Effect of nonlinearity of restrainer and supports on the elasto-plastic seismic response of continuous girder bridge

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ABSTRACT. During an earthquake, the nonlinearity of the bridge structure mainly occurs at the supports, bridge piers and restrainers. When entering nonlinear stage, members of the bridge structure affect the elasto-plastic seismic response of the whole structure to a certain extent; for multi-span continuous bridges, longitudinal restrainers can be installed on the movable piers to optimise the distribution of seismic force and enable the movable piers to bear a certain amount of seismic effect. In order to evaluate the effect of nonlinearity of restrainer and supports on the elasto-plastic seismic response of continuous girder bridge, analytical models of continuous girder bridge structure considering the nonlinearity of movable supports, restrainers and bridge piers were built and the nonlinear time history analysis was conducted to evaluate the effect of nonlinearity of restraining devices and supports on the elasto-plastic seismic response of continuous girder bridge. Relevant structural measures and recommendation were made to reduce the seismic response of the fixed piers of the continuous girder bridge.

KEYWORDS. Restraining devices; Supports; Elasto-plastic seismic response; Continuous girder bridge.

INTRODUCTION

The investigations of previous seismic hazards showed that the damage of the bridge piers were not significant if failure occurred at the support, which suggests that the response of supports and bridge pier is interrelated; meanwhile, caging devices play a certain role in distributing the seismic force to each piers and abutments. Under earthquake action, the girder, supports, piers, substructure and connecting members (restraining blocks and girder-connection devices) act as an integrated structure. As a certain portion of energy will be dissipated by movable supports during earthquake and a part of the inertia force of the superstructure will be passed to movable piers, especially when the movable supports fail and lose the sliding capacity, in which case the seismic force passed from the failed support to the movable pier would be magnified [1], the seismic response of the whole bridge structure will change. When studying the elasto-plastic seismic response of bridge structures, the effect of the nonlinearity of each component in the bridge structure on elasto-plastic seismic response of bridge structures should be considered [2].

In bridge engineering, restraining blocks are often used to prevent the falling of the girder and increase the safety of the supports during earthquake. For large-span long continuous bridge structures, the self-load of the integrated girder body is high, resulting in a substantial horizontal seismic force mainly concentrated on the fixed supports. To optimise the distribution of seismic force for each pier, anti-seismic pins or restraining blocks can be installed. At the same time, a certain gaps between the blocks (pins) and the girder should be preserved, so that the movable pier is able to carry a part of the horizontal seismic force without affecting the normal stretching of the girder, as shown in Fig. 1. It is pointed out by [3] that if the expected plastic hinge is located in the pier, more piers should be arranged to carry the horizontal seismic force. An ideal way is to install laminated rubber supports on all piers but the number of horizontal force bearing piers may be limited by other design factors which should be taken into consideration during design. Xie xu [4] stated that horizontal seismic force produced by the superstructure of the continuous bridge is good to be carried by all piers and abutments to prevent overbearing of the fixed piers. Relevant engineering procedures such as restraining devices were proposed.

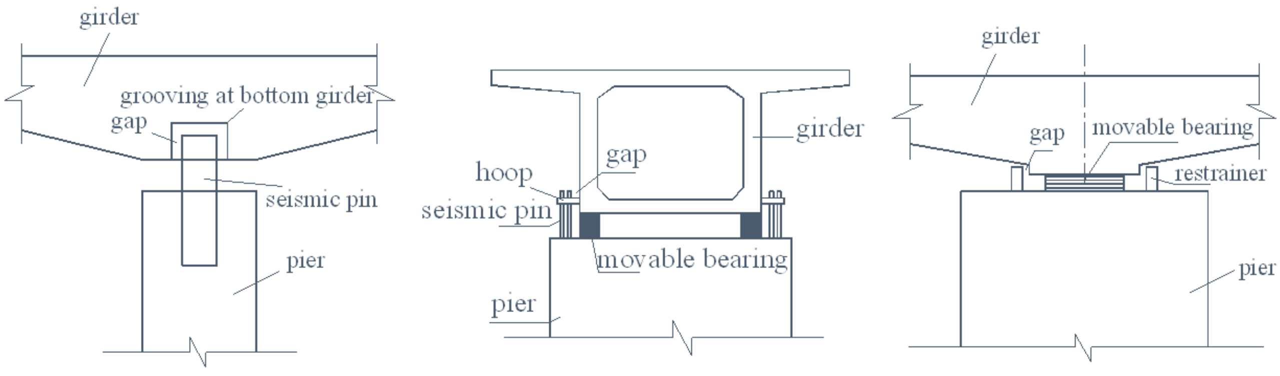


Figure 1: Seismic tectonic measure at movable piers. (a) Longitudinal seismic pin; (b) Lateral seismic pin; (c) Restrainer.

At present, few studies are carried out to evaluate the effect of restraining devices and supports on the nonlinear seismic response of the bridge structure. Restraining blocks are only considered as structural component without analysing the effect of them during seismic resisting process according to the seismic resistant standard of bridge engineering in China. Studies focusing separately on the nonlinearity of supports, seismic mitigation and isolation, restraining devices or elasto-plasticity of bridge piers are common [5,6] but studies considering simultaneously the nonlinearity of supports, contact of restraining devices and material nonlinearity are rare. Studies concerning the interaction of the nonlinearity of supports, restraining devices and the elasto-plastic analysis of bridge piers are also rare. At present, the effect of friction at supports and the nonlinearity of restraining devices on the elasto-plastic seismic response of the bridge are rarely considered during the elasto-plastic seismic response of continuous bridge.
In this study, on the basis of considering the nonlinearity of supports, piers and restraining devices, the effect of restraining devices and nonlinearity of supports on the elasto-plastic seismic response of continuous girder bridge is evaluated and structural procedures to reduce the seismic response of the fixed piers of continuous girder bridge are proposed.

ANALYTICAL MODELS OF EACH ELEMENT

Support elements

Nonlinear supports can be simulated by springs with bilinear hysteretic relationship. To simulate the sliding kinetic performance of the support in earthquake, bilinear hysteretic sliding support element [7] is used and the hysteretic model of the element is shown in Fig. 2.
Laminated rubber supports which are normally positioned at the top of the piers are not bolted with the top of the pier or the bottom of the girder. If the seismic force exceeds the critical sliding force between the supports and the surfaces of the pier or the beam bottom, sliding will occur. The laminated rubber supports in this case can be simulated by bilinear model; for tetrafluoroethylene movable supports, the support element is also simulated by bilinear model. The stiffness of movable support after sliding is taken as 0, which is the Coulomb friction model.

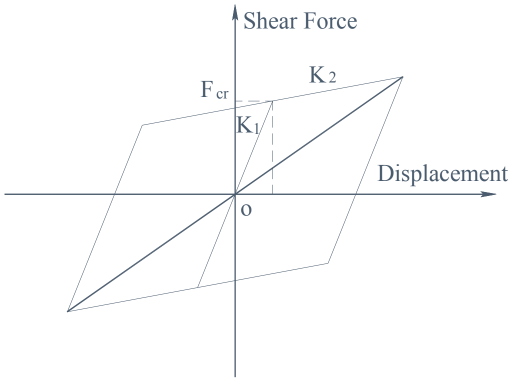
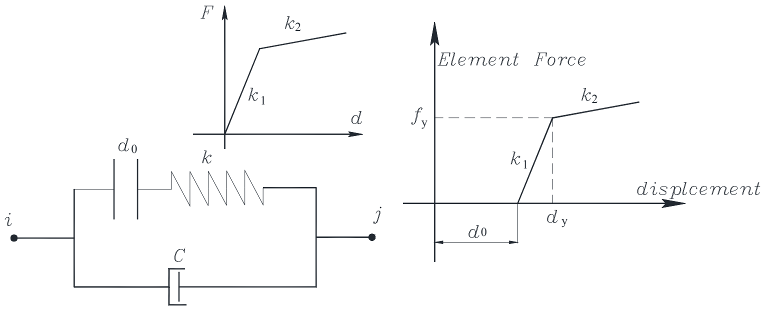


Figure 2: Bilinear element model of the support.

Contact and impact elements

Presently, analytical methods for contact and impact are mainly: coefficient of reconstitution, Lagrange multiplier and contact finite element method. The contact finite element method is mainly based on Kelvin impact model. Kelvin impact model is a parallel connection of spring and damper. The main parameters include: initial impact stiffness K_1, yield stiffness K_2, damping c and initial gap d_0. The nonlinearity of the restraining devices is generally not considered in existing studies. In this study, considering that the restraining device can be nonlinear, the element and hysteretic model is given in Fig. 3 [8, 9].



(a) (b)

Figure 3: Contact element: (a) Mechanical model of the contact element; (b) Hysteresis curve of the contact element.

The above model was used to simulate the impact of girder and restraining devices and the impact force is given in Eq. (1) [10, 11]:

$$\begin{cases} F = k_1(u_i - u_j - d) + c(\dot{u}_i - \dot{u}_j) & u_i - u_j - d \geq 0 \\ F = 0 & u_i - u_j - d < 0 \end{cases} \tag{1}$$

In which:

k_1: is the contact and impact stiffness;

d: Initial gap;

c: damping factor $c = 2\xi\sqrt{k_1 \dfrac{M_1 M_2}{M_1 + M_2}}, \xi = \dfrac{-\ln e}{\sqrt{\pi^2 + (\ln e)^2}}$;

e is the hysteretic factor which can be taken as 0.65 for concrete;

u_i, u_j: are respectively the end displacement of the adjacent girder of the contact element;

u_i, u_j: are respectively the end velocity of the adjacent girder of the contact element.

Elasto-plastic reinforced concrete model

The elasto-plasticity of bridge pier is simulated by Takeda tri-linear model and the skeleton curve of the element is controlled by the moment and curvature at cracking, yield and damage points, as shown in Fig. 4.

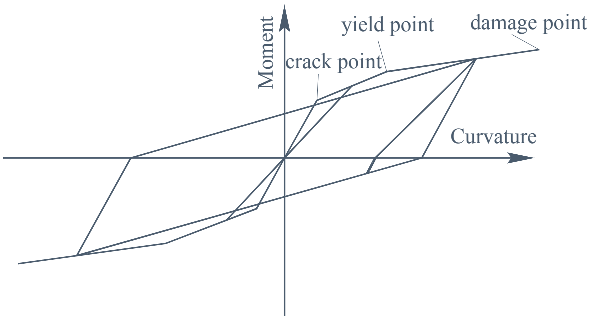


Figure 4: Takeda tri-line hysteresis model.

FINITE ELEMENT MODELLING

Project background

The superstructure of a 60+100+60 m prestressed concrete continuous railway girder bridge was selected as the background project. The pier has a height of 20 m. The cross-section of the pier is rectangular with a dimension of 6.75×2.8 m for side piers and 6.8×4.0m for middle piers. The girder is variable-section boxed girder with single cell box and vertical webs. The girder has a total weight of 14367248 kg. The vertical reaction force for side supports is 8793.74 kN and 63042.5 kN for middle supports.

The effect of ground and pier foundation is simplified as foundation springs applied at the cushion cap bottom. The proportionality factor is taken as 20000 kPa/m^2 according to the foundation factor. The spring stiffness is calculated by "m" method [12]. The nonlinearity of ground and pier foundation is ignored and the rotation spring stiffness of the cushion cap bottom is taken as identical for each model.

Analytical model

Nonlinear Takeda model is used for all bridge piers. Only longitudinal seismic response of the continuous bridge is studied in this research [13]. The length of the plastic hinge of the bridge pier is taken as 1.0 D (D is the height of calculation of the cross-section) and the plastic hinge is located at the bottom of the pier. The elasto-plasticity of the pier structure is considered within the range of plastic hinge and the nonlinearity is ignored outside the range. The reinforcement ratio of the bridge pier is taken as 0.5% and the control points of the moment-curvature curve of the cross-section of pier bottom are given in Tab. 1.

Pier	Cracking moment (kN·m)	Cracking curvature (rad/m)	Yield moment (kN·m)	Yield curvature (rad/m)	Ultimate moment (kN·m)	Ultimate curvature (rad/m)
Side pier	33265	0.00014	59050	0.00087	83684	0.03649
middle pier	102917	0.00012	203459	0.00068	237879	0.0081

Table 1: Control points of the moment-curvature curve for the bottom section of bridge pier.

The Beam and piers were simulated by spatial beam element, the beam was separated into 83 elements and each pier was separated into 12 elements. The numerical FE model was shown in Fig. 5.

In actual design, the effect of transversal seismic and vertical load is both considered and thus the reinforcing ratio of the fixed pier and middle movable piers are normally identical. Therefore, the same moment-curvature model is used for both middle movable piers and the fixed piers. Five different calculating models are incorporated for different scenarios where the nonlinearity of support is considered or not as well as different installation of restraining devices.

(1) Model 1: The nonlinearity of movable supports is ignored. Only the vertical degree of freedom of the movable supports is coupled with the girder, while both the vertical and horizontal degrees of freedom of the fixed supports are linked with the girder.

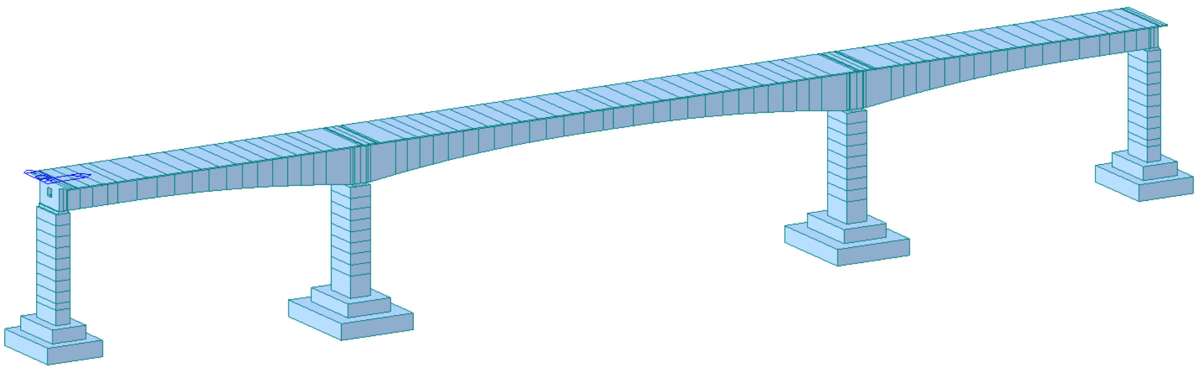


Figure 5: Numerical FE model.

(2) Model 2: The friction of the movable supports is considered with coefficient of friction taken as 0.02, 0.05, 0.10, 0.15, 0.20. No restraining devices are provided. As the stiffness of the supports is large before slipping occurs, the initial stiffness of the middle movable supports is taken as 1e6 kN/m and side movable supports, 4e5 kN/m during the analysis.

(3) Model 3: The elastic effect of the restraining devices is considered. When slipping occurs for a certain distance, the relative displacement of the girder and piers is restrained by the restraining devices. The restraining devices are considered elastic with a stiffness of 1e6 kN/m. The failure of the restraining devices is not considered.

(4) Model 4: The nonlinearity of the restraining devices is considered and the initial stiffness of the restraining devices is set identical as in Model 3. On the basis that the horizontal sliding force of the supports is considered, the critical yield force of the restraining devices is taken as 30% of the horizontal sliding force of the supports. In actual engineering, the critical yield force of the restraining devices can be determined by its mechanism. The analytical model of Model 4 is given in Fig. 6.

(5) Model 5: No longitudinal restraining devices are provided for side piers and only the friction of side movable supports is considered. The movable supports are identical as in Model 4. Both the friction of support and the nonlinearity of the restraining devices are considered.

During the time history analysis, three rare artificial seismic waves and Tianjin wave are incorporated with the peak value of the seismic wave adjusted to 0.4g.

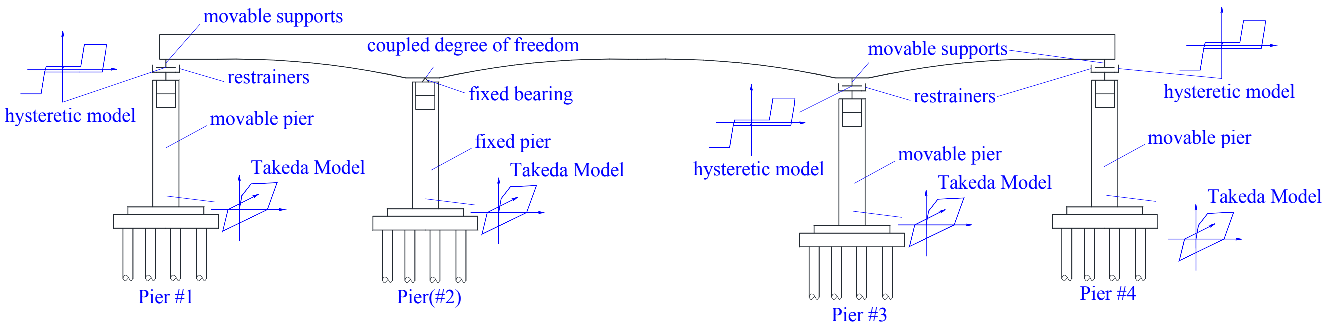


Figure 6: Calculation Diagram for Model 4.

EFFECT OF NONLINEARITY OF SUPPORTS AND RESTRAINING DEVICES ON THE ELASTO-PLASTIC SEISMIC RESPONSE OF BRIDGE STRUCTURE

Comparison of calculated moment and curvature of the bottom section of the fixed pier

When the nonlinearity of the movable supports and restraining devices is considered, the hysteretic energy dissipation of movable supports affects the energy dissipating mechanism of the bridge structure. The existence of restraining devices results in the redistribution of seismic effect on each pier and thus the seismic response of the structure (moment and curvature of the bottom section of the fixed pier and the displacement of the girder) is different from models where the friction of supports and the distribution of seismic force by the restraining devices are not considered. Results show that the analytical results and trend for the four seismic waves are basically identical and the analytical results of the seismic response for the first artificial seismic wave and Tianjin wave are shown in Fig. 7 and 8. The initial gap of the restraining devices is taken as ±10 cm .

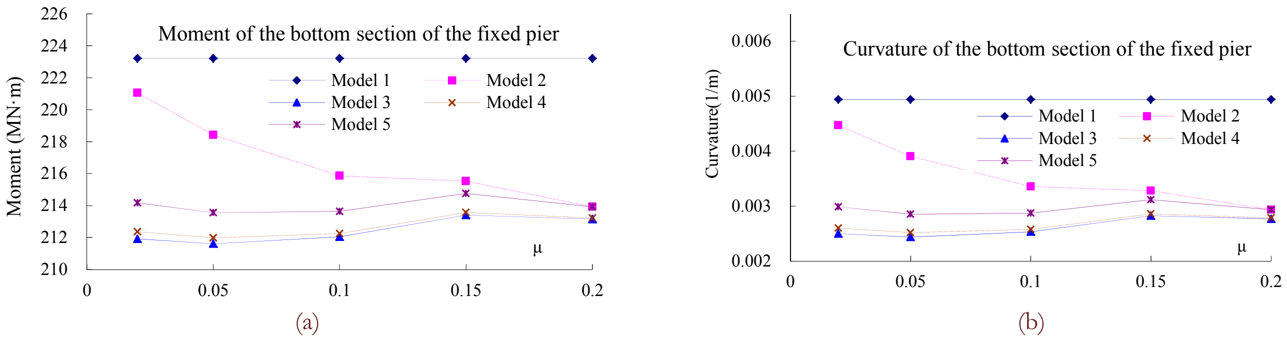


Figure 7: Moment and curvature of the bottom section of the fixed pier under the first artificial seismic wave.

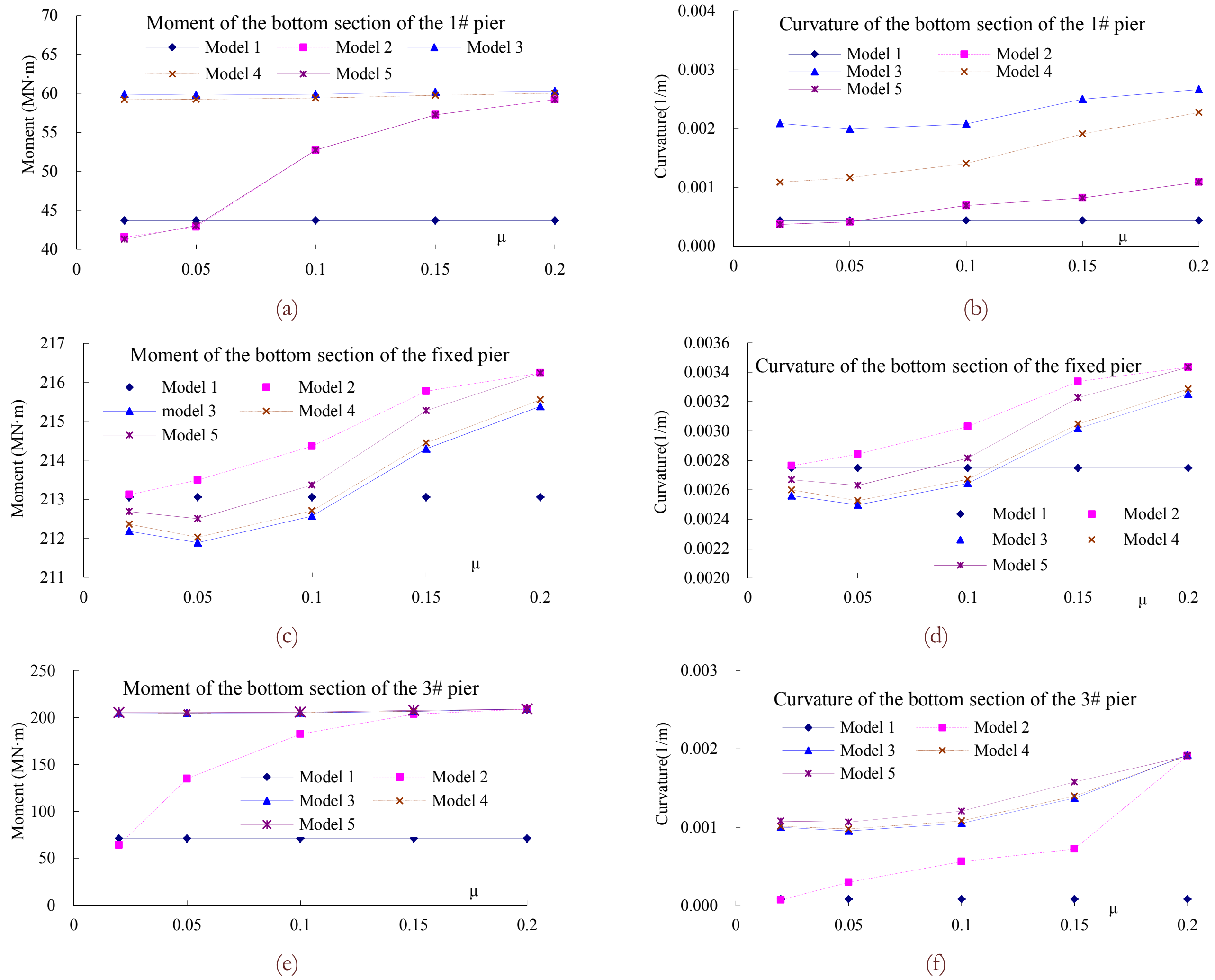


Figure 8: Moment and curvature of the bottom section under Tianjin seismic wave.

It can be seen from Fig. 7 and 8 that when the effect of the supports and restraining devices is considered:

(1) For movable piers, due to the effect of friction at movable supports, the moment and curvature of bottom section of the piers when the effect of friction at movable support is considered (Model 2) are larger than that in the case when the friction at movable supports is not considered (Model 1), and the seismic response increases with the increase of coefficient of friction; For fixed piers, under the action of artificial wave, the moment and curvature of bottom section of the piers when the effect of friction at movable supports is considered are smaller than that in the case when friction at movable supports is not considered, and the response decreases with the increase of coefficient of friction. However, the seismic response of the bottom section of the fixed piers when the friction at movable supports is considered under Tianjin Wave increases, which suggests that the friction at movable supports is not always favorable for the seismic resistance of bridge structure. The effect of friction at movable supports on the seismic resistance performance of bridge structures depends on the spectrum of the seismic wave and the characteristics of the structure. It is recommended that for structures of which the natural vibration period is similar to the period of the surrounding ground when the contribution of stiffness of movable supports is considered, or structures on soft ground foundation, the effect of friction at movable supports should be considered.

(2) When the effect of friction at movable supports and the elasticity of restraining devices are considered, the moment and curvature of bottom section of the movable piers increase and the response increases with the increase of the coefficient of friction at movable supports; the seismic response at the bottom section of the fixed piers in the case when restraining devices are considered (Models 3 to 5) is smaller than that in the case when only the friction at movable supports is considered (Model 2).

(3) When the nonlinearity of the restraining devices is considered (model 4), the seismic response of the bottom section of the movable piers is smaller or similar with that in the case when the elasticity of restraining devices is considered; the seismic response of the bottom section of the fixed piers is slightly larger than that in the case when the elasticity of restraining devices is considered due to the fact that the restraining devices are in nonlinear stage which limits the bearing of seismic force by movable supports. The restrainers should be designed energy intensive to protect the movable pier from being destroyed by the violet pounding force, so model 4 was suggested in practice [14-16]. The bump rubber can be also used to decrease the pounding force.

(4) If only the restraining effect of the middle piers is considered (Model 5), the seismic response of the bottom section of the side movable piers is smaller than that in the case where the nonlinearity of the restraining devices is considered (Model 4) but the seismic response of the middle movable piers and fixed piers increase.

(5) For side movable piers, the seismic response in the case when the effect of supports and elasticity of restraining devices is considered (Model 3) is the largest; for middle movable piers, the seismic response in the case when only the restraining effect of the 3# piers is considered (Model 5) is the largest; for fixed piers, the seismic response in the case when the effect of supports and elasticity of restraining devices is considered (Model 3) is the smallest, suggesting that restraining devices effectively reduce the seismic response of the bottom section of the fixed piers and enable the movable piers to bear a part of the seismic input energy to distribute and isolate the seismic effect.

Comparison of displacement of the girder and shear displacement of the supports

The vertical displacement of the girder and shear displacement of the movable supports in different models are given in Fig. 9 to 10.

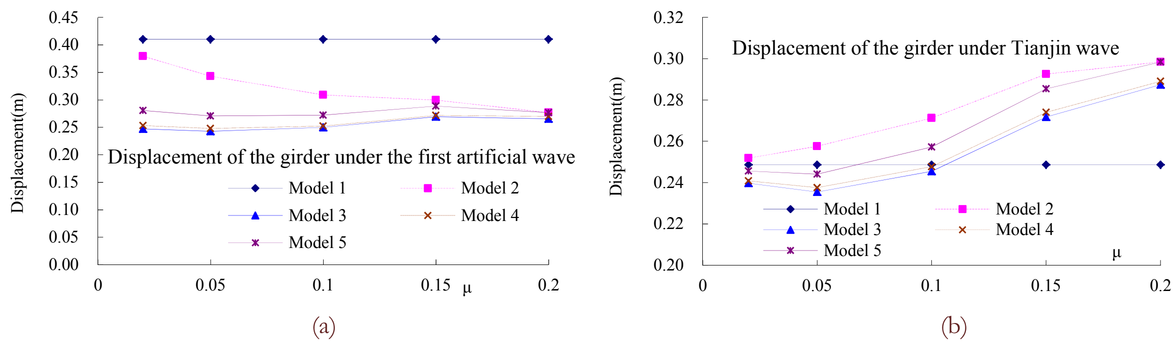


Figure 9: Comparison of displacement of girder in each model.

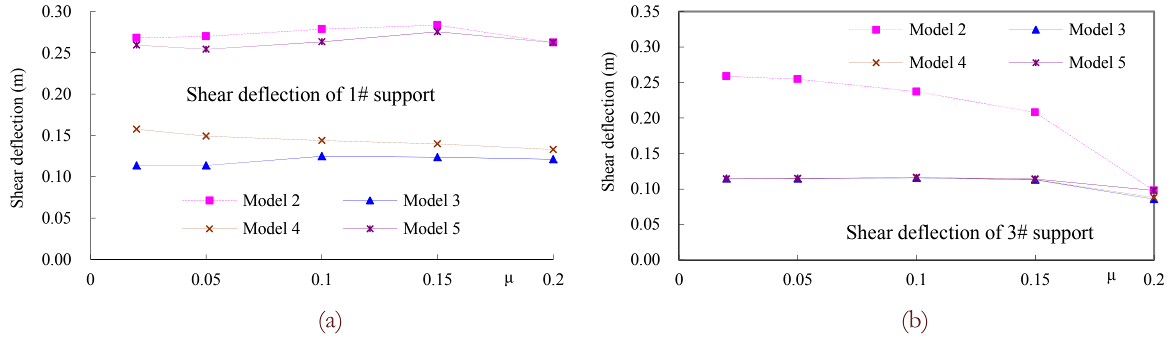


Figure 10: Shear deflection of movable supports under Tianjin Wave.

It can be seen from Fig. 9 to 10 that:

(1) The effect of restraining devices on the displacement of the girder is significant. The displacement of the girder in models with restraining devices is smaller than in models without them. The displacement of the girder in Model 3 where the friction of movable supports and elasticity of restraining devices are both considered is the smallest.

(2) The restraining devices have a certain level of effect on limiting the shear deflection of the movable supports. With the existence of restraining devices, the shear deflection of movable supports is mainly related to the initial gap between the restraining devices.

(3) The variation trend of displacement of the girder is similar to that of the moment of the bottom section of the fixed pier. The increase of displacement of the girder under Tianjin wave is witnessed when friction at movable supports is considered.

CONCLUSIONS

The effect of nonlinearity of supports and restraining devices on the elasto-plastic seismic response of continuous girder bridge is evaluated in this study. Finite element models considering the elasto-plasticity of supports, restraining devices and bridge piers are proposed. Elaso-plastic seismic response is analysed and the following conclusions are drawn:

(1) Results show that analysis ignoring the effect of friction at movable supports is not safe in some circumstances. As the friction of movable supports exists, when analysing bridge structures built on soft ground and structures with first order natural vibration period close to the predominant period of the ground when the stiffness contribution of movable supports is considered, the effect of friction at movable supports should be considered.

(2) In practical design, the restrainers installed on the movable pier should be designed energy intensive to protect the movable pier from being destroyed by the violet pounding force, so model 4 was suggested to analyse the seismic distribution of the seismic force for each pier.

(3) Restraining devices are effective in limiting the displacement of the girder in multi-span girder bridge, reducing the seismic response of the fixed piers and balancing the seismic distribution of each pier; for different structures, detailed finite element analysis can be conducted to modify the initial gap and stiffness of the restraining devices as well as the coefficient of friction and stiffness of the supports to reduce the seismic response of the fixed pier, balance the distribution of seismic input energy at each pier and prevent the input seismic effect from being carried by only the fixed piers.

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