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Theory and experiment of an inertia-type vertical isolation system for seismic protection of equipment

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ABSTRACT

Although it has been proven that seismic isolation is an effective technology for seismic protection of structures and equipment, most existing isolation systems are for mitigating horizontal ground motions, and in practice there are very few vertical isolation systems. Part of the reason is due to the conflict with regard to the demand for isolation stiffness. In other words, a vertical isolation system must have sufficient vertical rigidity to sustain the weight of the isolated object, while it must also have sufficient flexibility in order to elongate the vibration period under seismic excitation. In order to overcome this difficulty, a novel system is proposed in this study, called an inertia-type vertical isolation system (IVIS). The primary difference between the IVIS and a traditional system is that the former has an additional leverage mechanism with a counterweight. The counterweight will provide a static uplifting force and an extra dynamic inertia force, such that the effective vertical stiffness of the IVIS becomes higher in its static state and lower in the dynamic one. The theory underlying the IVIS is developed and verified experimentally by a seismic simulation test in this work. The results show that the IVIS leads to a less static settlement and at the same time a lower effective isolation frequency. The test results also demonstrate that the isolator displacement demand of the IVIS is only about 30–40 percent that of the traditional one in all kinds of earthquakes. With regard to the reduction of acceleration response, the IVIS is particularly effective for near-fault earthquakes or near-resonant excitations, but is less effective for far-field earthquakes with more high-frequency contents, as compared with the traditional system.

1. Introduction

Modern seismic design methods may be able to prevent the structure of a building from damage in an earthquake, but may not ensure the functionality and integrity of interior nonstructural components, such as precision equipment or art works. Many reconnaissance reports have revealed that precision equipment in a building structure can be severely damaged even in a moderate earthquake due to the rocking, falling, or slip motions of the equipment [1–4]. Although not life threatening, damage to these nonstructural components can increase the financial losses of factories, office buildings or other functional facilities due to downtime, in additional to the direct loss due to the replacement or repair of the damaged

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components. Conventional solutions to this problem may use a retrofitting technique by anchoring the equipment on the ground or structural floor [5]. However, equipment anchorage may be useful in moderate earthquakes, but may fail to provide seismic protection for precision equipment under earthquakes with higher intensities, since large ground acceleration can cause severe damage to the interior components of such equipment [6]. This disadvantage can be particularly critical for high-tech factories that contain expensive and vibration-sensitive equipment [7–9].

Alternatively, a more effective means for the seismic protection of equipment in buildings is to adopt a seismic isolation technique. The technique usually can be applied in three different ways, namely, structural base isolation, floor isolation, equipment isolation. The first approach, which is able to protect both the structure and interior equipment, is the most effective, but also the most costly [10]. If reducing construction cost is the major concern then the latter two approaches may be preferred, although their seismic protection only covers a set of equipment or an individual item [11,12], provided that the seismic safety of the main structure is already ensured. The isolation technique is now widely used as a standard anti-seismic measure for either structural systems or equipment [13–15]. Nevertheless, most of existing seismic isolation applications are for isolation of horizontal ground motions only. There are few isolation systems that are capable of mitigating vertical seismic excitations, due to a number of technical difficulties, as explained below. It is a well-known rule that a seismic isolation system should be flexible enough in the direction where the vibration response is to be mitigated; meanwhile, to ensure the system stability, the isolation system has be stiff enough to sustain the weight of the isolated subject [10]. The above requirements can be easily satisfied for a horizontal isolation system, in which the direction of isolation is perpendicular to that of the vertical gravity load. However, for vertical isolation the directions of isolation and the gravity load are in parallel, and thus the requirements are difficult to satisfy due to conflicts with the demand for stiffness.

On the other hand, even though the techniques of vertical isolation have been successfully applied to mitigate mechanical vibration [16], they may not be directly applied in seismic isolation, due to the significant difference in excitation characteristics. Seismic excitations usually have much lower frequency contents (lower than 1 Hz) and higher magnitudes than those of mechanical excitations. Consequently, to be effective, a vertical seismic isolation system must have an isolation period much longer than that of a mechanical isolator. This longer vertical isolation period implies a lower vertical stiffness, which will lead to several drawbacks, as follows: (1) The problem of rocking stability is more likely to occur with large vibrations. (2) A lower vertical stiffness will cause a huge initial settlement due to the self-weight of the isolated object. Notably, the initial settlement that is equal to $g(T/2\pi)^2$ can reach 0.99 m for an isolation period of $T=2$ s [17]. (3) It may incur a large isolation drift (stroke) for an earthquake of larger intensity or with more low-frequency components. The large initial settlement and dynamic stroke will together lead to an excessive demand on the total isolator displacement. These issues have hindered the development of vertical seismic isolation systems.

In an early study on vertical seismic isolation, Fujita [18] proposed a three-dimensional (3D) isolation device for light-weight equipment. In its vertical direction, the isolation device is equipped with a coil spring to provide the restoring force, and an oil damper for energy absorption. Designated for a heavy structure like a nuclear reactor building, Okada et al. [19] developed 3D seismic isolation devices. Each of the devices is composed of a rolling seal type air spring as the vertical isolator, and a laminated rubber bearing as the horizontal isolator, and the two isolators are placed in series. For vertical isolation of a reactor in a nuclear power plant, Kitamura et al. [20] proposed a large common deck supported by several vertical springs. Each of the springs is formed by a stack of large coned disks. Also for reactor isolation, Shimada et al. [21] suggested a 3D isolation system whose vertical isolation mechanism is composed of several hydraulic load-carrying cylinders and rocking suppression cylinders. Each load-carrying cylinder is connected to an accumulator with compressed gas, in order to carry the weight of the isolated structure and provide the restoring force of vertical isolation. To overcome the large initial settlement mentioned above, Araki et al. [17,22] presented a vertical isolation system consisting of several constant-force springs whose restoring forces remain constant regardless of stretching. As a result, the system has the feature of zero tangential stiffness, so that the acceleration response will be limited within an allowable level. Kimura et al. [23] presented a vertical vibration isolator that realizes a large stroke by converting the tensional force of a horizontally placed superelastic Cu–Al–Mn alloy bar to vertical restoring force. Tsuji et al. [24] proposed a nonlinear vertical isolator based on an inverted L-shaped post-buckled beam that is able to maintain a sufficient static stiffness while dramatically reducing its stiffness in the dynamic state. In order to reduce vertical floor acceleration in a horizontally base-isolated building, Unal and Warn [25] proposed a superstructural system that possesses distributed vertical flexibility within the structural members, by placing laterally restrained elastomeric bearings under the columns of one or more floor levels along the height of the building. Additionally, some researchers also proposed vertical isolators for ground excitations of lower amplitude or higher frequency, such as traffic vibration isolation [26,27].

In addition to the aforementioned difficulties, the near-fault ground motions that usually accompany a strong long-period pulse waveform pose another challenging problem when developing a vertical isolation system. Recent studies have revealed that horizontal isolation systems may encounter a resonance-like response when subjected to a near-fault earthquake with a long-period pulse [28–30]. The resonance-like response will cause an excessive isolator displacement far beyond the design level, and thus increase the failure risk of the isolation system and isolated object [31–34]. A vertical isolation system may also encounter a similar problem, since near-fault vertical earthquakes may have the same characteristics [35]. Therefore, focused on seismic protection of equipment, the objective of this study is to propose a novel vertical isolation system, called an inertia-type vertical isolation system (IVIS), that has sufficient static vertical rigidity to prevent large initial settlement due to the self-weight of the isolated object, while having enough dynamic flexibility to