ICSS (3): Seismic Response To Bidirectional Input Ground Motions

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SUMMARY
The Isolation Seismic Controlled Slide System (ICSS) is a newly proposed structural system for multi-span continuous girder bridges realized by the combined use of slide bearings, elastomeric bearings and seismic dampers. This system provides a mitigation measure for the indeterminate forces acting on the girder due to thermal expansion and contraction, while the seismic action is controlled with the isolation mechanism by low-friction slide bearings supporting the spans, elastomeric bearings and seismic dampers installed at concentrated locations. The seismic response of a bridge employing the ICSS to strong earthquake ground motions can involve complicated bidirectional action to the elastomeric bearings and seismic dampers to which the angle of orientation and associated damping force direction. In particular, a need of investigation on the bidirectional response to bidirectional input ground motions arises with the application of ICSS to a curved girder bridge, since reliability of the conventional seismic design assessment procedure using unidirectional input ground motions may not adequately reflect the bidirectional effect on the action of the ICSS components. For a rational design of bridges employing ICSS, development of the design assessment procedure based on bidirectional input for this purpose is motivated, and desirable bidirectional inputs suitable for the design purpose and their characteristics are discussed.

Keywords: Seismic isolation control, elastomeric bearing, seismic damper, slide bearing, ICSS

1. INTRODUCTION

Excessive elongation of the fundamental natural period of the structural system is discouraged for the seismic isolation design of bridges in accordance with the Road and Bridge Specifications of Japan Road Association (2004). This is because an isolated bridge can be subjected to an increased seismic action depending on the relationship between the bridge's natural period and the ground characteristics; the seismic isolation design (*Menshin* design) philosophy in Japan puts on emphasis on the enhancement of structural damping to reduce the seismic load. This concept can be further extended to limit the restoring force components as much as possible, while a high level of structural damping is introduced with the use of high capacity seismic dampers to utilize seismic force reduction effect of the isolation system. Based on this idea, the Isolation Seismic Controlled Slide System (ICSS) has been proposed as a new seismic structural type with an optimum combination of elastomeric bearings, seismic dampers, slide bearings and other devices for multi-span continuous girder bridges (Ueda et al., 2012) (Matsuda et al., 2012) (Tsushima et al., 2012).

In cases where seismic performance verification of a highway bridge is carried out by time history response analysis, a method of using standard accelerograms specified in the Specifications for Highway Bridges as the unidirectional input ground motion is generally used. However, if ICSS is applied to a long multi-span continuous girder bridge, bidirectional seismic response becomes complicated since hysteretic characteristics of elastomeric bearings, seismic dampers and slide bearings are nonlinear, and seismic dampers might be rotationally displaced within the horizontal plane, in addition to the complex dynamics of the curved girder. In view of this problem, bidirectional response effects induced by actual multidimensional seismic motion input are unlikely to be properly evaluated by the conventional assessment procedure based on unidirectional input in various directions.

In this study, seismic response of a bridge with ICSS under bidirectional ground acceleration input is investigated using numeric dynamic response analysis. Two types of bidirectional spectrum-compatible accelerograms are adopted as the input; the first type is the standard waves specified in the highway bridge design code in Japan (Japan Road Association, 2004) and their complementary orthogonal component counterparts (Igarashi et al., 2012), and the other type is simple combinations of two different standard waves. The differences between the two cases are discussed based on the analytical results.

2. CONCEPT OF ICSS

Long multi-span continuous girder bridges supported by elastomeric bearings or rubber bearings are generally susceptible to greater statically indeterminate forces caused by temperature changes, desiccation shrinkage and creeps; accordingly, it causes unfavorable effects to response displacement of bearings and post-yield response of bridge piers. On the other hand, in the case of long multi-span continuous girder bridges with application of ICSS, statically indeterminate forces can be significantly reduced. Figure 2.1 shows the typical layout of ICSS with an optimum combination of elastomeric bearings, seismic dampers and slide bearings all over bridges. It is expected that the system will have beneficial effects on surmounting technical issues as stated below:

1) Statically indeterminate forces caused by temperature changes and others can be effectively reduced so that their influence on the seismic performance of bridges can be lessened.
2) Since the statically indeterminate force becomes lower, works for adjusting the location of bearings with “post-slide” and other procedures can be eliminated.
3) Substructures supporting the slide bearings can be streamlined while the limited member of substructures supporting the elastomeric bearings and seismic dampers can increase in size. As a result, the cost of the entire substructure system can be reduced.
4) A high level of structural damping is achieved by means of non-linear energy dissipation mechanisms of applied devices.

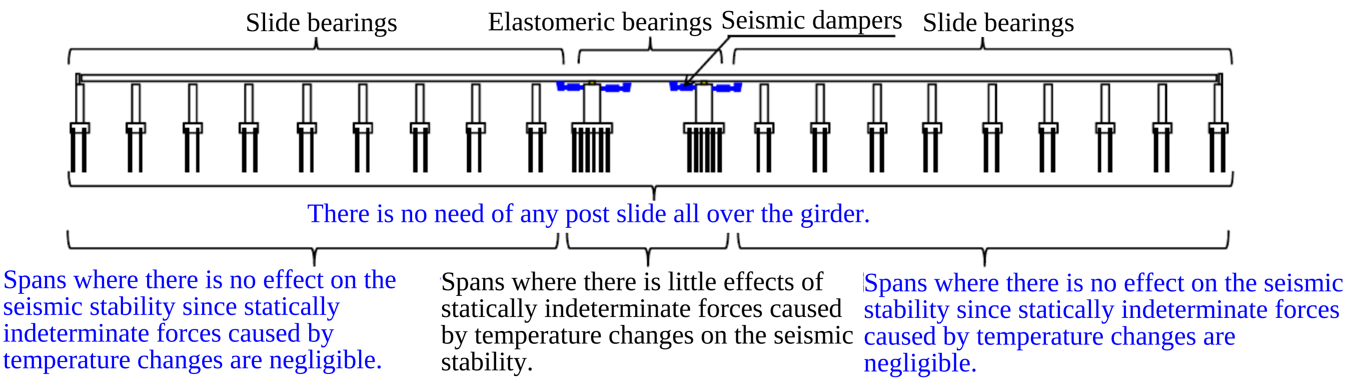


Figure 2.1. Application example of ICSS

3. ANALYSIS CONDITIONS

3.1 Bridge model

The bridge model considered in this study is a mixed steel box I-plate girder type 18-span continuous curved bridge with the maximum curvature radius of 750m and 1200m length, as shown in Figure 3.1. Bearing devices are arranged as shown in Figure 3.2. The 18-span continuous bridge girder consists of a steel box girder in the spans between piers P8 and P11 crossing a river, including the maximum span length of 135.5m and the two steel plate girders in the rest of the spans. The girder is supported by slide bearings with friction coefficients of 0.005-0.01 on the piers, except for piers P9 and P10 on which sets of slide bearings and an elastomeric bearing (LRB, laminated rubber bearing with lead plugs) are used together with seismic dampers, as shown in Figure 3.2(c). On the abutments A1 and A2, the girder is supported so that only the longitudinal displacement is allowed with the restrainers against the transverse movement. The resistance force of the seismic damper is assured to be proportional to 0.1th power of velocity and to be 1500kN at the velocity of 50kine. Three seismic dampers are attached on both sides of the bridge piers P9 and P10 respectively; i.e. six seismic dampers (9000kN) are fitted per bridge pier. The distance between the seismic dampers is 3850m and they are placed in the orientation of 45-degree direction from the local bridge axis. The finite deformation analysis was used in consideration of effects of displacements of the girders and seismic dampers.

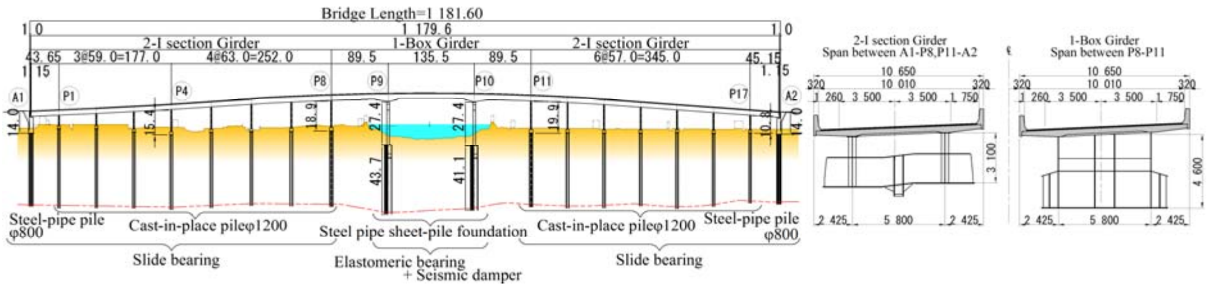
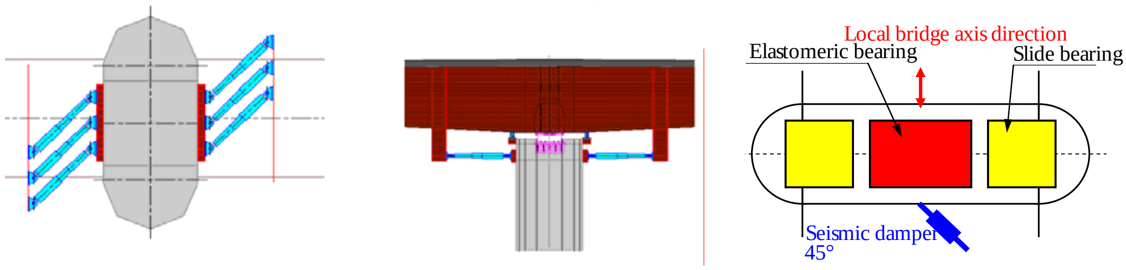


Figure 3.1. Model bridge for study



(a) Plan (b) Side view (c) Layout concept of each device

Figure 3.2. Allocation of bridge piers and bearing devices (P9 pier)

3.2 Input seismic ground motion

The bidirectional input seismic ground motions to be used for the study consist of two types: (1) Combinations of standard acceleration waveforms specified in the Specifications for Highway Bridges (spectrum-compatible accelerograms obtained by the observational records) (Japan Road Association, 2004) and (2) Combinations of the standard waves and their complementary orthogonal component counterparts (Igarashi et al., 2012) generated by Hilbert transform. The complementary orthogonal component wave is calculated based on the idea of another spectrum-compatible accelerograms associated with the standard wave, such that the maximum response of an isotropic elastic single-mass oscillator to the bidirectional input created by the pair coincides with the specified target spectrum. The standard acceleration waveforms II-III-2 specified in the V edition of the Specifications for

Highway Bridges (Japan Road Association, 2004) and its complementary waves are shown in Figure 3.3.

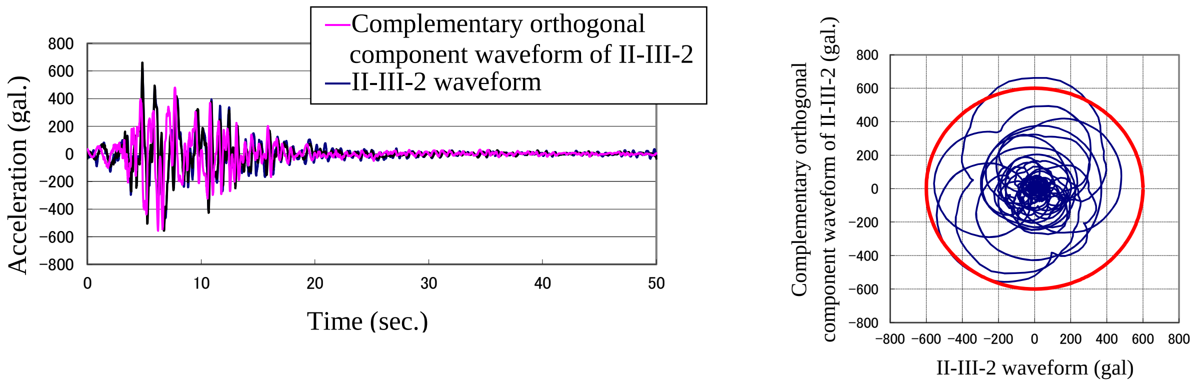
Three cases of the seismic inputs summarized in Table 3.2 were analyzed by the use of the time history response analysis and the results were compared focusing on the responses of the bearing devices; the first case is a unidirectional input based on the Specifications (Case-1, II-III-2), the second case is a bidirectional input created by a combination of the standard waveforms specified in the Specifications (Case-2, II-III-2 and II-III-3), and the third case is a bidirectional input of the standard waveforms specified in the Specifications and associated complementary waveform (Case-3, II-III-2). The orbits of the input waveforms and accelerogram of II-III-3 used in Case-2 are shown in Figure 3.4. The maximum amplitude of the input in Case-2 is approximately 1.3 times greater than that of Case-3. The input of Case-2 shows a tendency of directivity in the direction of 45 degrees. The peak values of input waveforms used are shown in Table 3.1. As for the input direction, the direction of the line connecting abutments A1 and A2 is designated as the X direction of the global coordinate system and the direction perpendicular to the X direction is defined as the Y direction.

Table3.1. Peak accelerations of input waveforms used

	Ⅱ-Ⅲ-2	Complementary orthogonal component waveform of II-III-2	Ⅱ-Ⅲ-3
Positive	480.3	661.6	619.2
Negative	-557.4	-557.3	-360.1

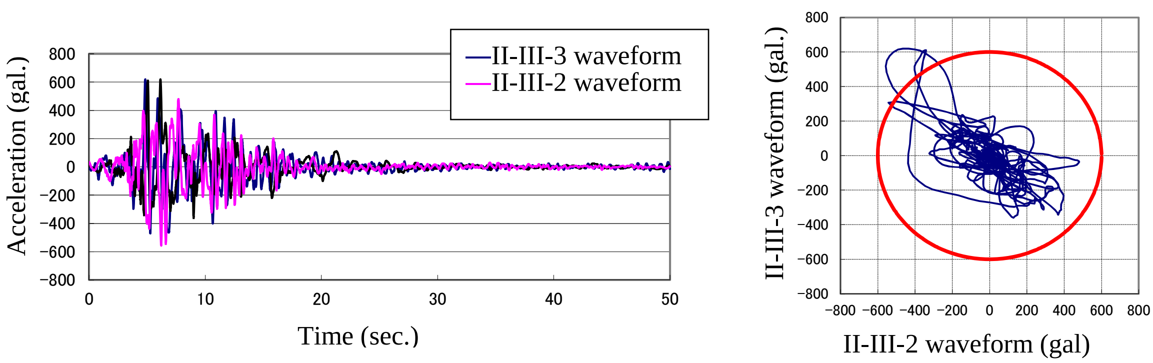
Table3.2. Seismic input waveforms and analysis cases

	X direction	Y direction
Case-1	Ⅱ-Ⅲ-2	—
Case-2	Ⅱ-Ⅲ-2	Ⅱ-Ⅲ-3
Case-3	Ⅱ-Ⅲ-2	Complementary orthogonal component waveform of II-III-2



(a) Accelerograms (b) Orbits of the bidirectional input

Figure 3.3. Standard waveform (II-III-2) specified in the Specifications for Highway Bridges of 2004 and associated complementary orthogonal component waveform (Case-3)

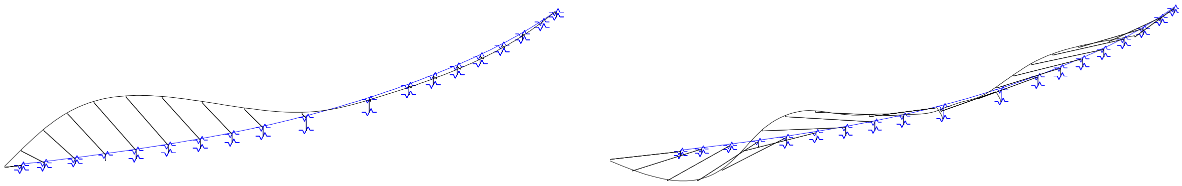


(a) Accelerograms (b) Orbits of the bidirectional input

Figure 3.4. Combination of standard waveforms specified in the Specifications for Highway Bridges of 2004 (Case-2, II-III-2 and II-III-3)

4. EIGENVALUE ANALYSIS

An eigenvalue analysis was performaed neglecting the effect of the seismic dampers and stiffness of slide bearings, while including the equivalent stiffness of the elastomeric bearings in the displacement amplitude of the response to the design earthquake. Representative natural modes are shown in Figure 4.1.



(a) Transverse fundamental mode (T=16.3s) (b) Longitudinal fundamental mode (T=5.3s)

Figure 4.1. Representative fundamental modes

5. NONLINEAR TIME HISTORY RESPONSE ANALYSIS

Damping of superstructures, bridge piers, elastomeric bearings, viscous dampers and the groundwork/ground were evaluated by means of Rayleigh damping and a nonlinear time history response analysis was conducted. The hysterestic damping of the slide bearings and the velocity-dependence of the resisting force of the seismic dampers were taken into account in the analysis. Equivalent damping ratios of the structural components used for adjusting Rayleigh damping coefficients range between 2% and 10%; 2% for the superstructure, 2% for the bridge piers, 5% for the elastomeric bearings and 10% for the groundwork/ground, respectively.

The Newmark-β method (β=1/4) was used as a direct numerical time integration scheme for the time history response analysis with the time interval of 0.001sec. In cases where any load imbalance occurred, an iterative calculation for convergence was carried out. The duration of the time history analysis is 20 seconds since particular attention is paid to the maximum response.

5.1 Comparison of seismic damper response

The time histories of the response of the installation point (girder side) of the seismic damper, the resistance force of the damper (Force), and displacement in the axial direction (R-Disp) on the P8 side of the pier P9 in the three cases is shown in Figurers 5.1 to 5.3, respectively. The notation X-Disp. indicates the displacement in the X direction defined to be the direction of the line connecting the abutments A1 and A2, while Y-Disp. indicates the displacement in the direction perpendicular to the X direction.

The largest displacement is observed in X direction of Case-2 among the three cases and extends up to 80cm. The character of the response time histories of three cases is almost similar. This implies that the effects of the input in the X direction are limited. At the same time, the difference between the maximum and minimum displacements in the Y direction is 60cm in Case-1, 80cm in Case-2 and 50cm in Case-3, respectively, indicating that the amplitude difference and phase lag between the components of the input acceleration components can considerably affect the dynamic response of the bridge. The results of the two horizontal orbits show comparatively significant directivity of the structural response in Case-2 and Case-3, and a time lag in the appearance of the maximum or minimum values in the X and Y directions.

It is already known in the past research that the axial displacement of a seismic damper is affected by the phase lag and amplitude difference between the two components of the input waveforms (Matsuda et al., 2011) and the estimation of these displacements are difficult based only on the magnitude correlation of the displacements in the X and Y directions. Provided that rigid-body rotation between the girder and pier installation points can be negligible, the resistance force and the axial displacement vary depending on the direction of the bidirectional input accelerations. The time histories of the axial displacements in the three cases are shown in Figure 5.4, indicating that the axial displacement does not change in the same manner as the girder displacement in each direction.

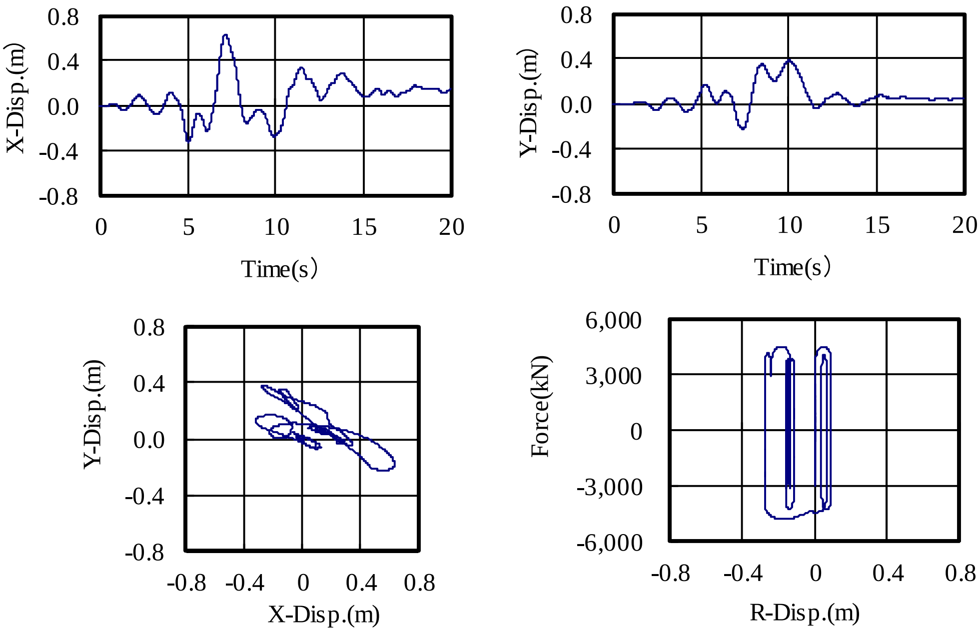


Figure 5.1. Seismic damper (P8 side of P9 bridge pier) response (Case-1)

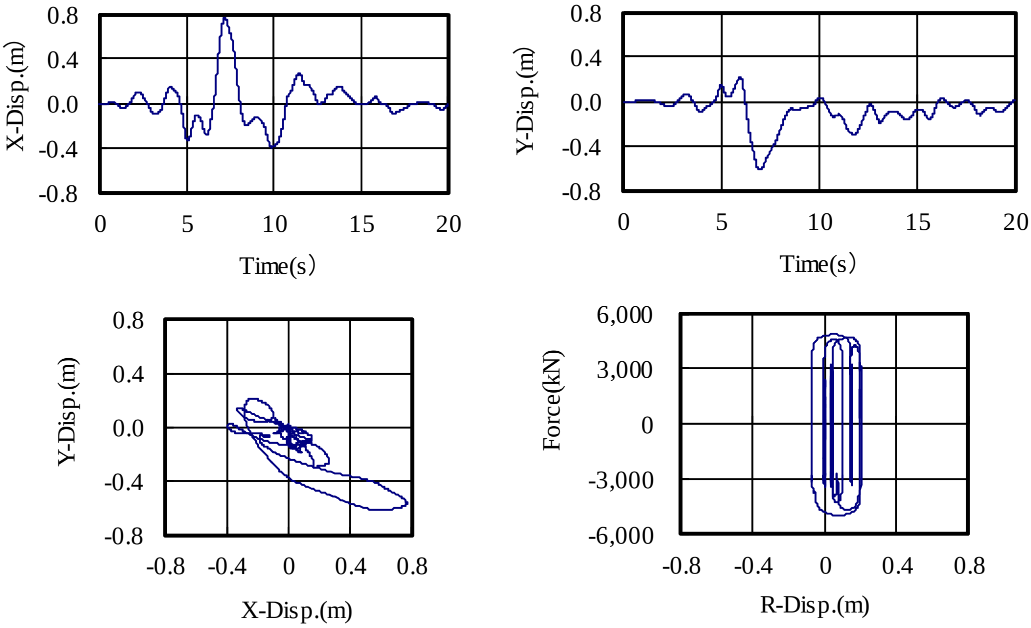


Figure 5.2. Seismic damper (P8 side of P9 bridge pier) response (Case-2)

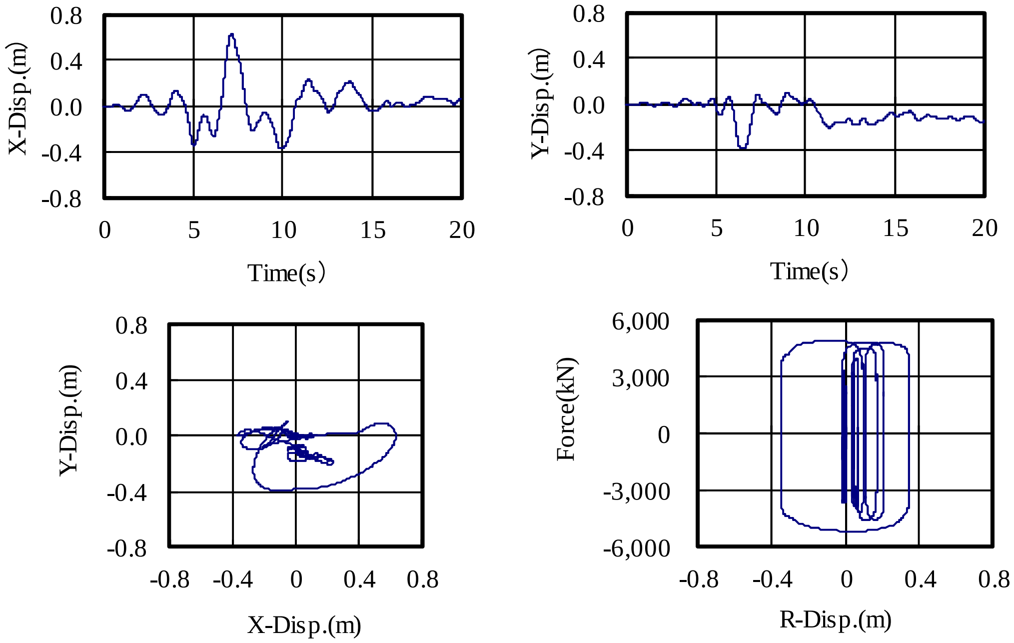


Figure 5.3. Seismic damper (P8 side of P9 bridge pier) response (Case-3)

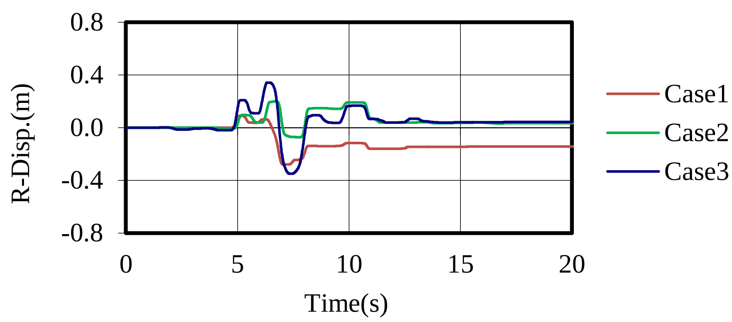


Figure 5.4. Comparison of axial displacements of seismic damper (P8 side of P9 bridge pier)

5.2 Comparison of elastomeric bearing response

It is known that the displacement at an installation point of a seismic damper is almost similar to the displacement of elastomeric bearing (Japan Road Association, 2004). This is because the elastomeric bearing generates active force regardless of the applicable direction of inertia force, while the seismic damper induces resistance force only for the axial deformation. The relationship between the active force and the relative displacement in the axial direction and the direction perpendicular to the bridge axis in the three cases is shown in Figure 5.5, indicating that the active force increases almost in proportion to the displacement amplitude.

5.3 Comparison of slide bearing response

The difference between the longitudinal responses of the slide bearings for the unidirectional (Case-1) and bidirectional inputs (Case-2 and Case-3) is found to be insignificant, and the calculated maximum displacement is approximately 1m, as shown in Figure 5.6.On the other hand, the transverse displacement of the girder is considerably larger in the bidirectional input cases than that of the unidirectional case, since the transverse deflection of the girder is resisted solely by the horizontal flexural rigidity of the girder and the elastomeric bearing's contribution is small, as opposed to the case of the longitudinal displacement. The maximum transverse displacement is found to be approximately 1.2m, which is within the gap width (1.5m) between the girder and the piers. This maximum transverse displacement can be regarded as allowable in avoiding collision between the girder and pier.

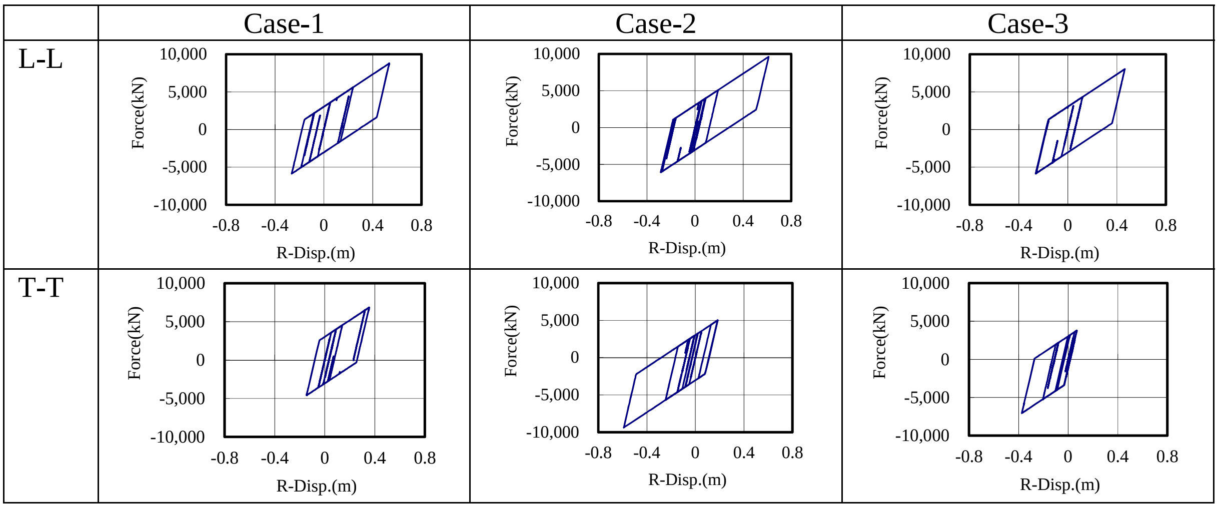
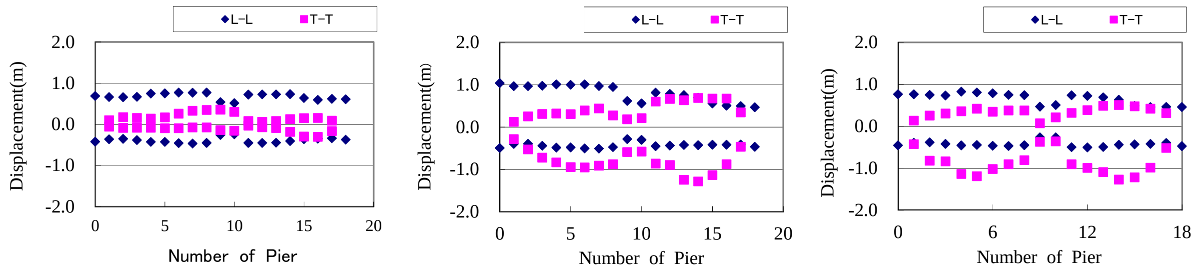


Figure 5.5. Comparison of hysteretic response of elastomeric bearing



(a) Case-1 (b) Case-2 (c) Case-3

Figure 5.6. Comparison of maximum response displacement of slide bearings

6. CONCLUSION

In this study, the difference in the behaviours of bearing devices (elastomeric bearings, seismic dampers and slide bearings) that constitute the key component of ICSS, among the unidirectional input case and two types of bidirectional input cases are examined. The unidirectional input conforms to the method specified by the conventional seismic design specifications. Findings obtained from the study are summarized as follows:

1) Responses of elastomeric bearings and slide bearings tend to increase under bidirectional input ground motions partly due to the increase of the resultant inertia force, compared with the ones under the unidirectional input ground motion.
2) Use of bidirectional ground motion input does not necessarily result in the increase of the axial displacement of seismic dampers, since the rigid-body rotational motion induced with varying influence of the phase difference in the components of bidirectional input on the damper displacements.
3) The bidirectional concurrent input with the combination of two standard waveforms as in Case-2 is likely to require increased seismic demand to the structure, exceeding the existing criterion standard. Therefore, the use of bidirectional input combined with the concept of the complementary orthogonal component waveform in Case-3 is regarded as a reasonable method for the assessment of the seismic performance under bidirectional seismic inputs.

REFERENCES

Japan Road Association (2004). *Specifications for Highway Bridges V. Seismic Design* (in Japanese).
Ueda, T. Igarashi, A. Matsuda, T. Sakate, M. Uno, H. Matsuda, H. (2012). ICSS (1) Concept and

Fundamental Characteristics of Seismic Response. *Proc. 15th World Conference on Earthquake Engineering*.

Matsuda, T. Igarashi, A. Ueda, T. Sakate, M. Uno, H. Matsuda, H. (2012). ICSS (2) Function and Contribution of Bearing Devices in Reduction of Seismic Action. *Proc. 15th World Conference on Earthquake Engineering*.

Tsushima, D. Igarashi, A. Ueda, T. Wada, Y. Matsuda, T. (2012). ICSS (4) A Design Applied for A Super Long Multi-Span Bridge. *Proc. 15th World Conference on Earthquake Engineering*.

Igarashi, A. Inoue, K. Furukawa, A. Uno, H. Matsuda, H. (2012). Synthesis of Bidirectional Seismic Ground Motion by Standard and Complementary Waves for Seismic Design of Bridges. *Journal of JSCE, Ser. A1*. (to appear).

Uno, H. Mazda, T. Miyamoto, H. Yunoki, K. Chou, S. Shinoda, R. (2010). Seismic Behavior of Bridges due to Girder Elongation and Shrinkage Caused by Temperature Changes. *Proc. 5th World Conference on Structural Control and Monitoring*. No.149. 1-12.

Matsuda, T. Ukai, K. Wada, Y. Uno, H. Matsuda, H. (2011). Concept and Features of Basic Structures of the Isolation Seismic Controlled Slide System Applied to Super Long Multi-span Continuous Curved Bridges. JSCE (in Japanese)