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Generic 3D formulation for sliding isolators with variable curvature and its experimental verification

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ABSTRACT

Sliding isolators with variable curvature (SIVCs), whose isolation stiffness can be continuously varied along with isolator displacement, allow a passive isolation system to adapt to seismic excitations. The variable stiffness also has the advantage of mitigating the long-period resonance effect when the isolation system is subjected to ground motion with strong long-period components. However, most previous studies on SIVCs were theoretical and adopted simplified models that omit the tri-directional coupled motion due to the geometric effect of the concave sliding surface. In order to provide a more precise analytical tool, this study developed a set of three-dimensional formulas based on Lagrange's equation of motion to predict the complete dynamic forces of an SIVC system transmitted to the superstructure. The formulas, which are applicable to all types of axially symmetric SIVCs, were then verified experimentally using a shaking table test that involved an SIVC system consisting of four polynomial friction pendulum isolators (PFPIs). The derived formulas show that the horizontal and vertical forces of the SIVC include two high-order nonlinear terms related to the curvature and slope of the SIVC sliding surface. In conjunction with the three-dimensional sliding motion of the isolator, these high-order terms cause the tri-directional coupling effect. The experimental results of the shaking table test verified the presence of this dynamic coupling effect and validated the proposed analytical model. Using the isolator parametrical values obtained from the test, the peak responses of the PFPI system subjected to 165 sets of bidirectional horizontal ground motions with various intensity levels were simulated. The simulation results indicate that the high-order coupling terms have a limited influence on isolator drift, but have a notable effect on the shear and vertical forces of the PFPIs when the motion of the isolation system is enlarged by increased seismic intensity.

1. Introduction

Seismic isolation technology is widely applied in seismic-prone areas to protect structural systems. The seismic performance of an isolated structure mainly relies on the properties of the underlying bearings or isolators. Based on their mechanical properties and constituent materials, most existing isolators can be divided into two major categories, namely elastomeric and sliding isolators [1]. In seismic isolation systems that use sliding bearings, the superstructure response is uncoupled from ground motion via a sliding layer. In order to provide a re-centering force, the sliding surface of the sliding isolator is usually made to be concave and spherical with a constant radius. This type of sliding bearing is called a friction pendulum system (FPS) since the seismic motion of an FPS resembles pendulum motion [2,3]. The main features of an FPS are as follows. (1) Its isolation period is solely determined by the radius of the sliding surface (i.e., it is independent of the mass of the isolated superstructure). (2) Because the stiffness of an FPS isolator is proportional to its vertical load, the horizontal rigidity center and mass center of the whole isolation system always coincide. This is advantageous for the isolation of torsional or unsymmetric structures. (3) Because the compression area of an FPS remains constant even under large isolation displacements, there is no lateral buckling problem, which is usually encountered with rubber-type bearings under large deformation. (4) Since an FPS is mostly composed of steel or metal, it has high vertical rigidity and stability. Due to the above advantages, isolation with an FPS is widely applied to new structures for seismic protection or existing structures for seismic retrofitting [4–6].

To mitigate the seismic force transmitted onto the superstructure, an FPS is usually designed to be a long-period system with constant fundamental frequency and damping ratio. The constant long period may lead to resonant-like behavior when the system is subjected to ground excitation with strong long-period components, such as a near-

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fault earthquake [7,8]. Many studies have revealed that a base-isolated structure with conventional sliding isolators may incur excessive isolator displacement in a near-fault earthquake that contains a long-period pulse-like waveform [9–12]. Furthermore, modern seismic performance-based design usually calls for an isolation system to have different performance objectives for different earthquake intensities [13,14]. Conventional sliding isolators with constant mechanical properties can only be designed to meet a single performance goal for a given earthquake intensity, e.g., design basis earthquake (DBE).

In order to prevent excessive isolator displacement in near-fault earthquakes and meet multiple performance requirements, some researchers have advocated the development of adaptive isolation systems, through passive or semi-active means, that are applicable to a wide range of earthquakes with different characteristics [15]. Previously reported passive sliding isolators that are adaptive and preserve the advantages of FPS isolators can be classified into two categories, namely sliding isolators with multiple sliding surfaces (SIMSSs) and sliding isolators with variable curvature (SIVCs). A SIMSS usually has multiple stacked spherical sliding layers, and is thus sometimes called a double or triple friction pendulum isolator depending on the number of sliding surfaces [16,17]. Since the sliding surfaces of the SIMSS can be designed with different radii and friction coefficients, the isolation stiffness and damping of the isolator change when different sliding surfaces are activated by different levels of earthquake [18–21]. The configuration of an SIVC is usually similar to that of an FPS isolator except that an SIVC has a sliding surface of variable curvature rather than a spherical surface with constant radius [22–24]. As a result, an SIVC has adaptive isolation stiffness and frequency that continuously vary with isolator drift. By simply prescribing the geometry of the sliding surface, the hysteretic property (i.e., force-displacement relationship) of an SIVC can be varied in a desired manner.

SIMSSs, which can be easily manufactured using existing technology, are considered to be more mature than SIVCs, and their feasibility and effectiveness have been verified experimentally by numerous studies [19,21]. Nevertheless, the variation of isolator stiffness of an SIMSS is usually step-wise or a discontinuous function of the isolator displacement since adaptability results from the activation of different sliding surfaces of different radii, friction coefficients, or both. These discontinuities may complicate analysis and lead to high-frequency responses unfavorable to nonstructural components. In contrast, the isolation stiffness of an SIVC, which solely depends on the geometry of the sliding surface, can be designed as a continuous function of the isolator displacement. The present study thus focuses on the development of an SIVC.

Since the force-displacement relationship of an SIVC greatly relies on the geometry of the concave sliding surface, various geometric (elevation) functions have been proposed in the literature. Pranesh and Sinha [22,25] proposed a type of SIVC, called the variable frequency pendulum isolator (VFPI), whose geometric function is based on the equation of an ellipse, with the semi-major axis being a linear function of the sliding displacement. A numerical study showed that a VFPI combines the advantages of an FPS and a pure friction isolation system. Using a combination of a circular function with a third-order polynomial for the geometric function, Tsai et al. [23] proposed the variable curvature friction pendulum (VCFP), for which the radius of curvature of the sliding surface increases with increasing isolator displacement. Their numerical analysis, conducted using a finite element program with a VCFP element, showed that the resonance that may occur with near-fault ground motion can be effectively mitigated by the VCFP. By modifying the shape of an FPS, Lu et al. [26,27] proposed the conical friction pendulum isolator (CFPI), whose sliding surface is initially identical to that of an FPS and then becomes tangential to the spherical surface when isolator drift increases beyond a preset threshold value. Their experimental and theoretical studies showed that the shear force of the CFPI remains constant after the threshold displacement, setting an upper bound for the transmitted seismic force. Using an exponential function to define the radius of curvature of the sliding surface, Krishnamoorthy [28] proposed the variable curvature pendulum isolator (VCPI), whose curvature decreases as the isolator displacement increases. To maintain isolation efficiency and reduce isolator displacement, the authors suggested combining the VCPI with additional viscous-type dampers. Lu et al. [24,29] proposed the polynomial friction pendulum isolator (PFPI), whose sliding surface is defined by a sixth-order polynomial function, allowing a PFPI to exhibit softening and then hardening mechanical behavior. The shaking table test conducted in their study demonstrated that the excessive isolator displacement that occurs with near-fault earthquakes or earthquakes with large peak ground acceleration can be effectively suppressed by the hardening part of the PFPI.

Shaikhzadeh and Karamoddin [30] conducted a comparative study on the isolation performance of the various SIVCs mentioned above, and concluded that the PFPI and VCFP are most effective in suppressing isolator drift, whereas the VFPI and CFPI are most effective in mitigating superstructure acceleration responses. Considering a VFPI-isolated structure subjected to bidirectional horizontal ground excitation, Panchal and Jangid [31] studied the bidirectional interaction effect of frictional forces on the VFPI and concluded that if the effect is neglected, isolator drift will be underestimated and the superstructure base shear will be overestimated. In addition, considering bidirectional horizontal ground motions, Sharma and Jangid [32,33] compared the isolation performance of the VFPI and VCFP with that of the FPS, and observed that the VFPI and VCFP improve the superstructural response at the cost of larger isolator displacement, which can be more efficiently reduced by adding viscous dampers as compared to increasing friction coefficient of the isolators.

The aforementioned research demonstrates that due to its adaptive nature, seismic isolation using an SIVC generally leads to better isolation performance and alleviates the resonance problem induced by long-period ground motions, as compared with conventional sliding isolation systems. Nevertheless, most previous studies on SIVCs are theoretical. The only experimental studies, those by Lu et al. [24,27,29], considered only unidirectional ground excitations. Therefore, more experimental studies on the bi- or tri-directional isolation behavior of SIVCs are needed to validate this technology. Furthermore, the mathematical models considered in previous theoretical studies on SIVC bidirectional responses assume that the restoring and friction forces in an SIVC are always horizontal, and thus omit the three-dimensional (3D) geometric (slope and curvature) effect of the sliding surface on isolator forces. Using a 3D FPS model, a study by Monti and Petrone [34] indicated that the 3D spherical sliding surface of an FPS causes coupling effects between the motions in three orthogonal directions for an FPS-isolated structure. If neglected, these effects may cause notable error in predictions of isolation responses when a smaller friction coefficient is adopted for FPS bearings. Since SIVCs have diverse geometric functions, the coupling effects due to the geometry of the 3D sliding surface on SIVC behavior may be even more obvious than those on FPSs. Therefore, the objective of the present study is to develop a more precise and general 3D analytical model that accounts for the aforementioned geometric coupling effects on the restoring and friction forces for all types of axially symmetric SIVC. This generic model was verified experimentally using a shaking table test.

2. Generic 3D equations of motion for structure with SIVC

2.1. Mathematical model

Fig. 1 shows the mathematical model adopted in this study. As shown, the model primarily consists of a superstructure, a base mat (isolation layer), and SIVCs. In order to focus on the seismic forces transmitted from the isolation layer to the superstructure, the following assumptions were made in the model: (1) the concave sliding surface of the SIVCs is axially symmetric about a vertical axis (z-axis in Fig. 2); (2)