

Seismic Pounding Response of Girder Bridges Considering Lateral Stiffness of Ground Motion

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Abstract: In order to study the effect of pounding at expansion joints of beam bridge on the seismic responses of bridge structure during earthquake, the research is based on multi-particle of single degree of freedom system, and the pounding effects of adjacent girders on seismic responses with 3 different of farming waves are studied by using nonlinear vibration equations of motion. The results indicated that the influence of ratio of peak moment on lateral rigidity may attenuate or increase with the reduce of lateral pier stiffness, which depends on a great extent on the effective peak acceleration (EPA) and duration. The smaller lateral pier stiffness is, the maximum collision force between beams first increased and then decreased, it has held stable. The main parameters influencing of collision number is effective peak acceleration(EPA) when lateral pier stiffness is big, otherwise, duration is the main parameters. The influence of the effective peak acceleration(EPA) is attenuated gradually with the reduce of the lateral pier stiffness, while the influence of duration increased. The influence of relative displacement between beams reduces with reducing the lateral pier stiffness.

Introduction

Under the earthquake, girder bridges will produce the vertical and transverse horizontal vibration along the axis of the bridge. For the symmetrical design of the general direction of the bridge, the coupling effect from vertical and transverse horizontal vibration of the bridge is neglected. Bridge collision can be considered as the displacement of pier and foundation which is caused by vertical horizontal vibration of the earthquake over the width of the gap between the beam and eventually cause the support failure and girder lowering and other diseases. This kind of bridge disease, especially the medium and small span bridge, appeared frequently in the earthquake in Wenchuan, Ya'an and so on, which led to the traffic function lost and rescue process delayed. Therefore, the impact of beam collision on the seismic response and seismic performance of bridge structures has become an urgent problem to be solved. At present, domestic and foreign scholars have carried out extensive research on the impact of the adjacent girder at the expansion joint. Such as Dwairi and Kowalskey^[1] point out that the relative stiffness of beam pier has an important influence on the regularity of continuous girder bridge, which can't be ignored. But they did not do more research. Yi Zheng^[2] considers the influence of the relative stiffness between the main girder and the bridge pier, and the stiffness distribution of the bridge pier on the regularity of bridge. But his research just has less example and only does the qualitative analysis. Yang Yumin^[3] considers the effect factors such as edge cross main span ratio, beam and pier stiffness, bearing units, and analyzes the seismic response of the structure and its fractal characteristics. But he only has adjusted the lateral bending stiffness to change the lateral bending stiffness ratio of the beam, and has not carried on studying the influence of the lateral rigidity of bridge pier. Chen Liang^[4] takes 4 spans continuous girder bridge as an example, and studies the relationship between the lateral stiffness ratio of beam and pier, the distribution of lateral stiffness of bridge pier and the regularity of the transverse direction of continuous girder bridge, and establishes the partition index of continuous girder bridge. But he

doesn't have further research on the collision influence at the expansion joints which is caused by the form of transition pier.

In this paper, selected a 30m span continuous bridge which has 4 spans as the research object, based on the multi particle single mode system and used the vibration equations of beam-pier system to study the influence of lateral stiffness of bridge pier on the seismic response of bridge under the action of 3 seismic waves.

Theoretical Model

A continuous bridge is selected as the research object. The spatial variation of ground motion along the bridge's longitudinal direction is neglected in the analysis. The beam element is used to simulate the main girder and the elastic plastic beam column element is used to simulate the pier column. The rubber bearing is simulated by the lagging system, and the expansion joints are the contact element, and the influence of the geometrical stiffness caused by the lateral load is considered as well. The overall layout of the bridge is shown in Fig. 1.

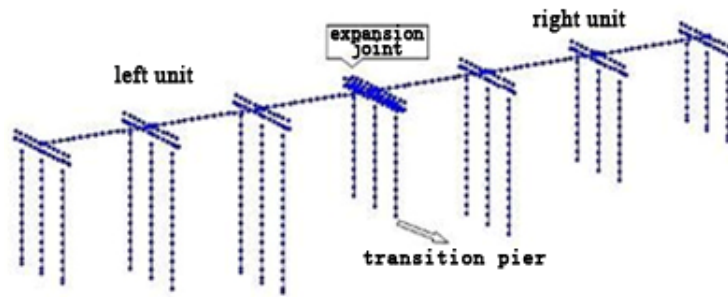


Fig.1 Schemes of bridge models

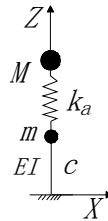


Fig.2 Analytical model

In order to facilitate the analysis of the influence of the lateral rigidity of the transitional pier on the impact of the beam bridge, the structure dynamic simplified model is established by bridge, isolation bearings and pier. The model is showed in Fig. 2. The main girder's vibration is simplified as the single degree of freedom nonlinear vibration system which the source is the ground displacement excitation. Considering the effect of the mass of the continuous beam, the mass of the deck and the transition pier can be simulated as the lumped mass M 、 m . The influence value of the supper structure on the pier is k_b , and the shearing deformation of the isolation bearing is $X_a(t)$, and the relative displacement of bearing to the deck is q_a . The expression of the restoring force of the isolation bearing T is^[5]

$$T(t) = k_a(t)x_a(t) + c_a\dot{x}_a(t) + f_a(t)z_a(t) \quad (1)$$

In the expression, K_a 、 c_a 、 f_a and z_a are the plastic stiffness, damping coefficient, yield force and hysteresis displacement of the isolation bearing.

Selected the deck mass M and the pier mass m as the research object, and considered the influence of end displacement excitation, and the equations of the system vibration are obtained:

$$\begin{cases} M(\ddot{x}_a + \ddot{q}_a) + [k_a(t)x_a(t) + c_a\dot{x}_a(t) + f_a(t)z_a(t)] + M\ddot{x}_a = 0 \\ m\ddot{q}_a + k_b q_a - [k_a(t)x_a(t) + c_a\dot{x}_a(t) + f_a(t)z_a(t)] + m\ddot{x}_a = 0 \end{cases} \quad (2)$$

The period of the two linked continuous bridge is respectively $T_1/T_2=0.7$. That is, the basic period of the two linked continuous girder is similar. The damping ratio of concrete structure is selected as 5% to simulate the collision effect between the two linked girders^[6-8]. Linear and nonlinear time history analysis is carried out by Rayleigh damping, and the discrete graph is shown in Fig. 3.

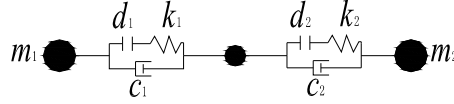


Fig.3 Pounding model of continuous bridge

In order to simulate the collision in the joint which is caused by different direction vibration between the adjacent girders, the contact element which is shown in Fig. 4 is used to simulate the expansion joint. The impact stiffness is taken as the longitudinal stiffness of the shorter main girder, and the recovery coefficient is 1.0^[9-10]. That is, the energy dissipation in the process of collision is not considered. The relationship of nonlinear force – displacement is:

$$f = \begin{cases} \lambda(d+x_s) & d+x_s < 0 \\ 0 & d+x_s \geq 0 \end{cases} \quad (3)$$

In the formula, d is the initial clearance of the expansion joint, and x_s is the relative displacement of the adjacent girder at the expansion joint, and the λ is the contact stiffness. The system is subjected to the same seismic acceleration, and the spatial variation of ground motion along the bridge is neglected.

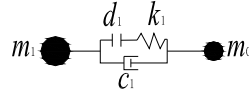
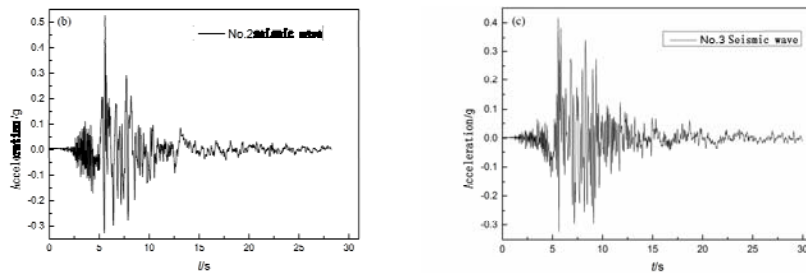


Fig.4 Schematic diagrams of contact element

Seismic Response of a Collision

Seismic Wave Input. In this paper, according to the characteristics of the site, the seismic intensity is 8 degree, and the peak acceleration coefficient of ground motion was 0.2g, and the design site is class II, and the design characteristic period T_g is 0.40 s, and adopted the PEER Ground Motion Database (PGMD) which is provided by American Pacific seismic center to get the adjusted seismic wave. In this paper, three waves which are similar to the acceleration response spectrum of the ground motion are selected. The peak acceleration values were 0.366 g, 0.526 g, 0.417g. Fig. 5~ Fig.6 showed the acceleration time-history curve. Compared the acceleration response spectra of the seismic wave with the acceleration response spectra in the code, and it can be seen that the duration of the No.1 seismic wave is longer, and has a lower peak value, the No.2 seismic wave is shorter, and has a higher peak value, the No.3 seismic wave is longer, and has a higher peak value.



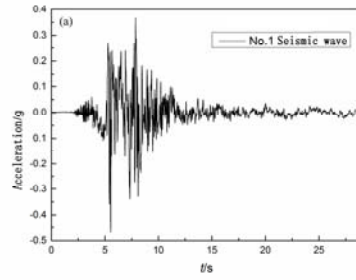


Fig.5 Longitudinal acceleration time-history curve

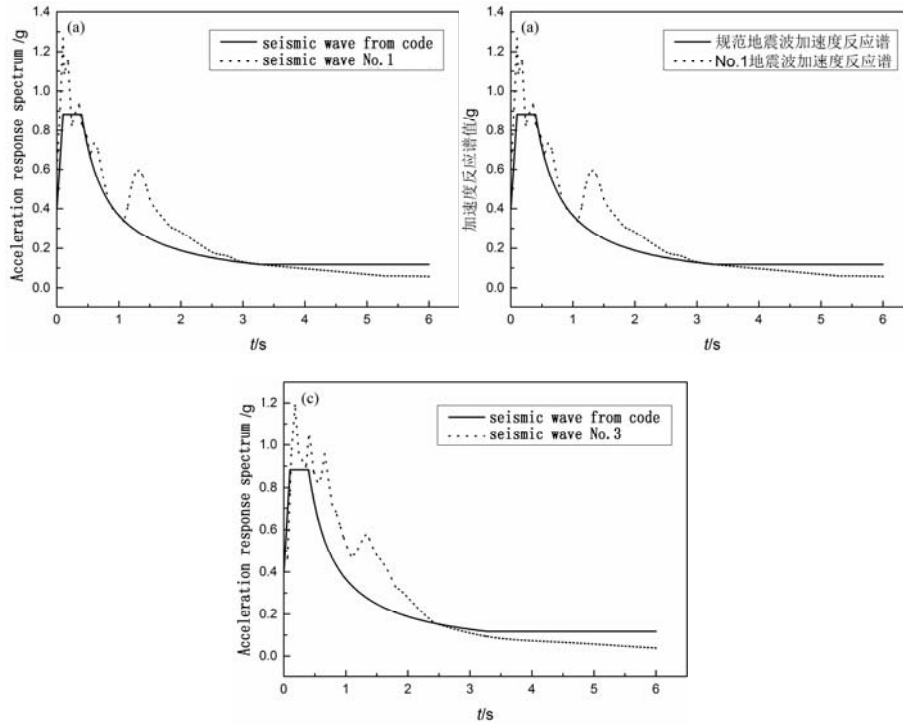


Fig.6 Response spectrum of artificial seismic waves comparing with standard

Result Analysis. In this paper, the lateral stiffness of the transition pier is changed by changing the pier height. The transition pier height H is selected as 20m、22m、24m、26m、28m、30m、32m、34m. According to the calculation and analysis, when the three seismic wave input, the curve of the ratio of peak moment of lateral pier stiffness M_p/M_n (p means the collision is considered while n means the collision is not considered) is showed as the Fig.7 and the curve of the peak value of pounding force is showed as Fig.8.

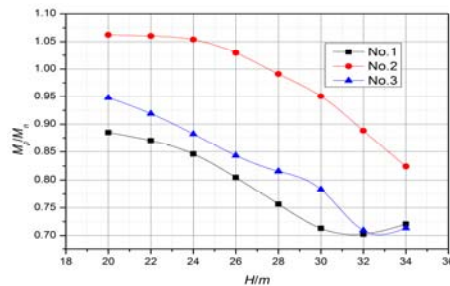


Fig.7 Ratio of peak moment of lateral pier stiffness

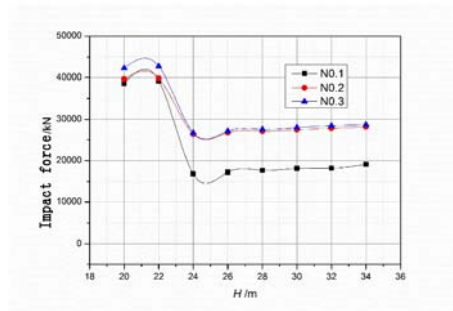


Fig.8 Peak value of pounding force

From Fig. 7, it is known that the impact has a great influence on the bending moment of the pier bottom. With the decrease of the lateral stiffness of the transition pier, the peak moment of the pier bottom caused by the impact effect M_p/M_n is decreased, which is close to the linear. However, when $H < 28\text{m}$ in seismic wave No.2, the moment in the bottom of the transitional pier which considered the collision is bigger than the moment which did not consider the collision, $M_p/M_n > 1$, while $H > 28\text{m}$, $M_p/M_n < 1$. Therefore, for the transitional pier, the changing of lateral stiffness of piers caused by the pier height changing, which may increase or decrease the peak value of the bending moment at the pier bottom. This is largely related to the effective peak of the acceleration and duration of seismic waves. From Fig.8, it can be seen that with the increase of the transition pier height H , the maximum collision force may increase or decrease. But the overall trend is that when the lateral stiffness of the transition pier is big ($H < 22\text{m}$), the impact force is very large, close to $4 \times 10^4 \text{kN}$. With the decrease of the stiffness of the transition pier, the collision force is also decreased rapidly, and the maximum decline of it is more than 40%. When $H=24\text{m}$, the collision force is close to the minimum and tends to be stable. We can see, setting reasonable height of transition pier can reduce the collision force between girders. Therefore, in the transition pier design, the height of pier should meet the requirement of the structure design, in addition, the effect of the anti impact performance of girders cannot be ignored as well.

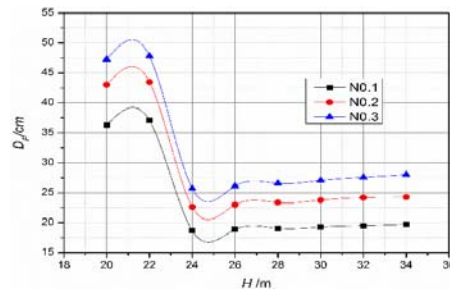


Fig.9 Peak displacement of girder between left girder and right girder

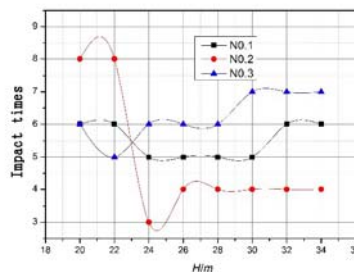


Fig.10 Numbers of collision

Fig. 9 shows the time history curve of the relative displacement of the expansion joints between adjacent girders. The smaller the lateral stiffness of the pier, the smaller the relative displacement of the girder under the effect of the collision. When the lateral stiffness of the bridge pier is large ($H < 22\text{m}$), the displacement of the girder under the effect of seismic wave reach the

peak value. The peak value in No.3 even reach 53cm, which is more than 50cm to the expansion joint, which the girder is very likely to fall down. With the decrease of lateral stiffness of the transition pier, the relative displacement of the expansion joints caused by the collision is beginning to fall. When $H=22\text{m}\sim 24\text{m}$, the amplitude reduction of the relative displacement is the largest, while the $H=25\text{m}$, the amplitude reduction of the relative displacement is the smallest. Although the relative displacement of the adjacent beam will have a small increase, but it will keep stable at the minimum rapidly. From Fig.10, the number of collision curve showed that the effective peak value of acceleration and the duration of the seismic wave is closely related to the number of collision within the adjacent girders which are under the seismic action. For the short duration of seismic wave in No.2, while the piers have a large lateral stiffness ($H=20\text{m}\sim 22\text{m}$), they will have more collisions. But the number of collisions will be decrease with the decrease of the lateral stiffness of transitional piers. Though the effective peak value of the acceleration in No.3 is close to No.2, the duration in No.3 is longer. So the variation of the number of the collision is similar to the No.2, but it has larger values. Therefore, when the lateral stiffness of the pier is large, the effective peak of acceleration is the main parameter which affects the number of collision. On the contrary, when the lateral stiffness of the pier is small, the duration of the seismic is the main parameter which affects the number of collision.

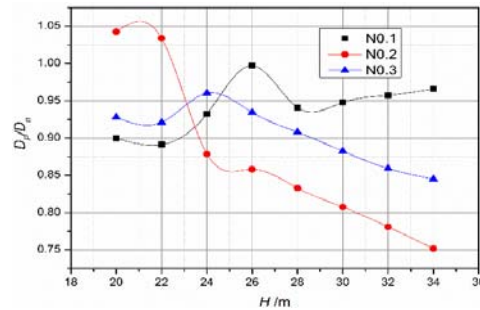


Fig.11 Peak displacement amplification of the transitional pier

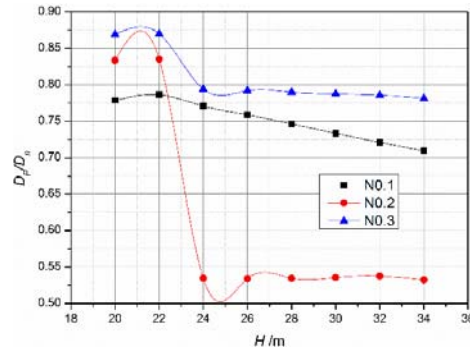


Fig.12 Relative displacement amplification between left girder and right girder

As is shown in Fig.11, with the decrease of lateral stiffness of transition pier, the ratio of the peak displacement of the transitional pier D_p/D_n keeps decreasing, which is led by the pounding effect. The maximum difference can be 25% (No.2). At the same time, in most cases, the displacement of the transitional pier caused by the pounding effect is less than the displacement which didn't consider the pounding effect. In other words, $D_p/D_n < 1$. However, when the lateral stiffness of the pier is large ($H < 22\text{m}$) and $D_p/D_n > 1$ in seismic wave No.2, the displacement of the transitional pier caused by the pounding effect is larger than the displacement which didn't consider the pounding effect. Therefore, the pounding effects may increase or decrease the peak displacement of the transitional pier. At the same time, for the minimum of the peak acceleration of the seismic wave in No.1, the influence of the pounding effect is the least. In other words, D_p/D_n is close to 1. Fig.12 showed the relative displacement amplification between left girder and right girder. Considering the collision effect of adjacent girders at the expansion joints, the maximum relative displacement of the adjacent girder at the expansion joint is smaller than the maximum relative displacement without

consideration. In addition, with the decrease of the lateral stiffness at the transitional piers, the relative displacement ratio between left girder and right girder at the expansion joint are reduced to 0.53 (No.2)、0.73 (No.1) and 0.8 (No.3) . When the seismic wave in No.2 and No.3 reach the minimum of the peak relative displacement, the corresponding height of the transition pier is: $H=24\text{m}$. In No.1, although the relative displacement cannot reach the minimum value 0.71 until $H=34\text{m}$, but D_p/D_n have already reduced to 0.76 when $H=24\text{m}$.

Conclusion

(1) Considering the seismic effect, the reduction of the lateral stiffness of pier may increase or decrease the ratio of peak moment of lateral pier stiffness. It is largely related to the effective peak and duration of the acceleration of seismic waves.

(2) With the decrease of lateral stiffness of the pier, the maximum collision force of the beam is first increased and then decreased and stabilized. The number of girder collision is related to the characteristics of seismic wave. When the pier has a large lateral stiffness, it depended on the effective peak acceleration. But when the pier has a small lateral stiffness, it depended on the duration of the seismic wave.

(3) With the decrease of the lateral stiffness of the pier, the effect of the peak acceleration of seismic wave on the relative displacement of the expansion joint is decreased, and the acceleration time is increased. In a word, with the decrease of the lateral stiffness of the pier, the collision effect will have less and less influence on the relative displacement of the girder. Therefore, it is feasible to improve the bridge collision problem by adjusting the lateral stiffness of the pier in the practical engineering.

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