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Research on Seismic Performance for Seismic Double-Layer Shear Key

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Abstract

To avoid happening span loss for the collision between main girder and shear keys during an earthquake, shear keys in the cap beam or abutment are usually set as seismic measures. Based on the mechanism of the seismic shear key, a new two-layer seismic shear keys which have seismic energy dissipation characteristics is proposed. The structure and design principle are introduced in this paper. A collision analysis model in transverse was built with contact element. Then a bridge was analyzed, some comparative analysis were conducted between the seismic response of the new two-layer seismic shear key and the seismic response of traditional shear key using nonlinear time history analysis method. The results show that the new two-layer seismic shear key can effectively reduce the maximum impact force between the main girder and the shear keys without significantly increase the structural internal force demand and displacement demand. This could reduce the damage of the bridge caused by the lateral collision. This could also reduce the risk of span loss for the collision between the main girder and the shear key in transverse. It could be noticed from the results that the selection of seismic waves has a critical influence to the bridge seismic calculation.

Keywords: bridge; seismic double -layer shear key; pounding effect; earthquake effect

1. Introduction

To restrict the lateral displacement of the bridge during an earthquake and to avoid happening span loss or other catastrophic damage, shear keys in the cap beam or abutment are usually set as seismic measures. In the previous earthquakes, varying degrees of damages occurred in seismic shear keys. In the Wenchuan earthquake, destructions hit most of the shear keys. The survey found that more than 720 groups of earthquake damages occurred in shear keys of the simply supported girder bridge. Furthermore, the shock loss rate in shear keys is close to the displacement rate in main girders [1]. It shows that inevitable collision will always be occurred between the main girder and the shear keys. In China, laminated rubber bearing is widely used in small and medium span bridges. Usually the bearings are placed directly on the top of the pier, and connected to the girder or the pier without any measures. Relative sliding can easily occur on the contact surface between the bearing and the girder or the pier, and larger relative displacement may lead to collisions between adjacent structures [2,3]. Damage to the shear keys can be caused by the collision. Also, the ductility demand of the substructure may be increased, and brittle shear failure of the bridge abutments can even be caused. Therefore, in view of the damages of seismic shear keys in Wenchuan earthquake, it can be significant to design seismic shear key for small and medium bridges of our country.

Based on the mechanism of the seismic shear key, a new seismic double-layer shear key which has seismic energy dissipation characteristics is proposed in this paper. A collision analysis model in transverse was built to calculate the impact of the shear key on the structure. By comparing to traditional shear keys, the results can provide a basis for the application of these shear keys.

2. Mechanism and Structure of the New Seismic Double-layer Shear key

For the design of the seismic shear key, not only the excessive lateral displacement of the main girder should be limited, but also the damage in piers and columns caused by the collision between the main girder and the shear keys should be avoided. Based on these considerations, a new seismic double-layer shear key is proposed, which had been applied for utility model patents [4~6]. The structure of the new seismic double-layer shear key is shown in Figure 1. The seismic double-layer shear key includes two shear keys: the inboard shear key is made by steel plates or reinforced concrete and the outboard shear key is made by reinforced concrete. When the main girder is a single-girder structure, such as box girder and plate girder, the shear keys should be placed on the surface of the cap beam, set on the outboard of the main girder, paralleled and spaced to each other. When the main girder is a multi-girder structure, such as T-beam and small box girder, multiple shear keys can be staggered placed along the cap beam with different distances between each shear key and the main girder. The shear keys may be individually or multiply destroyed under the seismic effect. The inboard shear key is designed as flexible sacrifice shear key. The main girder should be as close as possible to the upside of the shear key. The collision may firstly occur between the inboard shear key and the main girder. When the impact force exceeds the maximum bending capability of the inboard shear key, yield failure will occur in the shear key which can consume a portion of the seismic input energy. The inboard shear key will collapsed toward the lateral, thus a rough sliding surface can be formed between the shear key and the main girder. The rough sliding surface can continue to consume energy when the main girder sliding. If the main girder can continue to slip, a secondary collision will occur between the main girder and the lateral concrete, to ensure that the span loss will not happened during an anticipated strong earthquake.

（a）single-girder structure （b）multi-girder structure

Fig. 1 – Structure of the new double-layer shear key

(1.main girder, 2.outboard shear key, 3.inboard shear key, 4.cap beam)

3. Calculation Model

3.1 Engineering background

A three-span continuous girder bridge is analyzed in this paper. A 20m box girder is used in the superstructure, and the girder height is 1.5m. The width of the superstructure and the capping beam is respectively 8m and 1.5m. Double column piers are used in the substructure, and the pier height is 8m. Two round elastomeric pad bearings are set on each pier. The new double-layer shear keys are set up on both sides of the capping beam. The inboard shear key is made up of four sheet steels whose dimensions are 30cm×1cm×25cm, and the outboard shear key is made up of reinforced concrete shear key blocks whose dimensions are 160cm×25cm×50cm.

3.2 Unit model introduced

Due to the complexity of the dynamic response caused by collision, simplified methods are often used in solving problems. The results can provide macroscopic description of the collision process caused by object contacts. The contact element is widely used as it can simulate the contact force during the collision, the energy dissipation and the contact time[7]. This method simulate the contact impact by the units consist of linear or non-linear springs, dampers and spaces. In order to simulate the contingent collision between the girder and the new seismic double-layer shear keys, the relationship between the nonlinear force and the displacement is shown in Figure 2, which does not consider the energy loss during the collision. The relationship between the force and displacement of the element is shown as follows:

$$F(u)=\begin{cases} 0 & 0<u\le u_1 \\ k_1(u-u_1) & u_1<u\le u_2 \\ k_2(u-u_2)+k_1(u_2-u_1) & u\ge u_2 \end{cases} \tag{1}$$

where F is the contact element force, u is the relative displacement between the girder and the pier top during an earthquake, u_1 is the initial gap between the girder and the inboard shear key, u_2 is the initial gap between the girder and the outboard shear key, k_1 and k_2 is the contact stiffness of respectively u_1 and u_2 .

3.3 Model introduction

The girder and piers are simulated by line elements in the calculation model. Furthermore, the bearings are simulated by non-linear connecting elements, and the collision between the girder and the shear keys is simulated by Gap elements. Rayleigh damping is used for the structural damping ratio in the nonlinear time history analysis. The structural calculation model is shown in Figure 3, and the lateral collision model of a single pier is shown in Figure 4. The collision stiffness k in Gap element is connected with the sectional dimension and the failure mode of the shear key, so it is difficult to get the exact value of k. Since the failure mode of the inboard steel sheet shear key is bending failure, the stiffness k of the contact element is analyzed according to the sectional dimension and the material properties of an individual steel sheet. Taking the yield stiffness of the steel sheet as the collision stiffness of the contact element, the total stiffness of the unilateral lateral shear key could be 10^4kN/m. The outboard reinforced concrete shear key is generally brittle and mechanical complicated. Since the collision stiffness k of the outboard shear key is lack of experimental data, the collision stiffness takes the value of 5×10^4kN/m according to existing references [8].

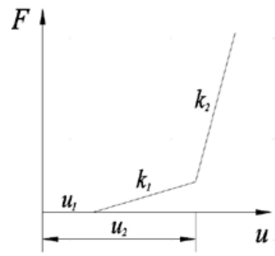


Fig. 2 –Contact element restoring model

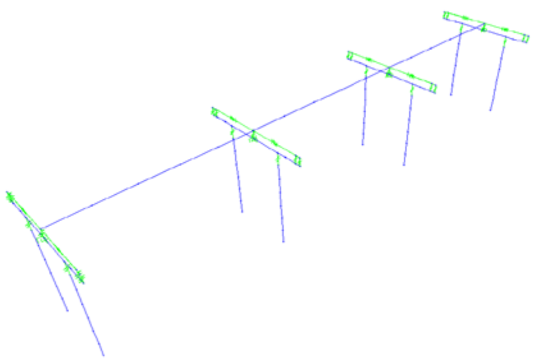


Fig. 3 –Structural calculation model

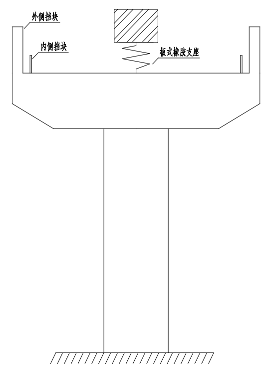


Fig. 4 –Lateral collision model of a single pier

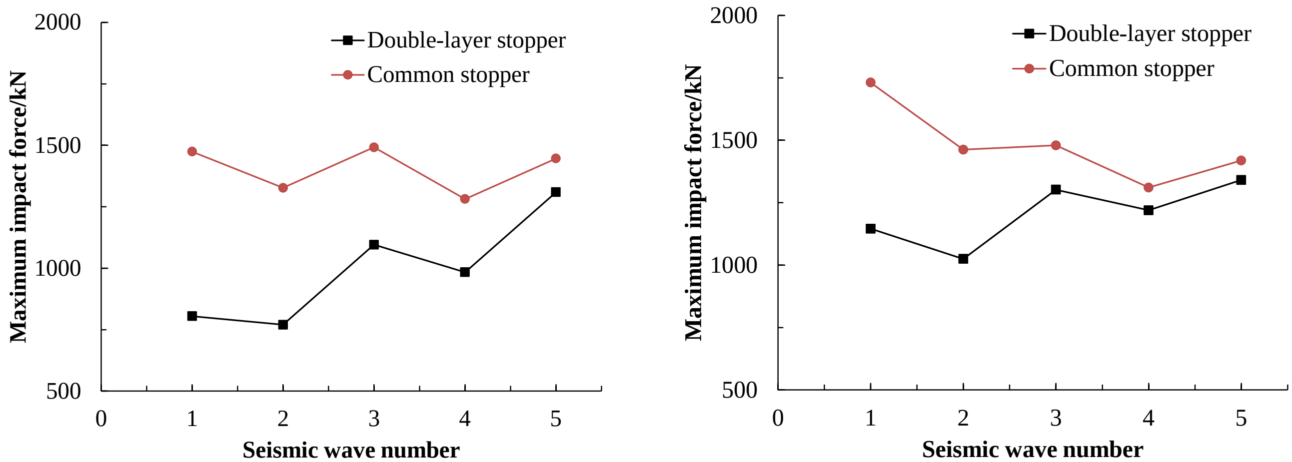
4. Collision response

Choose five seismic waves from the recent typical earthquakes as shown in Table 1, and input the seismic waves along the transverse direction of the bridge. Suppose the basic peak acceleration of the bridge site to be 0.2g, and adjust the peak acceleration of each seismic wave to 0.4g when considering seldom occurred earthquakes. Take the value of the initial gap between the girder and the inboard shear key to be 4cm and take the value of the initial gap between the girder and the outboard shear key to be 1cm. Comparing the seismic performance with the traditional shear keys, the sectional dimension of the shear key is taken as 160cm×30cm×50cm and the initial gap between the girder and the shear key is taken as 5cm according to the design dimensions of the shear keys used in similar bridges.

Table 1 – The parameters of the selected seismic waves

No.	Earthquake name	Position	Magnitude	PGA(g)	Site features	Adjustment coefficient
1	1940 Imperial Valley	EI Centro 270 Deg	6.9	0.357	III	1.120
2	1952 Kem County	Taft 339 Deg	7.4	0.179	II	2.235
3	1994 Northridge	Arleta 90 Deg	6.7	0.344	I	1.163
4	1971 San Femando	8244 Orion Blvd 90 Deg	6.6	0.255	II	1.569
5	1989 Loma Prieta	Oakland 270 Deg	6.9	0.276	II	1.449

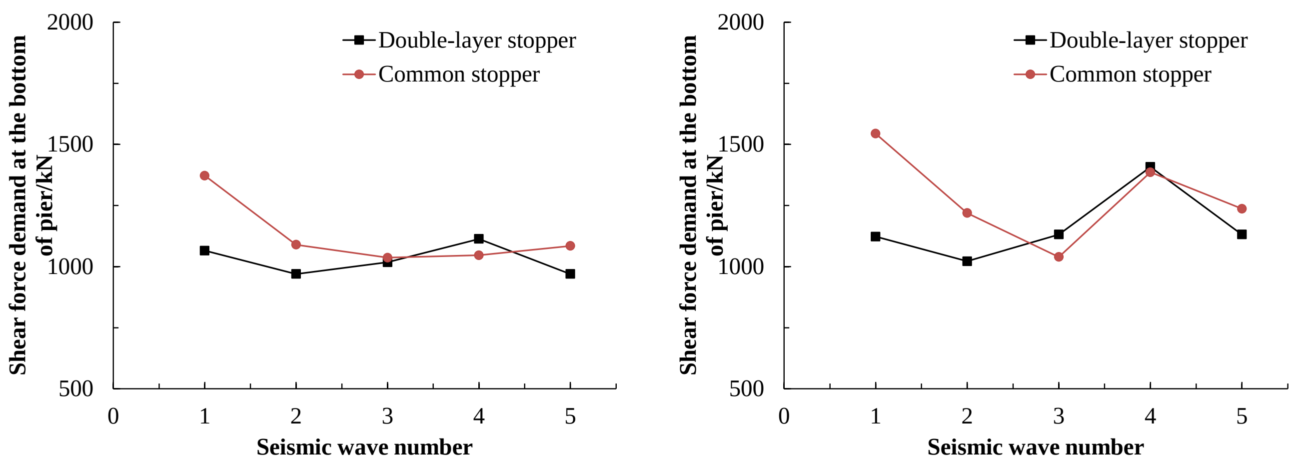
Under different seismic waves, the maximum impact force of each pier is different in the bridge using different shear keys. The comparisons of the maximum impact force between the brides that using traditional shear keys and new double-layer shear keys are shown in Figure 5 (due to structural symmetry, only the 1st and the 2nd pier are shown in Figure 5). Since the inboard shear keys firstly collide with the main girder during the earthquake and produce plastic deformation, the collision energy is consumed. Thus, the maximum impact force can be greatly reduced. As can be noticed in Figure 5, the collision response of the piers in the bridge using double-layer shear keys is obviously less than those using traditional shear keys. The maximum impact force of the piers in the bridge using double-layer shear keys is less than half of the traditional values. The difference of the maximum impact forces in Pier 1 under different seismic waves can even be double.



Pier 1 Pier 2

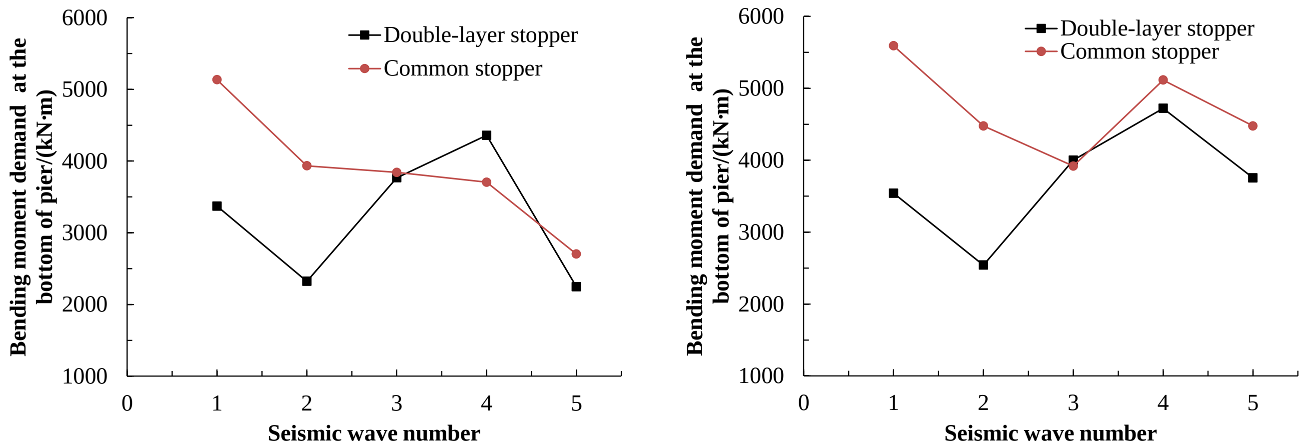
Fig. 5 –Maximum impact force

Under different seismic waves, the shear force and bending moment at the bottom of the piers in the bridge that dispose double-layer shear keys or traditional shear keys are respectively shown in Figure 6 and Figure 7. It can be noticed that the shear force demand and the bending moment demand at the bottom of the piers in the bridge that dispose double-layer shear keys is generally smaller than the other demands, apart from the demands under some individual seismic waves. The main reason given for this is that the overall collision stiffness of the double-layer shear keys is larger than that of the traditional shear keys. The difference in the collision stiffness of the shear keys can cause the difference between the global stiffness of the structure, so the response to seismic waves with different spectral characteristics is also different.



Pier 1 Pier 2

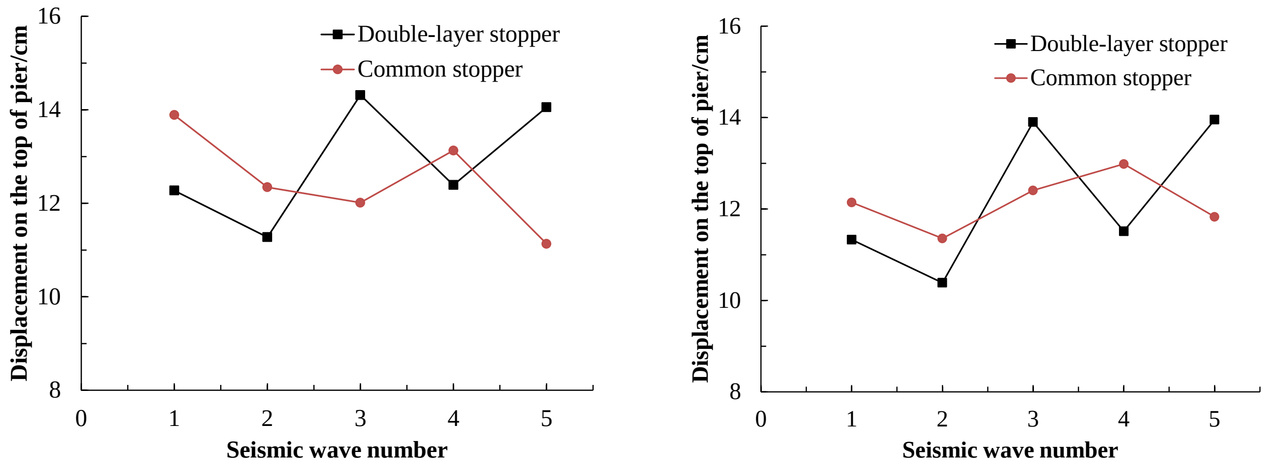
Fig. 6 –Maximum shear force demands at the bottom of piers



Pier 1 Pier 2

Fig. 7 –Maximum bending moment demands at the bottom of piers

Under different seismic waves, the displacements of the top of the piers that set double-layer shear keys or traditional shear keys are compared in Figure 8. As shown in the figure, the displacements of the top of the piers that set double-layer shear keys is generally smaller than the other displacements, apart from the demands under some individual seismic waves. It can also be noticed that, the difference between the maximum shear force demands of piers using different shear keys can be 50%, and the difference between the maximum bending moment demands can be 100%.



Pier 1 Pier 2

Fig. 8 –Maximum displacements on the top of piers

Overall, there is a great difference in seismic response of the bridge under the five different seismic waves. Also, there is also a great difference in the demands for the maximum impact force, bending moment, shear force and displacement under the seismic waves which have the same peak acceleration. Thus, the selection of seismic waves has a critical influence to the bridge seismic calculation. When setting the new double-layer shear keys, the inboard flexible shear keys can play as a buffer due to its low initial stiffness. As a result, these demands for maximum impact force, shear force and bending moment at the pier's bottom is generally smaller than those in the bridge proposing traditional shear keys. It is noteworthy that, the shaping yield in inboard shear keys and the sliding friction between the main girder and rough contact surface may dissipate energy, but these are not considered in the calculation since the model has been simplified. So there is a better seismic performance in the new shear keys than the traditional shear keys during an actual earthquake.

5. Conclusion

A new seismic double-layer shear key was introduced in this paper. Comparative analysis had been conducted between the seismic responses of the new double-layer shear keys and the traditional shear keys. The conclusion is as follows:

1. If not significantly increasing the demands for shear force and bending moment of the bottom of the pier, the displacement of the top of the pier under same conditions, the impact force between the shear keys and the main girder can be effectively reduced when using the new seismic double-layer shear keys. Thus, the damage in the bridge caused by the lateral collision can be reduced, and the risk of the damage to the substructure can be obviously lowered. This shear key is simple, low cost and effective, so it is suitable to apply the new double-layer shear keys to bridge engineering.

2. There is a great difference in seismic response of the bridge under different seismic waves, so the selection of seismic waves has a critical influence to the bridge seismic calculation.

6. Acknowledgements

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