A Study on Dynamic Response of a Curved Viaduct System with Integrated Sliding Bearing in Consideration of the Direction of Earthquake

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ABSTRACT

The purpose of the study is to investigate the seismic response of curved highway viaduct equipped with integrated sliding bearing system under 1995 Kobe earthquakes in consideration of the direction of earthquake. The results show that the maximum deck displacements, the maximum bearing deformation and force, and the maximum bending moment transmitted to the base of the pier were strongly influenced by the friction coefficient of sliding bearings, the stiffness of rubber bearings and the direction of earthquake. From the results, we can conclude an appropriate combination of the friction coefficient of sliding bearings and the stiffness of rubber bearings which could significantly reduce the bridge damages under Level Ⅱ Earthquakes.

Keywords: Integrated sliding bearing system, Earthquake direction, Seismic design

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 the meanwhile, 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 (Japan Road Association.2002).

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 in consideration of the direction of earthquake. In order to verify the seismic vulnerability of curved viaducts which equipped with integrated sliding bearing system, three kinds of friction sliding bearings (μ) and three different stiffness (k, MN/m) rubber bearings have been analyzed. The directions of earthquake (θ) are taken into account and changed from 0° to 90° by 15°. The overall three-dimensional seismic responses of the viaducts are investigated in the maximum deck displacements, the maximum bearing deformation and force, and the maximum bending moment transmitted to the base of the pier.

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2. ANALYTICAL MODEL OF VIADUCT

2.1. Deck superstructure and piers

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. The highway viaduct superstructure consists of a reinforced concrete deck slab that rests on three I-shape steel girders. 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 (Yoshitaro Nakai et al. 2008).

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 as shown in the 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 (μ) and three different stiffness (k, MN/m) rubber bearings are discussed. Both friction sliding bearings and rubber bearings are fixed in transverse direction and vertical direction. The structural properties of integrated sliding bearing system are shown in Table 1. (Rinna Tanaka et al. 2009; Mendez Galindo et al.2009).

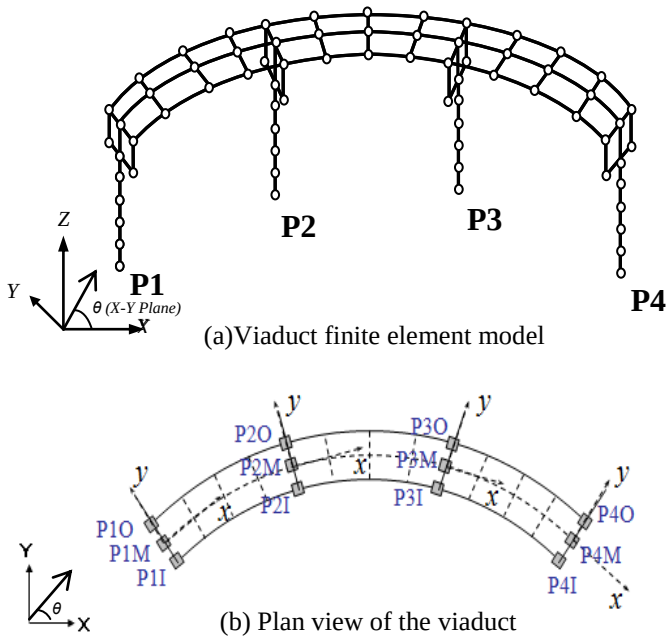


Fig.1 Analytical model of viaduct

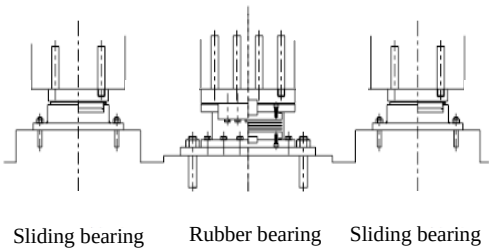


Fig.2 Arrangement of bearing supports

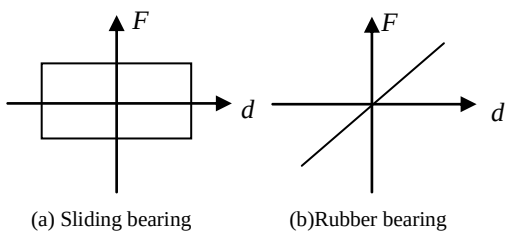


Fig.3 Analytical models of bearing supports

Table 1: Structural properties of integrated sliding bearing system

Bearing	K_1(MN/m)	K_2(MN/m)	K_3(MN/m)	F_1(MN)	F_2(MN)
Rubber I	9.3	—	—	—	—
Rubber II	8.1	—	—	—	—
Rubber III	6.2	—	—	—	—
Sliding I	5×10^3	9.8×10^{-4}	—	0.662	—
Sliding II	5×10^3	9.8×10^{-4}	—	0.331	—
Sliding III	5×10^3	9.8×10^{-4}	—	0.180	—

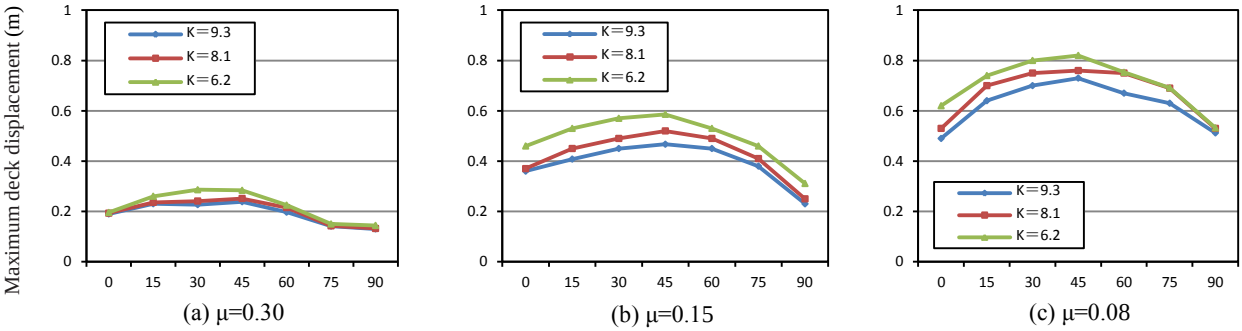


Fig.4 Maximum deck displacement in longitudinal direction

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 damping of the structure is supposed a Rayleigh's type, assuming a damping coefficient of the first two natural modes of 2% (Mendez Galindo et al. 2010).

4. NUMERICAL RESULTS

4.1. Deck superstructure response

The displacement at the top of the deck resting on I-section outside girders above the P3 pier in longitudinal direction is shown in Fig.4. The directions of earthquake are taken into account and changed from 0° to 90° by 15°. The results show that, if the friction coefficient of sliding bearings was set as a fixed value, with the increasing of the rubber stiffness, the maximum displacement decreased. On the other hand, if the rubber stiffness was set as a fixed value, with the increasing of the friction coefficient, the maximum displacement also decreased.

As for the effect of earthquake angles, we can see from the Fig.4, among all these cases, the maximum displacement of the deck in longitudinal direction was highly influenced by changing the direction of the earthquake ground motions and attained to the maximum at about 45 degrees.

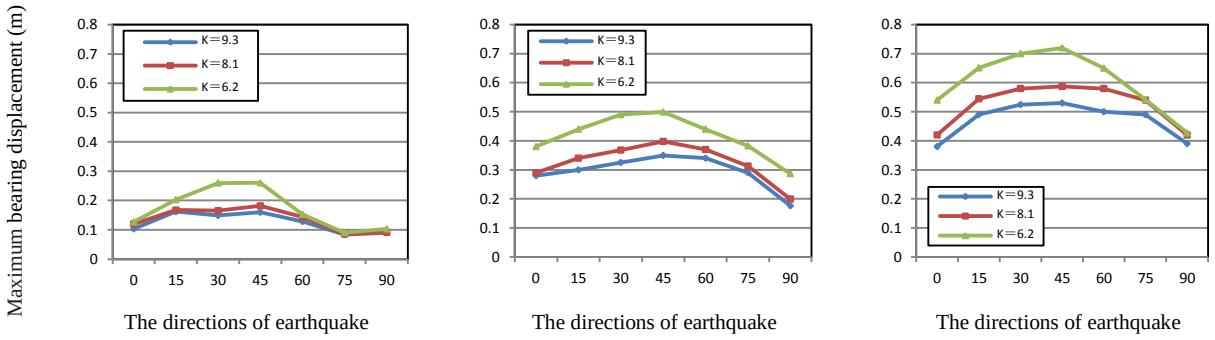
4.2. Bearing supports

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 in consideration of the direction of earthquake. These displacement and force was considered at the bearings resting on the top of the P3 pier in longitudinal direction. Since before an actual earthquake happens, it is impossible to know the direction of the earthquake ground motions which will effect on the structure, the earthquake angles which changed from 0° to 90° by 15° were taken into consideration.

Firstly, the calculated results of sliding bearings (above outside girders) are shown in Figs. 5 and 6, It can be seen that, if the friction coefficient of sliding bearings was set as a fixed value, with the increasing of the rubber stiffness, the maximum bearing displacement decreased, 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. Furthermore, if the rubber stiffness was set as a fixed value, higher maximum bearing displacement is always observed in cases which equipped with low friction coefficient sliding bearings. While highest maximum bearing force is observed in high friction coefficient cases and lowest force in low friction coefficient cases. This is because the maximum bearing force was decided by the friction coefficient and dead load as mentioned above.

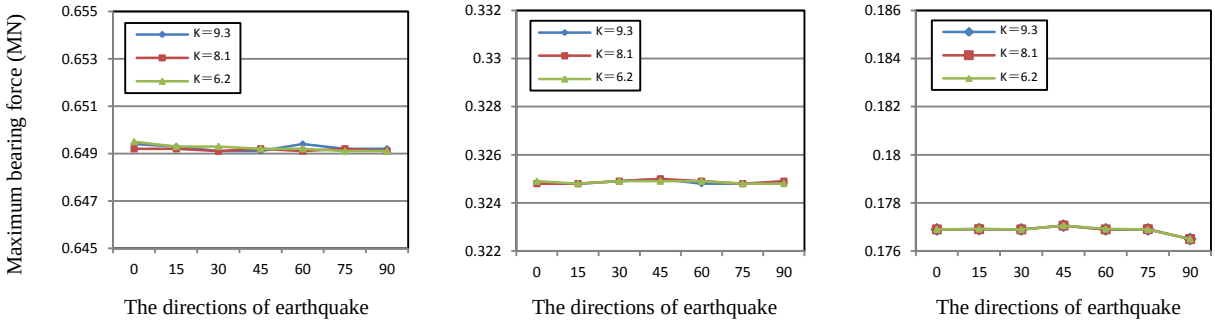
Secondly, the calculated results of rubber bearings (above middle girders) are shown in Figs. 7 and 8, It is quite clear that, if the friction coefficient of sliding bearings was set as a fixed value, with the increasing of the rubber stiffness, the maximum bearing displacement decreased, on the contrary, the maximum bearing force increased. On the other hand, if the rubber stiffness was set as a fixed value, among all the cases, higher maximum bearing displacement is always observed in those cases which equipped with low friction coefficient sliding bearings. As for the bearing force, higher bearing force of rubber bearings was also observed in the cases with low friction coefficient sliding bearings.

As for the effect of the direction of earthquake ground motions, we can see from the Fig.5 to Fig.8, except the maximum bearing force of sliding bearings, in all these cases, the maximum displacement of both bearings and the maximum bearing force of rubber bearings was highly influenced by changing the direction of the earthquake ground motions and attained to the maximum at about 45 degrees. As for the maximum bearing force of sliding bearings, since the maximum bearing force was decided by the friction coefficient and dead load which are fixed value already as mentioned above, no obvious influence was observed by changing the direction of earthquake ground motions.



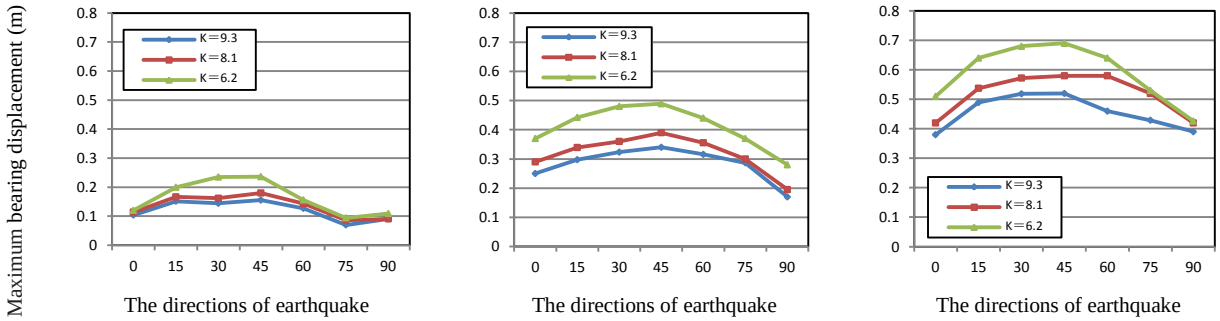
(a) μ=0.30 (b) μ=0.15 (c) μ=0.08

Fig.5 Maximum displacement of sliding bearings



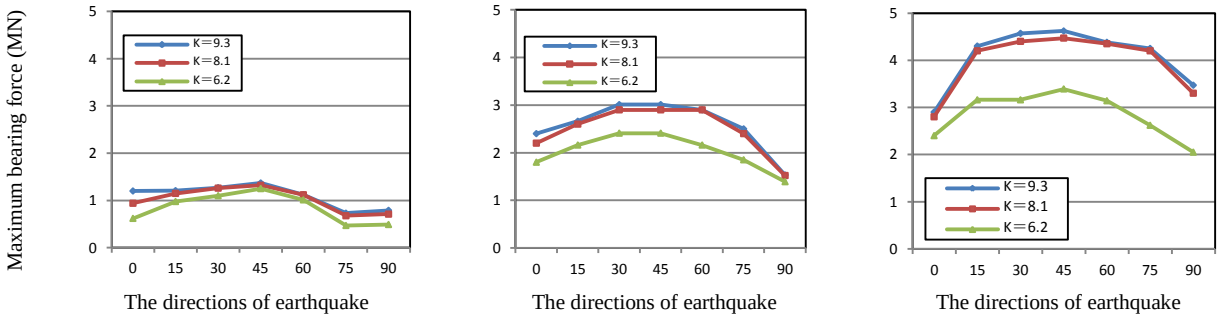
(a) μ=0.30 (b) μ=0.15 (c) μ=0.08

Fig.6 Maximum force of sliding bearings



(a) μ=0.30 (b) μ=0.15 (c) μ=0.08

Fig.7 Maximum displacement of rubber bearings



(a) μ=0.30 (b) μ=0.15 (c) μ=0.08

Fig.8 Maximum force of rubber bearings

4.3. Pier damage

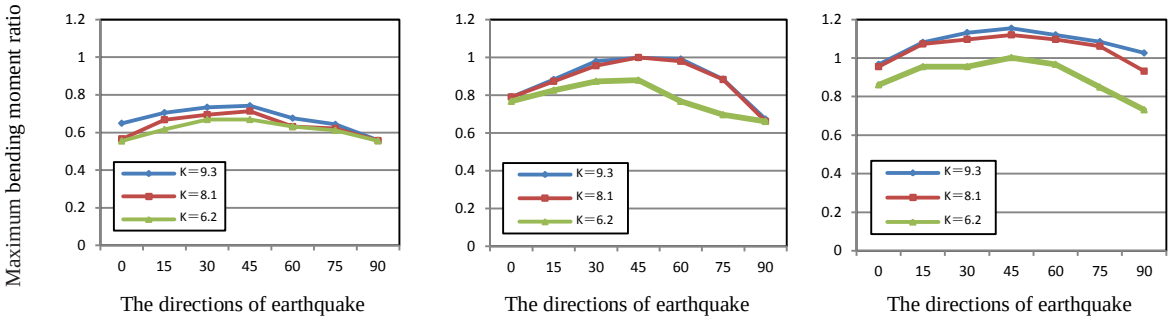
When a bridge is subjected to strong earthquake shaking, the supporting piers may suffer severe seismic damage at their bases. Thus, the bending moment ratio, the maximum bending moment over the yield bending moment (84.8 MN), have been adopted as an important response factor in the present study. The directions of earthquake are taken into account and changed from 0° to 90° by 15°. As the analytical model is a symmetric structure, only the bending moment ratio in X and Y direction of P1 and P3 are shown in the Fig 9 to Fig 12 for a better appreciation of the pier responses.

Firstly, on the X direction, the bending moment ratio of all the piers is lower than one, which means all the piers behave elastically. Furthermore, the results also show that, with the increasing of the rubber stiffness or the decreasing of the friction coefficient, the maximum bending moment ratio increased, which means the maximum bending moment increased. Since it was confirmed in 4.2, for the rubber bearings, with the increasing of the rubber stiffness or the decreasing of the friction coefficient, the bearing force increased. 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 quantity value is relatively small. Therefore, the maximum bending moment transmitted to the base of the pier is strongly influenced by the maximum bearing force of rubber bearings was confirmed. Thus, 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 bending moment ratio 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 P3 are significantly larger than that transmitted to the base of P1. Such behavior was expected because P2 and P3 were afforded larger dead load than P1 and P4.

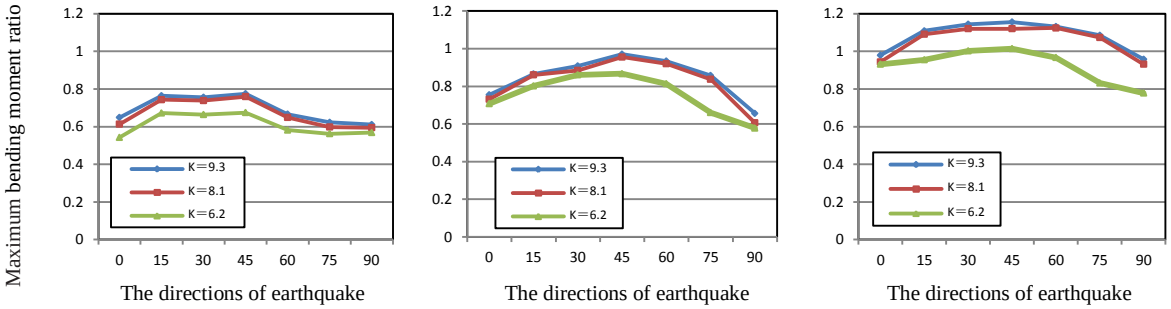
As for the effect of the direction of earthquake ground motions on the X direction, we can see from the Figs. 9 and 10, in all these cases, both in P1 and P3, the maximum bending moment ratio of each pier was highly influenced by changing the direction of the earthquake ground motions and attained to the maximum at about 45 degrees. On the other hand, the effect of the direction of earthquake ground motions on the Y direction, Figs. 11 and 12, show that in all these cases, the maximum bending moment ratio of each pier was highly influenced by changing the earthquake angle and attained to the peak at about 90 degrees both in P1 and P3.

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.



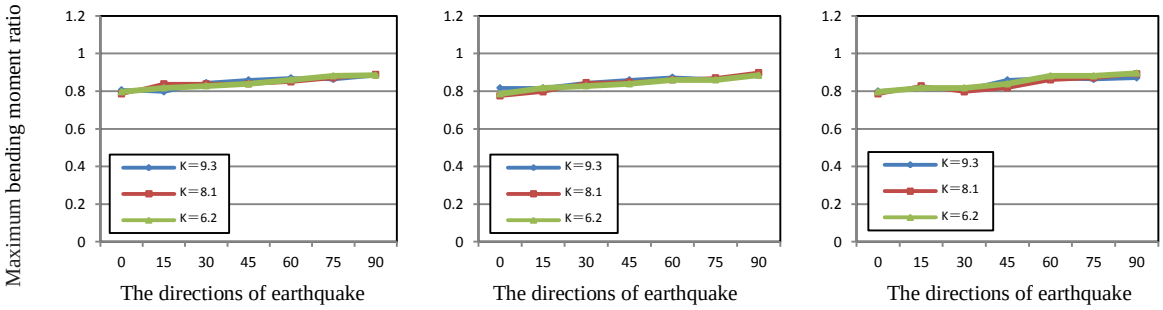
(a) μ=0.30 (b) μ=0.15 (c) μ=0.08

Fig.9 Maximum bending moment ratio on X direction of P1



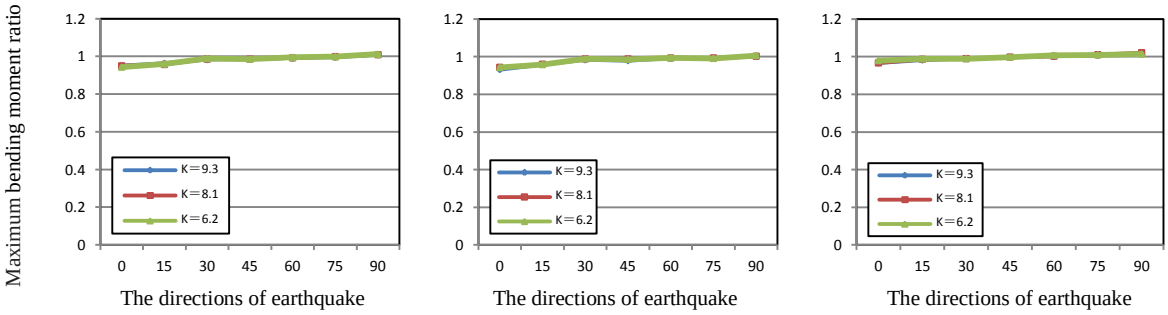
(a) μ=0.30 (b) μ=0.15 (c) μ=0.08

Fig.10 Maximum bending moment ratio on X direction of P3



(a) μ=0.30 (b) μ=0.15 (c) μ=0.08

Fig.11 Maximum bending moment ratio on Y direction of P1



(a) μ=0.30 (b) μ=0.15 (c) μ=0.08

Fig.12 Maximum bending moment ratio on Y direction of P3

5. CONCLUSIONS

In order to verify the seismic vulnerability of curved viaducts which equipped with integrated sliding bearing system in consideration of the direction of earthquake, above-mentioned cases have been analyzed. The directions of earthquake are changed from 0° to 90° by 15°. 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) In order to restrain the displacement of deck superstructure，to avoid the significant bearing displacement and force and protect the piers from damage, which 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.

(2) As for the effect of the direction of earthquake ground motions, the maximum displacement of the deck superstructure in longitudinal direction, the maximum displacement of both bearings, the maximum bearing force of rubber bearings and the maximum bending moment ratio of each pier on X direction was highly influenced by changing the direction of the earthquake ground motions and attained to the maximum at about 45 degrees. The maximum bending moment ratio of each pier on Y direction attained to the maximum at about 90 degrees. As for the maximum bearing force of sliding bearings, no obvious influence was observed. As a result, the direction of earthquake ground motions has a great influence on the viaduct was confirmed and it is recommended to be taken into consideration in actual design.

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