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Study on Nonlinear Dynamic Response of a Curved Viaduct System with Integrated Sliding Bearing System under LevelⅡEarthquakes

Hokkaido University　Student member　○ Di BAI
Hokkaido University　Fellow member　Toshiro HAYASHIKAWA
Hokkaido University　Member　Takashi MATSUMOTO
Hokkaido University　Member　Xingwen HE
Hokkaido University　Student member　Qin TIAN

1. Introduction

In the past decades, horizontally curved viaducts have become an important component in modern highway systems. They represent a viable option at complicated interchanges or river crossings. In addition, the curved alignments result in better aesthetics, an increase in traffic sight distances and economically competitive construction costs compared with straight bridges. On the other hand, bridges with curved configurations may sustain severe damage owing to rotation of the superstructure or displacement towards the outside of the curve due to the complex vibrations that occur during an earthquake [1].

On the other hand, for the purpose of reducing the construction costs, a new type of bearing system, integrated sliding bearing system has been adopted. Integrated sliding bearing system consists of friction sliding bearings and rubber bearings. According to the friction coefficient, there are three kinds of friction sliding bearings, high friction coefficient, middle friction coefficient and low friction coefficient sliding bearing. Low friction coefficient sliding bearings always show a good performance in respect of isolating earthquake force. On the contrary, high friction coefficient sliding bearings are always being outstanding in respect of damping performance. Generally, middle friction coefficient sliding bearings always show a medium performance both in isolating earthquake force and damping [2-4].

Therefore, the purpose of the present study is to analyze the seismic response of curved highway viaduct equipped with integrated sliding bearing system under 1995 Kobe earthquakes. The study combines non-linear dynamic analysis with a three-dimensional bridge model in order to evaluate the seismic response accurately.

2. Analytical Model of Viaduct

The great complexity associated with the seismic analysis of highway viaducts means that a realistic prediction of the bridge structural responses is difficult. Therefore, the seismic analysis of the viaduct employs a non-linear computer model that simulates the highly non-linear response caused by level II earthquakes. Non-linearity is also considered for characterization of the non-linear structural elements of piers and bearings [5]. The highway viaduct considered in the analysis is composed of a three-span continuous superstructure. The overall viaduct length of 120 m is divided into equal spans of 40 m as shown in Fig. 1. The bridge alignment curves in a horizontal, circular arc. A 200 m radius of curvature, measured from the origin of the circular arc to the centerline of the bridge deck is taken into consideration. Tangential configuration for both piers and bearing supports is adopted with respect to the global coordinate system for the bridge, as shown in the figure. The X- and Y-axes lie in the horizontal plane, the Z-axis is vertical.

2.1 Deck superstructure and piers

The highway viaduct superstructure consists of a reinforced concrete deck slab that rests on three I-shape steel girders, equally spaced at an interval of 2.1 m. The total weight of superstructure is 8.82 MN. The deck weight is supported on four hollow box section steel piers with 20 m high, 2.4 m width and 0.05 m thickness designed according to the Japanese seismic code [1]. Characterization of structural pier elements is based on the fiber element modeling where the inelasticity of the flexure element is accounted for by the division of the cross-section into a discrete number of longitudinal and transverse fiber regions with the constitutive model based on uniaxial stress-strain relationship for each zone [6].

2.2 Bearing supports

As the viaduct model has three girders, outside girder and inside girder are equipped with friction sliding bearings, while the middle girder is equipped with rubber bearings shown in Fig.2. The friction sliding bearings are represented by the bilinear force-displacement hysteric loop using high stiffness property to pre-yield stiffness and approximate zero to post-yield stiffness [2]as shown in Fig. 3 (a).The rubber bearings are represented by the linear displacement-load relationship as shown in Fig. 3(b). Three kinds of friction sliding bearings and

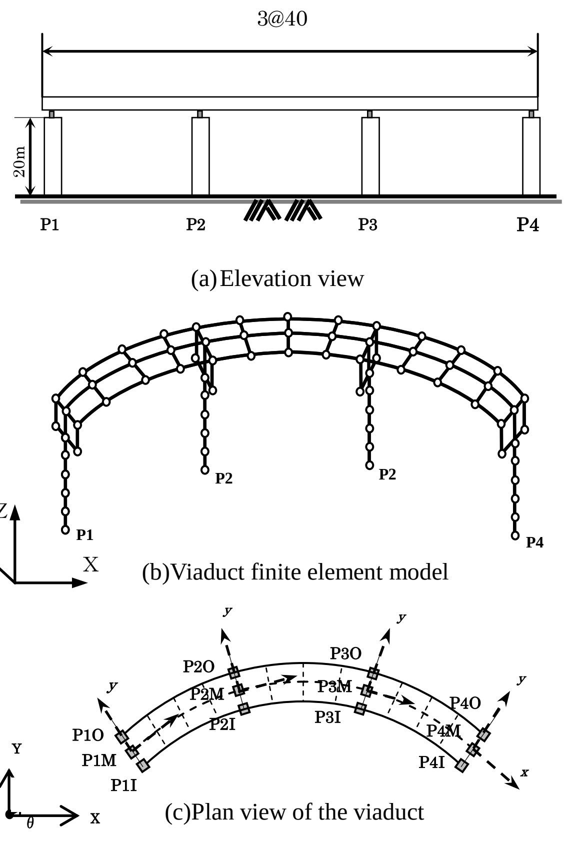


Fig.1 Analytical model of viaduct

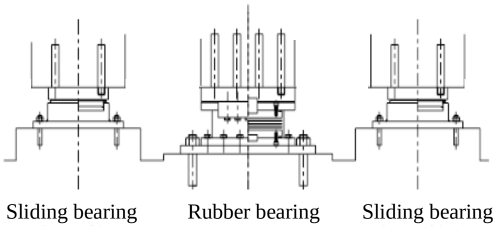


Fig.2 Arrangement of bearing supports

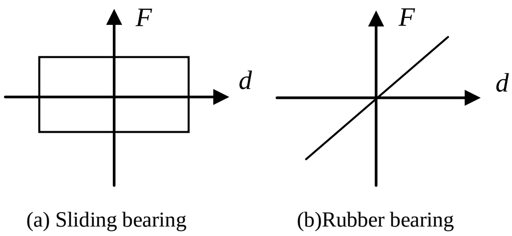


Fig.3 Analytical models of bearing supports

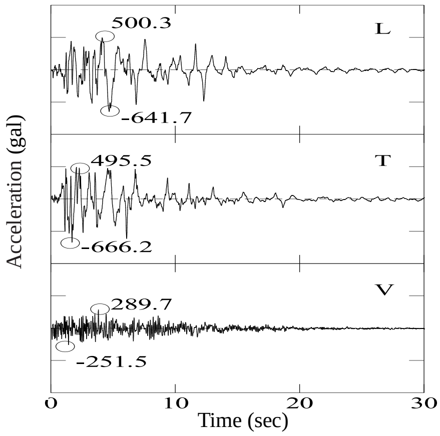


Fig.4 JR Takatori st. record 1995 Kobe earthquake

five different stiffness rubber bearings are discussed. Both friction sliding bearings and rubber bearings are fixed in transverse direction and vertical direction.

3. Method of Analysis

The analysis on the highway viaduct model is conducted using an analytical method based on the elasto-plastic finite displacement dynamic response analysis. The tangent stiffness matrix, considering both geometric and material nonlinearities is adopted in this study, being the cross sectional properties of the nonlinear elements prescribed by using fiber elements. The stress-strain relationship of the beam-column element is modeled as a bilinear type. The yield stress is 235.4 MPa, the elastic modulus is 200 GPa and the strain hardening in plastic area is 0.01. The implicit time integration Newmark scheme is formulated and used to directly calculate the responses, while the Newton-Raphson iteration method is used to achieve the acceptable accuracy in the response calculations. The damping of the structure is supposed a Rayleigh's type, assuming a damping coefficient of the first two natural modes of 2%.

To assess the seismic performance of the viaduct, the nonlinear bridge model is subjected to the longitudinal, transverse and vertical components of a strong ground motion records from the Takatori Station during the 1995 Kobe Earthquake as shown in Fig.4. The longitudinal earthquake component shakes the highway viaduct parallel to the X-axis of the global coordinate system, while the transverse and vertical components are acting in the Y- and Z-axes, respectively.

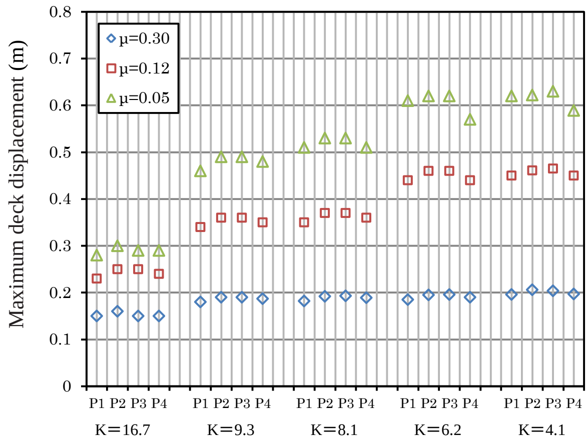


Fig.5 Maximum deck displacement in longitudinal direction

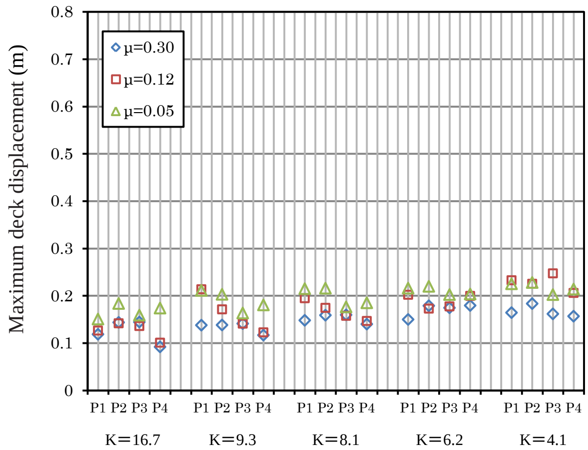


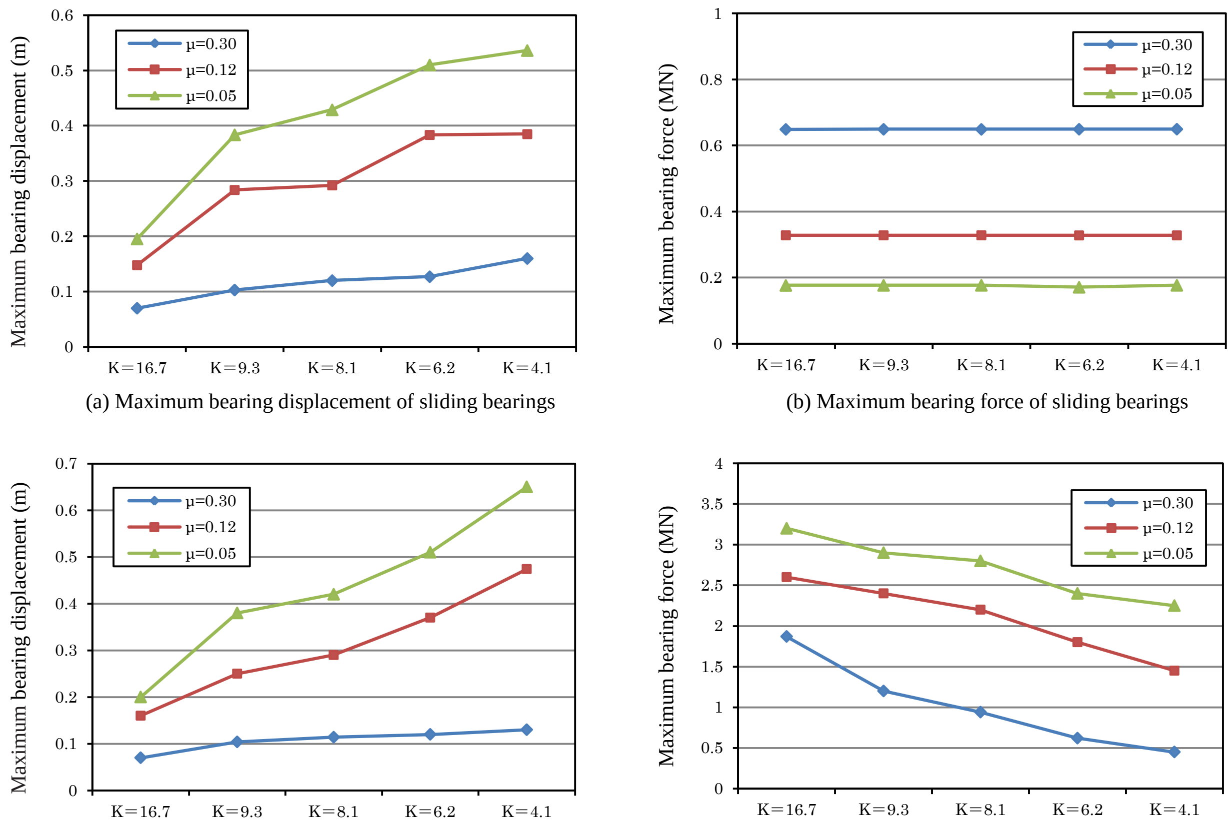
Fig.6 Maximum deck displacement in transverse direction

4. Numerical Results

The overall three-dimensional seismic responses of the viaducts were investigated in details by the way of non-linear dynamic response analysis. Particular attention was paid to the maximum deck displacement, the maximum bearing displacement and force, and the maximum bending moment transmitted to the base of the pier.

4.1 Deck superstructure response

In order to evaluate the effects of the installation of integrated sliding bearing system, the maximum deck displacement of all the cases was evaluated both in longitudinal and transverse direction. The displacement at the top of the deck resting on I-section outside girders is shown in Fig.5 and Fig.6. In longitudinal direction (Fig.5), firstly, the effectiveness of the friction coefficient of sliding bearings was assessed by three different friction coefficients. The results show that, for those cases which equipped with same stiffness rubber bearings, the higher maximum deck displacement was always observed in the cases which equipped with low friction coefficient sliding bearings. On the contrary, the maximum deck displacement is lowest in those cases which equipped with high friction coefficient sliding bearings. Secondly, the effectiveness of the stiffness of rubber bearings was studied here by five different stiffness rubber bearings. From the figure it is quite clear that, for those cases which equipped with same friction coefficient sliding bearings, the higher maximum displacement were exhibited by the small stiffness rubber bearings, in the meanwhile, with the increasing of rubber stiffness, the



(a) Maximum bearing displacement of sliding bearings

(b) Maximum bearing force of sliding bearings

(c) Maximum bearing displacement of rubber bearings

(d) Maximum bearing force of rubber bearings

Fig.7 Maximum bearing displacement and Maximum bearing force in longitudinal direction (P3)

maximum deck displacement decreased. On the other hand, in transverse direction (Fig.6), the maximum deck displacement is obviously lower than that in longitudinal direction since all the bearings were fixed in this direction. Furthermore, no obvious influence on the maximum deck displacement was observed by changing the rubber stiffness or the friction coefficient.

Thus, from the results shown in Fig. 5 and Fig. 6, it can be seen that, in terms of deck displacement, the cases with high friction coefficient sliding bearings or larger stiffness rubber bearings, would prove to be a suitable solution.

4.2 Bearing supports

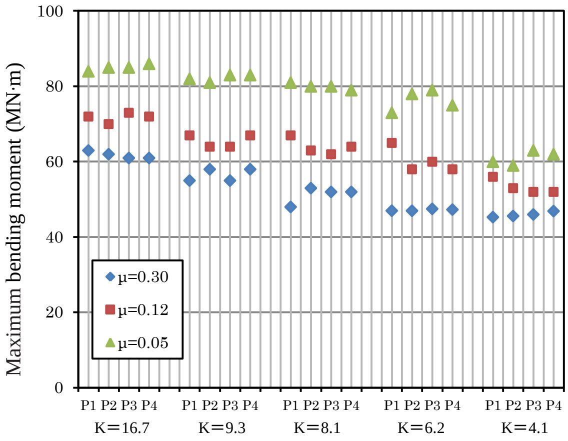
This section clarifies the selection of the optimum stiffness of rubber bearings and friction coefficient of sliding bearings in integrated sliding bearing system by comparing the calculated results in terms of maximum bearing displacements and maximum bearing force (Fig. 7). These displacement and force was considered at the bearings resting on the top of the P3 pier in longitudinal direction. Firstly, the calculated results of sliding bearings (outside girders) are shown in Fig. 7(a) and (b). It can be seen that, if the friction coefficient of sliding bearings was set as a fixed value, with the decreasing of the rubber stiffness, the maximum bearing displacement increased, in the meanwhile, the maximum bearing force almost remained unchanged. When sliding bearings start to slide, the maximum bearing force will turn into a constant value, since the friction coefficient was set as a fixed value and dead load is also a constant value. Thus, from these cases, it can be confirmed that the sliding bearings have already started to slide.

Secondly, the calculated results of rubber bearings (middle girders) are shown in Fig. 7(c) and (d). It is quite clear that, if the friction coefficient of sliding bearings was set as a fixed value, with the decreasing of the rubber stiffness, the maximum bearing displacement increased, on the contrary, the maximum bearing force decreased.

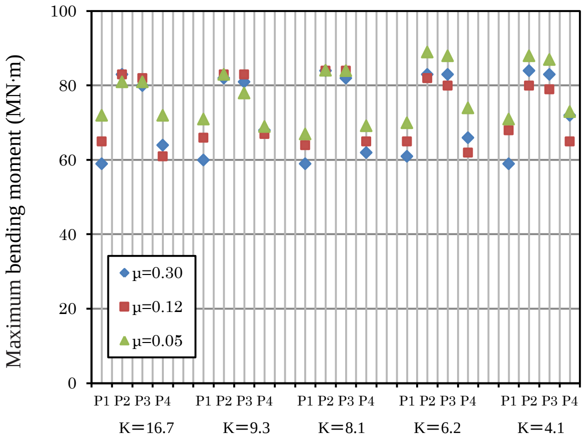
On the other hand, if the rubber stiffness was set as a fixed value, it can be seen from the Fig. 7, among all the cases, higher maximum bearing displacement is always observed in those cases which equipped with low friction coefficient sliding bearings. On the contrary, the maximum bearing displacements is lowest in those cases which equipped with high friction coefficient sliding bearings. Furthermore, for sliding bearings, highest maximum bearing force observed in high friction coefficient cases and lowest force in low friction coefficient cases. While, the rubber bearings cases are on the contrary. This is because for the sliding bearings, the maximum bearing force was decided by the friction coefficient, while for rubber bearings, if the rubber stiffness was set as a fixed value, the bearing force will be influenced by the bearing displacement. Higher bearing force of rubber bearings was observed in the cases with higher rubber bearing displacement.

4.3 Pier damage

When a bridge is subjected to strong earthquake shaking, the supporting piers may suffer severe seismic damage at their bases. It is well known that maximum bending moment transmitted to the base of the pier can be considered to be an appropriate measure of seismic structural damage, and for this reason they have been adopted as an important response factor in the present study. The maximum bending moment of each pier in X and Y direction are shown in the Fig 8(a) and (b) for a better appreciation of the pier responses. Firstly, on the X direction, the maximum bending moment of all the piers is lower than the yield bending moment, 84.8 MN, which means all the piers behave elastically. Furthermore, the results also show that, with the decreasing of the rubber stiffness or the



(a) Maximum bending moment on X direction



(b) Maximum bending moment on Y direction

Fig.8 Maximum bending moment transmitted to the base of the piers

increasing of the friction coefficient, the maximum bending moment decreased. Since it was confirmed in 4.2, for the rubber bearings, with the decreasing of the rubber stiffness or the increasing of the friction coefficient, the bearing force decreased. However for the sliding bearings, changing the rubber stiffness makes no influence on bearing force. On the other hand, although the increasing of the friction coefficient lead into the increasing of sliding bearing force, but comparing with the rubber bearings force, the numerical value is relatively small. Thus, the maximum bending moment transmitted to the base of the pier is strongly influenced by the maximum bearing force of rubber bearings was confirmed. For the purpose of reducing pier damage, to restrain the bearing force of rubber bearings would prove to be a suitable solution.

Secondly, on the Y direction, most of the piers behaved elastically and since all the bearings were fixed in the transverse direction, no obvious influence on the maximum bending moment was observed by changing the rubber stiffness or the friction coefficient. However, it is worth mentioning that, the maximum bending moment transmitted to the base of the P2 and P3 are significantly higher than that transmitted to the base of P1 and P4. Such behavior was expected because P2 and P3 were afforded larger dead load than P1 and P4.

5. Conclusions

In order to verify the seismic vulnerability of curved viaducts which equipped with integrated sliding bearing system, above-mentioned cases have been analyzed. The overall three-dimensional seismic responses of the viaducts were investigated in the maximum deck displacement, the maximum bearing displacement and force, and the maximum bending moment transmitted to the base of the pier.

(1)The results show that the maximum displacement of deck superstructure in longitudinal direction was strongly influenced by the friction coefficient of sliding bearings and the stiffness of rubber bearings. Equipping with high friction coefficient sliding bearings or large stiffness rubber bearings would prove to be an effective solution to restrain the displacement of deck superstructure in earthquake.

(2)The results of maximum bearing displacement and force show that, for rubber bearings, combining with high friction coefficient sliding bearings or adopting medium stiffness rubber bearings can avoid the significantly large bearing displacement and force. On the other hand, for sliding bearings, combining with large stiffness rubber bearings or adopting high friction coefficient sliding bearings can effectively restrain the displacement, while since the sliding bearings have already started to slide, no obviously influence on the bearing force was observed by changing the stiffness of rubber bearings. Thus, equipping high friction coefficient sliding bearings or medium stiffness rubber bearings would prove to be a suitable way.

(3)The calculated results of maximum bending moment transmitted to the base of the pier perfectly appreciated that, on the X directions, adopting high friction coefficient sliding bearings or small stiffness rubber bearings can restrain the bending moment effectively. In the meanwhile, On the Y directions, no obvious influence on maximum bending moment was observed by changing the rubber stiffness or the friction coefficient. Thus, equipping high friction coefficient sliding bearings or small stiffness rubber bearings would prove to be an effective way to protect the piers from damage.

(4)As a result, considering all the vulnerability of the curved viaducts which equipped with integrated sliding bearing system, combining high friction coefficients sliding bearings with medium stiffness rubber bearings would prove to be a best solution.

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