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Seismic behavior of rocking base-isolated structures

Chin-Tung Cheng*, Chih-Hung Chao

Department of Construction Engineering, National Kaohsiung First University of Science & Technology, 1 University Road, Yenchao, Kaohsiung 824, Taiwan

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ABSTRACT

It has been known that base-isolation structures may have long-period response under earthquakes. Many researchers have pointed out that long-period resonant-like response of isolated structure may be induced by a ground motion containing strong long-period frequency spectra. To mitigate this problem, isolation systems with variable mechanical properties such as different isolating stiffness or various frictional damping with respect to isolator displacement have been proposed recently. In this paper, a new type of isolator called variable-frequency rocking bearing is proposed. The system allows the bearings to remain still under a moderate seismic load but start to rock back-and-forth during severe earthquakes. The vibration is damped throughout each impact of the bearings on structural footing and foundation surface. Based on the force-displacement relations and analytical damping of the system, the seismic response of the structure may be estimated through a modified elastic response spectrum. To validate the proposed idea, a one-bay-one-story spaced structure base-isolated with rocking bearings was constructed. In total, 261 shaking table tests were conducted with various investigated parameters including aspect ratio of the bearing, shapes of rocking plate (plane, spherical or polynomial surface), spring stiffness and waveform of ground motion etc. Test results showed that the vibration behavior was nonlinear with respect to the rocking amplitudes. It is also found that damping ratio of rocking base-isolated structures can be approximately estimated by the proposed theory.

1. Introduction

Literatures have proved that seismic isolation is an effective technology to protect structures from earthquake attacks [1]. Typically seismic isolation is achieved through the installation of a soft layer below the protected structures, so that seismic energy transmitted up to the super-structure due to a ground motion is terminated. The flexibility required to reduce seismic response in isolation system may be alternatively obtained by allowing part of structure to uplift, rocking or stepping during large horizontal motions [2]. For example, bridges with insufficient tensile pile capacity at footings allow the uplift of structures during strong earthquakes. This rocking behavior dominates the pier response that minimizes the damage to the footing and columns. In practice, the South Rangitikei Railway Bridge in New Zealand built in 1971 was the first structure designed in accordance with rocking and stepping concept. Since the bridge pier is 70 m high above the riverbed, the column base was cut so that lateral rocking of the portal frame piers is possible under the control of torsion-beam energy dissipater [2]. In recent research, control rocking behavior of steel braced frames has been investigated by many researchers [3–5]. The system consists of three main components: a steel braced frame that remains essentially elastic by uplifting at the column bases during ground motions, vertical post-tensioning (PT) that provides resistance to overturning and provides self-centering forces, and replaceable energy-dissipating elements that resist overturning and act as structural fuses that yield, effectively limiting the forces imposed on the rest of the structure [3]. The system is capable of preventing major structural damage and residual drift when subjected to severe maximum considered earthquake (MCE) level ground motion intensities.

In general, the isolated structure is designed to exhibit a fixed long-period vibration and constant damping ratio under earthquakes. Consequently, seismic response of structures such as roof acceleration (inertial loads) and inter story drift etc. can be significantly reduced due to this lengthened vibrating period. However, long-period resonant-like response of isolated structure may be induced by a ground motion containing strong long-period frequency spectra [6]. To mitigate the resonant-like response that conventional isolation systems may encounter in long-period earthquakes, researchers have proposed using isolation systems with variable mechanical properties, so that the isolation system

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* Corresponding author.
E-mail addresses: ctcheng@nkfust.edu.tw (C.-T. Cheng), gn1095102142@gmail.com (C.-H. Chao).

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can be more adaptive to a wider range of earthquakes with various spectral compositions [7]. Based on current research, Lu and Hsu [8] have classified six categories of isolation systems with variable mechanical properties as:

1. Multiple friction pendulum isolators (MFPIs) [9–11]: this type of friction isolator has multiple spherical sliding surfaces that are designed to have different radii and friction coefficients. Each of the MFPI sliding surfaces will be activated in different seismic loads, and thus the stiffness and friction damping of the isolator will vary when activated sliding surface is switched from one to another. Nevertheless, the variation of isolator stiffness is usually step-wise or discontinuous with respect to isolator displacement, as sliding surface with different radius is switched.
2. Sliding isolators with variable curvature (SIVC) [12–13]: this type of isolator usually has one or two sliding surfaces with variable curvature, which has a different stiffness that is a continuous function of the isolator displacement. However, in order to accommodate the continuous change in curvature, the sliders of this isolator were made of ductile polymer that may not have sufficient compressive resistance for heavy structures.
3. Sliding isolators with variable friction (SIVF) [14]: this type of isolator has constant stiffness, but the friction coefficient of the isolators is assumed to be a continuous function of the isolator displacement. Therefore, a SIVF has the property of variable friction damping. However, since feasible sliding materials that possess exactly the desired variable friction properties are rare and challenging to manufacture, the concept of the SIVF has not been verified experimentally.
4. Rocking pier isolation (RPI) [15–19]: the seismic isolation effect is achieved through the rocking motion of bridge piers or footings during an earthquake. The vibration behavior is nonlinear with respect to rocking amplitude. Since the radiation damping due to pier impact on foundation surface is usually lower than the desired value, supplementary damping devices are needed for this isolation system.
5. Rolling bearings (RB) [20–21]: this type of bearing consists of spherical balls (or rods) rolling on plates (or surfaces) with pre-designed shapes (conical or V-shape). Since rolling mechanism usually has a very low friction coefficient, insufficient isolation damping is commonly encountered for rolling-type bearings, and thus supplementary damping devices are also needed.
6. Eccentric rolling bearings (ERB) [22–23]: this type of isolator usually has a circular (or spherical) rolling surface whose rolling center dose not coincide with its geometric center, in order to provide a restoring force for the bearings. Due to this eccentricity, the ERB is a linear isolator for small displacement; while it becomes a softening nonlinear isolator with variable frequency for larger displacements. Nevertheless, since the initial value and softening rate of the ERB stiffness are correlated and depend on the eccentricity of rolling center, the variation of its isolation frequency cannot freely designed by the designer.

In this paper, a new type of rocking isolator is proposed as shown in Fig. 1. Similar to the concept of rocking-control steel braced frames, the system consists of two main components: a steel braced frame that remains essentially elastic base-isolated by rocking bearing at the column bases during ground motions, and springs that provide resistance to overturning and self-centering forces. If it is necessary, supplementary damping devices may be added at the rocking interface. If in-plan mass eccentricity occurs in floor configuration, it may amplify the floor displacement (bi-directional) on seismic response, and then spring stiffness can be tuned to reduce this torsional effect. The designer can choose appropriate aspect ratio of the bearing based on seismic hazards at engineering site, such that the rocking motion of the bearing will remain still under a moderate seismic load but start to rock back-and-forth during severe earthquakes. The superstructure will move in a rigid body motion to release the ductility demand on the plastic hinge of the superstructure. To validate the proposed idea, a one-bay-one-story spaced structure base-isolated with rocking bearings was constructed and tested by a shaking table. The structural response varied with investigated parameters is evaluated to investigate the optimal design of rocking bearings.

2. Experimental program

Fig. 2 shows the structure base-isolated with four rocking bearings. The superstructure is a one-bay-one-story spaced structure laterally resisted with two braced frames parallel to the force direction. As shown in Fig. 2, the top and bottom floors of the superstructure are assembled by steel beams with 200 × 200 × 8 × 12 mm in size and concrete block weighting 3 tons acted as inertial mass. The braced frame consists of columns with channel 75 × 40 × 5 × 7.5 mm in size and V-shape braces made of two back to back channels of 100 × 50 × 5 × 7.5 mm. The steel rocking bearing is composed of top and bottom rocking plates and four 30 mm diameter rods in the middle, locked together by bolts as shown in Fig. 3. The bearings in Fig. 3 have aspect ratio of 1, whose width of plane surface and height of rocking bearing are all 187 mm. The middle rods can be lengthened so that the bearings have aspect ratios of 1.5, 2, 2.4 and 2.9 with increasing height of 281 mm, 374 mm, 441 mm and 535 mm, respectively. The higher the aspect ratio of the bearing; the lower the ground acceleration can initiate the bearing rocking. The designer can choose appropriate aspect ratio of the bearing based on design seismicity. To form the rocking interface, the rocking plate rocks on top and bottom base plates, which are respectively fixed underneath the floor beam or on top of four steel tubes seating on the shaking table. In order to force the bearing to rock

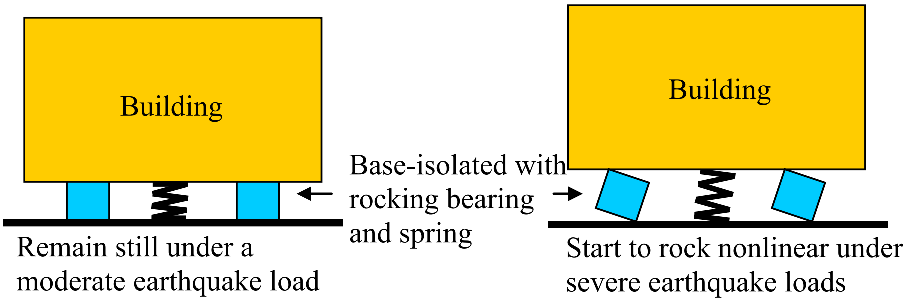

Fig. 1. Schematic drawings showing basic function of a newly designed rocking base-isolated structure.