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Vibration Control System Combining Rocking Isolation with Seismic Dampers for Bridge Structures Subjected to Strong Ground Motions

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Abstract

Dynamic rocking response of structures has been studied over the past four decades. Several studies have shown that rocking response of direct foundations subjected to strong ground motions may result in uplift of the foundation, and such foundation uplift functioned as a type of seismic isolation effect against the response of bridge structures. This isolation system is known as rocking isolation. However, the isolation system may increase seismic responses of bridge structures in some cases. On the other hand, seismic dampers have emerged as effective measures to improve the seismic performance of bridge structures. Seismic dampers also enable control responses of bridge structures. This paper presents a vibration control system, which is combined rocking isolation with seismic dampers, for bridge structures subjected to strong ground motions. Dynamic analysis is performed for evaluating fundamental seismic performance of the system. A two-dimensional finite element program that can account for foundation uplift is used for the analysis of bridge structures. Foundation is modeled with beam on winkler springs and foundation uplift is taken into account by ignoring tensile force of winkler springs. Takeda's model is used for restoring force characteristics of bridge piers in the program. The seismic damper is modeled with non-linear viscous damper. The viscous damper is connected to abutment. The system is modeled as two cases; (1) rocking isolation with seismic damper and, (2) rocking isolation without seismic damper. Several strong ground motions are used as input ground motions in the models. As a result of the examination, the bridge system combining the rocking isolation and the seismic damper has significantly smaller curvature of the plastic hinge and higher seismic performance than only the rocking isolation, regardless of the type of seismic motion. This indicates that the bridge system combining the rocking isolation and the seismic damper can be a highly robust bridge system.

Keywords: highway bridge, direct foundation, rocking isolation, seismic damper

1. Introduction

In order to improve the seismic performance of bridge structures, it is conceivable to use earthquake resistant structures, seismic isolation systems, and seismic control systems. It is known that the external force due to an earthquake has a high degree of uncertainty, and it is important to understand how to deal with this problem. In recent years, the importance of structural systems (structural systems with high robustness) that are insensitive to functional loss due to seismic effects has been shown, and such structural systems are required [1]. So far, efforts have been made to realize a highly robust bridge structure by combining a seismic isolation system and a seismic control system. Matsuda *et al.* have proposed new aseismic systems for multi-span continuous girder bridges that combine seismic isolation bearings, seismic control devices, and sliding bearings in an appropriate manner [2]. Such a system is aimed at stable seismic behavior.

On the other hand, dynamic rocking response of structures has been studied over the past four decades. Several studies have shown that rocking response of direct foundations subjected to strong ground motions may result in uplift of the foundation, and such foundation uplift functions as a type of seismic isolation effect against that of bridge structures [3, 4]. This isolation system is known as rocking isolation.

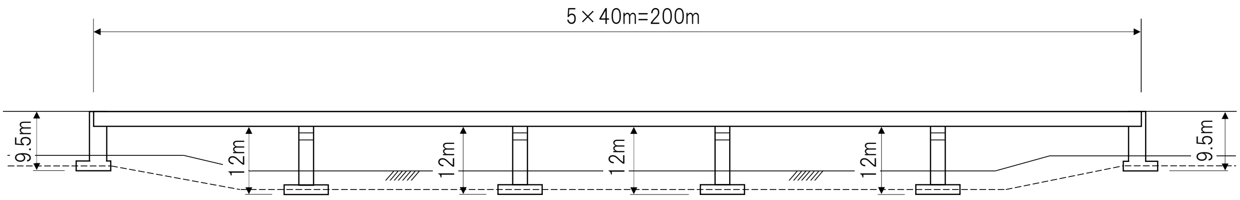


Fig. 1 – Highway bridge [6]

In this study, we investigated whether a robust bridge system can be realized by combining rocking isolation and seismic dampers.

2. Research method

In this study, we investigated typical highway bridges by seismic response analysis. By comparing seismic response of the analysis model considering the rocking isolation and seismic damper with the seismic response of the analysis model considering only rocking isolation, the robustness of a seismic resistant structure combining the rocking isolation and the seismic damper was investigated. General purpose dynamic analysis software (TDAPIII [5]) was used for seismic response analysis of the bridge.

2.1 Analysis model

In this study, we examined the highway bridge shown in Fig.1 [6]. The superstructure is a steel girder bridge, and reinforced concrete piers are used. The bearing conditions were assumed to be fixed. One substructure and the superstructure supported by it were considered as one design vibration unit. This was used as an analysis model for the bridge. Response in the direction of the bridge axis, which is considered to be critical in earthquake resistant design, was studied. Here, the seismic damper is connected to abutment. Fig.2 shows a conceptual diagram of the analytical model modeled as a discrete frame structure model. Table 1 shows the parameters. The superstructure, pier and foundation were modeled by lumped mass and linear beam elements. The superstructure was modeled as one mass, and the overhang of the pier and the foundation were

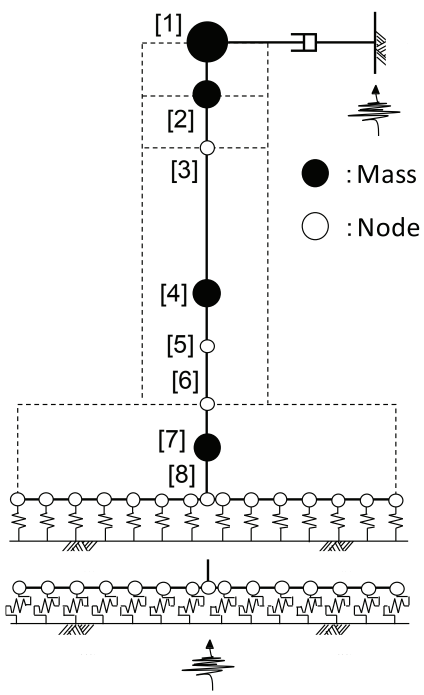


Fig. 2 – Conceptual diagram

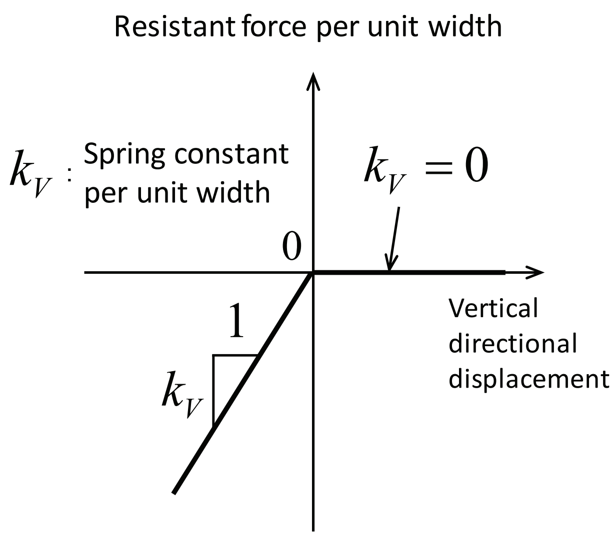


Fig. 3 – Historical law of vertical ground spring

Table 1 – Parameters of analytical model

Parameters		Value
Superstructure	Lumped mass of Node[1] (t)	710
Bridge pier	Young's modulus of beam element (kN/m^2)	6890000
	Lumped mass of Node[3] (t)	140
	Lumped mass of Node[5] (t)	206
	Lumped mass of Node[8] (t)	228
	Moment of inertia of Node[8] (t・m^2)	877
	Yield curvature of non-linear beam element (1/m)	0.00114
	Length of plastic hinge (m)	0.637
Soil	Stiffness of vertical soil spring per unit width (kN/m^2)	7310000
	Stiffness of horizontal soil spring per unit width (kN/m^2)	7310000
Damper	Damping coefficient (kNs$^{0.1}$/m$^{0.1}$)	3000

Table 2 – Input ground motions

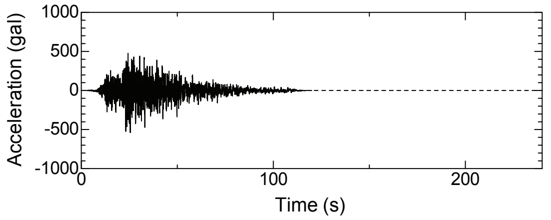
Earthquake	name
2003 Tokachi-Oki Earthquake	I - I - 1
2011 Touhoku-Oki Earthquake	I - I - 2
	I - I - 3
1995 Hyogo-ken Nanbu Earthquake	II - I - 1
	II - I - 2
	II - I - 3

assumed to be rigid. The plastic hinge section was modeled by a nonlinear beam element, and the bending moment-curvature relationship was Takeda type, having a complete elasto-plastic skeleton curve. As ground conditions, we assumed a sandy ground with an N value of about 50 and an S-wave velocity, Vs, of about 295 m/s. The ground was modeled by Winkler-type vertical and horizontal ground springs. It is considered that the ground partly yields with uplift of the foundation, but here, it is assumed that the ground does not yield in order to simplify the analysis. In this study, in order to take into account uplift of the foundation, reaction force on the tension side of the vertical ground spring was ignored (Fig.3). Effects of earth cover and suction at the bottom of the foundation were ignored. The first natural frequency of the linear system is 1.64 Hz. The damping matrix was set using Rayleigh damping. Damping coefficients were assumed to be 3% for rubber bearings, 2% for pier plastic hinge sections, 5% for outside pier plastic hinge sections, and 10% for foundation-soil system. Damping coefficients in the first and fourth modes of the linear system were obtained from the strain energy proportional damping method, and two coefficients of Rayleigh damping were obtained from these. In addition, seismic response analysis was carried out following the self-weight analysis. As a seismic damper, a friction history type viscous damper, which has been widely used, was used. Viscous damper was modeled as follows:

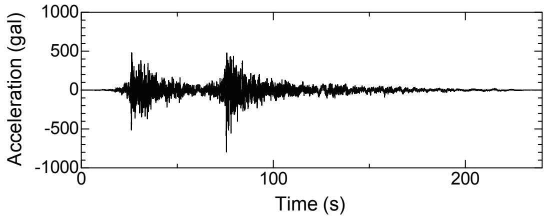
$$F = CV^{0.1} \tag{1}$$

Where, F is damping force, C is damping coefficient and V is velocity. In the non-linear seismic response analysis, the time step was set to 0.001 seconds, and Newmark's β method (β = 0.25) was used as the time integration method.

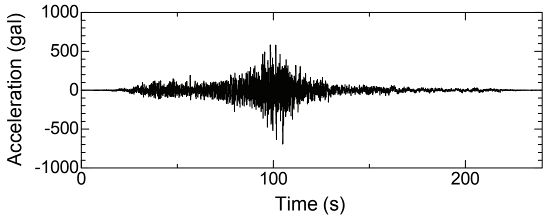
2.2 Input ground motion



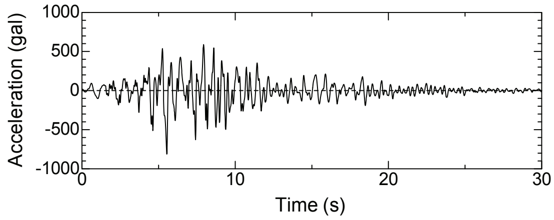
(a) I - I - 1



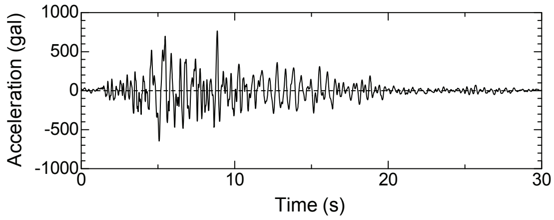
(b) I - I - 2



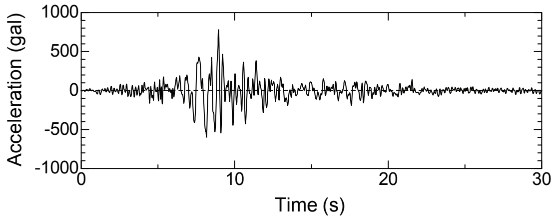
(c) I - I - 3



(d) II - I - 1

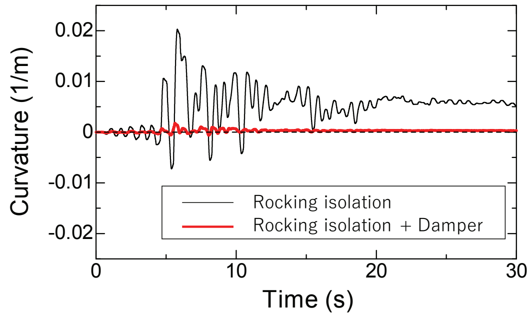


(e) II - I - 2

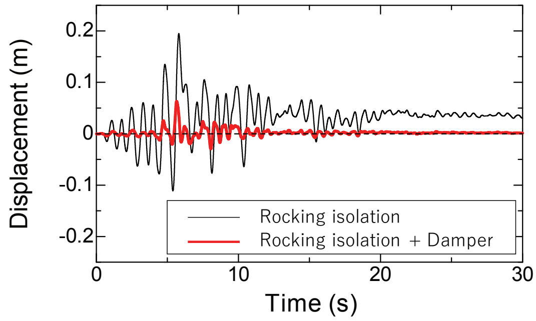


(f) II - I - 3

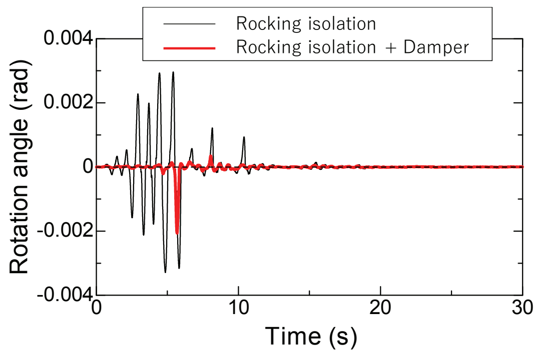
Fig. 4 – Input ground motions



(a) Curvature



(b) Displacement



(c) Rotation angle

Fig. 5 – Time history waveform

As input ground motions for the models, three inland earthquakes and three subduction earthquakes shown in the Japanease Design Specifications for Highway Bridges [7] were used (Table2). Fig.4 shows the acceleration time histories.

3. Results

Results of the investigation using the set analysis model and the input ground motion are presented. As an example, Fig. 5 shows the time history waveform of curvature of the plastic hinge,

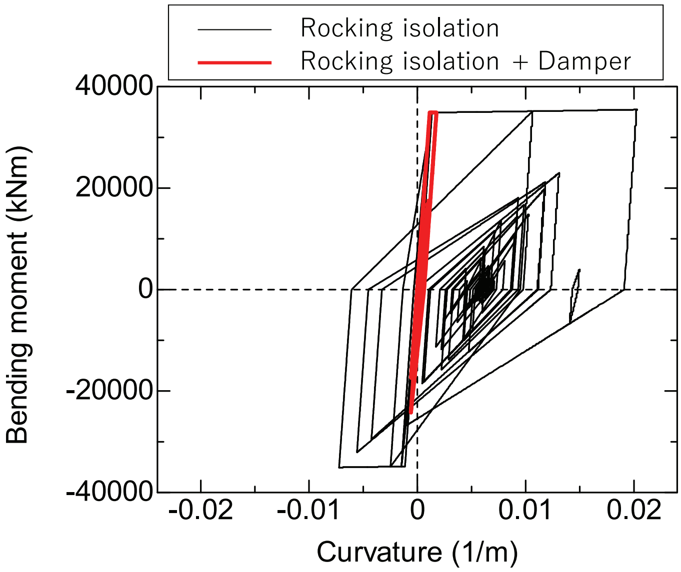


Fig. 6 – Bending moment-curvature relation of plastic hinge

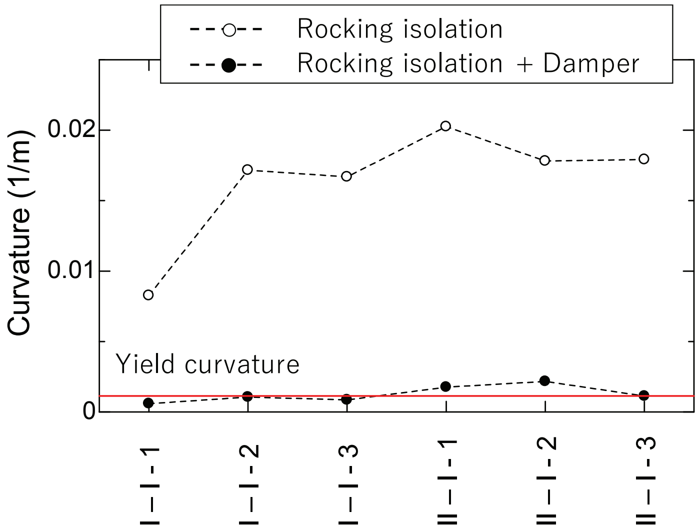
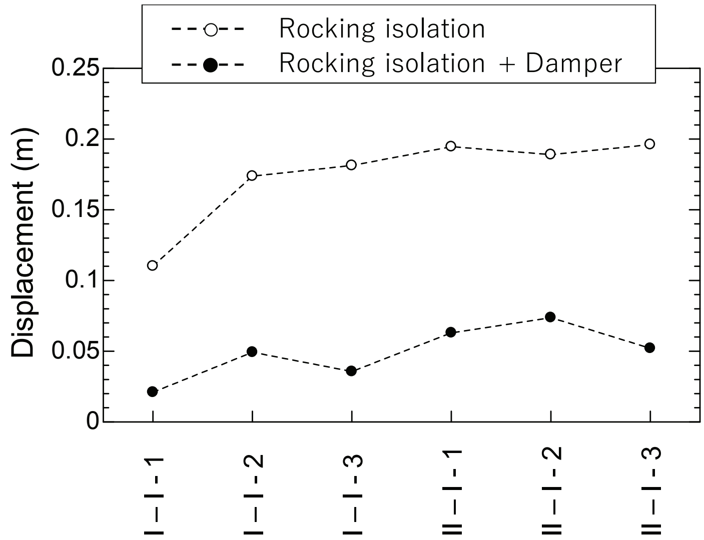
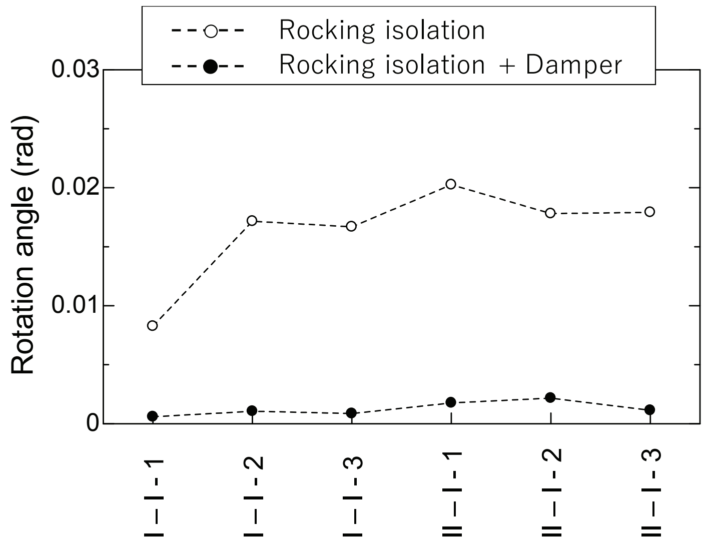


Fig. 7 – Maximum values of the curvature of the plastic hinge

horizontal displacement of the girder, and rotation angle of the foundation and Fig. 6 shows the bending moment-curvature relation of plastic hinge when II-I-1 is the input ground motion. In both Fig. 5 and Fig. 6, a thick red line indicates the case where the rocking seismic isolation and seismic damper are considered, and a thin black line indicates the case where only the rocking seismic isolation was used. It can be seen that the structure combining rocking seismic isolation and seismic damper has significantly smaller curvature and higher seismic performance than the rocking seismic isolation based only on the uplifting of the foundation. Fig. 7 and Fig. 8 show the maximum values of curvature of the plastic hinge, horizontal displacement of the girder, and rotation angle of the foundation for each input ground motions. It can be seen that the structure combining the rocking seismic isolation and the seismic damper has significantly smaller curvature and higher seismic performance than the rocking seismic isolation, regardless of the type of seismic motion. This



(a) Maximum values of horizontal displacement of the girder



(b) Maximum values of rotation angle of the foundation

Fig. 8 – Maximum values of horizontal displacement of the girder and the rotation angle of the foundation

indicates that the bridge system combining rocking seismic isolation and seismic damper can be a highly robust bridge system.

4. Conclusion

In this study, we investigated whether a robust bridge system can be realized by combining rocking isolation and seismic dampers. As a result of the examination, it was found that bridge system combining rocking isolation and seismic damper has significantly smaller curvature and higher seismic performance than only rocking isolation, regardless of the type of seismic motion. This indicates that the bridge system combining rocking isolation and seismic damper can be a highly robust bridge system.

5. References

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