FRAMEWORK FOR PERFORMANCE-BASED EVALUATION AND DESIGN OF SEISMIC ISOLATION FOR NUCLEAR ENERGY FACILITY STRUCTURES

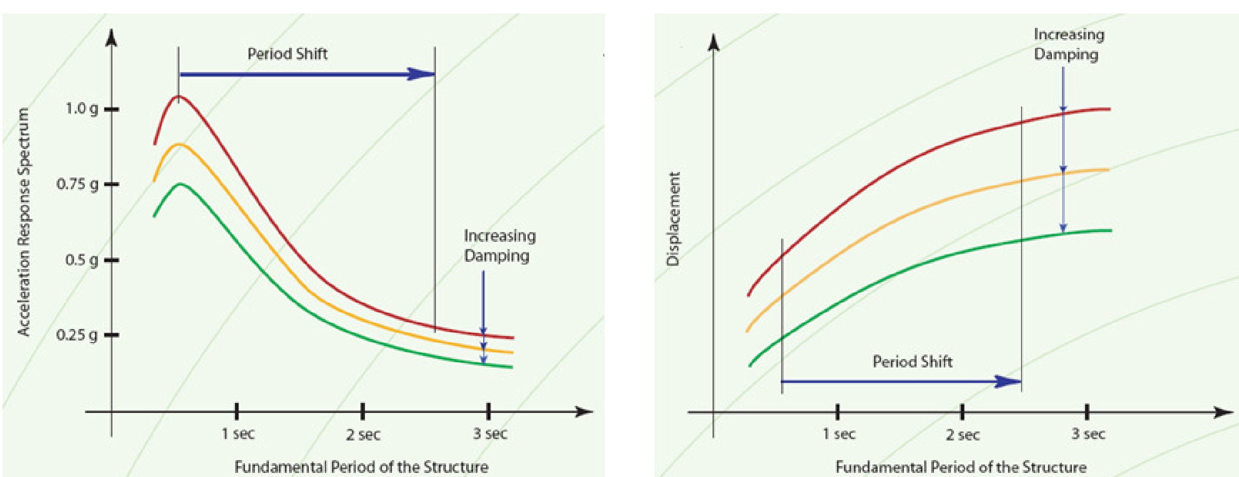
E. Keldrauk[1], P.F. Peterson[2], B. Stojadinovic[3]
[1]Doctoral Candidate, Dept. of Civil and Env. Eng. Univ. of California, Berkeley, USA
[2]Professor, Dept. of Nuclear Eng. Univ. of California, Berkeley, USA
[3]Professor, Dept. of Civil and Env. Eng. Univ. of California, Berkeley, USA

ABSTRACT

Seismic isolation response modification technology has been used for buildings and non-building structures for more than forty years. Advances in this technology have spurred the use of seismic isolation systems for safety-related nuclear facility structures because of the ability to standardize the design above the isolation plane (i.e. superstructure) and, thus, significantly improve the economy of new facilities while maintaining the required levels of seismic safety and performance. The successful design and licensing of new plants requires a well-defined, risk-informed, performance-based framework for seismic isolation of safety-related nuclear facility structures. The elements of such framework addressing the beyond-design basis earthquake and aircraft impact loads are presented. Basic analyses of the structural response of idealized nuclear power structures to beyond-design basis events enable design recommendations for location, layout, and protective systems.

INTRODUCTION

Seismic isolation is a means of reducing structural accelerations and forces by introducing a laterally flexible layer which decouples the responses of the superstructure and foundation [1]. The subsequent reduction of lateral stiffness results in a lengthening of the fundamental structural period well past the predominant period range of typical seismic activity. **Error! Reference source not found.** illustrates the reduction in spectral accelerations as a result of this so-called “period shift”.



(a) (b)

Fig. 1 The effect of period shift on (a) spectral acceleration response, and (b) displacement response [2]

A seemingly unfortunate corollary of the shift is the increase of induced spectral displacements, however, within the primary mode of the isolated structure, interstory drifts are almost exclusively concentrated in the isolation layer. The isolation system is designed to accept this displacement, thereby minimizing deformation in the superstructure from the fundamental mode. Additionally for elastomeric bearings, the first mode shape closely resembles the force-influence vector due to earthquake excitation, meaning higher modes are "filtered-out" of the response as a result of the principle of modal orthogonality. Thus, seismic isolation works dually by reducing negative spectral effects in the superstructure from the fundamental mode, and additionally reducing the influence of higher-frequency modes on the total response.

Seismic Isolation Types

The practice of seismic isolation in the US is focused on two main types of passive seismic isolators. The first type is an elastomeric bearing, typically comprised of alternating steel and natural rubber laminates which assure the rubber deforms in shear and remains stable under compressive loading. The rubber supplies the large deformation capacity and low shear stiffness which is a function of bonded rubber area, height, and shear modulus. Various types of elastomeric bearings are differentiated by their methods of energy dissipation. Low-damping rubber (LDR) bearings use natural rubber with very little inherent damping and, therefore, systems utilizing these bearings often employ supplemental dampers. High-damping rubber (HDR) bearings use rubber infused with fillers (i.e. carbon black, oils, and resins) which absorb energy during extension of molecular chains. Because the response of HDR bearings is highly non-linear and degrades under repeated loading, it is not preferred for nuclear application. Lead rubber (LR) bearings use one or more embedded vertical lead plugs which absorb energy by yielding and may considerably soften under repeated cyclic loading.

The second type of seismic isolators are sliding bearings, which limit the force transmitted to the superstructure by introducing one or more low-friction interfaces for sliding. The first widely-used sliding isolation bearings were friction pendulum (FP) bearings. These bearings have Teflon-coated sliding surfaces which are concave to provide restoring action after deformation. It can be shown that the isolated period of these bearings depends only on these radii of curvature. Energy dissipation is determined by the friction coefficient of the surfaces, which defines the width of the hysteretic loop upon load reversal. By placing smaller sliding "disks" between the outer concaves, multiple pendulum mechanisms can form which enable the engineer to design a bearing with optimal stiffness and damping properties at various levels of displacement. Thus the resulting triple pendulum (TP) bearing is considered a more robust design, capable of a stiff response to low amplitude wind and seismic excitation, flexible response to moderate seismicity, and stiffening under high-amplitude excitation to dissipate energy and limit maximum displacements.

Existing Seismically-Isolated Nuclear Energy Facilities and Codes

Given the high level of safety and reliability required of nuclear power plant structures, seismic isolation has been considered since the late 1970's [3]. As a result of intense research and engineering work in France, there are now six seismically isolated PWR units: Four at the Cruas-Meysse site in France and two at the Koeberg site in South Africa [4]. All of these plants use large neoprene pads which have since been deemed improper for nuclear application in the US [5]. In Japan, a number of industry and regulatory research and development programs [6] resulted not only in development and proof-testing of new seismic isolator units, but also in regulatory documents [7][8].

DYNAMIC ANALYSIS

To ascertain the approximate dynamic response of nuclear power plants to beyond-design basis lateral excitation, computer simulations were undertaken. Focusing on the displacement and acceleration response of the structure will assist in developing design recommendations and illuminating potential design issues which require further research.

Structural Model

Separate structural models are used for the seismic and impact analyses. In each case, all analyses are unidirectional, with no coupled lateral bidirectionality or vertical component considered. The seismic model has a single-degree-of-freedom elastic superstructure ("lollipop") with a fixed-based period of 0.3 seconds. This superstructure is mounted atop 3 separate systems: a rigid system representing the non-isolated case, an LDR-like, linear-elastic isolation system with an isolated period of 3 seconds, and an LRB-like, bilinear system with the same isolated period and a pre-yield to post-yield stiffness ratio of 10. For each ground motion, the latter two isolated responses are compared to the fixed-base case.

The impacted superstructure model is a three-story structure with shear columns (floors idealized as rigid) used as part of a parametric analysis comparing nine different structures with varying isolated periods (1.35, 2.00, and 2.99 seconds) and masses (20,000 metric tons [44,000 kips], 50,000 metric tons [110,000 kips], and 100,000 metric tons [220,000 kips]). Although impact is expected to impart inelastic deformations, the superstructure is modeled as linear-elastic and acceleration levels are used to determine if inelasticity is expected. The isolators are assumed to be linear-elastic, with 10% supplemental damping.

Seismic Excitation Records and Impact Forces Used

The groundmotion records chosen were created for the SAC project at a hazard level of 2% in 50 years (4×10^{-4} annual) probability of exceedence [9]. Although this hazard level is below the design level for nuclear structures, they are adequate for displaying the beneficial effects of seismic isolation. The 60 ground motions are comprised of three groups of 10 two-component records representing three separate US sites: Boston, Seattle, and Los Angeles. These three sites represent a variety of tectonic regions with associated issues. The East Coast site has high-frequency motions, whereas the West Coast motions represent higher amplitude seismicity and poorer soil conditions.

The aircraft loading time history was formulated through scaling of the original Riera [10] time history in both time and magnitude for the Boeing 747-400 and 737-900. The large increase in peak forces are a result of the longer, heavier aircrafts that exist today, as well as the increased speed that results from not only the newer planes, but also from considering malicious impacts above cruising velocity. These time histories are applied at the center of the top floor of the isolated model structure, orthogonal to the building face.

Results

The results demonstrate the reduction in acceleration response compared to the fixed-based structure. The linear isolator model showed median peak acceleration reductions of 97%, 92%, and 80% in comparison to the non-isolated structure in response to the Boston, Seattle, and Los Angeles ground motions, respectively, and reductions of 90%, 80%, and 56% from the PGA [11]. The bilinear isolator model had similar median peak acceleration reductions of 93%, 90%, and 75% compared to the fixed base structure as well as 84%, 73% and 41% compared to the PGA for the respective ground motion groups. The peak deformations were also shown to have much less scatter than the peak accelerations suggesting the design of the isolation gap may depend almost solely on the period.

The impact analysis showed that peak structural accelerations were large for most cases [11]. Median peak elastic accelerations for 747 (737) collisions were found to be 7.6g (2.1g) for the smallest reactor, 3.0g (0.85g) for the middle-weight reactor, and 1.5g (0.43g) for the heaviest reactor. The analysis proved that period has a very small effect of less than 10% on the acceleration response of impacted structures, and that aircraft impacts for smaller plants are almost impossible to accommodate by the reactor superstructure. Thus, extensive inelasticity is expected in the superstructure as a result of aircraft impact.

The deformation of the base isolation system when an aircraft impacts a seismically isolated nuclear facility structures depends on the ratio of the masses of the aircraft and the balance of the facility above the isolation layer. This is because the duration of the impact (about 0.3 sec) and the time when the structure attains peak acceleration is significantly shorter than the isolated period of the structure (about 2.0 sec), making the impulse momentum balance the primary determinant of peak post-impact isolation system displacement. Therefore, given that the mass of the model aircraft is constant, the displacement of the isolation system will be inversely proportional to the weight of the plant above isolation layer. In contrast, deformation of the isolation system under seismic loading depends on the fundamental period of the isolated system, making it, in general, directly proportional to the weight of the balance of the plant above the isolation layer. Therefore, deformation of the seismic isolation layer of a relatively light plant may be controlled by aircraft impact, while that of a relatively heavy plant is likely to be controlled by seismic demands. This situation is further complicated by the different seismicity in the West and the Central and Eastern US, and different estimates of the magnitude of beyond-design basis seismic demand.

ISOLATION OF NEW NUCLEAR ENERGY FACILITIES

Initial preparations for the new Generation III nuclear power plants in the US have already started. Consequently, commercial development of the next generation of nuclear power structures and reactors, based on Small Modular Reactor technologies, in North America is imminent. There are strong indications that nuclear power plant vendors are considering seismic isolation in their designs to maintain and improve safety. Isolation technology is capable of offering many design and safety benefits enumerated below, as well as some design challenges which must be considered and solved prior to full implementation into a functioning nuclear energy facility.

Benefits

The motivation for implementing seismic isolation is, first and foremost, to improve the safety and reliability of nuclear power plants. A properly engineered seismically-isolated superstructure will, with high confidence, be decoupled from the earthquake-induced motion of its foundation and experience significantly smaller inertial forces than its non-isolated counterpart. The reduced forces make it easier to design the superstructure to remain essentially elastic: this, in turn, ensures that the deformations of the structure will remain small and in the acceptable range, improving its seismic performance and protecting the internal systems and components. Taken together, reduction in inertial forces and deformations experienced by the superstructure achieved by the seismic isolation system, and the repeatable performance of seismic isolator units, can substantially reduce the contribution of seismic hazard to the total probability of large radiation release. This directly increases the safety margins of seismically isolated nuclear facilities. Seismic isolation can be custom-engineered to specific nuclear facility site characteristics, both with respect to site seismic hazard exposure and to local soil conditions and configurations. Engineering the substructure and the seismic isolation system provides an opportunity to engineer the isolated superstructure for essentially the same level of seismic demand regardless of the site characteristics. This, in turn, facilitates standardization of nuclear facility design and makes the seismic behavior of the isolated superstructure more predictable, leading to increased reliability of isolated nuclear facilities. Equally important, standardization facilitates regulatory review and design certification of seismically isolated nuclear facilities.

While seismic isolation adds a structural system between the substructure and superstructure, the added cost and complexity is very likely to be compensated for by the savings realized through the increase of safety margins despite the smaller strength, size and complexity of the superstructure. However, a significantly larger economy can be derived from simplified, standardized designs made to suite modular construction methodology. Today, modular construction is being implemented at the level of components and systems: the use of seismic isolation enables expansion of the modular concept to the entire isolated superstructure and provides the all-important cost driver for use of seismic isolation in new nuclear power plants.

Challenges

The use of seismic isolation systems brings about a number of challenges. Seismic hazard analysis for seismically isolated structures must consider the long fundamental vibration period of such structures, typically 2 seconds or longer. Thus, ground motion records must be filtered differently to provide reliable data in this long-period (low-frequency) range, ground motion attenuation relations must be developed accordingly, and design spectra and ground motion selection procedures must be modified. Maximum horizontal deformation of the isolator units occurs under combined effects of the horizontal components of ground motion and the relative eccentricity of the isolated superstructure with respect to the isolation system. The effect of the vertical motion of the isolated superstructure on the isolator units must be accounted for, regardless of the cause: overturning moment in the superstructure, ground motion in the vertical direction, or the rotational (rolling) components of the ground motions. Therefore, ground motion selection and scaling must account for all components of ground motion. Modeling of the response of seismically isolated structures must directly account for the three-dimensional, non-linear behavior of seismic isolators under both design-basis and beyond-design-basis earthquake ground motions. This is particularly challenging for the traditional frequency-domain methods used to evaluate the effects of soil-structure interaction on the structural demands and floor spectra. To overcome this challenge, it is imperative to develop effective time-domain non-linear modeling and analysis methods to account for soil-structure interaction between the foundation, the seismic isolation system, and the isolated superstructure, as well as to develop validated and verified models of the isolator units.

Non-redundancy of the seismic isolation system is a profound challenge. The seismic isolation system comprises a large number of essentially identical seismic isolation units that act in parallel. The performance of the seismic isolation system will not be significantly affected by failure of a one or even a few seismic isolation units or components. However, the seismic isolation layer connects the isolated superstructure to the substructure forming a series system. As such, the seismic isolation layer, as a whole, is not redundant. Therefore, engineering measures must be taken to prevent simultaneous or cascading failure of many seismic isolation units due to exceeding their deformation or force capacities. Such engineering measures include fail-safe system such as deformation limiters achieved by physical (bumpers, stoppers, walls) or mechanical (increasing isolator unit stiffness, slider breaks) means, and additional passive or semi-active dampers. These measures, when engaged, may result in impact and/or gradual increase in forces transmitted to the isolated superstructure. The engineering objective is to provide sufficient space for the isolation system to move without obstacles and for graceful degradation of the seismic isolation layer in extreme situations: a cliff-edge sudden seizure of its isolation function must be avoided.

This engineering objective is particularly challenging when another important beyond-design basis load is considered: aircraft impact. The U.S. Nuclear Regulatory Commission issued a final rule that requires new reactor applicants to assess the ability of their reactor designs to avoid or mitigate the effects of a large commercial aircraft impact. The specific aircraft attributes the USNRC requires applicants to consider are considered to be “safeguarded” information and are restricted from public disclosure. This was the motivation behind the dynamic impact analyses previously described. The results of these simulations showed high accelerations for all 747 impacts as well as 737 impacts with lighter reactors. As such, the recommendation is to shield the isolated reactor structure from the possibility of aircraft collision through the use of protective “barrier” walls, undergrounding, or some combination of the two. Each of these has inherent cost and design considerations which must be handled.

PERFORMANCED-BASED EVALUATION AND DESIGN FRAMEWORK

A framework, defined as a consistent set of requirements and guidelines for design and regulatory approval, is needed to successfully design seismically isolated nuclear power plant structures. The framework proposed in this paper builds on the design framework for conventional seismically isolated structures defined in Chapter 17 of ASCE 7-10, on the design objectives for nuclear facility structures contained in ASCE 43-05 [12] and on design provisions proposed for the upcoming ASCE 4-11 standard.

The proposed framework is performance-based. It comprises the following phases: 1) setting the performance objectives for the seismic isolation system; 2) preliminary design of the seismic isolation system for seismic and aircraft impact loads; 3) design, manufacturing and prototype testing of the seismic isolation units; 4) detailed modeling of the seismically isolated structure; 5) evaluation of the design-basis and beyond-design-basis performance under seismic and aircraft impact loads; 6) specification of quality acceptance and quality control for manufacturing and installation of seismic isolator units; and 7) specification of in-service monitoring of the seismic isolation system.

Performance Objectives for a Seismically Isolated Nuclear Power Plant Structure

ASCE 43-05 [12] sets the performance objective for seismically isolated nuclear power plants as Seismic Design Category 5 with Limit State 4 (SDC5-4). These designate the structure as nuclear facility with the requirement that it remain operational (i.e. no significant damage) under the design loading, the strictest case. It also defines the Design Basis Earthquake (DBE) using a Probabilistic Seismic Hazard Assessment (PSHA) to derive a Uniform (or Equal) Hazard Response Spectrum (UHRS) for the site and modifies it further using a Design Factor. The Design Factor is calibrated to achieve a mean annual seismic core damage frequency of 10^{-6} considering the failure probabilities inherent to current design codes and the design goal proposed in ASCE 43-05 [13]. The design goal for structural components not explicitly covered in ASCE 43- 05 is to reasonably achieve both of the following design objectives (Section 2.0 of ASCE 43-05):

1. Less than 1% probability of unacceptable performance for the DBE ground motion.
2. Less than 10% probability of unacceptable performance for 150% of the DBE ground motion.

Acceptable performance of the seismically isolated structure is defined through acceptable behavior of its components. The foundation and the seismically isolated superstructure are expected to remain in Limit State D, i.e. “essentially elastic”, even if some of the isolator units fail. Additionally, the structures, systems and components are expected to remain operational in case of impact generated by failure of the seismic isolation system. The seismic isolation system is expected to also develop no significant damage and remain in operational condition. Unacceptable performance of the seismic isolator units under seismic and aircraft impact loads is defined as:

1. Permanent damage to the seismic isolator unit, such as tearing, buckling or disassembly, that prevents it from functioning as intended;
2. Exceedance of the design displacement limit of the seismic isolator unit.

It is important to note that ASCE 43-05 is calibrated to the mean annual frequency. US NRC requires a design to achieve high confidence of low probability of failure (HCLPF).

Preliminary Design of the Isolation System

A preliminary assessment of seismically isolated nuclear structures for design and beyond-design basis ground motions at three different sites has recently been conducted by Huang, Whittaker, Kennedy and Mayes [14] The main outcome of this study is a triplet of performance statements aimed at achieving the two ASCE 43-05 probability-based design goals. Namely:

1. Individual isolators shall suffer no damage in DBE shaking.
2. The probability of the isolated nuclear structure impacting the surrounding structure (moat) for 100% (150%) DBE shaking is 1% (10%) or less.
3. Individual isolators shall sustain gravity and earthquake-induced axial loads at 90th percentile lateral displacements consistent with 150% DBE shaking.

These performance statements, derived for seismic loading, are extended to aircraft impact loading by considering it as beyond-design basis event in the same category as the 150% DBE event. Preliminary design of the seismic isolator units can be conducted using the following procedure. A target isolation system horizontal fundamental vibration period can be at least 4 times longer than the fundamental vibration period of the isolated superstructure, and outside any regions where UHRS has an unusual amplification. Typical values are between 2 and 4 seconds. A target characteristic horizontal strength of the isolation system may be between 3% and 9% of the weight of the isolated superstructure. These values are based on the ranges of parameters considered in Huang, et. al [14]. A target effective damping may be between 15% and 20% of critical damping [1].

Performance statements 1 and 2 can be utilized for preliminary assessment of the design displacement of the seismic isolator unit. To do this, a stick model representing the principal mass and stiffness characteristics of the isolated superstructure should be combined with a model of the seismic isolator unit capable of representing the force-deformation response of the unit in two horizontal directions. Best-estimate values for mechanical properties of the units should be used at this stage. Huang, et. al [14] found that the seismic displacement with a 10% exceedance probability in 150% DBE shaking governs the design. Using their Approach I, select or generate 11 seed three-component ground motions to appropriately represent the site conditions and the controlling hazard, spectrally match these motions to the DBE spectra, perform 11 non-linear response history analyses, compute the vector-sum maximum displacement of the seismic isolator units in each analysis and then find the median value of these maxima. Multiply this median value by 3 to determine the seismic design displacement of the isolator unit. The aircraft impact displacement can be computed using the same computer model of the facility used for preliminary seismic analysis as well as the scaled aircraft impact models [10][11] and the USNRC aircraft impact model. The resultant aircraft impact displacements are expected to represent the mean and HCLPF displacements, respectively. The mean aircraft impact and the mean seismic displacements of the isolation system should be compared to determine the governing displacement for the next design phase. A procedure suggested in [1] or in [15] can be used to compute the remaining properties of the seismic isolator unit and to design the unit. Using a procedure suggested in [1], a manufacturer should be selected and a proof-test isolator unit should be manufactured. The proof-test should be conducted using a test procedure suggested in [15].

Modeling and Evaluation

Design of the seismic isolation system may also include design of supplemental dampers intended to further reduce design displacements, vertical restraint or isolation devices, and fail-safe devices intended to reduce or eliminate adverse consequence of superstructure impact on the surrounding soil or structure. A detailed model of the seismically isolated nuclear power plant can then be made. This model should be used to evaluate the response of the nuclear power plant structure under design and beyond-design basis earthquake shaking. The limit states associated with the seismic isolation system include (but are not limited to): 1) failure of isolator units due to exceedance of design displacement; 2) failure due to tearing or instability such as buckling, rollout or disassembly; 3) impact of the isolated superstructure against the isolation mote; and 4) vertical motion and uplift due to ground motion, and overturning or rocking due to aircraft impact.

The challenge posed by seismic isolation response modification technology is that the seismic isolator units are expected, and relied upon in design, to behave in a non-linear manner during design-basis and beyond-design-basis earthquake shaking. Even though the isolated superstructure is expected to remain essentially elastic (and can be modeled assuming it remains within its elastic response range), and the soil and the foundation may behave in a manner such that they can be modeled using equivalent elastic properties, the seismic isolator units must be modeled as non-linear using at least a bi-linear model capable of accurately computing the isolator force-deformation response under bi-directional horizontal excitation. Even such relatively simple non-linear models cannot be linearized with sufficient accuracy to represent the response of the seismically isolated structure over the range of excitations of interest. Yet, it is likely that more sophisticated models of seismic isolators and other devices, such as dampers and displacement restrainers if used in design, will be needed to demonstrate satisfactory performance of the seismically isolated structure with the high confidence required by licensing regulators.

Development of verified and validated tools for time-domain non-linear analysis of seismically isolated structures and soil is on the critical path for successful design and licensing of new seismically isolated nuclear power plants. Such tools should include sophisticated 3-directional interaction models of seismic isolators, models of contact, uplift and impact, and non-linear models of soil. Ideally, such models should enable propagation of seismic wave excitation from the source (or rock layer), eliminating the need for additional software. Finally, these tools should enable non-linear modeling of the response of the isolated superstructure capable of capturing its response in higher vibration modes, propagation of horizontal and vertical excitation through the isolation system and into the structure, and the corresponding floor response spectra to enable coupling to equipment fragility evaluation. The time scales of the response quantities of interest span approximately three orders of magnitude (0.1Hz to 10 Hz). The dimensions of the model elements also span roughly four orders of magnitude (0.1m to 100m). Even without non-linear behavior, the time and length scales present a significant challenge for development and implementation of efficient and accurate solution algorithms. Nevertheless, some of solid finite element software package used by industry today can handle such complex problems. But, they need to be verified and validated for seismically isolated structures, and sped-up, simplified and hardened for use in design practice.

CONCLUSIONS

Seismic isolation response modification technology is mature and ready for application in safety critical nuclear power plants. The benefits of using seismic isolation (improved safety, reliability and economy) clearly outweigh the challenges of this technology. Three major issues are on the critical path for adoption of seismic isolation in nuclear engineering practice and regulation. The first is the development of the regulatory guidelines to define the way seismically isolated nuclear power plant license applications are going to be evaluated. Work in this direction is ongoing. The second is the development of practical non-linear seismic and aircraft impact soil-structure interaction response analysis of the seismically isolated nuclear power plants. Research in this direction is starting. Third is the work by vendors to develop seismically isolated nuclear power plant designs and the willingness of the utilities to support the licensing process of the first such license application. The risk for such first movers is significant, but taking this risk on is essential.

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