam of a continuous girder bridge in different stages under traveling wave inputs. They arrived at the following conclusions: if the cycle ratio is small ($T_1/T_2 < 0.5$), then the effect of pounding is the largest; if the cycle ratio is great ($T_1/T_2 > 0.7$), then the effect of pounding is large; if the cycle ratio is moderate, then the effect of pounding is small. Reginald Des Roches[7] conducted a preliminary study on the effect of two-sided pounding and found that two-sided pounding can reduce the displacement of the soft frame and increase the displacement of the rigid frame. R. Jankowski[8] investigated the effect of pounding on the expansion joint between the adjacent beams of a multi-span continuous beam bridge, which is a result of the traveling wave effect. Nawawi Chouw[9] concluded from an analysis of the relatively simple two-span bridge model that the fundamental frequencies of an adjacent span are close and that the spatial variation of ground motion is the major factor that causes relative displacement.

However, most studies focus on a simply supported girder bridge or short-span continuous beam bridge. In addition, studies on the effect of pounding on the expansion joint between a cable-stayed bridge and an approach bridge are rare. In many earthquake disasters, the approach bridge of a long-span bridge is usually damaged, and the beam of an approach bridge always falls. This phenomenon is attributable to the effect of pounding on the expansion joint between the main bridge and approach bridge. To reveal the effect of pounding on the expansion joint during the seismic response of a long-span cable-stayed bridge, the present study uses a typical cable-stayed bridge as an example in simplifying the formation of a cable-stayed bridge and approach bridge into a one-sided pounding and two-sided pounding model. These models are used to comparatively analyze the effect of one-sided pounding on the left approach bridge, one-sided pounding on right approach bridge, and two-sided pounding on the structure of the bridge, and therefore obtain the relative law that provides the theoretical reference for the seismic resistance design of the relative bridge.

II. BASIC THEORY

A. Method of dynamic time history analysis

The method of dynamic time history analysis is used to make ground motion or an artificial seismic wave act on the structure. It is also used to formulate an integral structural equation of motion and obtain a seismic response from the structure at any moment. Thus, this method is also called as the direct integral method. At present, this method is used for the seismic design of important and complex bridges in most countries, and the response spectrum method is used for the design of short-span bridges. Using the method of dynamic time history analysis to analyze the response of the structure, the rational dynamic analysis model and the vibration equation of the structure are first established. To solve the equation of the structure and obtain its displacement and internal force response at any moment, the whole response process of the structure under the action of ground motion is obtained. The nonlinear vibration equation of structure generally assumes the following incremental form (1):

$$[M]\{\Delta\ddot{\delta}\}+[C]\{\Delta\dot{\delta}\}+[K]\{\Delta\delta\} = -[M][I]\Delta\ddot{\delta}_g(t) \quad (1)$$

where $[M]$ and $[C]$ refer to the mass matrix and damping matrix, respectively; $[K]$ refers to the tangent stiffness matrix; $\Delta\delta$ refers to the incremental vector of the relative displacement between the particle and the ground within a time step; and $\Delta\ddot{\delta}_g(t)$ refers to the incremental vector of the ground vibration acceleration time history.

B. Rigid-Body Collision Theory

The rigid-body collision theory introduces the pounding contact element as an issue of collision analysis. The contact element is activated at the time of collision. Collision contact elements occur in many types and generally consist of a spring element and a parallel damping element. The spring element provides rigidity to prevent the invasion of the body of collision. A damping matrix is also used to simulate the energy loss in the process of collision. Fig. 1 shows four common contact-element models.

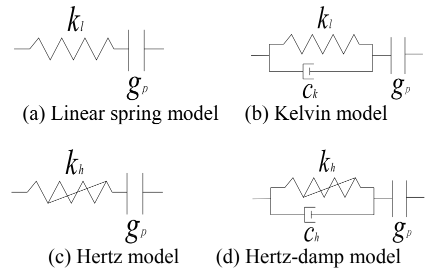

Fig. 1 Four common contact-element models

(1) Linear spring model

The linear spring model, which is the most simple contact-element model, consists of a contact spring and a gap element, as shown in Fig. 1(a). This kind of contact element model does not consider the energy loss in the process of collision. The collision force between the adjacent two-span beams can be expressed as:

$$F_c = k_l(u_1-u_2-g_p), \quad \text{if } u_1-u_2-g_p \geq 0 \quad (2)$$

$$F_c = 0 \quad \text{if } u_1-u_2-g_p < 0 \quad (3)$$

where k_l refers to the linear rigidity of a contact spring; g_p refers to the space between the beams; F_c refers to the force resulting from the collision; u_1 and u_2 refer to the displacement of two adjacent beams.

(2) Kelvin model

The Kelvin model consists of a contact spring and a damper in parallel, as shown in Fig. 1(b). This model considers the energy loss in the process of collision. The collision force can be expressed as:

$$F_c = k_k(u_1-u_2-g_p)+c_k(v_{01}-v_{02}),$$
$$\text{if } u_1-u_2-g_p \geq 0 \quad (4)$$

$$F_c = 0 \quad \text{if } u_1-u_2-g_p < 0 \quad (5)$$

where v_{01} and v_{02} refer to the velocity of two adjacent beams before collision; k_k refers to the rigidity of the contact spring; c_k refers to the coefficient of damping, expressed as follows:

$$c_k = 2\zeta\sqrt{k_k \frac{m_1 m_2}{m_1 + m_2}} \tag{6}$$

where, ζ is related to the collision coefficient e, expressed as follows:

$$\zeta = -\frac{\ln e}{\sqrt{\pi^2 + (\ln e)^2}} \tag{7}$$

where m_1 and m_2 refer to the mass of the adjacent beams at the expansion joint.

(3) Hertz model

The Hertz model is similar to the linear spring model. However, the contact spring is nonlinear, as shown in Fig. 1(c). This contact-element model also does not consider the energy loss in the process of collision, and the collision force may be expressed as follows:

$$F_c = k_h(u_1 - u_2 - g_p)^{3/2}, \text{ if } u_1 - u_2 - g_p \geq 0 \tag{8}$$

$$F_c = 0 \qquad \text{if } u_1 - u_2 - g_p < 0 \tag{9}$$

where k_h refers to the nonlinear rigidity of the spring.

(4) Hertz-damp model

The Hertz-damp model represents an improvement on the Hertz model. This model aims to describe the energy loss in a collision by connecting the nonlinear damper with the contact spring of the Hertz model in parallel, as shown in Fig. 1(d). The collision force of the Hertz-damp model may be expressed as

$$F_c = k_h(u_1 - u_2 - g_p)^{3/2} + c_h(v_{01} - v_{02}),$$

$$\text{if } u_1 - u_2 - g_p \geq 0 \tag{10}$$

$$F_c = 0 \qquad \text{if } u_1 - u_2 - g_p < 0 \tag{11}$$

where c_h refers to the nonlinear damping coefficient. The corresponding formula is

$$c_h = \zeta(u_1 - u_2 - g_p)^n \tag{12}$$

where ζ refers to the damping constant based on the conservation of energy, expressed as shown below:

$$\zeta = \frac{3k_h(1 - e^2)}{4(v_1 - v_2)} \tag{13}$$

III. FINITE ELEMENT MODEL

This study uses a typical cable-stayed bridge as an example to investigate the influencing law of pounding on the expansion joint between the main and approach bridges during the seismic response of the structure. The general design of the bridges is shown in Fig. 2. The bridge span has a symmetric structure. The main bridge refers to a cable-stayed bridge in the twin-tower floating system. The bridge span is arranged as 45 + 67 + 416 + 67 + 45 m. The approach bridge is found in the box girder structure of a pre-stressed concrete with a section of 4 × 40 m. To analyze the effect of pounding on the expansion joint during the seismic response of the structure of the bridge, the adjacent segments are separated for refinement in a pounding model, as shown in Fig. 2. Each segment is simplified into a single free oscillator. The mass of the left approach, main bridge, and right approach are recorded as m_1, m_2, and m_3, respectively; the basic cycles are recorded as T_1, T_2, and T_3; the damps are recorded as c_1, c_2, and c_3; and the gap between expansion joints 1 and 2 is g_p. The main bridge is connected to the approach bridge through the pier at the bearing.

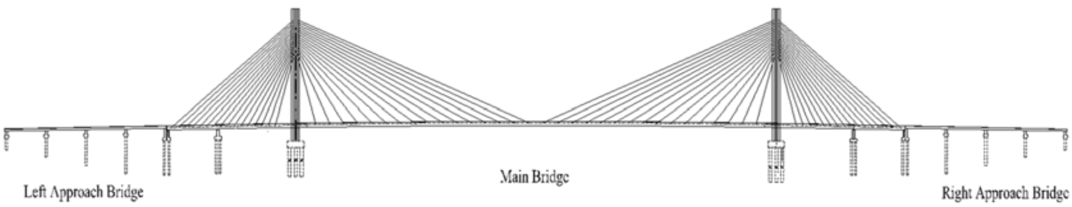

Fig. 2 General design of the bridges.

To analyze and compare the effect of two-sided pounding and one-sided pounding on the bridge, this study considers the following six cases:

(1) Case 1: two-sided pounding model shown in Fig. 3(a).
(2) Case 2: one-sided pounding model shown in Fig. 3(b). This model neglects the effect of the right approach and considers only the interaction between the left approach bridge and main bridge.
(3) Case 3: one-sided pounding model shown in Fig. 3(c). This model neglects the effect of the left approach and considers only the interaction between the right approach bridge and main bridge.
(4) Case 4: to comparatively analyze two-sided pounding response and the seismic response of only the main bridge based on case 4.

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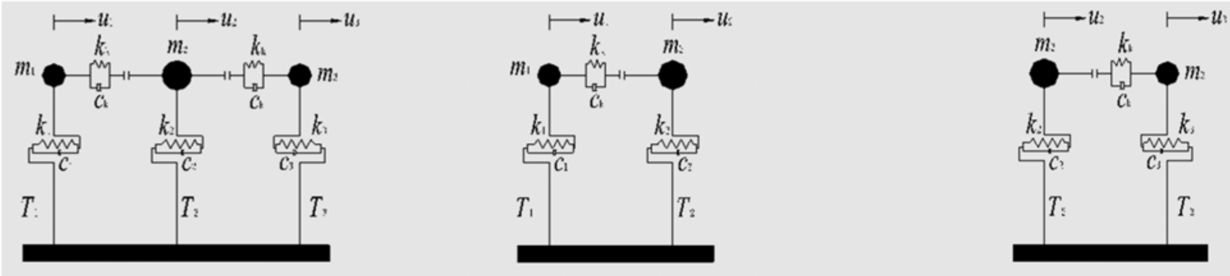
(5) Case 5: to comparatively analyze the one-sided pounding of the left approach and seismic response of only the main bridge based on case 2.

(6) Case 6: to comparatively analyze the one-sided pounding of the right approach and seismic response of only the main bridge based on case 3.



(a) Two-sided pounding model (b) Left approach bridge pounding model (c) Right approach bridge pounding model

Fig. 3. Pounding analysis model.

This study adopts the method of dynamic time history analysis to analyze the seismic response of the structure. The Kelvin model is used in the contact element at the expansion joint. The damping ratio of the structure is 0.05. The coefficient of restitution is e = 0.65.[10] The impact stiffness is the longitudinal stiffness of the shorter beam, which is 6×10^6 kN/m.[11]

IV. SEISMIC WAVE INPUT

Based on the characteristics of the site, the seismic fortification intensity is 8; the acceleration coefficient of ground motion peak is 0.2 g; the site category is designed as Class II; and the designed feature cycle Tg is 0.40 s in this study. A total of eight seismic records in Table 1 are selected as the longitudinal seismic input load; the horizontal seismic input load of the longitudinal seismic input load is 0.85; and the vertical seismic load of the longitudinal seismic load is 0.65. In addition, the acceleration peak of each seismic wave is adjusted to 0.2 g.

TABLE 1 SELECTED FREE-FIELD GROUND MOTIONS

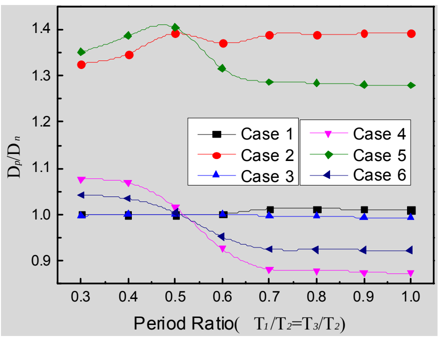
NO	Seismic record	Station	Magnitude	PGA (g)	Excellent cycle (s)	AM coefficient
1	1999 ChiChi	TCU045	7.2	0.181	0.57	1.1050
2	1976 Friuli	TOLMEZZO(000)	6.5	0.3513	0.29	0.5693
3	1961 Hollister	USGS 1028	5.6	0.1948	0.38	1.0267
4	1979 Imperial_Valley	USGS 5115	6.6	0.2899	0.39	0.6899
5	1995 Kobe	KAKOGAWA(CUE90)	6.9	0.3447	0.52	0.5802
6	1992 Landers	SCE 24	7.5	0.6418	0.25	0.3116
7	1989 Loma_Prieta	090 CDMG 47381	7.1	0.3674	0.55	0.5444
8	1994 Northridge	090 CDMG 24278	6.7	0.5683	0.43	0.3519

V. EFFECT OF POUNDING ON THE SEISMIC RESPONSE OF THE STRUCTUREPOUNDING ANALYSIS OF CABLE-STAYED BRIDGE

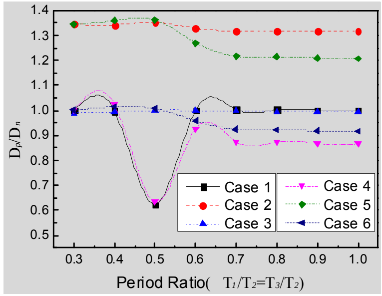
This study adopts the dynamic analysis theory to perform an in-depth analysis of the effect of two-sided pounding and one-sided pounding on the displacement of the bridge structure. The major factors of the influencing pounding response are the period ratio of the adjacent beams and basic period.[12] As such, the period ratio of the approach bridge to the main bridge T_1/T_2 is used as a parameter (period of left approach bridge T_1 is equal to the period of right approach bridge T_3) to calculate the effect of pounding on the seismic response of the structure when the period ratio T_1/T_2 is 0.3–1. The peak displacement amplification D_p/D_n and peak moment amplification M_p/M_n are introduced. D_p and M_p refer to the peak displacement and peak moment, respectively, with consideration of the effect of pounding; and D_n and M_n refer to the peak displacement and peak moment, respectively, without consideration of the effect of pounding. For cases 4– 6, D_p, and M_p refer to the peak displacement and peak moment that considers the effects of two-sided pounding, left-approach pounding and right-approach pounding; D_n and M_n refer to the peak displacement and peak moment of the single main bridge under an earthquake load, respectively. The obtained values are the mean values of the above eight earthquake records.

A. Effect of pounding on the displacement of the main bridge

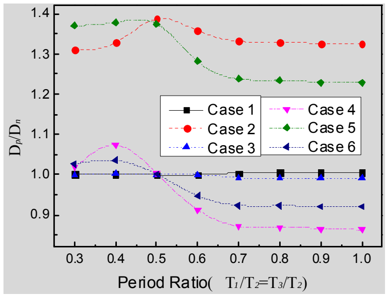
Figs. 4(a), (b), and (c) show the peak displacement ratio of the left end, mid-span, and right end of the main bridge, respectively. Fig. 4 shows that the one-sided pounding of the left approach increases the left end, mid-span, and right end of main bridge by 39.1%, 35.2%, and 38.7%, respectively, thereby resulting in the highest T_1/T_2 = 0.5. With an increase in the period ratio, the effect of pounding is reduced to become gradually stable; two-sided pounding has little effect on the left displacement of the main bridge with the highest value of 1.01 and the lowest value of 0.99. However, the effect on mid-span displacement is complex: If T_1/T_2 is equal to 0.5, then two-sided pounding reduces the peak-displacement of the mid-span of the main bridge by 37.5%. The one-sided pounding of the right approach has almost no effect on the displacement of the left end in the main bridge with the highest value of 1.0 and the lowest value of 0.99. If the period ratio T_1/T_2 is less than 0.5, then the two-sided and one-sided pounding of the right approach increase the displacement of the main bridge relative to that of the single main bridge under an earthquake load (Case 4 and Case 6). If the period ratio T_1/T_2 is greater than 0.5, then the pounding reduces the displacement of the main bridge and tends to be stable. The one-sided pounding of the left approach increases the displacement of the main bridge relative to that of a single main bridge under an earthquake load (Case 5). However, the pounding response to the displacement of the main bridge is consistent with the changing trends of the two-sided and one-sided pounding of the right approach.



(a) The left end of the main bridge



(b) The mid-span of the main bridge.



(c) The right end of the main bridge.

Fig. 4 Peak displacement ratio of the main bridge.

B. Effect of pounding on the displacement of the approach bridge

Figs. 5(a) and (b) show the peak displacement ratio of the left and right approaches, respectively. The results show that the one-sided pounding of the left approach increases the displacement of the left approach and that the approximate linear increase with an increase in the period ratio becomes stable until T_1/T_2 is equal to 0.7–1.0. If the period ratio is equal to 0.6, then the peak-displacement ratio reaches the highest value of 1.35, which is 35% higher than that when pounding effect is not considered. Two-sided pounding has little effect on the displacement of the left approach and increase in a small scale if the period ratio is greater than 0.6, which tends to be stable if the period ratio is equal to 0.7–1.0, and the peak-displacement ratio is 1.04. The two-sided and one-sided pounding of the right approach reduces the displacement of the right approach, and if the cycle ratio T_1/T_2 is equal to 0.6–1.0, the peak-displacement amplification tends to be a straight line. The one-sided pounding of the left approach shows a completely opposite direction to the one-sided pounding of the right approach. The effect of the one-sided pounding of the left approach should be significantly higher than that of the right approach, which indicates that the different severities of the pounding effect are caused by the input direction of the earthquake wave.

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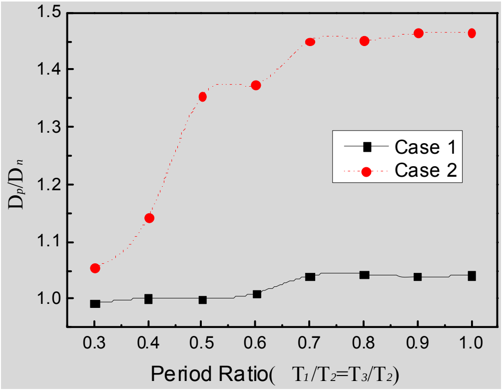
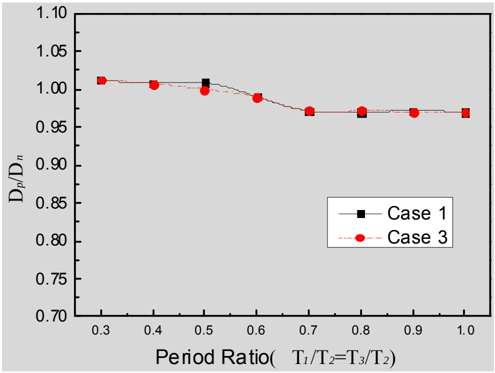


(a) The left approach bridge.

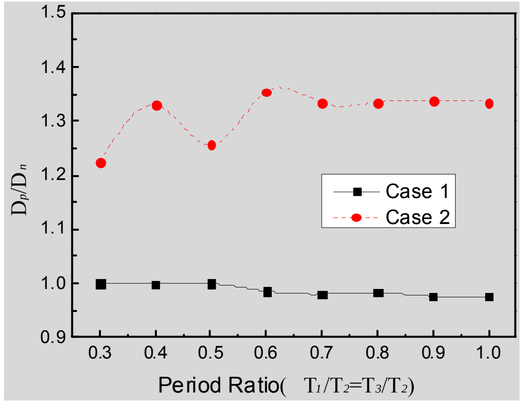


(b) The right approach bridge

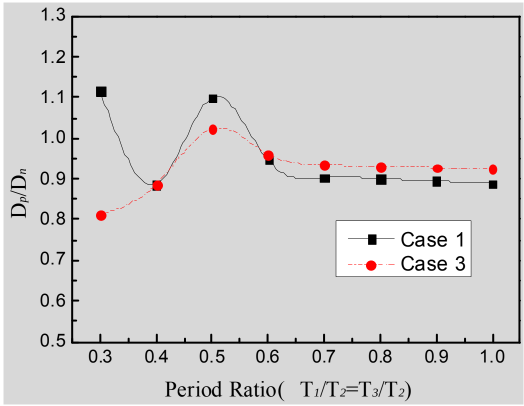
Fig. 5 Peak displacement ratio of the approach bridge.

C. Effect of pounding on the relative displacement

Figs.6(a)and(b)show the peak relative displacement ratio of the left and right approaches, respectively. Fig. 6(a) shows that the two-sided pounding on the relative displacement of left approach gradually decreases with an increase in the period ratio, although the reduction in the ratio is not high. This value is the lowest because the period ratio is 1 and reduces by 3.5% to the highest. The one-sided pounding of the left approach causes the relative displacement of the left approach to be higher in $T_1/T_2>$ 0.3–0.6, which shows a wavy change with the highest amplification of displacement, which is 35.4%. If $T_1/T_2>$ 0.6, then the ratio is reduced and becomes stable with an increase in the period ratio. Fig. 6(b) shows that if T_1/T_2 is equal to 0.3–0.6, then the two-sided pounding in the relative displacement of the right approach shows a wavy change with the change in the ratio from 11%–12%. If $T_1/T_2>$ 0.6, then the relative displacement of the right approach is gradually reduced and becomes stable with an increase in the period ratio with the lowest reducing amplification of displacement at 12%. The one-sided pounding of the right approach reduces the relative displacement of the right-approach bridge, which shows an inclining trend in T_1/T_2 = 0.3–0.5 to the highest value (1.02) in T_1/T_2=0.5. Given an increase in the period ratio, the one-sided pounding of the right approach reduces the relative displacement of the right-approach bridge, which then becomes stable.



(a) The left approach bridge.

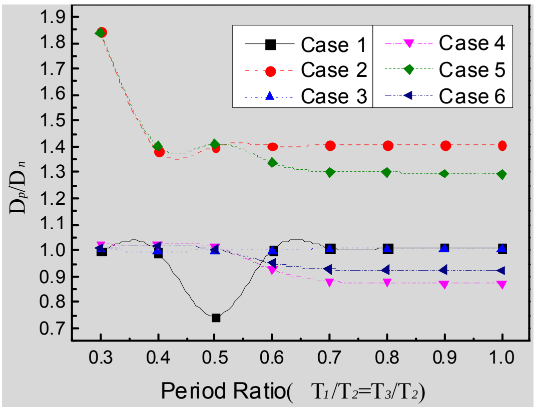


(b) The right approach bridge.

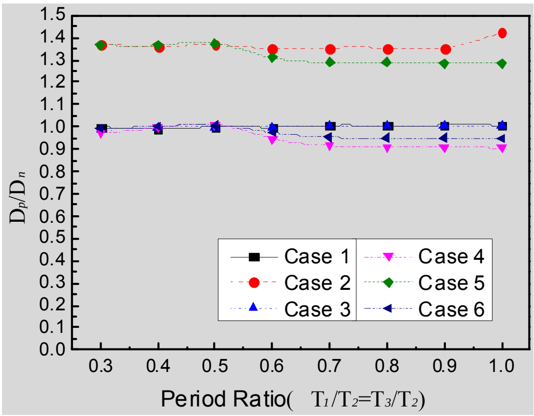
Fig. 6 Peak relative displacement ratio.

D. Effect of pounding on the top displacement of the tower

The peak-displacement ratio of the top of the left and right towers is shown in Fig.7, respectively. The analysis results show that the top displacement of the tower is increased under the one-sided pounding effect. If T_1/T_2 is equal to 0.3, then the peak displacement ratio of the top of the left tower reaches the highest with an ratio of 84.2%. If T_1/T_2 is greater than 0.4, then the ratio tends to be stable, and the peak displacement ratio of the top of the right tower is 40.4% with a low change because of the one-sided pounding of left approach bridge. The two-sided pounding in the displacement of the top of the tower tends to be small with little ratio. If T_1/T_2 is equal to 0.5, then the reduction of the displacement of the top of the left tower caused by two-sided pounding is the highest with an ratio of 25.7%. The one-sided pounding of the right approach bridge decreases the displacement of the top of the left and right towers , and its effect is small in T_1/T_2 = 0.3–0.5. If T_1/T_2 is equal to 0.6–1.0, then the displacement ratios of the top of the tower increases and becomes stable.



(a) The top of the left tower.

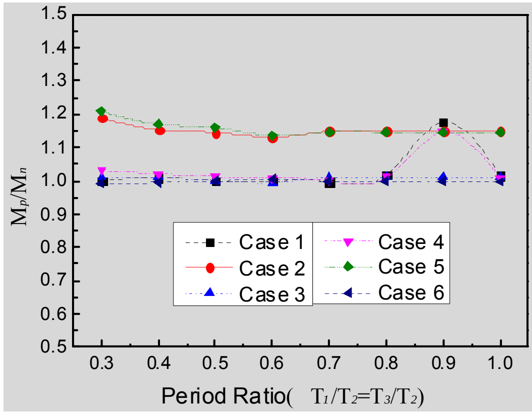


(b)The top of the right tower.

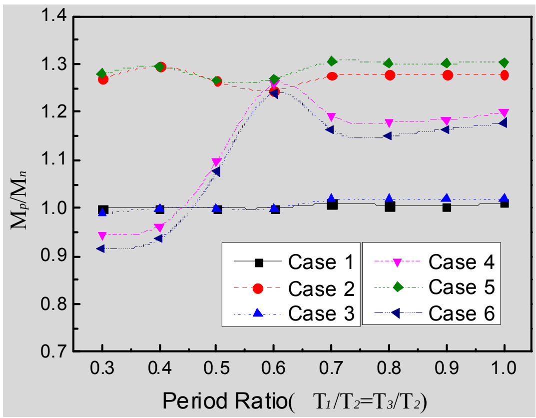
Fig. 7 Peak displacement ratio of the top of the tower.

E. Effect of pounding on the bending moment at bottom of the tower

It is important to control the bending moment of the bottom cross section for concrete tower. When earthquake happened, shear failure of the bottom section of the concrete tower would be taken place possibly. The research conclusions show that the one-sided pounding of the left approach bridge increases the bending moment at the bottom of the left and right towers and that the ratio of the bending moment at the bottom of the right tower is higher than that at the bottom of the left tower as shown in Fig.8. If T_1/T_2 is less than 0.7, then the effect of two-sided pounding on the bending moment at the bottom of the left tower is small. If the period ratio is 0.9, then the bending moment ratio is large, reaching up to 17.6%. Two-sided pounding has almost no influence on the bending moment at the bottom of the right tower. The one-sided pounding of the right approach bridge has a small effect on the bending moment at the bottom of the left and right towers. If T_1/T_2 is equal to 0.4–0.6, then the two-sided and one-sided pounding of the right-approach bridge gradually increase the bending moment at the bottom of the right tower relative to that in a single main bridge under an earthquake load (Case 4 and Case 6), with the highest value of T_1/T_2 = 0.6 and an amplification of 25.8%. If T_1/T_2 = 0.7–1.0, then the pounding increases the bending moment at the bottom of the right tower and makes it stable. This result indicates that the effect of one-sided and two-sided pounding on the bending moment at the bottom of the right tower is higher than that on the bending moment at the bottom of the left tower. In other words, the stress situation of the long-span cable-stayed bridges with approach bridge under an earthquake load is better than that on cable-stayed bridges without approach bridges.



(a) The bottom of the left tower.



(b) The bottom of the right tower.

Fig. 8 Peak moment ratio at the bottom of the tower.

VI. CONCLUSION

In view of the importance of pounding effect for bridge safety, this study simplifies the long-span cable-stayed bridge and its approach bridge into a two-sided pounding model, left approach bridge pounding model, and right approach bridge pounding model to comparatively analyze the structure response under earthquake load. The conclusions of this study are as follows:

(1) The one-sided pounding effect of the left approach bridge on the structural displacement of the

bridge is higher than that of the right approach bridge. This result indicates that the effect of one-sided pounding on the seismic response of the structure of the bridge is related to the input direction of the seismic wave. The effect of pounding on the structure which seismic wave passes firstly is more significant.

(2) In the case of one-sided pounding, if the period ratio T_1/T_2 is greater than 0.6, then the effect of pounding on the structural displacement and bending moment at the bottom of the tower gradually becomes small and tends to be steady with an increase in period ratio.

(3) In the case of two-sided pounding, the pounding effect on the displacement of the structure is not great. Moreover, if the period ratio T_1/T_2 is greater than 0.6, then the peak-displacement ratio tends to be stable with an increase in the period ratio. The effect of two-sided pounding on the bending moment at the bottom of the tower is remarkable. The two-sided pounding effect on the bending moment at the bottom of the left tower is small. If T_1/T_2 is greater than 0.5, then two-sided pounding increases the bending moment at the bottom of the right tower.

For cable-stayed bridge seismic resistance design, prior consideration should be given to the connection of the two-sided approach bridge and long-span cable-stayed bridge for seismic resistance design. Moreover, the period ratio of the approach bridge to the cable-stayed bridge should be more than 0.6. In addition, the strength and rigidity at the bottom of the tower should be considered. If only one approach bridge is constructed unilaterally because of limited conditions, then the length of the expansion joint between the approach and main bridges should be lengthened. Moreover, some limitations device can be installed at the expansion joint to reduce the relative displacement between the approach and main bridges, thereby decreasing the possibility of a falling beam.

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