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A STUDY ON THE SEISMIC PERFORMANCE OF A SLIDING TYPED SEISMIC ISOLATION SYSTEM APPLIED FOR BRIDGES

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SUMMARY

This paper reports the seismic performance of ordinary girder-typed bridges incorporating a sliding typed seismic isolation system for level 2 earthquake motions. The analytical study with three-dimensional framed models is carried out to make a clear understanding of bridge response considering not only the interactive dependency of friction coefficient for pressure and velocity but also bearing stiffness of the sliding typed seismic isolation system. This paper also mentions desirable range of parameters such as friction coefficient and bearing stiffness in order to obtain better seismic performance of seismically isolated bridges. From the analytical study, suitable analysis conditions to obtain reliable calculated results are found. The outcome from the abovementioned study can give efficient information for designers when they choose the sliding typed seismic isolation system in order to design bridges with better seismic performance.

INTRODUCTION

Seismic isolation of bridges is an effective way to rationally reduce the influence of earthquake motions in countries with high seismic activity like Japan. In the field of bridges in Japan, laminated rubber bearings with damping devices such as lead plugs and steel bars, and so on are widely known as typical seismic isolation systems. On the other hand, seismic isolation systems using sliding bearings have been in used for some time [1] in the field of buildings in Japan. In the field of bridges, a number of studies have been undertaken [2,3,4] on seismic isolation systems using sliding bearings, and a number of such systems have been put to practical use [5]. Izuno et al. termed seismic isolation systems using such sliding bearings as "separately functional bearing systems" consisting of (1) sliding bearings that carry vertical loads and absorb rotational displacement of girders (normal functions) and reduce earthquake loads by damping (seismic function) and (2) horizontal load distribution devices that distribute the inertia force of superstructure, make the vibration period longer and provide restoring force (hereafter in this paper referred to as "sliding isolation bearing systems"). This concept has come to be recognized widely. Studies on such systems include many concerning the determination of the friction coefficient of sliding bearings

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including the bearing pressure dependence and velocity dependence of the friction coefficient. Previous studies concerning the velocity dependence of the friction coefficient for bearing systems concluded that the influence of such dependence is small. The loading velocities for which verification was made, however, are as low as several tens of kine (1 kine=1 cm/s), and the little data are available on the influence of loading velocity on the friction coefficient and hysteresis characteristics at higher velocities (higher than 100 kine) that are likely to occur in times of earthquakes.

In general, sliding isolation bearing systems (separated-function type) are superior to ordinary (laminated rubber typed) isolation bearings (integrated-function type) in the degree of freedom in designing seismically isolated bridges. Friction coefficients of sliding bearings, however, vary widely, however, and the effects of such variation need to be taken into account in the design process. In the seismic design of a bridge with sliding isolation bearing systems, it is necessary to model the entire structure and conduct dynamic analysis in order to achieve rationality and accuracy goals because the behavior of such a bridge during an earthquake is not simple.

This paper reports the results of a multi-parameter sensitivity analysis conducted using a model of a viaduct equipped with a sliding isolation bearing system. In the dynamic analysis of the entire viaduct structure, coupling characteristics of the friction coefficients of sliding bearings depending on both bearing pressure and velocity that were determined according to the results of separately conducted tests were incorporated into the analysis model as faithfully as possible. The bridge model thus defined was used to investigate the effects of the friction coefficients of sliding bearings and the stiffness of horizontal load distribution devices on the relative horizontal displacements of the superstructure and the substructure and plasticization at the pier column base. The study results thus obtained are reported in this paper. This study also discusses the effects of several patterns of velocity dependence characteristics of the friction coefficient (although the characteristics of the friction coefficient in the high velocity range are not known clearly) on bridge response, and considerations in seismic design. Taking into account the study results mentioned above, this paper proposes a simple approach to the seismic design of sliding isolation bearing systems, paying attention to the friction coefficient and the modeling of sliding isolation bearing systems.

OUTLINE OF THE CASE STUDY BRIDGE AND CONDITIONS FOR ANALYSIS

(1) Structural details of the case study bridge
The case study bridge is a 3-span continuous steel twin-box-girder bridge equipped with sliding isolation bearing systems. The substructure consists of reinforced concrete single-column piers, and the foundation structure consists of cast-in-place piles. The sliding isolation bearing systems of the bridge include sliding bearings that use PTFE and steel plates and laminated rubber bearings used as horizontal load distribution devices. Figure 1 shows the structure of the bridge.

(2) Modeling of the bridge
The bridge to be studied parametrically through dynamic analysis was modeled using three-dimensional beam and spring elements shown in Figure 2. Bearings, which are the most important consideration in the study, were modeled as follows: the sliding bearings and horizontal load distribution devices were modeled individually with spring elements, and the sliding bearings were assumed to have bilinear nonlinear hysteresis characteristics to allow for changes in vertical force. To investigate the effect of changes in vertical force due to rocking vibration of the girder, elements on the same bearing lines were not aggregated; instead, they were modeled individually and were connected to the girder and the pier tops by using rigid elements.

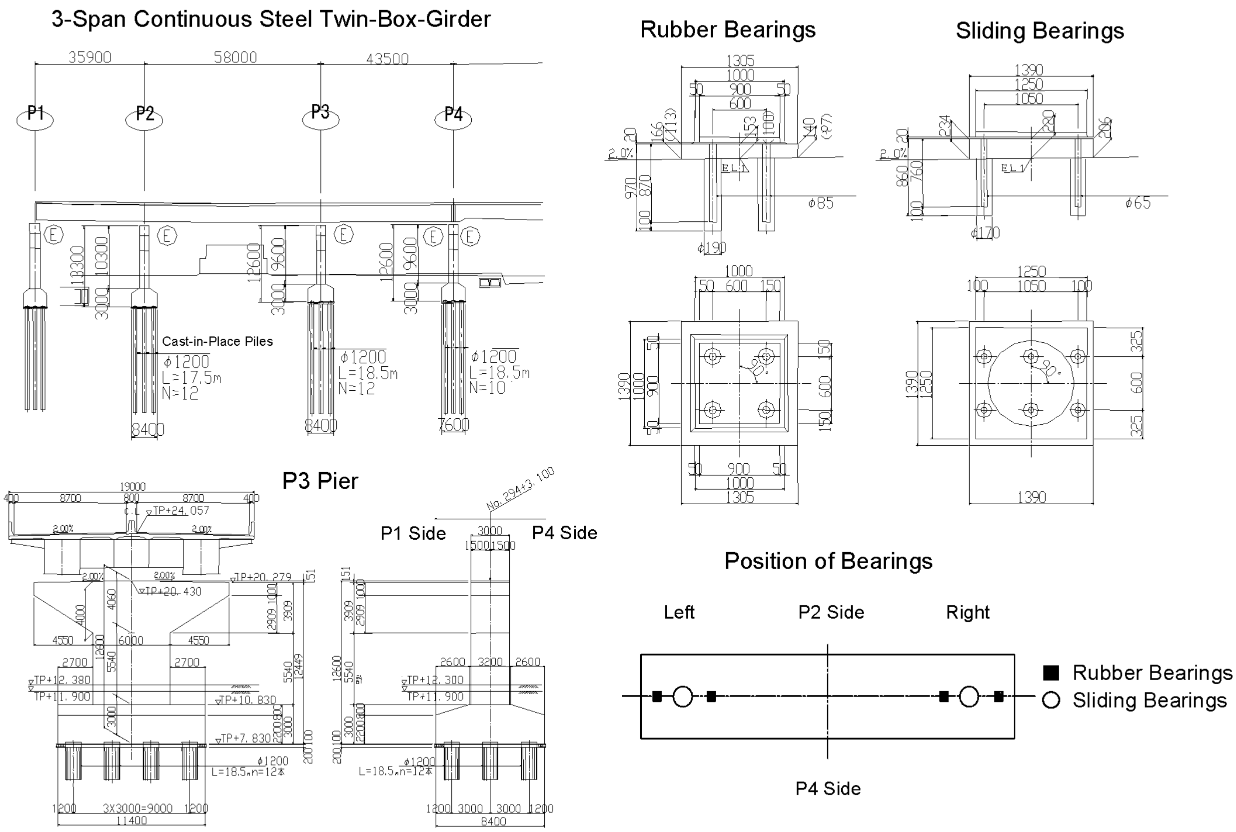

Figure 1. Structure of the Bridge

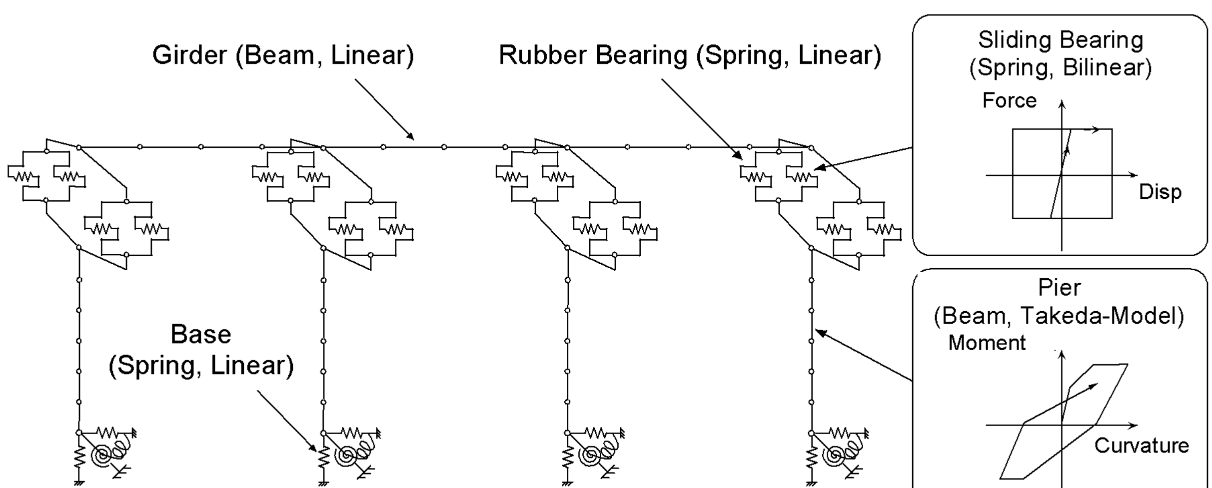

Figure 2. Model of the Bridge

The piers were modeled with beam elements, and the modified Takeda model, which is widely used for analyzing reinforced concrete members, was used to express nonlinear hysteresis characteristics. The foundation and ground were modeled as lumped springs (linear spring elements) in accordance with the method described in the Specifications for Highway Bridges: Part V, Seismic Design [6] (hereafter referred to as the "SHB V").

Since the bridge is one of a series of viaducts, the influence of the adjoining bridges cannot be ignored in analyzing the structural behavior during earthquakes. The bearings supporting the adjoining spans, therefore, were modeled as spring elements resting on the common piers, and the mass of one half of each of the adjoining spans was added to the spring end.

(3) Conditions for dynamic analysis

The dynamic analysis in the study was performed by nonlinear time history response analysis based on the direct integration method, and the parameters were set as shown in Table 1. The material damping factors for different parts of the model were determined by referring to SHB V, but the ordinary Rayleigh damping was not assumed for the viscous damping matrix for the entire system; instead, a Rayleigh damping matrix was defined for each of the elements such as the girder and piers, and damping matrices thus obtained were superimposed.

Bilinear nonlinearity was assumed for the sliding bearings in the model. Because of high initial stiffness, however, if Rayleigh damping is simply applied to the entire structure, stiffness-proportional damping at the sliding bearings will become so high as to reduce the accuracy of analysis (unrealistically large damping will be indicated in addition to hysteretic damping). To avoid this problem, the proportionality constants at the bearings were assumed to be zero so that viscous damping was excluded.

Table 1. Conditions for Analysis

Analytical method		Direct integration method, Nonlinear analysis
Numerical integration method		Newmark's β method
Time interval		0.001 sec.
Damping type		Member based Rayleigh damping
Damping ratios of elements	girder	0.02
	bearing	0.00
	pier	0.02
	foundation	0.20
Input seismic motions		SHB V Level1-II
		SHB V Level2 Type1-II-1
		SHB V Level2 Type2-II-1
		K-net record at Chokubetsu (EW)
		JMA record at Wakuya (EW)

A total of five input earthquake motions, consisting of two earthquake motions with adjusted amplitudes and three observed earthquake motions, were used. The former are three types (level 1, T1-II-1, T2-II-1) of time history acceleration waveforms for Type II ground described in SHB V, and the latter are a K-NET (Kyoshin Network) record [7] obtained at Chokubetsu (Hokkaido) during the Tokachi-oki Earthquake of 2003 and a JMA (Japan Meteorological Agency) record [8] obtained at Wakuya (Miyagi Prefecture) during the Miyagi-ken Hokubu Earthquake of 2003 (Figure 3). The cases in which an acceleration wave is input only in the bridge axis direction or the direction perpendicular to the bridge axis, and the cases in which acceleration waves are input in the two directions simultaneously were analyzed.

MODELING OF SLIDING BEARINGS

(1) Consideration of the effect of vertical force

If vertical force is constant, the hysteretic restoring force characteristics of sliding bearings can be expressed with a bilinear model that approximates perfect elastoplasticity. If, however, vertical force changes, friction force also changes even if the friction coefficient remains constant, and hysteretic restoring force characteristics become too complex to be expressed with a simple bilinear model. In this study, a hysteresis model that faithfully reflects this effect was used to take into account the influence of changes in vertical force on the dynamic behavior of the structure in the analysis.

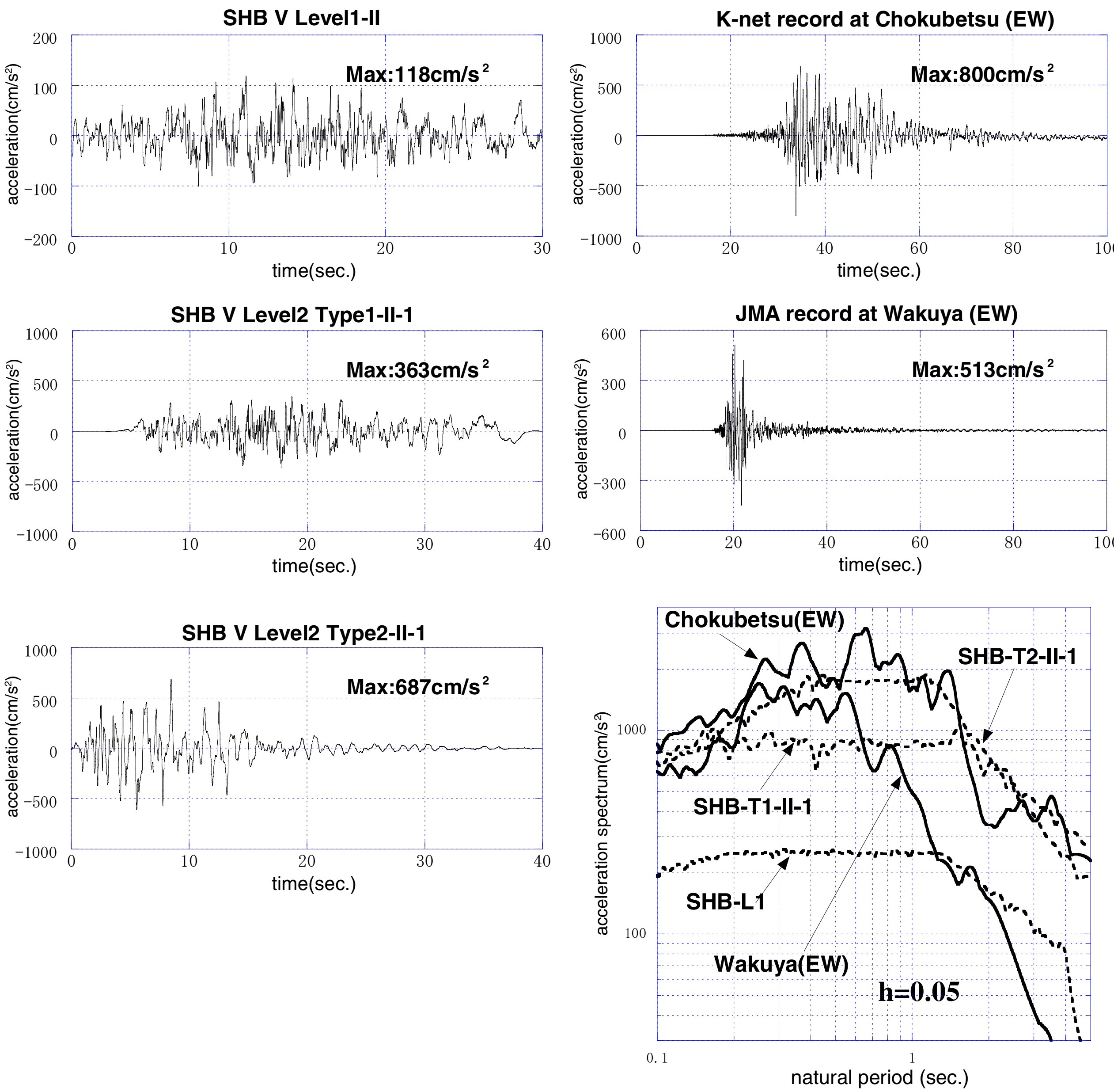

Figure 3. Input Earthquake Motions

(2) Consideration of the velocity/bearing pressure dependence of the friction coefficient
It is generally known that in sliding, not only friction force changes in proportion to the change in vertical force, but also the friction coefficient changes as sliding velocity or bearing pressure (vertical force) changes. Analytical studies taking these dependence characteristics have been undertaken, but many of those studies paid attention only to either velocity dependence or bearing pressure dependence. In this study, both the case in which these two types of dependence are taken into account and the cases in which only one of the two types of dependence is taken into account were considered.

For velocity and bearing pressure dependence characteristics, the model proposed by Takahashi et al. [9] was used (Figure 4). It is an empirical equation formulated to express velocity and bearing pressure dependence on the basis of the results of tests on the same bridge that is being considered in the present study. The equation is written as follows:

$$\mu = 1.3787 \times [1-\exp(-0.1967v)] \times \frac{[1-\exp(-0.1017P)]}{P} + 0.0458$$

μ : friction coefficient of sliding bearings

v : sliding velocity

P: bearing pressure

In cases where only velocity dependence is taken into consideration, bearing pressure is fixed at a value (12 MPa) under the dead load. In the cases where only bearing pressure is taken into consideration, sliding velocity was fixed at 0.4 m/s (maximum value of the model).

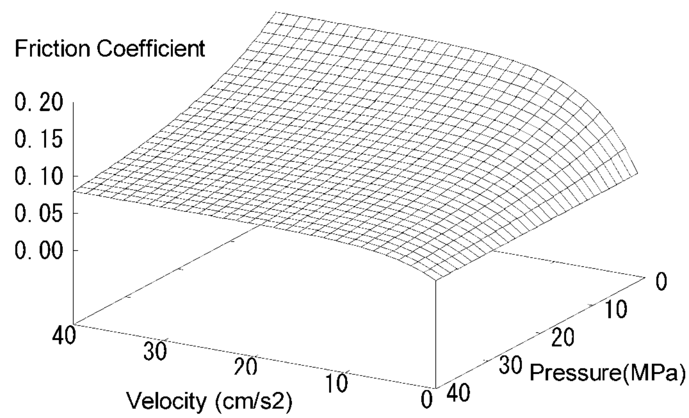

Figure 4. Dependence of Friction Coefficient

In the case of velocity dependence, the friction coefficient may decrease as sliding velocity increases depending on the type of sliding material. A comparison was made, therefore, with the results obtained in the case where the model as shown in Figure 5 was used.

(3) Simple modeling by using a bilinear model
It may be that modeling performed by the method described above is somewhat inconvenient, though detailed, if it is to be applied to a real bridge because there are many parameters to be set and many elements. Since the hysteretic restoring force characteristics of the sliding bearings and horizontal load distribution devices constituting the sliding isolation bearing systems are bilinear (post-yield stiffness=0.0) and linear, respectively, the system as a whole has bilinear hysteretic restoring force characteristics (Figure 6). For the purposes of this study, a comparison was made between the case where nonlinearity of sliding isolation bearing systems is approximated by an ordinary bilinear model and the case where it is approximated by the detailed model mentioned earlier to verify the applicability of the simple method.

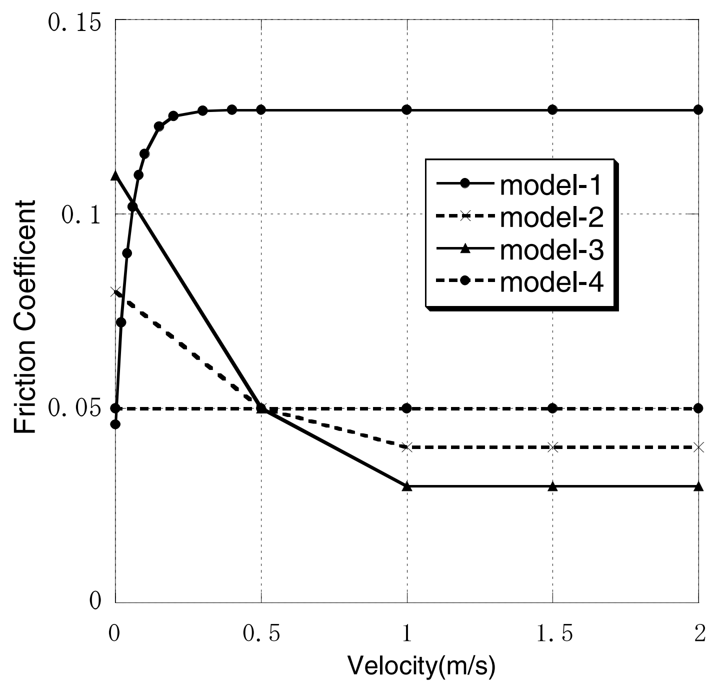

Figure 5. Velocity Dependence of Friction Coefficient

CONSIDERATIONS ON PARAMETER STUDY RESULTS

(1) Analysis cases and considerations in evaluation

Analysis cases were determined as shown in Table 2 in consideration of factors such as the velocity and bearing pressure dependence and friction coefficients of the sliding bearings and the stiffness of the horizontal load distribution devices.

The analytical results were evaluated by paying attention to maximum response values, which are important for design purposes. The amounts of displacement of bearings (relative displacement between superstructure and substructure) and curvature ductility factors in different cases were compared. For the purposes of this analysis, the end piers, which are prone to be affected by boundary conditions, were avoided, and attention was paid to pier an intermediate pier (P3).

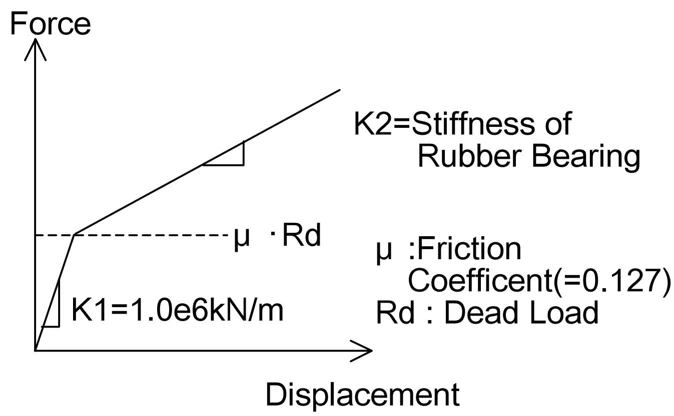

Figure 6. Simple Bilinear Model of Isolation System

Table 2. Analysis Cases

parameter	analysis cases
Velocity/pressure dependence of the friction coefficient	(1)case-1(no dependence) (2)case-2(both velocity/pressure dependence) (3)case-3(only velocity dependence) (4)case-4(only pressure dependence)
Characteristics of velocity dependence	(1)model-1(empirical model) (2)model-2(μ=0.04 at high-velocity range) (3)model-3(μ=0.03 at high-velocity range) (4)model-4(μ=0.05, constant)
Stiffness of rubber bearings and the friction coefficient of sliding bearings	combination of below parameters(21cases) 1) stiffness of rubber bearings=(K、2K、0.5K) 2) μ=(0.05,0.07,0.10,0.15,0.20,0.30,0.40)
Modeling method of the sliding typed seismic isolation system	(1)detailed modeling (2)simple modeling (bilinear)
Direction of earthquake motion input	(1)the bridge axis direction (LG) (2)perpendicular to the bridge axis (TR) (3)two directions simultaniously

(2) Analysis paying attention to velocity and bearing pressure dependence of the friction coefficient

Figure 7 shows the results of analysis of different cases in which either or both or none of velocity dependence and bearing pressure dependence is taken into consideration. As shown, in all cases the curvature ductility factor at the pier base ranges from 5.0 to 6.0, indicating that the maximum response value is not very sensitive to velocity dependence or bearing pressure dependence. Differences in bearing displacement between the three cases other than the case in which no dependence was taken into account were also small (only 1.0 cm or so).

A possible reason why the sensitivity of the maximum response value is low is that the response values of the bridge are governed by the stiffness of the horizontal load distribution devices. This means that occurrence of sliding caused the stiffness of the seismic isolation systems to be governed by that of the horizontal load distribution devices. Since the period characteristics of the entire bridge also are dependent on the stiffness of the horizontal load distribution devices, similar response characteristics of the bridge were indicated in all cases although the friction coefficient showed changes over time.

A likely reason why the response values in the "no dependence" case were greater than the values in the other three cases is that the assumed friction coefficient (0.1) was smaller than the average friction coefficient (about 0.13) in the cases in which dependence was taken into consideration, with the result that the damping effect of the seismic isolation systems became small.

As a next step, response values were compared using the velocity dependence characteristics shown in Figure 5. The results are shown in Figure 8. As shown, neither bearing displacement nor the curvature ductility factor at the pier base showed significant differences. In general, velocity dependence of the friction coefficient is such that as velocity increases, the friction coefficient tends to increase or decrease until it ceases to increase or decrease when velocity reaches a certain level. Since Level 2 eathquake motions were assumed in this study, the maximum response velocity was around 1.5 m/s so that the friction coefficient reached the range in which no more change occurred. This is thought to be the reason why the influence of velocity dependence, which was particularly noticeable in the low velocity range, on the maximum response values was small.

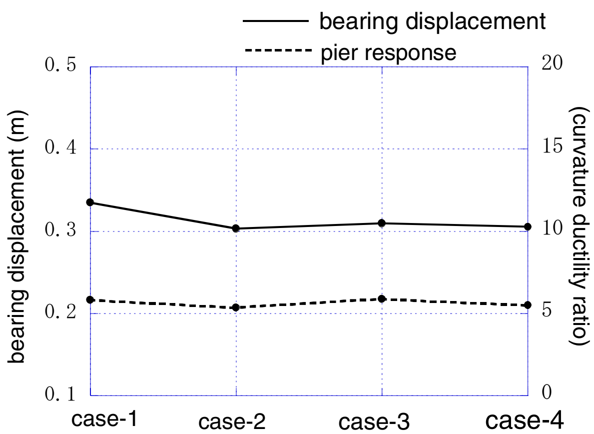

Figure 7. Result of Analysis paying Attention to Velocity and Bearing Pressure Dependence of the Friction coefficient

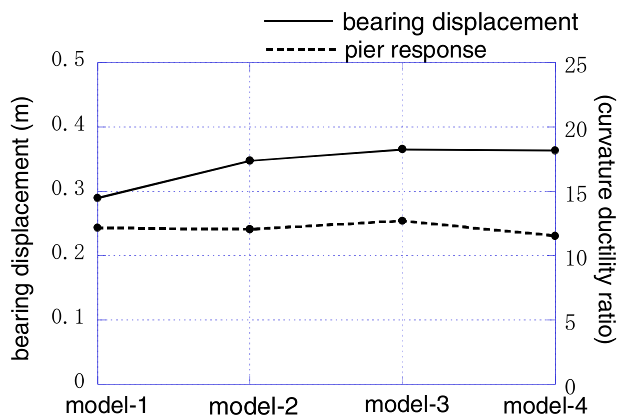

Figure 8. Result of Analysis paying Attention to Velocity Dependence Variation

(3) Analysis paying attention to the stiffness of horizontal load distribution devices and the friction coefficient of sliding bearings
This section describes the results of an analysis performed paying attention to the stiffness of the horizontal load distribution devices and the friction coefficients of the sliding bearings. The analysis described in Section (2) has confirmed that sensitivity of the friction coefficient to velocity and bearing pressure dependence is low. In the analysis reported in this section, therefore, the friction coefficient was assumed to be constant.

Figure 9 shows the maximum response values in different cases. Examination of the stiffness of the horizontal load distribution devices reveals that as stiffness increases, bearing displacement tended to decrease and, conversely, pier response tended to increase. These tendencies were particularly strong in the small friction coefficient range (0.05–0.20). It was also shown that as the friction coefficient approached 0.4, sensitivity of the response values of the bearings and piers to stiffness became low.

Examination of the friction coefficient reveals that as the friction coefficient became small, bearing displacement tended to increase and the response values of the piers tended to decrease. The amounts of change were large when the friction coefficient was greater than 0.2, and sensitivity was low when the friction coefficient was smaller than 0.2.

There results show that as the stiffness of the horizontal load distribution devices and the friction coefficient decreased, bearing displacement tended to increase and the response values of the piers tended to decrease. The results also showed that bearing displacement and the response values of the piers are in a trade-off relationship, regardless of the values of the two parameters.

The most likely cause of these tendencies is that as the stiffness of the horizontal load distribution devices decreases and the friction coefficient decreases, inertia force acting from the superstructure on the piers decreases so that the response values of the piers become smaller, though depending on the amount of bearing displacement. Because the stiffness of the horizontal load distribution devices is directly related to natural vibration characteristics, it is also possible that the response values of the piers are reduced by the lengthening of the natural period under the influence of input earthquake motions.

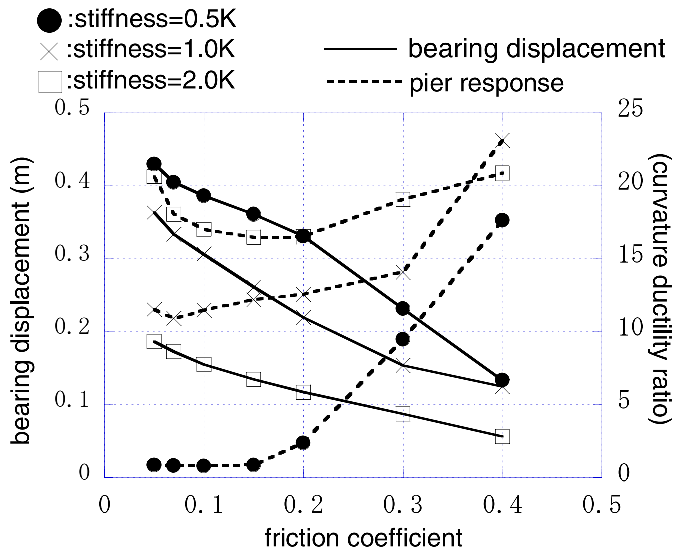

Figure 9. Result of Analysis paying Attention to the Stiffness of Rubber Bearings and the Friction Coefficient of Sliding Bearings

(4) Analysis on applicability of bilinear model

For both detailed modeling and simple bilinear modeling of the sliding isolation bearing systems, response to two-direction simultaneous input of the five acceleration waves was analyzed. The results of the analysis are shown in Table 3. Comparison of the response values obtained from the different modeling methods reveals that in the "SHB V Level 2" (Type I, Type II) cases and K-NET Chokubetsu case, in which response values are relatively large, reveals that there are considerable response value differences between the bearings and the piers. The bearings showed differences of up to 45%. The reason for this is thought to be that the detailed model indicated smaller response values because the effect of friction force changes induced by the vertical force acting on the sliding bearings was taken into account in the model. In the "SHB V Level 1" and "JMA Wakuya" cases, in which response values were small, differences between the two models were small.

Although there were considerable overall differences in bearing residual displacements, the absolute value of difference was only 7 mm, which was deemed small enough to conclude that there would be no serious accuracy problem for design calculation purposes. However it should be noted that, depending on the characteristics of input earthquake motions, larger differences could occur between the two models.

Let us now consider the behavior of the sliding isolation bearing systems in detail. Figure 10 shows the responses of the sliding bearings and the bearing systems in the case where "SHB V Type II" acceleration wave was input into the detailed model. As shown, the hysteresis loops for the sliding bearings are more or less trapezoidal because of the influence of vertical force. Under the influence of changes in the friction coefficient, small-scale changes in horizontal reaction force occurred even while sliding was in progress, indicating complexity of behavior. However, hysteresis loops for the entire bearing system reflecting the response of the horizontal load distribution devices show smooth, nearly-bilinear shapes.

Comparison of the average of the right and left bearing results and the bilinear model shows close agreement in shape as shown in Figure 11, though there are differences in maximum displacement. This indicates that the simple bilinear model expresses the average behavior of the sliding isolation bearing systems with fair accuracy.

Table 3. Result of Analysis on Applicability of Bilinear Model

	modeling method	SHB V Level 1		SHB V Level 2				K-NET Chokubetsu		JMA Wakuya	
				Type1-II-1		Type2-II-1					
		LG	TR	LG	TR	LG	TR	LG	TR	LG	TR
bearing displacement (mm)	detailed	13	23	119	107	265	303	230	239	83	88
	simple	13	20	162	155	300	360	268	299	92	89
simple/detailed		1.00	0.87	1.36	1.45	1.13	1.19	1.17	1.25	1.11	1.01
curvature ductility ratio	detailed	0.10	0.07	0.71	0.31	11.12	5.55	4.31	0.99	0.59	0.20
	simple	0.09	0.07	0.91	0.67	12.51	7.50	8.67	3.19	0.56	0.12
simple/detailed		0.90	1.00	1.28	2.16	1.13	1.35	2.01	3.22	0.95	0.60
residual displacement (mm)	detailed	3	1	7	1	14	10	12	6	7	5
	simple	5	0	14	7	13	14	16	11	13	2
simple/detailed		1.67	0.00	2.00	7.00	0.93	1.40	1.33	1.83	1.86	0.40

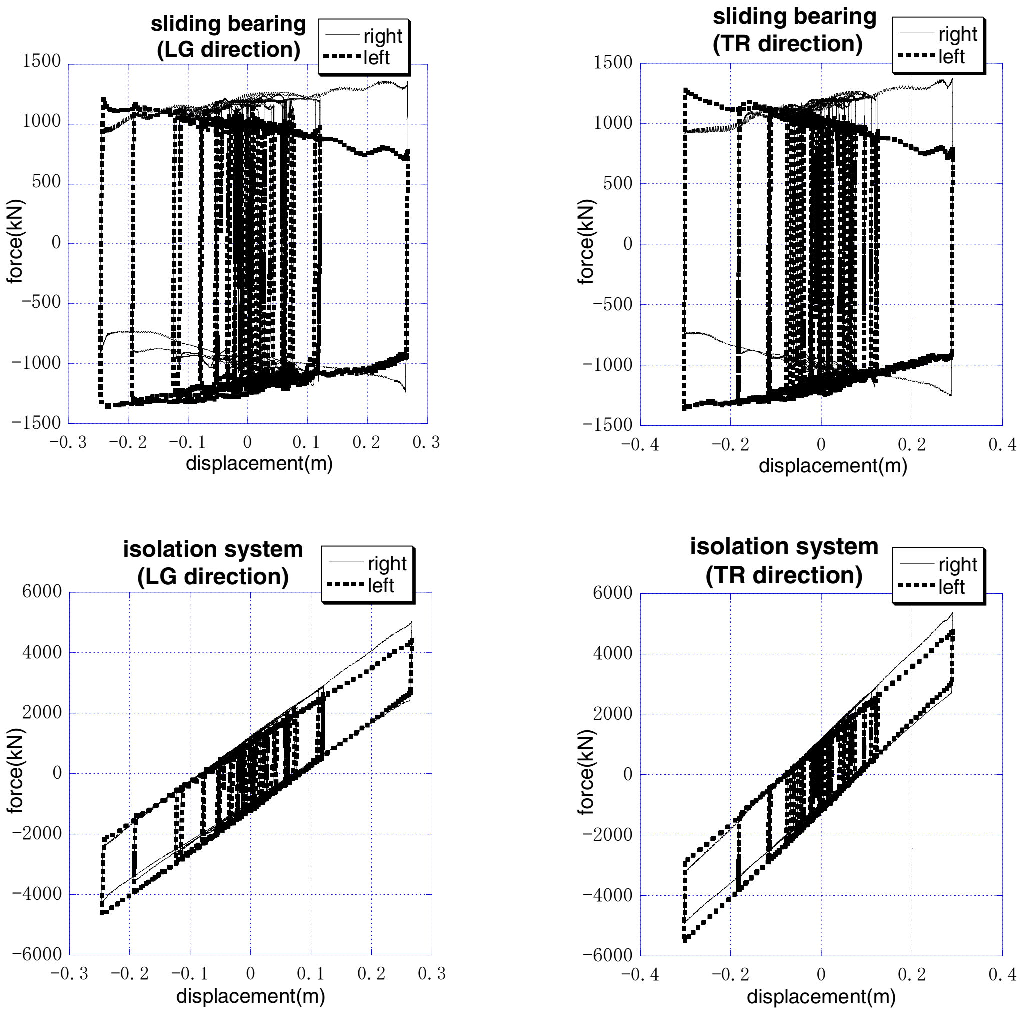

Figure 10. Hysteresis Loops of Sliding Bearings and Isolation Systems

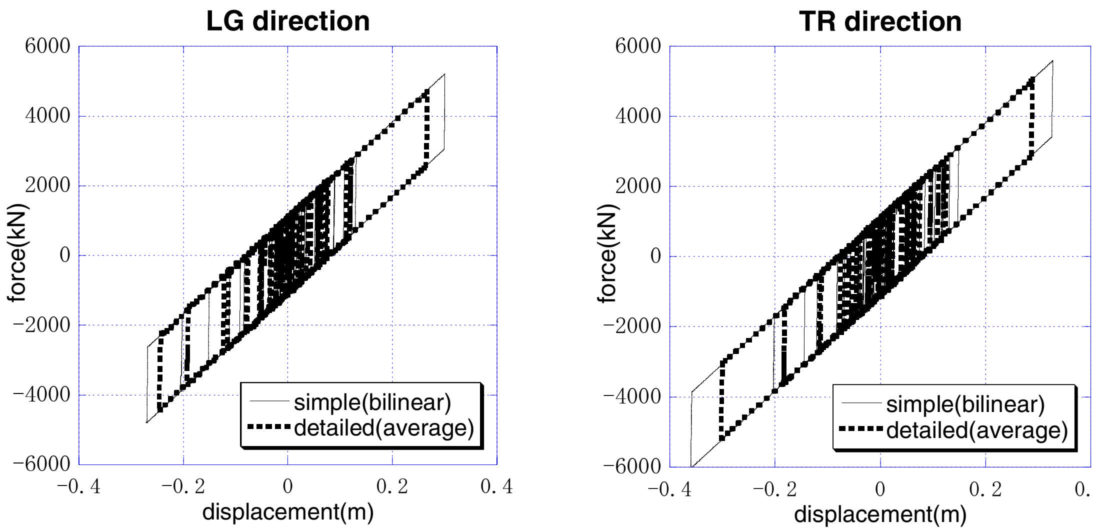

Figure 11. Comparison of the Simple Model and the Detailed Model

(5) Analysis paying attention to the direction of earthquake motion input

Table 4 shows the results of an analysis of the cases in which each of the five acceleration waves is input in one direction or in two directions simultaneously into the detailed model described in Section 3 (1). As mentioned earlier, changes in hysteretic restoring force characteristics of the sliding bearings are accompanied by changes in vertical force (bearing pressure). Rocking vibration of the girder caused by excitation in the direction perpendicular to the bridge axis is thought to influence the behavior in the bridge axis direction, and the purpose of the analysis here is to evaluate this influence. Through the analyses, maximum values were determined paying attention to the amount of bearing displacement, the curvature ductility factor at the pier base, and residual displacement of the bearings.

Table 4. Result of Analysis paying Attention to the Direction of Earthquake Motion Input

	input direction	SHB V Level 1		SHB V Level 2				K-NET Chokubetsu		JMA Wakuya	
				Type1-II-1		Type2-II-1					
		LG	TR	LG	TR	LG	TR	LG	TR	LG	TR
bearing displacement (mm)	one	13	22	126	108	274	303	242	244	84	88
	two	13	23	119	107	265	303	230	239	83	88
one/two		1.00	0.96	1.06	1.01	1.03	1.00	1.05	1.02	1.01	1.00
curvature ductility ratio	one	0.10	0.07	0.72	0.32	11.53	5.37	5.05	1.08	0.58	0.20
	two	0.10	0.07	0.71	0.31	11.12	5.55	4.31	0.99	0.59	0.20
one/two		1.00	1.00	1.01	1.03	1.04	0.97	1.17	1.09	0.98	1.00
residual displacement (mm)	one	3	1	7	1	16	12	13	5	6	4
	two	3	1	7	1	14	10	12	6	7	5
one/two		1.00	1.00	1.00	1.00	1.14	1.20	1.08	0.83	0.86	0.80

Comparison of the results obtained from one-direction input and two-direction input reveals differences in the maximum response value although there are variations due to the type of input earthquake motion and the direction of input (the bridge axis direction or the direction perpendicular to the bridge axis). These differences are thought to be caused by changes in vertical force acting on the sliding bearings. Bearing displacement results show that response values in the case of one-direction input are greater than those in the case of two-direction input except in the case of "SHB V Level 1" input in the direction perpendicular to the bridge axis. One likely reason is that excitation in the perpendicular direction caused the vertical force acting on the sliding bearings to increase so as to increase friction resistance. The maximum difference between one-direction input and two-direction input, however, was as small as 6%.

As in the case of the bearings, pier response values resulting from one-direction input were greater than those resulting from two-direction input except in some cases. Results like this are thought to have occurred because loads acting on the piers increase if bearing displacement increases. The maximum differences between one-direction input and two-direction input were somewhat large (17%), but the absolute value difference is smaller than a curvature ductility factor of 1, so the differences are thought to be small as in the case of the bearings. With regard to the residual displacement of the sliding bearings, there are cases in which differences in residual displacement large even when differences in the maximum displacements of bearings or piers are small. This is true of the "SHB V Type II" and "JMA Wakuya" cases, as can be seen from the differences as large as 20% or so. One likely cause for this is the influence of the phase characteristics of input earthquake motions on the amount of residual displacement. The maximum absolute value difference, however, is as small as 2 mm.

The above results confirm that the direction-by-direction input approach is justifiable because the influence of rocking vibration of the girder on the behavior in the bridge axis direction is small. Care must be taken, however, in the cases where different acceleration waves are input in the two directions because such input could complicate the behavior.

Comparison of the response values resulting from different input earthquake motions shows that the response values for the "SHB V Type II," "K-NET Chokubetsu," "SHB V Type I," "JMA Wakuya" and "SHB V Level I" earthquake motions are greater in that order. The natural period of the first mode of the bridge is about 1.6 seconds. The magnitudes of acceleration response spectra in that period range are as follows: SHB V Level 2 (Type I, Type II) and K-NET Chokubetsu, about 1,000 gal; JMA Wakuya an d SHB V Level I, about 200 gal. Thus, the magnitudes of acceleration response spectra do not necessarily show agreement with the response results. Although response spectra do not necessarily agree with the maximum response values of the bearings because multi-degree-of-freedom nonlinear analysis is involved, it is possible that the influence of higher modes is reflected in the response values.

SUMMARY

The findings from the results described above can be summarized as follows:

1) A dynamic analysis of a 3-span continuous steel twin-box-girder bridge equipped with sliding isolation bearing systems was conducted, taking into consideration the velocity and bearing pressure dependence of the friction coefficient of sliding bearings. The analysis confirmed that the influence of each dependence on the maximum response values of the entire bridge structure is small. It can be concluded, therefore, that when trying to determine the maximum response of a structure of the type considered in this study in response to Level 2 earthquake motions, it is usually not necessary to strictly model the velocity and bearing pressure dependence of the friction coefficient of sliding bearings.

2) In the case of velocity dependence, the friction coefficient usually varies considerably in the low-velocity (less than 0.5 m/s or so) range and varies very little in the high-velocity range. It can be concluded, therefore, that when trying to determine the maximum response to strong inputs such as Level 2 earthquake motions, it is usually not necessary to take velocity dependence into account.

3) When the stiffness of the horizontal load distribution devices and the friction coefficient of the sliding bearings were reduced, bearing displacement tended to increase and the ductility factor of the bridge piers tended to decrease. Depending on parameter settings, therefore, it was possible to reduce pier response to lower than the yield level. It has been confirmed that the maximum response of the bridge can be controlled to some degree by adjusting the two parameters.

4) Because it was thought that it was possible to express a seismic isolation system with a simple bilinear model if velocity dependence and bearing pressure dependence were not taken into account, a simple bilinear model was compared with a detailed model. As a result of the comparison, it was concluded that since the hysteretic restoring force characteristics of the bearings were reproduced with fair accuracy though the maximum response values indicated by the two models differed slightly, reasonably accurate results can be obtained by using a bilinear model in design calculation.

CONCLUDING REMARKS

This study focused on a continuous viaduct equipped with sliding isolation bearing systems. A dynamic analysis of the bridge was conducted, modeling the bearing pressure and velocity dependence of the friction coefficient of the sliding bearings as faithfully to test results as possible, to investigate the influence of bearing pressure and velocity dependence and identify considerations in seismic design.

As a result, it has been confirmed that the method of replacing the complex behavior of a sliding isolation bearing system with a simple bilinear hysteresis model is justifiable, though under a limited range of conditions considered in this study. Changes in the friction coefficient and hysteresis characteristics (damping characteristics) of sliding bearings in the high-velocity range are still unknown because of lack of data. Within the range of conditions assumed in the present study, however, the influence on bridge response was small, and it is believed that knowledge useful for seismic design has been gained.

In order to verify the applicability of sliding isolation bearing systems to a wider range of conditions, it is hoped that attention will be paid also to the verification of the sliding behavior of materials of different types and to the determination of the influence of the period and amplitude characteristics of input earthquake motions and the characteristics of resultant residual displacement. It is also hoped that further research efforts will be made to investigate the applicability of sliding isolation bearing systems to various other types of structure.

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