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Seismic isolation of nuclear power plants: Past, present and future

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ABSTRACT

Seismic isolation of nuclear power plants is in its infancy, with only a small number of applications worldwide. This outcome is due in part to the construction of only a small number of new build nuclear power plants since base-isolation technology became mainstream in the 1990s, perceived concerns regarding the long-term mechanical properties of isolation bearings, and a lack of guidance, codes and standards related to isolation of safety-related nuclear facilities. This paper charts the history of seismic isolation, identifies the research that led to the first implementation of isolation for buildings and bridges in the modern era, summarizes the first applications of the technology to nuclear facilities, and describes important research and developments, including the writing of nuclear standards, in the past 20 years. Future research and development needs are identified.

1. Introduction

This paper has broad goals, many in support of the state-of-the-art session on seismic isolation at the 24th International Conference on Structural Mechanics in Reactor Technology, held in Busan, South Korea, in August 2017. One purpose of this paper is to compile and distil information on seismic isolation developed by researchers and practitioners in the modern era, with a focus on applications to nuclear structures (including nuclear power plants) and nuclear safety. A second goal is to identify recent developments in the field in the United States, Europe, Korea, and Japan with which some practitioners might not be familiar. A third goal is to be forward looking, which involves identification of future opportunities and technical needs.

Seismic isolation of buildings, nuclear facilities, infrastructure and bridges typically involves the installation of vertically stiff and horizontally flexible devices (hereafter described as isolators or bearings) beneath the points of gravity-load support. Isolation is generally provided in the horizontal direction only. Fig. 1 illustrates the effect of installing a horizontal isolation system beneath a building, namely, a period shift (increase) that reduces horizontal spectral acceleration (Fig. 1a), and an increase in horizontal spectral displacement that is typically mitigated by the addition of energy dissipation or damping (Fig. 1b). Nearly all of the spectral displacement is accommodated over the height of the seismic isolators and the drift demand on the superstructure is substantially smaller in the isolated building than in its conventional (non-isolated) counterpart.

Fig. 2 presents photographs of two seismic isolators used in the United States: the lead-rubber (LR) bearing in Fig. 2a, and the single-concave, sliding Friction PendulumTM (FP) bearing in Fig. 2b. The cutaway view of the lead-rubber (LR) bearing shows its internal construction, namely, alternating layers of *natural* rubber and steel shims. A lead core (or plug) is installed in the center of the bearing to provide energy dissipation, which aids in reducing the horizontal displacement of the seismic isolation system. The diameter of the lead core ranges between one-sixth and one-third of the bonded diameter of the elastomeric bearing. The natural rubber in this bearing, which provides the horizontal flexibility, has a shear modulus of between 60 psi (0.41 MPa) and 100 psi (0.69 MPa); the damping in the *natural rubber* of the bearing is between 2% and 4% of critical. The damping in the LR bearing is effectively a function of the diameter of the lead core, the dynamic yield strength of the lead, and the horizontal displacement of the bearing, with respect to its at-rest position. The lead core is not necessarily needed in a bearing if the horizontal displacement demands are small. Such a bearing is described here as a low-damping rubber (LDR) bearing. The LR, LDR and FP bearings are deemed appropriate for use in nuclear facilities in the United States (ASCE, 2017, Kammerer et al., 2018) because their mechanical properties are stable and well characterized.

Fig. 2b shows the parts of the single-concave FP bearing. This bearing, with a rated axial load capacity greater than 15,000 tonnes, was used as part of a four-bearing seismic isolation system for an offshore platform. The upper part, known as the housing plate, is inverted upon installation and placed atop the hemispherical (articulated) slider seen in the lower part. Horizontal isolation is achieved as the articulated slider moves across the concave sliding surface, seen below the slider in the lower part of the figure. The assembly (housing plate,

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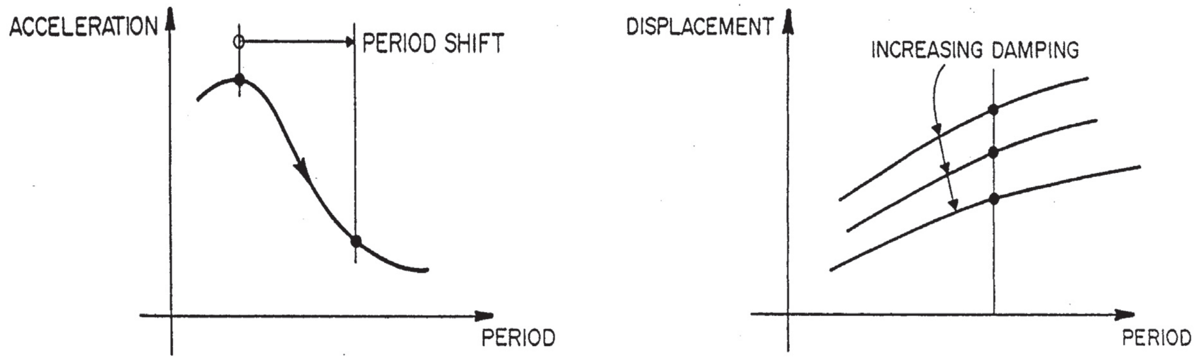
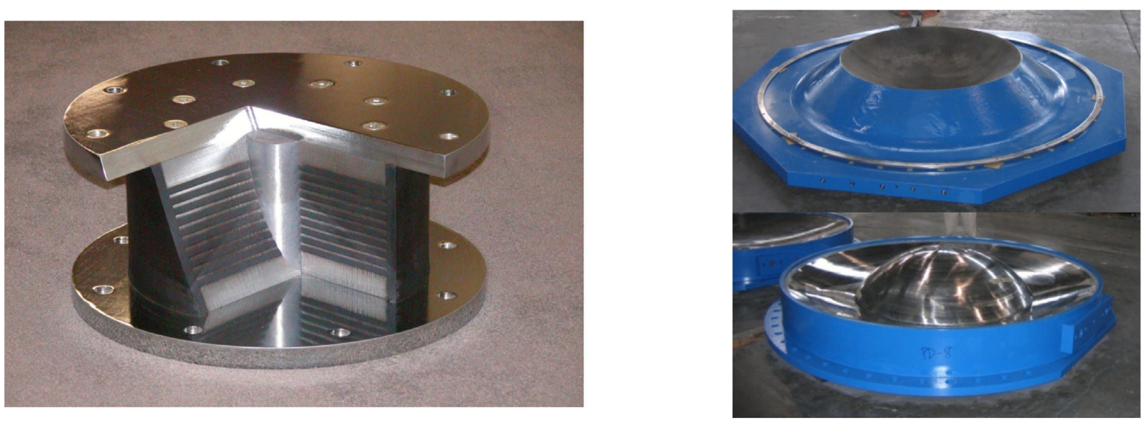


a. reduction in spectral acceleration b. increase in spectral displacement

Fig. 1. Principles of horizontal seismic isolation (courtesy of Dynamic Isolation Systems).



a. lead-rubber bearing b. single concave Friction Pendulum™ bearing

Fig. 2. Types of seismic isolation bearings.

slider, concave sliding surface) can be installed with the housing plate at the bottom or the top, and this will dictate how second-order moments are shared between the substructure and the isolated superstructure (e.g., Mosqueda et al., 2004a, 2004b).

There are a number of variations on the isolators of Fig. 2 that are used outside of the United States. The low-damping rubber in the bearing of Fig. 2a can be replaced with high-damping rubber (HDR) or a synthetic rubber. High-damping rubbers, with damping of the order of 10–12% of critical, have been used for some applications in Japan. Polychloroprene rubber has been used in bearings fabricated in France for application to nuclear facilities since the early 1980s (AFCEN, 2015, Labbe, 2010); the damping in this synthetic elastomer is of the same order as that in a natural rubber.

Variations on the single concave bearing of Fig. 2b include the double concave FP bearing (two concave sliding surfaces; see Fenz and Constantinou, 2006) and the triple FP bearing (see Fenz and Constantinou, 2008a,b; Sarlis and Constantinou, 2016). The chief attribute of the double concave bearing is compactness: because sliding is achieved on two surfaces simultaneously, its overall diameter is much smaller than that of the single concave bearing for a given displacement capacity. The triple FP bearing enables trilinear hysteresis, which is potentially useful for seismic isolation systems not equipped with a stop.

Three-dimensional isolation systems have been applied in a limited number of cases to diesel generators and spent fuel pools in nuclear power plants in Switzerland (Nawrotzki et al., 2009). The components of these systems are vertically installed steel springs and viscous dashpots. Applications have been limited to sites of low seismic hazard.

2. Historical developments

Constantinou (2017) documented historical developments of seismic isolation, although those applications did not utilize the seismic isolation devices described above. A rudimentary sliding system was employed in Persia around 530 BCE for the Tomb of King Cyrus the Great (stone blocks above the foundation installed without mortar to allow sliding). Monolithic columns permitted to rock were used to construct the Temple of Apollo in Corinth, Greece around 540 BCE and the Library of Celsus in Ephesus, Turkey around 120 CE. The Obelisk of Theodosius, originally erected in Egypt around 1450 BCE, was transported to Constantinople and re-erected in the hippodrome, on a marble base equipped with rocking supports and a sliding foundation. More recent developments include a US patent to Joules Touaillon in 1870 for an isolation system composed of a substructure and a superstructure, each with multiple, vertically aligned, hemispherical sliding surfaces, separated by one sphere per pair of surfaces: similar in some regards to the double concave FP bearing. Patents were also issued in 1907 to J. Bechtold and Dr. Calantarients for (impractical) isolation systems involving a foundation supported by a bed of spheres and a foundation sliding on talc, respectively. A three-story apartment building, with columns supported by cables, was constructed in 1955 in Ashkhabad, Turkmenistan (then the Soviet Union), and was the first isolation system involving devices: similar in operation to an undamped FP isolation system. Soviet engineers continued the development of isolators in the 1960s, with roller bearings of different shapes, and with rocking columns.