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Original Article

Potentiality of Using Vertical and Three-dimensional Isolation Systems in Nuclear Structures

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ABSTRACT

Although the horizontal component of an earthquake response can be significantly reduced through the use of conventional seismic isolators, the vertical component of excitation is still transmitted directly into the structure. Records from instrumented structures, and some recent tests and analyses have actually seen increases in vertical responses in base isolated structures under the combined effects of horizontal and vertical ground motions. This issue becomes a great concern to facilities such as a Nuclear Power Plants (NPP), with specialized equipment and machinery that is not only expensive, but critical to safe operation. As such, there is considerable interest worldwide in vertical and three-dimensional (3D) isolation systems. This paper examines several vertical and 3D isolation systems that have been proposed and their potential application to modern nuclear facilities. In particular, a series of case study analyses of a modern NPP model are performed to examine the benefits and challenges associated with 3D isolation compared with horizontal isolation. It was found that compared with the general horizontal isolators, isolators that have vertical frequencies of no more than 3 Hz can effectively reduce the vertical in-structure responses for the studied NPP model. Among the studied cases, the case that has a vertical isolation frequency of 3 Hz is the one that can keep the horizontal period of the isolators as the first period while having the most flexible vertical isolator properties. When the vertical frequency of isolators reduces to 1 Hz, the rocking effect is obvious and rocking restraining devices are necessary.

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1. Introduction

Conventional isolation systems are generally intended to reduce seismic demands due to the horizontal components of ground shaking. However, they do not prevent vertical seismic forces from being transmitted directly into the structure. Under certain circumstances, isolation systems can amplify or add to the vertical vibrations similar to that experienced in a fixed-base structure. For instance, elastomeric bearings can have flexibilities by themselves or in combination with the flexibility of the structural system shift the effective vertical frequency of the isolated system into an amplified range of the vertical pseudo-acceleration spectrum. As such, the vertical response could be worse than that experienced by a fixed-base structure. Sliding bearings are typically stiff in the vertical direction, so the vertical response may be similar to a fixed-base structure. However, if vertical excitations become large, uplift can occur unless tension-capable bearings are used. While moderate uplift may be acceptable in some applications, the uplift and reseating behavior of the bearing system may result in impact loads that produce additional vertical vibrations in the structure.

Various attempts have been made to provide enhanced protection against the vertical component of response by: (1) using a complete three-dimensional (3D) seismic isolation solution; and (2) adding localized vertical isolation systems to individual parts of a horizontally isolated structure [1–11].

Early efforts to develop 3D isolation systems focused on modifying the design parameters of laminated rubber bearings. In 1986, Kajima Corporation (3-1, Motoakasaka 1-chome, Minato-ku, Tokyo 107-8388, Japan) utilized this approach to construct a two-story reinforced concrete (RC) acoustic laboratory building in Japan [12]. This approach was also investigated by the USA nuclear industry using laminated rubber bearings [13]. More recently, a type of laminated thick rubber bearing was adopted for the seismic isolation design of the Japan sodium-cooled fast reactor (JSFR) [14].

Moving beyond design parameter modifications, other 3D systems have been introduced. The GERB System consists of helical springs that are flexible horizontally and vertically. This system was used in the residential and industrial sector for various applications. In Japan, a number of important development studies have been completed related to 3D isolation of nuclear facilities. A project was started in 2000 for the development of 3D seismic isolation technologies for use in the Japanese fast breeder reactors (FBR), under the sponsorship of the Japanese Ministry of Economy, Trade and Industry. This was motivated to achieve more economical designs for the FBR designs than could be achieved using only the horizontal isolation systems. Three promising ideas for 3D isolation were examined by the FBR project, i.e., "Rolling Seal Type Air Spring," "Hydraulic 3D Isolation System," and "Cable Reinforced Air Spring" [2]. Kozo Keikaku Engineering Inc. (4-38-13 Honcho, Nakano-ku, Tokyo164-0012, Japan) in conjunction with Shimizu Corporation (2-16-1 Kyobashi, Chuo-ku, Tokyo 104-8370, Japan) has extended the basic ideas from these 3D isolation projects and applied it to an actual three-story reinforced concrete apartment building in Tokyo, Japan [3,4]. The 3D isolation system installed in the building performed as expected in the 2011 East Japan Earthquake.

Vertical isolation systems provide flexible supports in the vertical direction by a combination of metallic or air springs and supplemental damping devices. For example, the European FBR project considers isolating the reactor vault from the horizontally isolated base mat using vertical springs [15]. For the Japanese FBR, a vertical isolation system was explored using a series of coned disk springs surrounding a central vertical guide [2].

These vertical and 3D isolation systems and their potential application to modern nuclear facilities are examined in this paper. Moreover, a series of case study analyses of a modern nuclear power plant (NPP) model are performed to examine the benefits and challenges associated with 3D isolation compared with horizontal isolation.

2. Choices of vertical and 3D isolation systems for nuclear structures

2.1. Thick-rubber-layer bearing

3D isolation systems can be achieved by using thick rubber layers for rubber bearings [16]. A sketch of thick rubber-layer bearing is illustrated in Fig. 1. In 1986, Kajima Corporation built a two-story RC acoustic laboratory building supported on 18 steel laminated natural rubber bearings [12]. The bearings were designed to be more flexible in the vertical direction than other bearings used in Japan. Fourteen round steel bars were used to provide damping. In addition, oil dampers were added to reduce vertical and rocking motions during earthquakes. The vertical isolation frequency is 5 Hz. The effectiveness of the isolation system was demonstrated during both earthquakes and traffic vibrations.

Three dimensional isolation system using laminated rubber bearings was also investigated for the USA nuclear industry [13,17]. The target horizontal and vertical frequencies of the proposed system were 0.5 Hz and 3 Hz, respectively. The investigation showed that rubber bearings could be designed to provide isolation in the horizontal and vertical directions.

Mitsubishi FBR Systems Inc. (2-34-17 Jingumae, Shibuya-ku, Tokyo 150-0001, Japan) has proposed a thick rubber-layer

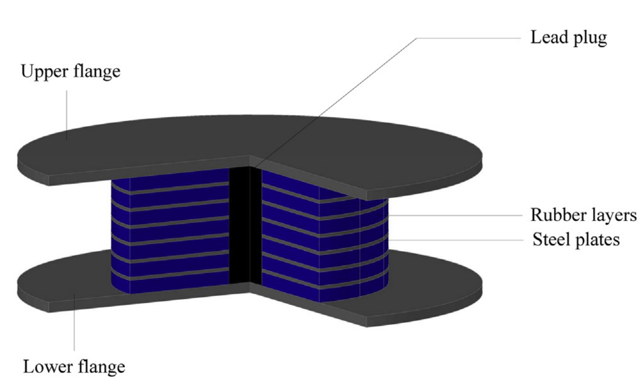

Fig. 1 – Sketch of thick-rubber-layer bearing after ref [14].

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