Study on seismic mitigation Performance of Long-span High-speed Railway Continuous Beam Bridge with Viscous Damper

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Abstract. Taking the 128m long-span high-speed railway continuous beam bridge commonly used in China as the example, a reasonable finite element analysis model with seismic mitigation devices of the bridges is established, and nonlinear dynamic time history analysis is used to analyze the seismic mitigation of viscous dampers. Three seismic waves with the same peak acceleration but different spectral components are selected to perform optimization analysis on the viscous damper parameters, damping index and damping coefficient. Numerical analysis results show that: (1) The viscous damper can play a very good damping effect. (2) Under the action of the El Centro wave and Tianjin wave, the damping rates of the fixed pier reached more than 81%. Under the action of Taft wave, except for the relative displacement of the fixed pier, the damping rates of the structure reached more than 74%. The internal force of the other piers and the displacement of the top of the pier increase, but the increase is not large compared with the response value of the fixed pier, and the forces on the piers tend to be uniform and reasonable. (3) The three kinds of seismic wave have different optimization results for the mechanical parameters of the viscous damper model. When selecting the actual devices parameters, the ground motion with the corresponding spectral characteristics should be selected according to the bridge site for optimization analysis. Besides, the devices structure, size requirement and other reason should be considered comprehensively.

Keywords. High-speed railway continuous beam bridge; viscous damper; optimization analysis

1. Introduction

High-speed railway long-span bridges often adopt seismic mitigation design to meet seismic requirements in high seismic intensity region. For this kind of bridges, their dead load is relatively heavy, and the upper structure generally has only one fixed pier, which makes it very difficult for aseismic design under rare earthquakes. Under the action of seismic load, the viscous damper which is installed in the bridge produces a large damping force, making the movable bearing of the bridge equal to the fixed bearing, sharing the internal force of the original fixed pier. It makes the piers of the whole bridge bear the same earthquake force, so as to achieve the effect of vibration mitigation.

LIU Hong-xu[1] carried out the application research of the liquid viscous damper in the Yellow River Bridge on the Wulashan-Xining line, and demonstrated the effectiveness of the liquid viscous damper in the seismic mitigation design. SONG Zi-wei[2] et al. studied the vibration mitigation of a...
high-speed railway long-span continuous girder bridge with viscous dampers. The nonlinear dynamic
time history analysis method is used, and the response comparison values before and after mitigation
were given. MAO Yu-dong[3] et al. studied the effects of viscous dampers, lock-up devices and
hyperboloid spherical seismic isolating bearings on long-span continuous girder bridges on the
vibration mitigation effect, and made a comparative analysis. The discussion gave the scope of
application of the three vibration mitigation devices. YIN Hai-jun[4] et al. established a finite element
model installing a viscous damper on a 7-span continuous girder bridge with a pier height of 10m, and
analyzed its mechanical parameters. The results showed that the viscous damper can significantly
reduce seismic response of continuous beam bridge which has only one fixed pier. DENG Wen-ping[5]
studied the effect of viscous dampers on the seismic response of reinforced concrete continuous beam
bridges, and analyzed the damping coefficient and damping index of the viscous damper. The results
show that the response is reduced significantly after the viscous dampers are set, and the force on each
pier becomes more uniform. The different values of the two mechanical parameters will affect the
structural dynamic response.

The viscous damper set in the bridge can increase the structural damping and suppress the
vibration of the main structure. For special structures, large pier height gaps and long span bridges,
when using viscous dampers as shock-absorbers, a full bridge model must be established, and analysis
method adopts time history analysis methods to adjust and optimize the important parameters of the
viscous dampers. The purpose is to achieve the best vibration mitigation effect finally[7].

Taking the 128m long-span continuous beam bridge commonly used in high-speed railways in
China as the research subject, the detailed optimization analysis on the vibration mitigation and
mechanical parameters of viscous dampers is conducted. The impact of engineering site conditions is
considering. Three natural seismic waves that have been amplitude-modulated to the same peak
acceleration are used. The numerical law of the seismic mitigation effect of the model with different
spectrum components is analyzed. A reference for the application of viscous dampers is provided.

2. Engineering brief introduction

The bridge elevation of 128m long-span high-speed railway continuous girder is shown in Figure 1. The calculated span is (80.6+128+80.6) m. The main bridge adopts a prestressed concrete
continuous box girder structure. The distance between center line of the end bearing to the girder end
is 0.85m, and the whole unit length is 290.9m. The single box single cell and variable cross-section
straight web structure are adopted in the cross section. The width of the box girder roof and floor is
12.6 and 7m respectively. The height of the beam at the center fulcrum section is 9.6m, at the straight
section is 9m and at the side span straight web section is 5.6m. The piers are round-ended. The pier
number from left to right is No. 1 to 4, and the heights of the piers are 16.5m, 14.2m, 14.5m, and
16.5m in sequence. The fixed pier of the bridge with common bearings is set at the No. 2 pier. Viscous
dampers are used to carry on the aseismic design, and each pier is equipped with two viscous dampers
longitudinally, with 8 in total. The longitudinal restraints of fixed piers are released under rare
earthquake.

The seismic intensity of the main bridge is VIII, and the design peak acceleration of seismic motion
Ag=0.2g. The characteristic period of the seismic motion is Zone 3, and the site soil category is Type
II.

3. Aseismic calculation model

Midas software is used for bridge model, and the x, y, and z axes are the along, transverse, and
vertical bridge direction respectively. The main bridge, piers, and pile caps are simulated by beam
elements. Common bearings are simulated by spring connections, and seismic devices are simulated
by general connections. The effect of the ground and foundation on the structure is simplified as
springs, which are applied in the pile cap bottom. The full bridge finite element model has a total of 167 elements and 196 nodes is shown in Figure 2.

![Whole bridge finite element model](image)

**Figure 2.** Whole bridge finite element model

### 3.1. Mechanical model of viscous damper

The damper mainly uses the reciprocal motion of the damping medium in the cylinder to convert the kinetic energy input by the earthquake into heat energy to achieve the purpose of energy dissipation. It is mainly composed of end cover seals, pistons, control valves, piston rods, damping medium, and cylinder block and other compositions, as shown in Figure 3. The viscous damper is a component installed between the main bridge and the pier to reduce the relative pier-beam displacement. The damping force-displacement hysteresis loop of the viscous damper is shown in Figure 4. The shape of the resilience force model is similar to an oval, the overall shape is full, and the energy dissipation and restraint ability are strong.

![Viscous damper schematic](image)

**Figure 3.** Viscous damper schematic

![Damping force-displacement hysteresis model](image)

**Figure 4.** Damping force-displacement hysteresis model

### 3.2. Simulation of viscous damper

The simulation of the viscous damper in this bridge uses the viscoelastic energy dissipation device in the general connection that comes from the Midas software. The Maxwell model is selected as the damping type. The mechanical model is composed of linear springs and viscous damping in series, as shown in Figure 5.

The relationship between force and deformation of Maxwell model is described by a first-order equation, as shown in formula (1):

$$ F = C \nu^\alpha \text{sign}(\nu) $$

In formula (1), $F$ represents the damping force; $C$ represents the damping coefficient; $\nu$ represents the relative velocity between piers and beams; sign is the sign function; $\alpha$ represents the damping index, with a value range of 0.1$\sim$2.0, and the value commonly used in bridge seismic engineering is 0.2$\sim$1.
Since the fixed pier and the main beam are connected rigidly, and the aseismic design is difficult to meet the requirements [7]. Therefore, when simulating the viscous damper, the longitudinal restraint of the fixed pier is released under rare earthquake. The parameters are optimized to give a reasonable plan for aseismic design.

4. Ground motion input

Considering the influence of engineering site conditions, three classic natural seismic waves that have been amplitude-modulated to the same peak acceleration are selected. They are El Centro wave, Taft wave and Tianjin wave respectively. The numerical law of ground motions with different frequency components on the aseismic effects of the model is analyzed. The strong ground motion records are shown in Figure 6. The input direction of ground motion is along bridge (x direction).

5. Parameter optimization analysis of damper

The damping index $\alpha$ and the damping coefficient $C$ of the damper are optimized and analyzed. The arrangement combination is performed, and there are 36 working conditions. Among them, No. 1 and 4 piers (which are two side piers on both sides) are set to fixed values due to the small bearing tonnage, and the parameter is set to $\alpha=0.4$, $C=4$ MN/(m/s)$^2$ in each working condition. The parameter values of damping index $\alpha$ and damping coefficient $C$ of the main piers No. 2 and 3 are optimized according to Table 1. The unit of the damping coefficient $C$ below is MN/(m/s)$^2$. Only the optimization analysis process under the action of El Centro wave is given.

| Parameters            | Value |
|-----------------------|-------|
| Damping index $\alpha$| 0.2   |
| Damping coefficient $C$| 2     |
| Damping index $\alpha$| 0.3   |
| Damping coefficient $C$| 4     |
| Damping index $\alpha$| 0.4   |
| Damping coefficient $C$| 8     |
| Damping index $\alpha$| 0.5   |
| Damping coefficient $C$| 12    |
| Damping index $\alpha$| 0.6   |
| Damping coefficient $C$| 16    |
| Damping index $\alpha$| 0.7   |
| Damping coefficient $C$| 20    |

Figure 5. Maxwell mechanical model

(a) El Centro wave  (b) Taft wave  (c) Tianjin wave

Figure 6. Three classic ground motion acceleration time history curves

Since the internal force and displacement response of the two main piers (No.2 and 3 piers) and the two side piers (No.1 and 4 piers) are close. The piers No.1 and 2 are taken as the analysis objects respectively. The curves of the maximum longitudinal bending moment of pier bottom, the maximum longitudinal shear force of pier bottom, the maximum longitudinal displacement of pier top, the
relative pier-beam displacement change with the mechanical parameters of the viscous damper are shown in Figures 7 and 8.

![Graph](image-url)

(a) Maximum pier bottom shear force relative pier-beam displacement

(b) Maximum pier bottom bending moment relative pier-beam displacement

**Figure 7.** Response curve of Pier No.1 with devices parameters under El Centro wave

(1) It can be seen from Figure 7(a) that when the damping coefficient is 2 to 8 MN/(m/s)$^a$, the maximum longitudinal shear force at the bottom of the side pier decreases with the increase of the damping index basically. When the damping coefficient is greater than 8 MN/(m/s)$^a$, as the damping index increases, the maximum shear response value decreases first and then increases. Except that the damping index is 0.2 and 0.3, the maximum shear response value of the side piers increases first and then decreases with the increase of the damping coefficient.

(2) It can be seen from Figure 7(b) and (c) that the maximum longitudinal bending moment at the bottom of the side pier and the maximum longitudinal displacement at the top of the pier are basically the same. With the increase of damping index, the decrease of damping coefficient, and the bending moment and displacement response values decrease.

(3) It can be seen from Figure 7(d) that, except that the damping coefficient is 20 MN/(m/s)$^a$, the relative pier-beam displacement of the side pier increases with the increase of the damping index. When the damping index is 0.2 and 0.3, with the increase of the damping coefficient, the relative pier-beam displacement decreases first and then increases slightly. When the damping index is greater than 0.3, the relative pier-beam displacement decreases monotonously with the increase of the damping coefficient.

Overall, for the side piers, except that the damping coefficients of the main piers are 16 and 20 MN/(m/s)$^a$, the larger the damping index is, the smaller the internal force and displacement response value are, which is more beneficial. The smaller the damping coefficient is, the smaller internal force and the displacement response are, which is also more favorable. But from the overall point of the relative pier-beam displacement response value, when the damping coefficient is large and the damping index is small, the relative pier-beam displacement is small.
(1) It can be seen from Figure 8(a) that when the damping coefficient is 2 and 4 MN/(m/s)$^2$, the maximum longitudinal shear force at the bottom of the main pier increases with the increase of the damping index. The damping coefficient is greater than 4 MN/(m/s)$^2$, as the damping index increases, the maximum shear response decreases. When the damping index is constant, the maximum shear response of the main pier will decrease first and then increase with the increase of the damping coefficient.

(2) It can be seen from Figure 8(b) and (c) that the maximum longitudinal bending moment at the bottom of the main pier and the maximum longitudinal displacement at the top of the pier are the same basically. When the damping coefficient is 2 MN/(m/s)$^2$, the bending moment and displacement response of the main pier increase slowly with the increase of the damping index. When the damping coefficient is greater than 2 MN/(m/s)$^2$, the bending moment and displacement response decreases with the increase of the damping index, and the bending moment and displacement response of the main pier increase with the increase of the damping coefficient.

(3) It can be seen from Figure 8(d) that, except that the damping coefficient is 20 MN/(m/s)$^2$, the relative pier-beam displacement increases with the increase of the damping index. When the damping index is 0.2, the main pier relative pier-beam displacement decreases first and then increases slightly with the increase of the damping coefficient. When the damping index is greater than 0.2, the relative pier-beam displacement decreases monotonously with the increase of the damping coefficient.

In summary, for the main pier, except that the damping coefficient is 2 and 4 MN/(m/s)$^2$, the larger the damping index is, the smaller the internal force response at the pier bottom and the displacement response at the top of the pier are, which is more beneficial. The smaller the damping coefficient is, the smaller the internal force response of the pier bottom and the displacement response of the pier top are, which is also more favorable. But judging from the relative pier-beam displacement response value, when the damping coefficient is large and the damping index is small, the response value is small.
Figure 9 shows the hysteresis loop of the viscous dampers at each pier under El Centro wave. It can be seen from the figure that the hysteresis loop is relatively full, and the shape of it is close to ellipse, which conforms to the viscous curve shown in Figure 4. The simplified mechanical model of the viscous damper shows that the viscous damper set in this bridge has a good effect of seismic mitigation.

### 6. Analysis of Aseismic effect

To test the seismic mitigation effects of the bridge model with viscous dampers under the action of three waves, the optimization results of the mechanical parameters of the viscous dampers are combined. The seismic response results of the bridge model with viscous dampers and the ordinary bearings are compared and analyzed, the results are shown in Tables 2 to 14. The damping rate is used to express the seismic mitigation effect of the bearing. The damping rate calculation formula is as follows:

\[
\delta = \frac{J - J'}{J} \times 100\%
\]

Where \(\delta\) is the damping rate, \(J\) is the response value of ordinary bearings, and \(J'\) is the response value of the bridge structure with viscous dampers.

#### 6.1. Seismic mitigation effect under El Centro wave

The seismic response results of the ordinary bearing and the bridge model \((\alpha=0.6, C=8)\) with viscous damper under El Centro wave are extracted. The results are shown in Table 2 to 5 below.

| Number of pier | \(J\) (MN) | \(J'\) (MN) | \(\delta\) (%) |
|----------------|-------------|-------------|---------------|
| 1              | 18.54       | 10.26       | 44.66         |
| 2              | 77.1        | 14.62       | 81.04         |
| 3              | 41.77       | 14.85       | 64.45         |
| 4              | 20.76       | 9.96        | 52.02         |

| Number of pier | \(J\) (MNm) | \(J'\) (MNm) | \(\delta\) (%) |
|----------------|-------------|-------------|---------------|
| 1              | 151.67      | 196.71      | -29.70        |
| 2              | 2032.77     | 322.18      | 84.15         |
| 3              | 340.59      | 331.79      | 2.58          |
| 4              | 173.07      | 180.48      | -4.28         |

| Number of pier | \(J\) (mm) | \(J'\) (mm) | \(\delta\) (%) |
|----------------|-------------|-------------|---------------|
| 1              | 18.54       | 10.26       | 44.66         |
| 2              | 77.1        | 14.62       | 81.04         |
| 3              | 41.77       | 14.85       | 64.45         |
| 4              | 20.76       | 9.96        | 52.02         |

| Number of pier | \(J\) (mm) | \(J'\) (mm) | \(\delta\) (%) |
|----------------|-------------|-------------|---------------|
| 1              | 100         | 83          | 17.00         |
| 2              | 8           | 88          | -1000         |
| 3              | 105         | 88          | 16.19         |
| 4              | 103         | 82          | 20.39         |
It can be seen from Tables 2 to 5 that under the El Centro wave, the bridge with viscous dampers reduces the internal force and displacement response of the No.2 fixed pier effectively, and the damping rates are above 81%. Because the No.2 pier is fixed pier, the relative pier-beam displacement is close to 0. After the viscous damper is set, the No.2 pier has the relative pier-beam displacement due to the earthquake. The shear force and the relative pier-beam displacement of the other piers have also been reduced in different level, and the damping rates are between 16% and 65%. The response values of the bending moment and the displacement of the top of the side pier increased, but the increase is not large compared with the fixed pier. This is due to that the side piers are equipped with viscous dampers to generate damping force during the earthquake, which limits their relative pier-beam displacement. So that the side piers can share the seismic effects with the fixed piers, which can make the piers bear more uniform and reasonable force. The piers can endure the seismic action together, and it avoids the situation where the fixed pier endures greater force.

6.2. Seismic mitigation effect under Tianjin wave

The seismic response results of the ordinary bearing and the bridge model (α=0.7, C=8) with viscous damper under Tianjin wave are extracted. The results are shown in Table 6 to 9 below.

| Number of pier | J(MN) | J(MN) | δ(%) |
|---------------|-------|-------|------|
| 1             | 12.54 | 17.15 | -36.76 |
| 2             | 176.19| 28.34 | 83.92 |
| 3             | 22.94 | 28.39 | -23.76 |
| 4             | 12.37 | 17.12 | -38.40 |

| Number of pier | J(MN) | J(MN) | δ(%) |
|---------------|-------|-------|------|
| 1             | 108.1 | 188.41| -74.29 |
| 2             | 4162.96| 291.82| 92.99 |
| 3             | 178.15| 299.41| -68.07 |
| 4             | 92.47 | 183.43| -98.37 |

| Number of pier | J(mm) | J(mm) | δ(%) |
|---------------|-------|-------|------|
| 1             | 12    | 22    | -83.33 |
| 2             | 228   | 17    | 92.54 |
| 3             | 11    | 17    | -54.55 |
| 4             | 13    | 25    | -92.31 |

| Number of pier | J(mm) | J(mm) | δ(%) |
|---------------|-------|-------|------|
| 1             | 241   | 111   | 53.94 |
| 2             | 53    | 117   | -120.75 |
| 3             | 266   | 117   | 56.02 |
| 4             | 281   | 108   | 61.57 |

It can be seen from Tables 6 to 9 that under Tianjin wave, the response values of the fixed piers of ordinary bearing are relatively large. After the viscous dampers are set, the internal force and displacement values of the No.2 fixed pier are reduced significantly. The damping rates are above 83%. Except for the significant reduction in the relative pier-beam displacement, the damping rates of the other three piers are negative, and the internal force and displacement values have increased to a certain extent. Compared with the response value of the fixed pier, the increase is not large. For the seismic response of the fixed pier, the force on the two side piers and the two main piers tend to be the same in the perspective of the force of each pier after the seismic mitigation. And the force on each pier is more uniform and reasonable than before damping.

6.3. Seismic mitigation effect under Taft wave

The seismic response results of the ordinary bearing and the bridge model (α=0.7, C=8) with viscous damper under Taft wave are extracted. The results are shown in Table 10 to 13 below.

| Number of pier | J(MN) | J(MN) | δ(%) |
|---------------|-------|-------|------|
| 1             | 16.95 | 11.42 | 32.63 |
| 2             | 86.49 | 21.16 | 75.53 |

| Number of pier | J(MN) | J(MN) | δ(%) |
|---------------|-------|-------|------|
| 1             | 197.33| 158.07| 19.90 |
| 2             | 1649.81| 280.91| 82.97 |
the damping rates reached more than 75%. The internal forces and displacement values of other piers are also reduced in different level, and especially the damping ratios of shear force and relative pier-beam displacement can reach 28.8% to 76.83%.

7. Conclusion

Taking the 128m long-span high-speed railway continuous beam bridge as the example, the viscous dampers are set to carry out the research on the seismic mitigation performance. The following conclusions are proposed:

(1) Under the action of the three seismic waves, the viscous dampers can reduce the internal force and displacement calculation results of the whole bridge.

(2) Under the action of El Centro wave and Tianjin wave, the internal force and the displacement of the top of the No.2 fixed pier were reduced effectively, and the damping rates reached more than 81%. The internal force and the displacement of the top of the pier have increased to a certain extent, but the increase is not large compared with the response value of the fixed pier. Under the Taft wave, except for the relative pier-beam displacement in the fixed pier, the seismic response of the bridge is reduced, and the damping rates are all over 75%. The relative pier-beam displacement in the other three piers has been reduced significantly.

(3) Through comparative analysis, three kinds of seismic waves with the same acceleration peak but different spectral components have different mechanical parameter optimization results for the same bridge with viscous dampers. When determining the actual devices parameters, the ground motion with the corresponding frequency spectrum characteristics should be selected, according to the site conditions where the bridge is located to carry out optimization.

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9. References

[1] LIU HX 2016 Application and research of fluid viscous damper to yellow river extra-long bridge on wu-xi railway Railway Standard Design 60(01) pp 79-83

[2] SONG ZW and CAI XP 2012 Application of viscous damper devices in the seismic design of long span unit continuous girders on high speed railway Journal of Tsinghua University (Natural Science) 52(08) pp 1102-1105

[3] MAO YD and LI JZ 2016 Analysis of seismic mitigation mechanism and effect on longitudinal direction of long-span continuous bridge Journal of Tongji University (Natural Science) 44(02) pp 185-191

[4] YIN HJ, WANG ZQ and HU SD 2004 Analysis of continuous bridge adopted damper Journal of Tongji University (Natural Science) 2004(11) pp 1437-1441

[5] DENG WP and WANG H 2012 Parametric analysis of viscous damper for earthquake mitigation of continuous bridges in high intensity region Journal of Vibration and Shock 31(16) pp 92-97

[6] ZHUANG SJ 2012 Seismic mitigation and isolation bearings and devices China Railway Press 15 pp 733-746

[7] ZHANG CY, WANG ZY and WANG HB 2015 Study on seismic mitigation and isolation design for a long-span continuous steel truss beam bridge Journal of Highway and Transportation Research and Development 32(08) pp 80-88