Seismic Response Control of Bridges Using UPSS Combined with Energy Dissipation Devices

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SUMMARY

The Uplifting Slide Shoe (UPSS) bearing is proposed to deal with the thermal expansion and contraction of bridge girders and to disperse the seismic horizontal forces to multiple columns, as well as to control horizontal response displacement of the continuous girder. In this study, a combination of the UPSS bearings and seismic dampers for girder bridges is investigated. The aim of the system is to effectively enhance the energy dissipation mechanism utilizing vertical motions of the girder induced by UPSS bearings with limited girder displacements and horizontal restoring force, in addition to the existing horizontal energy dissipation capabilities. Numerical dynamic response analysis is conducted using various combinations of parameters of the UPSS-damper system, and the effectiveness of the system in reducing the seismic response of the bridge and the validity of the assumed optimal parameter design criteria for the most effective response control is successfully shown.

Keywords: Uplifting slide shoe, slide bearing, seismic design, seismic damper, optimal design, friction

1. INTRODUCTION

The multi-span continuous girder bridges have been employed as the structural form of elevated highways for the purpose of solving the traffic noise problem and reducing the maintenance cost. At the same time, seismic isolation has been widely used to this type of bridges to ensure enhanced seismic performance. The advantage of the isolated bridge girder system can be accounted by two functionalities: girder's thermal expansion and contraction are not restrained, and seismic loads are distributed to multiple columns. However, it also has an inherent disadvantage of potential large girder displacements in the event of strong earthquakes. A great size of expansion joints, which is determined by anticipated girder displacements, tends to be problematic in maintenance and life-cycle cost of the bridges of this type. For this reason, reduction of expected girder displacements for seismic design of isolated multi-span continuous girder bridges would be an important concept for efficient bridge construction.

As one of the solutions of this problem, the Uplifting Slide Bearing, which is referred to as the UPSS, was developed as a seismic response control device for multi-span continuous girder bridges (Igarashi et al. 2009a). An experimental study on the unidirectional behaviour of UPSS was conducted (Igarashi et al. 2009b) and accuracy of the numerical UPSS model represented by a combination of springs in the normal and friction elements for each sliding was validated by shake table test results (Sato et al. 2010). In this study, enhancement at the seismic performance of bridge structures by using a combination of UPSS and seismic dampers is investigated, expecting higher energy dissipation in the limited girder displacement range by the particular feature of UPSS. In addition, design criteria of the UPSS-damper system are discussed.

1. FEATURES OF UPSS-DAMPER SYSTEM

1.1. Concept of UPSS

The UPSS has been proposed as a seismic response control device for multi-span continuous girder bridges. The idea of the UPSS bearing is represented by the use of combination of horizontal and inclined sliding surfaces of the sliding bearings (Figure 2.1).

The use of UPSS bearings is expected to reduce girder displacements in the event of strong earthquakes, by providing restoring force generated by the sliding along the inclined slope. Moreover, the problem of thermal expansion and contraction of the girders is effectively circumvented by the horizontal sliding surface. The distance from the neutral position to either of the slopes is defined as the 'clearance, *e*'.

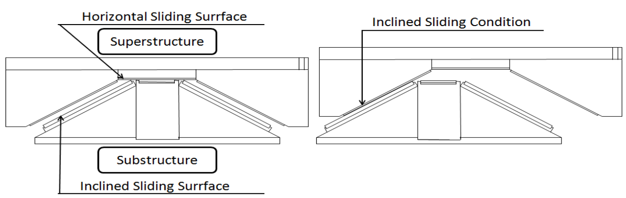


Figure 1.1. UPSS bearing

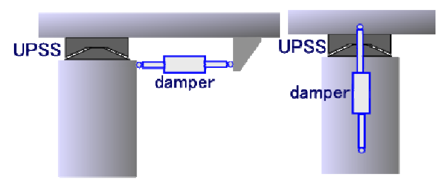


Figure 1.2. UPSS bearing-damper system

1.2. Concept and aim of UPSS-damper system

Although the UPSS bearings are shown to have advantage in fulfilling the requirements for multi-span continuous girder bridges, damping characteristics are not explicitly accounted in the design. The use of a combination of UPSS and seismic dampers is expected to enhance the seismic performance of the bridge. Seismic dampers have been conventionally installed with a horizontal orientation on the top of the piers; however, the unique dynamic behaviour of the UPSS bearing enables the damper to be configured in various angles. The aim of the system is to effectively enhance the energy dissipation mechanism utilizing vertical motions of the girder induced by UPSS with limited horizontal girder displacements and restoring forces, in addition to the existing horizontal energy dissipation capabilities. In this study, the cases such that the damper is installed either in the horizontal or vertical directions are considered as typical examples (Figure 2.2).

2. HYSTERETIC BEHAVIOR

The hysteretic behaviours of UPSS and UPSS-damper systems are analytically evaluated by the equilibrium of forces acting on the sliding surfaces, assuming that the motion of the girder is subjected to constant acceleration along the sliding surfaces (Figure 3.1). The motion of the point mass *m* represents the girder movement of the superstructure, and the horizontal and vertical reaction forces are represented by Q_x and Q_y, respectively, acting on the girder in the negative direction of the girder displacement *x* and *y*. A friction type damper with a constant restoring force F_F is assumed to be implemented for simplicity. Only the cases in which the girder is sliding on the horizontal plane and on the right inclined surface are described because the configuration of UPSS is symmetric about the *x*-axis. Based on the assumptions, the restoring forces can be expressed as follows for the cases in which the girder is sliding on the horizontal plane.

- UPSS and UPSS-vertical damper system

$$Q_x = \mathrm{sgn}(\dot{x}) \cdot \mu\, mg$$
$$Q_y = 0 \tag{2.1}$$

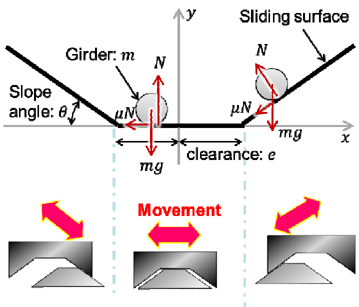
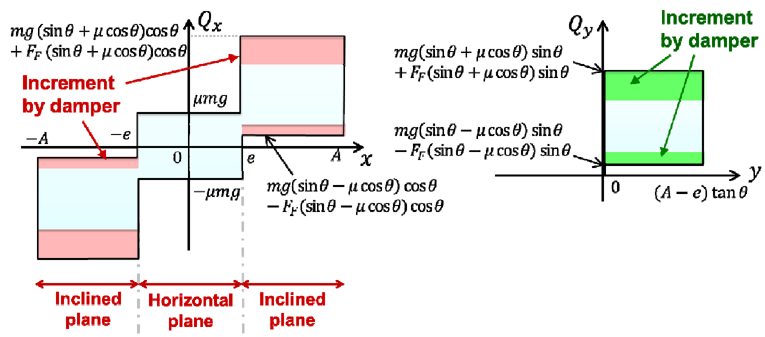
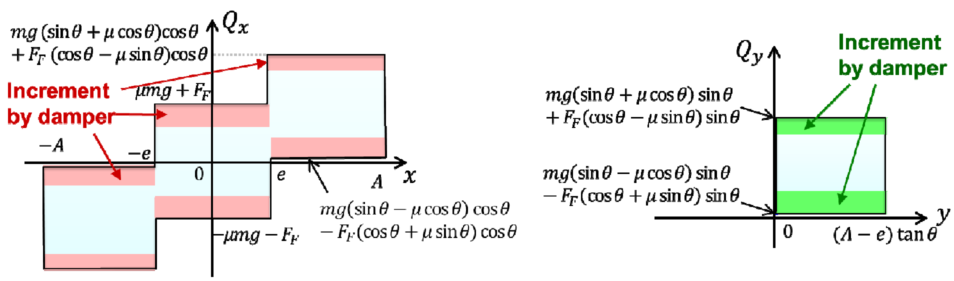


Figure 2.1. Mechanical model of UPSS



(a) Horizontal hysteretic behavior (b) Vertical hysteretic behavior

Figure 2.2. Idealized hysteretic behavior of UPSS-vertical damper system



(a)Horizontal hysteretic behavior (b)Vertical hysteretic behavior

Figure 2.3. Idealized hysteresis behavior of UPSS-horizontal damper system

- UPSS-horizontal damper system

$$Q_x = \mathrm{sgn}(\dot{x}) \cdot (\mu mg + F_F)$$
$$Q_y = 0 \tag{2.2}$$

where sgn() is the signum function. When the girder is sliding on the horizontal surface, vertical movement is not induced: Therefore, the vertical damper does not restrain the horizontal movement. For the cases where the girder is sliding along the right inclined surfaces, the restoring forces can be expressed as follows:

- UPSS

$$Q_x = mg(\sin\theta \pm \mu\cos\theta)\cos\theta$$
$$Q_y = mg(\sin\theta \pm \mu\cos\theta)\sin\theta \tag{2.3}$$

- UPSS-horizontal damper system

$$Q_x = mg(\sin\theta \pm \mu\cos\theta)\cos\theta + F_F(\cos\theta \mp \mu\sin\theta)\cos\theta$$
$$Q_y = mg(\sin\theta \pm \mu\cos\theta)\sin\theta + F_F(\cos\theta \mp \mu\sin\theta)\sin\theta \tag{2.4}$$

- UPSS-vertical damper system

$$Q_x = (mg \pm F_F)(\sin\theta \pm \mu\cos\theta)\cos\theta$$
$$Q_y = (mg \pm F_F)(\sin\theta \pm \mu\cos\theta)\sin\theta \tag{2.5}$$

where θ is the angle of the inclined slope and μ is the friction coefficient of the sliding surfaces. Figure 3.2 shows the idealized horizontal and vertical hysteretic behaviours, including the effect of forces generated by the vertical damper. Figure 3.3 shows the idealized hysteretic response of the UPSS-horizontal damper system.

The amount of hysteretic energy dissipated per cycle is evaluated by the area enclosed by the force-displacement hysteresis loop. Energy dissipation derived from horizontal and vertical hysteresis loops (ΔW_x and ΔW_y respectively) and total energy dissipation ΔW are expressed as follows:

- UPSS

$$\begin{aligned} \Delta W_x &= 4\mu mge - 4\mu mg(A-e)\cos^2\theta \\ \Delta W_y &= 4\mu mg(A-e)\sin^2\theta \\ \Delta W &= \Delta W_x + \Delta W_y = 4\mu mgA \end{aligned} \tag{2.6}$$

- UPSS-horizontal damper system

$$\begin{aligned} \Delta W_x &= 4e(\mu mg + F_F) + 4(\mu mg + F_F)(A-e)\cos^2\theta \\ \Delta W_y &= 4(\mu mg + F_F)(A-e)\sin^2\theta \\ \Delta W &= 4\mu mgA + 4F_F A \end{aligned} \tag{2.7}$$

- UPSS-vertical damper system

$$\begin{aligned} \Delta W_x &= 4\mu mgA - 4\mu mg(A-e)\sin^2\theta + 4F_F(A-e)\cos^2\theta\tan\theta \\ \Delta W_y &= 4\mu mg(A-e)\sin^2\theta + 4F_F(A-e)\sin^2\theta\tan\theta \\ \Delta W &= 4\mu mgA + 4F_F(A-e)\tan\theta \end{aligned} \tag{2.8}$$

The additional energy absorption effect by the damper appears in the hysteresis loops corresponding to horizontal and vertical motions, and it can be shown that the proportion of the horizontal energy dissipation to the vertical one is "1 : $\tan^2\theta$", regardless of the orientation of the damper.

3. SEISMIC RESPONSE ANALYSIS

3.1. Numerical Model

A practical model of UPSS is required to investigate the efficiency of the UPSS-damper system for seismic response control. In this chapter, development of numerical UPSS model based on the results of past shaking table tests (Igarashi et al. 2009b) and material tests is described.

3.1.1. Numerical model of UPSS

Fundamental feature of UPSS is expressed by the model consisting of a mass of the girder, springs and sliding surface elements as shown in Figure 4.1 (Sato et al. 2010). Each sliding surface consists of a combination of springs in the normal and the sliding friction elements. Areas A, B and C in Figure 4.2 are used as criteria to determine the spring to be activated during the analysis. When the girder displacement represented by a mass is in the areas A and B, springs of the horizontal sliding surface and the ones of inclined sliding surface are activated, respectively. In the area C, both of the springs of the horizontal and inclined sliding surfaces are in contact with the mass.

In the past shaking table test, the girder slid along the sliding surfaces of UPSS without take-off behaviour. In addition to the springs for normal and friction forces, linear springs for impact force are incorporated to represent the dynamic behaviour of UPSS and energy dissipation at the time of collisions which were observed in the test. Energy dissipation ratio r_E during the impact is defined by Eq.(4.1).

$$r_E = \frac{mv^2/2 - mv'^2/2}{mv^2/2} = 1 - \left(\frac{v'}{v}\right)^2 \tag{3.1}$$

where v is the approaching velocity of the colliding mass m before the impact, v' is the separation velocity after the impact, ϕ and ϕ' are the incident angle and the reflection angle, respectively. Formulation of the impact using linear springs is based on the idea of a simplified situation such that a point mass colliding to a flat plane, as shown in Figure 4.3. In order to represent the sliding motion of the girder without jumping at the edge of the slope, the angle of the direction of motion altered by the impact should be equal to the inclined slope angle, θ. Hence, the relationship $\theta = \phi + \phi'$ should be satisfied.

The reaction force from the flat plane can be divided into the tangential component, F_η, and the perpendicular one, F_ξ. The relationship between F_η and F_ξ is assumed to obey the Coulomb friction law as follows.

$$\left|\frac{F_\xi}{F_\eta}\right| = \mu' \tag{3.2}$$

where μ' is an apparent friction coefficient. If no damping is assumed in the collision on the flat plane, the coefficient of restitution is unity, and the perpendicular velocity of the point mass is conserved after the collision.

$$v\cos\phi = v'\cos\phi' \tag{3.3}$$

Hence, the apparent friction coefficient μ' is represented as Eq. (4.4) by using the change of momentum.

$$\mu' = \left|\frac{\int F_\xi dt}{\int F_\eta dt}\right| = \left|\frac{v'\sin\phi' - v\sin\phi}{v'\cos\phi' - (-v\cos\phi)}\right| = \left|\frac{v'\sin\phi' - v\sin\phi}{2v\cos\phi}\right| \tag{3.4}$$

Relationship between the energy dissipation ratio r_E and apparent friction coefficient μ' under the condition of the given inclined slope angle is derived from Eqs. (4.1) through (4.4). Figure 4.4 shows the relationship between r_E and μ' for the case of $\theta = 15$ and 30 degrees.

If the point mass slides down on the slope to collide to the horizontal sliding surface, the amount of energy dissipation can be calculated from the change of momentum in the same manner as the case of the mass sliding toward the inclined sliding surface. Therefore, the collision phenomena can be expressed by a dynamic behaviour of a point mass colliding to the flat plane with friction coefficient μ' and incident angle ϕ'. In the numerical model, a hypothetical inclined flat plane with the angle of $\theta/2$, which is the average of ϕ and ϕ', are incorporated at the corner of the sliding surfaces.

The stiffness of the normal springs is 62,700kN/m based on the result of material tests of actual slider specimen of UPSS. The damping ratio of the spring is assumed to be 10% to avoid excessive oscillatory response of the bearing in the areas A and B. Normal springs in the area C and impact springs have no damping to avoid excessive viscous attenuation of the mass at the time of collision.

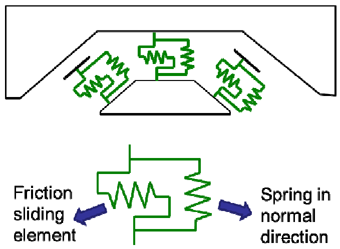


Figure 4.1. Numerical model of UPSS

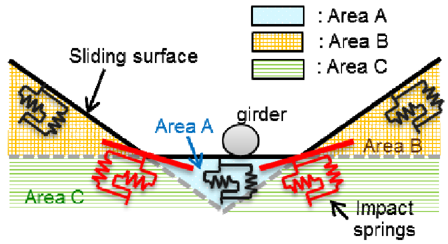


Figure 4.2. Alignment of springs in UPSS model

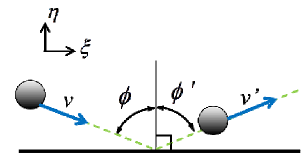
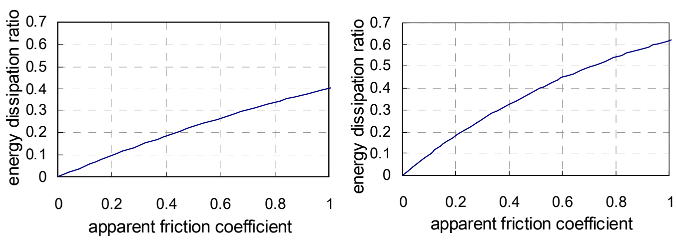


Figure 4.3. Collision of mass and flat plane

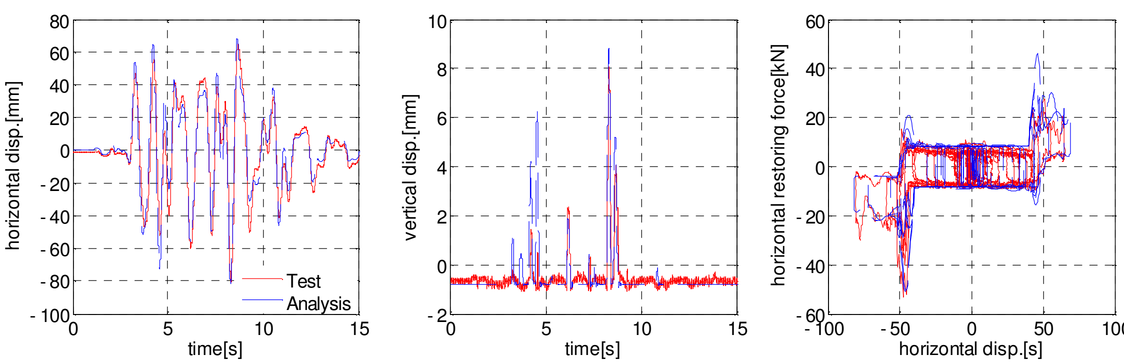


(a) Slope angle 15 deg. (b) Slope angle 30 deg.

Figure 4.4. Relationship between energy dissipation and apparent friction coefficient

Table 4.1. Parameters of UPSS model

Normal spring	Stiffness	62,700 kN/m	
	Damping ratio	Area A,B	Area C
		0.1	0
Impact spring	stiffness	125,400 kN/m	
	Damping ratio	0	
	Apparent friction coefficient	Friction coefficient of sliding surface*2.25	



(a) Horizontal disp. response (b) Vertical disp. response (c) Hysteretic behavior of UPSS

Figure 4.5. Test result and analytical response; Type 2-II-2 earthquake, e=42mm, θ=15deg

The stiffness of the impact springs and the apparent friction coefficient are adjusted so that the response similar to the test result is obtained on a trial-and-error basis. The parameters of UPSS are shown in Table 4.1. Figure 4.5 shows the comparison between the test result and analytical response. It is evident that the proposed analytical model captures the experimental response satisfactorily.

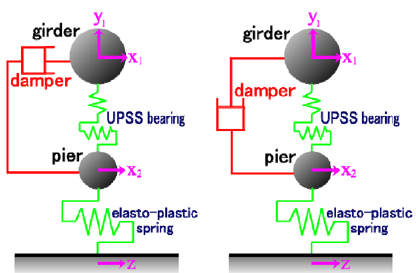
3.1.2. Numerical model of bridge

A simplified nonlinear multi-degree-of-freedom system consisting of two lumped masses incorporating numerical models of an UPSS and a damper shown in Figure 4.6 is used for nonlinear seismic response analysis. The nonlinear hysteretic behaviour of the RC bridge pier supporting the UPSS bearing is numerically represented by Clough's degrading stiffness model, with the yield strength corresponding to 0.66g lateral force. In the series of analysis, the initial stiffness of the RC pier is specified so that the elastic natural period for the non-isolated (fixed bearing) condition becomes 0.5sec (Figure 4.7). The damper load is expressed by a model using fractional exponential of velocity. The damper load F_D [kN] developed by the damper is given by Eq. (4.5).

$$F_D = C \cdot \mathrm{sgn}(\dot{x}_D) \cdot |\dot{x}_D|^{0.1} \tag{3.5}$$

where $\dot{x}_D$ is the relative velocity between the two ends of the damper and C is a constant.

The input seismic ground accelations used in the analysis are representative Level-2 (Type-2) earthquake accelerograms for soil type II specified in the highway bridge design specifications in Japan. The parameter values for the UPSS bearing and the damper used in the nonlinear response analysis are shown in Table 4.2. Analysis is conducted using all the combinations of the parameter values in the table.



(a) Horizontal damper system (b) Vertical damper system

Figure 4.6. Lumped mass model

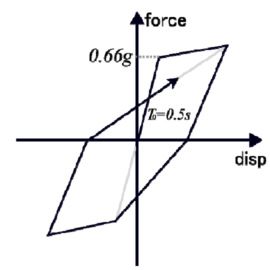


Figure 4.7. Clough-type pier spring model

Table 4.2. Parameters for UPSS-damper system

Parameter		Value
Angle of inclined slope(degree)		5, 10, 15, 20, 25, 30
Clearance (mm)		10, 20, 30
Friction coefficient		0.05, 0.10, 0.15
Damper force (kN)	horizontal damper	450, 900, 1350, 1800, 2250, 2700
	vertical damper	900, 1800, 2700, 3600, 4500, 5400, 6300, 7200, 8100

3.2. Results

Typical simulation results are shown in Figure 4.8. The input ground motion is a Level-2 (Type-2) earthquake ground motion and the setting of parameters is μ=0.10, θ=20°, e=30mm, C=1,350 (for the horizontal damper), and C=2,700 (for the vertical damper). The results demonstrate the efficiency of the UPSS-damper system, showing the maximum girder displacement, bearing displacement and pier ductility are effectively reduced. In comparing the response of the system incorporating the horizontal damper to the one for the case with UPSS alone, the maximum displacement of the girder is reduced to 41%, and the maximum response ductility factor for the pier is reduced to 46% in this example. For the UPSS-vertical damper system, the maximum displacement of the girder and the pier ductility are reduced to 50% and 62%, respectively, compared to the response of the system incorporating UPSS only.

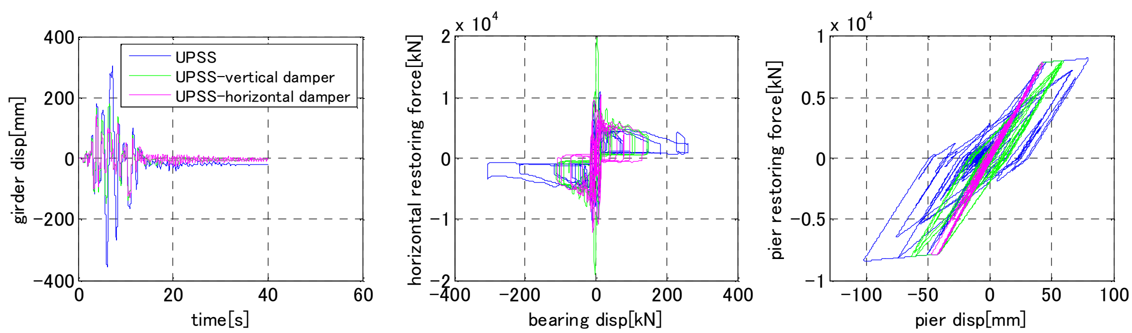


Figure 4.8. Comparison of the response with UPSS and UPSS-damper system (μ=0.15, θ=15°, e=10mm)

4. DISCUSSION ON SEISMIC PERFORMANCE AND DESIGN

As described in the previous section, the nonlinear seismic response analysis results for various combinations of the parameters of the UPSS-damper system are obtained. The plot of the relationship between the maximum girder displacement and pier response ductility for all the combinations is shown in Figure 5.1. The relationship between the maximum bearing displacement and pier response ductility is shown in Figure 5.2. The cases in the vicinity of the origin are supposed to be desirable because it implies that the two values are small at the same time. From this perspective, the figures can be used as representations of the effectiveness of UPSS-damper system. In addition, it can be observed that combinations of girder displacement and pier ductility represented as points are distributed in a certain region in the plot. It is obvious that there is a trade-off relationship between the girder displacements and pier ductility, implying that minimizing the two values at the same time is difficult. The cases located on the lower/leftmost envelope of the region in the plot can be regarded as desirable in the sense that each of them achieves the minimum girder displacement for a given pier ductility.

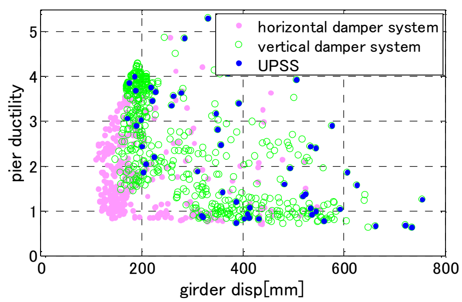


Figure 5.1. Maximum girder displacement and pier ductility

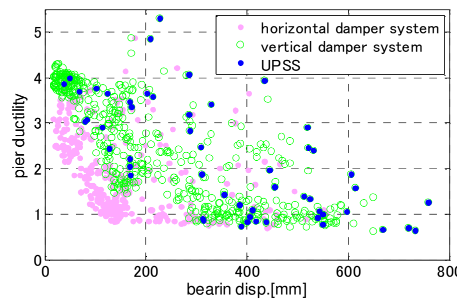
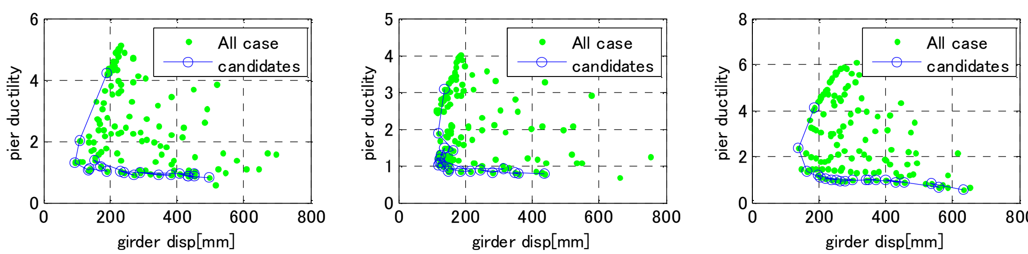
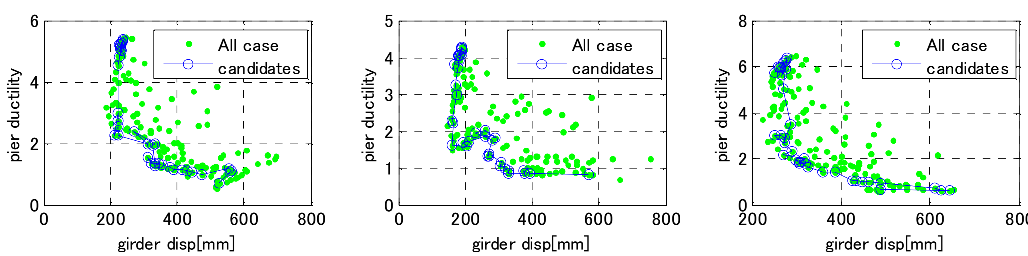


Figure 5.2. Maximum bearing displacement and pier ductility



(a) Type2-II-1 (b) Type2-II-2 (c) Type2-II-3

Figure 5.3. Candidates of desirable design (UPSS-horizontal damper system)



(a) Type2-II-1 (b) Type2-II-2 (c) Type2-II-3

Figure 5.4. Candidates of desirable design (UPSS-vertical damper system)

The maximum horizontal reaction forces acting on the pier and the hysteretic energy absorption are assumed to be the factors that affect the maximum seismic response. From this assumption, a condition to achieve the maximum hysteretic energy absorption within a given limitation of horizontal force is proposed as the hypothetical design criteria to obtain desirable response. Candidates for the desirable designs are selected by maximizing the amount of hysteretic energy absorption calculated by Eqs. (3.1) through (3.8), under the restriction on the range of horizontal restoring forces. The locations of the points of all the combinations (with the clearance e=10[mm]) and of the candidates are shown in Figures 5.3 and 5.4. The candidates are found to be located close to the envelope for all the input seismic ground accelerations, implying that the condition proposed above are considered to be relevant. The combinations with the other values of clearance also produce similar results.

5. CONCLUSIONS

The concept of a combination of the UPSS bearings and seismic dampers is proposed to control the seismic response of bridges. The hysteretic behaviour of the UPSS-damper system is analytically evaluated and the effectiveness of the system is investigated by numerical seismic response analysis using a simplified bridge model. The results of the analysis indicate that the UPSS-damper system is effective in reducing the maximum girder displacement and response ductility factor of the pier. Furthermore, the criteria to achieve desirable design of the system are discussed in consideration of the restoring force and hysteretic energy absorption which are analytically evaluated by the equilibrium of forces acting on the sliding surfaces. Desirable design can be obtained by maximizing the amount of hysteretic energy absorption under the restriction on the range of horizontal restoring forces, with the use of the analytical evaluation developed in this study. Validity of the proposed criteria for the most effective response control is successfully shown.

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