Control of excessive bridge responses under unanticipated earthquakes through an innovative rocking isolation bearing system (RIBS)

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Abstract. In general, bridge structures are designed to resist the maximum considered earthquake (MCE) specified in design specifications. Given the threat of the occurrence of unanticipated earthquakes, the development of the bridge with anti-catastrophic or damage-free capability becomes essential. An innovative rocking isolation bearing system (RIBS) was proposed to control the excessive pier displacement as well as girder displacement under unanticipated earthquakes. The rocking motion of RIBS is activated to provide seismic isolation effect when the seismic action exceeds a specified level. The seismic energy is dissipated by the collision between the bottom plate of RIBS and the top of the bridge pier. The dynamics of an example bridge featuring such RIBS were characterized as a simplified model. Two coefficient of restitution (COR) models were used to investigate the effects of energy dissipation during the impact: the Housner model and a model derived from the conservation of the angular momentum and the linear momentum in the horizontal direction. A series of nonlinear time-history analyses were performed for the example bridge under varying intensities of the design ground motions corresponding to MCE in Japan. When an appropriate selection of the design parameters of RIBS is achieved, the maximum pier displacement shows insensitive against varying intensities of ground motions, since the mechanical fuse of RIBS limits the maximum reaction force acting on the piers; the rocking bearing is not overturned until the design ground motion is scaled over several times its original intensity, implying its anti-catastrophic or damage-free capability.

Keywords: rocking isolation bearing system (RIBS), bridges, maximum response control effectiveness, unanticipated earthquakes.

1 Introduction

Earthquakes that exceed design expectations cause damage to bridges, such as falling girders and collapse of bridge piers. Given the threat of the occurrence of unanticipated earthquakes, e.g., the 2016 Kumamoto earthquake, the development of the bridge with anti-catastrophic or damage-free capability becomes essential.

Although rubber-type seismic isolation bearings have been extensively used in bridge construction in Japan to enhance the seismic performance of the bridges, problems due to excessive seismic response of the bearings were frequently observed in past earthquakes, e.g., breakage of rubber bearings and offset of girders [1]. Exceeded displacement of these bearings could also leave a higher reaction force, which is problematic for controlling the bridge pier response.

The application of the rocking mechanism in modern structures has been recognized as an unconventional but effective seismic response modification technique. These structures provide several advantages in – recentering capability without residual deformation, larger displacement stroke, negative stiffness, and mechanical fuse effect that limits the generated reaction forces. Various strategies have been proposed to address their application, such as rocking wall systems and rocking podium systems in buildings [2–4] and rocking foundations and rocking piers in bridges [5–7].

Past earthquake reports point out that when the rocking motion of the conventional pin bearings, followed by the pulling-out of their anchor bolts, was observed after strong earthquakes, the damages to the substructure piers and to the flange of the girder were significantly mitigated due to the peculiar seismic isolation effect of the bearing's rocking motion.

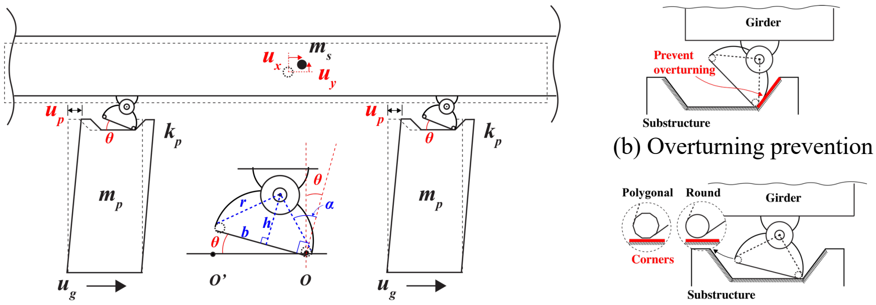
In light of the above discussions, a new rocking isolation bearing system (RIBS) was proposed to control the maximum seismic response of bridge structures in our previous study [8]. When the seismic action exceeds a specified level, the rocking motion of RIBS is activated to provide a seismic isolation effect. The maximum horizontal reaction force of this bearing can be easily adjusted by the height and width of the bearing. The energy is absorbed by the collision at the bottom of the bearing during its rocking vibration. In the present study, the maximum response control effectiveness of RIBS on an example bridge under varying intensities of MCE was explored. Two different coefficient-of-restitution (COR) models were used to show the effects of energy dissipation during the collision on different performance indices.

2 Bridge with RIBS: fundamental characteristics

2.1 Possible application and behavior

An example bridge with RIBS is presented in Fig. 1(a). RIBS was designed as a pin-bearing-like bearing consisting of the upper plate, the pin, and the bottom plate. Distinguished from the conventional pin bearing system, the constraints between the bottom plate and the substructure are released. Once the seismic action exceeds a specific criterion, the rocking motion of the bearing around its corners is triggered, and the centroid of the superstructure girder is uplifted to provide restoring force for the rocking motion.

In practical application, RIBS is placed in a groove formed by three flat surfaces, as shown in Fig. 1(b). The two inclined surfaces were designed to restrain the excessive rotation of the bearing so as to obviate concerns about overturning. The two toes of the bottom plate were designed as polygonal or round to avert stress concentration at the rotation corners, as shown in Fig. 1(c).



(a) Rocking motion of RIBS in bridge (b) Overturning prevention (c) Corner details

Fig. 1. Possible application of RIBS in bridges

2.2 Modeling and nonlinear restoring force characteristics of RIBS

Under horizontal seismic action, the girder supported by the RIBS is treated as a rigid body, the mechanical properties of the bridge piers are assumed to be constant, and the sliding and bouncing of the bearings are neglected. The mass of the girder is denoted by m_s; the mass, stiffness, and damping of the bridge piers are denoted by m_p, k_p, and c_p, respectively. The dynamic features of RIBS are governed by the height and half-width of the lower plate, denoted as h and b, respectively, so that the bearing has the size of $r = \sqrt{h^2 + b^2}$ and the inclined angle of $\alpha = \arctan(b/h)$.

Once the rocking motion of RIBS is triggered, the dynamic model of the system can be completely described by the two independent generalized quantities, $\theta(t)$ and $u_p(t)$, namely the rotation angle of the rocking motion of the bearing and the top drift of the pier, respectively. The sign of θ is positive when the rocking motion is around the right pivot (O) and negative when it is around the left pivot (O').

An intermediate variable θ_2 is defined as:

$$\theta_2 = \begin{cases} \alpha - \theta, & \theta > 0 \\ \alpha + \theta, & \theta < 0 \end{cases} \tag{1}$$

During the rocking motion, the positions of the girder P_p and of the piers P_s are:

$$P_p = \begin{pmatrix} u_g + u_p \\ 0 \end{pmatrix}, \qquad P_s = P_p + \begin{pmatrix} \pm b \mp r \sin\theta_2 \\ r\cos\theta_2 \end{pmatrix} \tag{2}$$

where u_g is the horizontal displacement of ground motions.

The kinetic energy K and the potential energy U of this system can be expressed as:

$$K = \frac{1}{2} m_p \dot{P}_p^T \dot{P}_p + \frac{1}{2} m_s \dot{P}_s^T \dot{P}_s, \qquad U = \frac{1}{2} k_p u_p^2 + m_s g r \cos\theta_2 \tag{3}$$

where g is the gravitational acceleration.

Substitution the above equations into the Lagrange equation, combined with the damping force of the pier treated as external force, yields:

$$
\begin{aligned}
(m_p + m_s)\ddot{u}_p + m_s r \cos\theta_2\, \ddot{\theta} \pm m_s r \sin\theta_2\, \dot{\theta}^2 + c_p \dot{u}_p + k_p u_p \\
= -(m_p + m_s)\ddot{u}_g \\
m_s r^2 \ddot{\theta} + m_s r \cos\theta_2\, \ddot{u}_p \pm m_s g r \sin\theta_2 = -m_s r \cos\theta_2\, \ddot{u}_g
\end{aligned} \tag{4}
$$

where the top sign of the double sign ($\pm$) is for $\theta > 0$, and the bottom sign is for $\theta < 0$.

Although a direct evaluation of the control effectiveness of RIBS on the pier response is difficult, the complex interaction between the bearing and the substructure can be reasonably approximated on the basis of the static equilibrium condition, see Fig. 2. In this context, the restoring force of the bearing with an onset value at the equilibrium position shows a negative stiffness characteristic. This offers a desirable cutoff effect on the maximum reaction force transmitting to the substructure pier, regardless of the intensity of earthquakes.

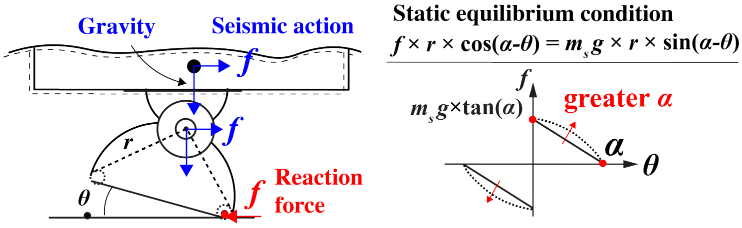


Fig. 2. Negative stiffness property of the nonlinear restoring force of RIBS

2.3 Assessment of energy dissipation by coefficient of restitution

The energy is dissipated by the collision between the bottom plate of RIBS and the interfaces when the sign of the rotation of the bearing gets reversed. The amount of energy dissipated by the collision can be evaluated by various methods. Based on the Housner model [8,9], the coefficient of restitution (COR) is given as:

$$
e_1 = \frac{\dot{\theta}_+}{\dot{\theta}_-} = 1 - 2\sin^2\alpha \tag{5}
$$

where $\dot{\theta}_-$ denotes the angular velocity immediately before impact and $\dot{\theta}_+$ denotes the angular velocity immediately after impact. Since the velocity is related to the kinetic energy, a smaller value of COR represents a greater energy dissipation.

An alternative model [8] derived from the conservation of the angular momentum and the linear momentum in the horizontal direction is given as:

$$
\begin{aligned}
e_2 = 1 - \frac{(\beta + 1)}{2(\beta + 1) - \beta\cos^2\alpha} 2\sin^2\alpha \\
\dot{u}_{p,+} = \frac{\beta}{\beta + 1}(1 - e_2) h \dot{\theta}_- + \dot{u}_{p,-}
\end{aligned} \tag{6}
$$

where $\dot{u}_{p,-}$ and $\dot{u}_{p,+}$ are the horizontal velocities of the piers immediately before and after the impact, respectively; and β denotes the mass ratio of the superstructure to the substructure. Note that, in the Houser model, the pier's velocity will remain constant during the impact [8].

As for a comparison, the COR value of the two models is depicted in Fig. 3. The e_1 COR model associates a higher energy dissipation evaluation for the collision than the e_2 model.

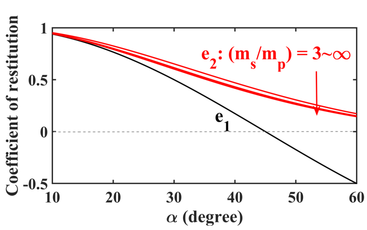


Fig. 3. Evaluation of COR for two models

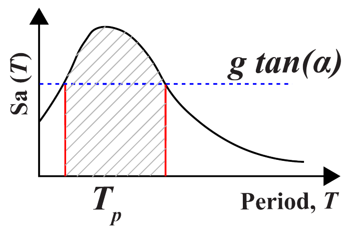


Fig. 4. Onset of rocking and response spectrum

2.4 Initiation condition and effective parameter selection principle

The rocking motion will be triggered when the overturning moment of the inertia force acting on the centroid of the girder, namely the multiplication of the absolute acceleration of the pier and the superstructure girder mass, satisfies the following inequality:

$$|\ddot{u}_g + \ddot{u}_p| \geq g \tan \alpha \tag{6}$$

where the rocking direction is leftwards, around the O' pivot ($\theta < 0$), when $\ddot{u}_g + \ddot{u}_p > 0$ is satisfied. When $\ddot{u}_g + \ddot{u}_p < 0$ is satisfied the rocking direction is rightwards, around the O pivot ($\theta > 0$).

When the bearing remains in the rest state, namely the fixed bearing condition, the governing equation can be expressed as:

$$(m_p + m_s)\ddot{u}_p + c_p\dot{u}_p + k_p u_p = -(m_p + m_s)\ddot{u}_g \tag{7}$$

It can be pointed out that a RIBS with a specified α only functions for piers with a natural period in a certain range when the intensity of earthquakes is prescribed, as shown in Fig. 4. In particular, under a mild assumption for the pier, i.e., linear-elastic properties and 5% damping ratio, the maximum resultant acceleration of the pier in the fixed bearing condition will be exactly the 5% response spectrum value. To trigger the rocking motion, the response spectrum value at the given pier period is supposed to exceed the initiation condition. This provides a straightforward condition to select the valid parameters of RIBS in the preliminary design stage.

3 Maximum response control effectiveness of RIBS under unanticipated earthquake scenarios

The example bridge structure featuring RIBS, with structural parameters as presented in Table 1, was used to illustrate the maximum response control effectiveness of RIBS. The two COR models were considered. The I-I-2 design ground motion in seismic specifications in Japan [10] corresponds to the maximum considered earthquake; the amplitude of the accelerogram was scaled to various levels to represent unanticipated earthquakes; see Fig. 5. According to the onset condition, it can easily know that when the maximum considered earthquake happens to occur, indicating a scaling factor of 1.0, the rocking motion of RIBS is triggered only in the $\alpha = 35°$ case. This can be confirmed in the following simulation results.

Table 1. Parameters of simulations

Mass ratio	$m_s/m_p = 5$	Inclined angle	$\alpha = 35°, 55°$
Pier stiffness	$T_p = 0.5$ sec	Size	$r = 0.9$ m
Pier damping ratio	$\xi = 0.03$	COR models	e_1 or e_2

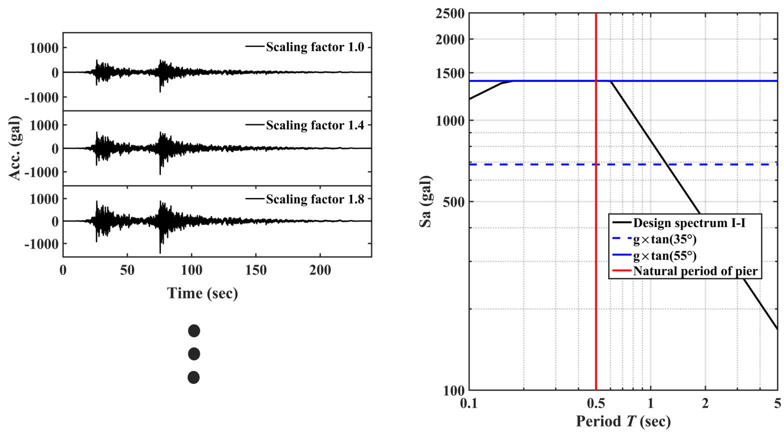
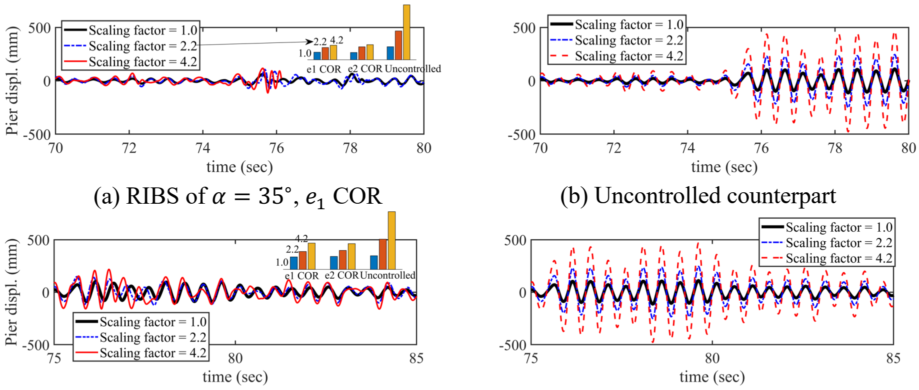


Fig. 5. Accelerogram of design ground motion I-I-2 in Japan Road Association (JRA) scaled to various levels, and its response spectrum (5% critical damping ratio)

The time-history analysis results of the pier response for the proposed bridge model with RIBS and the counterpart with the conventional pin bearing systems (referred to as uncontrolled) are presented in Fig. 6. The time period of dominant vibration is focused on and zoomed in. It can be found that the maximum pier displacement in the RIBS case is significantly mitigated from the uncontrolled counterpart. In particular, even if the intensity of ground motion increases up to several folds, the maximum pier displacement of RIBS shows a minor increment, regardless of the selection of the COR model; see the inserted bar graphs. This demonstrates the attractive cutoff effect of RIBS in controlling the maximum force transmitting to the substructure. On the other hand, the RIBS with a larger $\alpha = 55°$ tends to lead to a higher pier displacement since a greater inclined angle α is directly related to a greater amount of the maximum reaction force.

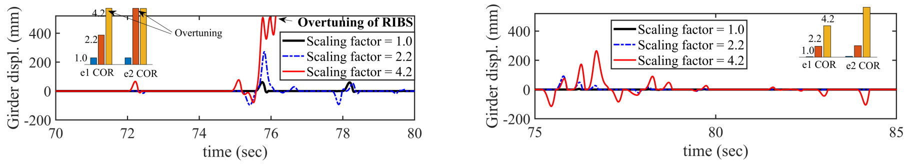


(a) RIBS of $\alpha = 35°$, e_1 COR (b) Uncontrolled counterpart

(c) RIBS of $\alpha = 55°$, e_1 COR (d) Uncontrolled counterpart

Fig. 6. Pier displacement under varying intensities of the unanticipated earthquake

The simulation results of the girder response displacement relative to the substructure are presented in Fig. 7. It is seen that as the ground motion intensity goes up, the maximum girder relative displacement in the $\alpha = 35°$ case will exceed its limitation, associated with the overturning of the bearing ($\max\theta(t) \geq \alpha$). This quantity can be effectively controlled by a greater α, since it provides greater restoring force to the girder. Notably, the energy dissipation during the collision is also a critical factor in controlling the maximum girder relative displacement. The cases with e_1 COR show smaller girder displacements than those with e_2 COR. Considering the implication of higher energy dissipation capability of the e_1 COR model, the combination of RIBS with energy dissipation devices in the bearing part could be a potential strategy to address exceeded girder response in the future study.



(a) RIBS of $\alpha = 35°$, e_1 COR (b) RIBS of $\alpha = 55°$, e_1 COR

Fig. 7. Girder relative displacement under varying intensities of the unanticipated earthquake

4 Conclusions

The fundamental dynamic characteristics and maximum seismic response control effectiveness of a newly proposed isolation bearing RIBS were investigated in the present study. A simple method to select the valid parameters of RIBS was present by combining the widely used 5% response spectrum and RIBS's initiation condition. The accelerogram corresponding to the maximum considered earthquake specified in JRA was scaled to several folds of its original intensity to represent unanticipated earthquake scenarios. It was found that the maximum pier displacement of RIBS constantly remains at a low level in comparison with its uncontrolled counterparts, even in an extremely severe earthquake intensity. While a smaller inclined angle α benefits a better pier response reduction, the girder response gets increased. The selection of different COR models makes little difference in the evaluation of the pier displacement, but the e_1 COR model with higher energy dissipation capability leads to a smaller girder displacement assessment.

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