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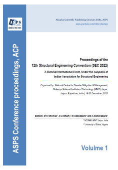

# A State of The Art Review on Soil-Structure Interaction and Seismic Protection System of Nuclear Power Plant

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## Abstract

Soil-structure interaction (SSI) is conventionally considered to be advantageous to the seismic response of a structure. Designers proposed that the least consideration of SSI in structural design results in conservative design. Indian Standard codes allow seismic coefficient ignorance or total reduction of SSI. However, advancements made in developing methods by adding SSI in design to avoid the SSI problem becomes a rarity. This paper summarizes several guidelines and techniques related to SSI analysis of structures. Seismic protection systems (SPS) are successfully installed in conventional designs, but most of the nuclear power plants (NPPs) are not equipped with SPS. Besides, considerable research was carried out to comprise SPS in nuclear power plant design. Currently, horizontal isolation is provided in for structures in active seismic zones. This may be insufficient and vertical isolation has also been required. The results of this review indicated that the future construction of nuclear plants in seismic zones should be equipped with advanced SPS to fulfill the standardised design.

*Keywords*: Soil-structure interaction (SSI), Seismic Protection System, Nuclear Power Plant (NPP), isolation

## 1. Introduction

The seismic response of NPP is imperative because they are massive and stiff compared with conventional buildings. The influence of SSI should be considered in the earthquake-resistant design of nuclear structures. If a substructure is subjected to the effect of seismic events, it should be impulsively studied that ground and structural translation are not interrelated with each other. Martelli et al. [1] define as the process of the interdependence of structural and soil response is termed as soil-structure interaction (SSI). The current research related to SSI of NPPs in seismic zones has been presented in this paper. Due to rising energy demand, the consumption of nuclear energy has been increased. This situation prompted the governing bodies to construct many numbers of NPPs. An increase in the count has raised the concern related to safety and prevention of structural damages of nuclear reactors, which pose a severe threat of radiation to human beings and the environment. Nuclear disasters in Japan (Fukushima Daiichi) in 2011 endorse the importance of the situation [2]. Seismic activity is a critical factor that may pose catastrophic structural damage to NPPs. Around 1/5 th of the nuclear power plants are situated in seismic zones. In India, most NPPs are located in seismic zone II and III (Fig. 1). Therefore, precise modelling systems and design methodology must be confirmed for seismic resistant NPP structures.

## 2. Soil-Structure Interaction (SSI)

Housner [4] studied the effects of SSI on NPP structures and hypothetically indicated the probable impact of foundation rocking on nuclear reactors. Similarly, Newmark and Hall [5] examined the influence of soil–foundation interaction and site amplification on the seismic response of NPP structures. Newmark and Hall [5] pioneered the dynamic analysis of NPP structures using frequency-domain methods. Similarly, [6] investigated the non-linear 3D effects of foundation uplift using seismic vibration analysis on NPP reactor building.

Ghiocel and Dan [7] investigated the impact of SSI response and behavior of NPP at a rock site. They observed that in high-frequency ranges, the motion incoherency considerably reduced the seismic response. Later, Van Nguyen et al. [8] established a 3D non-linear model for NPP structures by considering uplift pressure and SSI to assess building insubstantiality for safety. Saxena et al. [9] deliberated the influence of slip and structural distress due to SSI on the NPP system by 3D FE analysis.

Saxena and Paul [10] observed that up to a certain limit increase in embedment tends to reduce vertical separation and the horizontal slip of the reactor. Bhaumik Raychowdhury [11] analysed the seismic response of a shear wall of the NPP reactor by 2D finite element model

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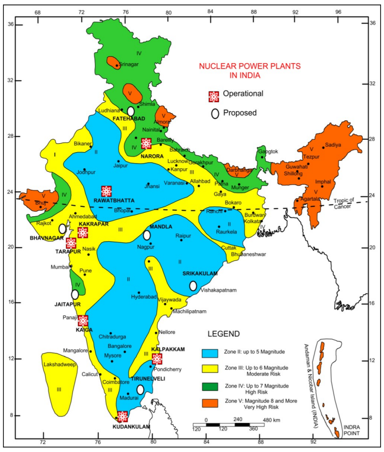

Fig. 1 Nuclear Power Plants location in India [3]

considering SSI. Umpteen studies considered elastic or simplified structural or SSI model. Besides, many researchers have neglected the bi-directional consequences of ground motion.

Particularly contact problems associated with the surface of a structural element should be considered in the SSI analysis [12]. Many works of literature indicating that the following three ways of SSI affect the dynamic behavior of a structure:

1) Movement of the free surface lying on base rock is dissimilar from that at the base rock itself. This consideration in the open field response of the site is called a soil amplification effect. By and large, based on the frequency content, the motion will get amplified.
2) Additional digging and implanting the stable base may slightly modify the motion. The rigid body motion of the foundation converted into inertial loads and varied concerning the elevation of the structure. This effect is due to the reflection of waves from the surface of the foundation. Therefore, it is called the wave scattering effect.
3) The inertial loads may induce overturning effect and shear in the transverse direction of the base. These cause additional deformation soil, resulting in further modification of base motion. This phenomenon, termed as inertial interaction, is mainly considered in the design of massive structures. It indicates the necessity of SSI analysis in the creation of practical systems.

SSI contains two components – kinematic and inertial. Generally, kinematic elements are influential at small and large levels of ground shaking. Kinematic interaction is characterized by the kinematics of pile and input motion of base slab averaging. In base slab averaging, the spatially varied ground motion of foundation is averaged. Pile kinematics is unique for piles, and this is due to the interaction of banks with wave propagation inertial interaction results in two main changes: Time elongation and Damping modification.

These are signified by Equations 1, and 2. m, h, and k are structural mass, height, and lateral stiffness, respectively. T and TSSI are, respectively, structural period and extended SSI period. kx and kyy are horizontal and rotational soil springs shown in Fig. 2.

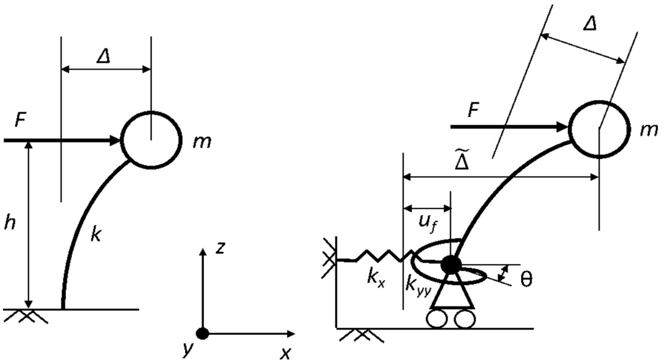

Fig. 2 Soil-Structure Interaction system [13]

The radiation damping components ($\beta_x$,$\beta_{yy}$) are added to soil material ($\beta_s$) and structural ($\beta_i$) damping component ($\beta_0$). $T_x$ and $T_{yy}$ denote fictitious time periods $2\pi\sqrt{\ }(m/\ k_x)$ and $2\ \pi\sqrt{\ }(m/\ k_{yy})$ . Coefficients n, nx, and nyy depend on the type of damping and can be obtained from Givens et al. [14].

$$\frac{T_{SSI}}{T} = \sqrt{1 + \frac{k}{k_x} + \frac{kh^2}{k_{yy}}} \tag{1}$$

$$\beta_0 = \left\{\frac{1}{\left(\frac{T_{SSI}}{T}\right)^n}\right\}\beta_i + \left\{1 - \frac{1}{\left(\frac{T_{SSI}}{T}\right)^n}\right\}\beta_s + \left\{\frac{1}{\left(\frac{T_{SSI}}{T_x}\right)^{nx}}\right\}\beta_x + \left\{\frac{1}{\left(\frac{T_{SSI}}{T_{yy}}\right)^{nyy}}\right\}\beta_{yy} \tag{2}$$

However, recent studies demonstrate the importance of considering SSI in structural design. Presently, considering SSI status in design becomes a rarity, possibly due to a lack of guidelines in design codes worldwide. This gap should be bridged by the development of design guidelines uniting SSI in the design arena. These guidelines should be framed with a proper understanding of various approaches to solve SSI problems.

### *2.1 Important of the SSI*

Considering SSI in design poses beneficial effects on the seismic response of a structure. Codal provisions may allow a reduction in seismic coefficient or ignore on account of SSI. The common perceptive is considering the effects of SSI makes the structure more flexible, enhances its damping ratio and its natural period. These modifications suggest that the base shear reduction of a structure is considered and compared to its fixed-base counterpart. Generally, SSI has been marginalized to minimize the difficulties in the analysis. Various parametric studies have been conducted to establish the importance of SSI in structural design. The researchers suggest that the geometry of superstructure, soil modulus, substructure characteristics, and shear wave velocity profile may affect their seismic response.

Far and Harry [15] assessed the aspect ratio of structure and structure-to-soil stiffness ratio to formulates the phenomenon. Van Nguyen et al. [16] pioneered the importance of foundation characteristics by considering the dimensions of foundations, a load-bearing mechanism in pile foundations, dynamic response of soil-structure systems. Jarernprasert et al. [17] conducted a study on the effects of SSI on single-story structures rested in elastic soil. In the case of inelastic structures, displacements and ductility may increase due to the SSI effect. However, current codes suggest either SSI can be ignored, or base shear can be reduced in design. Building components may reveal inelasticity during earthquakes; hence the guidelines provided in current codes are inadequate. To avoid this problem, [17] suggested integrating SSI by considering the seismic design coefficient that may allow the structure to reach its target ductility demand. Tabatabaiefar and Fatahi [18] assessed the inadequacy of seismic design in warranting structural safety, particularly in soft soils. Hence considering SSI effects in the design of inelastic structures becomes a need of the hour. Bearing in mind of huge capital involved, post-disaster situations, and hazards, the addition of SSI in the design of turbines, dams, nuclear reactors, and bridges, is of principal importance. Even though a substantial amount of research carried out in this area, incorporating SSI in structural design becomes a rarity. This is due to insufficiently laid SSI provisions in seismic codes.

## 3. Codal guidelines on SSI

Despite the development of an infinite array of solution techniques, some codes recommend few guidelines about considering SSI in seismic-resistant design. Most probably, this may be due to a lack of consent about SSI on the seismic response of structures. From the previous studies, it is evident that adding SSI provisions in seismic codes becomes a need of the hour. To enable the stakeholders in various code committees, this section deals with the guidelines related to SSI in existing international codes. IS-1893-3 [19] and IS-1893-4 [20]indicate about considering SSI in the design of bridges and industrial structures, respectively. The effects of SSI should be added to the design of structures resting on deep foundations. Considering SSI may reduce seismic forces and enhanced lateral deflections, neither guidelines for computing SSI effects nor specialist literature have been mentioned. Few seismic codes like IS-1893-1 [20], IS-1893-2 [20], general buildings, and liquid retaining structures are entirely silent about this phenomenon.

## 4. Approaches to solving an SSI problem

Initial attempts are often aimed at addressing an SSI problem with an analytical approach. [21] used Green's formula to analyse the dynamic response of pile groups with seismic analysis. However, these solutions are responsive to most of the problems, and the acceptability becomes a problem due to complexities and computational cost. Gazetas and Stoke [22] assessed the accuracy of impedance functions by performing shake table tests. [23] conducted dynamic centrifuge experiments to explore the effects of structural components and soil properties on SSI effects. He arrived at an investigational dataset to serve as a reference for engineering practice. Many researchers performed neither dynamic centrifuge model tests nor shake table tests on SSI. Generally, full-scale dynamic testing is burdensome and expensive, so most of the investigators devised modelling strategies to analyse SSI effects. Modelling strategies are simple to assess and economical to be used in design offices. Far suggested some familiar modelling strategies for dynamic SSI analysis. It may serve as a guide for novice researchers in the domain.

### *4.1 Discrete and continuum modelling*

Dutta and Roy [24] conducted a literature survey on the modelling of soil interaction with several components of the foundation-structure system. Based on the structure-soil interface, modelling strategies are categorised into discrete and continuum. In discrete modelling, dashpots and springs are generally used as interface elements. The discrete modelling includes the Beam column analogy model, Filonenko-Borodich foundation, Pasternak foundation, Winkler model, Kerr Foundation, Hetenyi's foundation, and continuous Winkler model. Continuum modelling is performed by boundary or finite element methods. Kucukarslan et al. [25] developed an empirical model with linear finite element and soil half-space modelling validated by static load experiments. Givens et al. [14] analysed the discrete modelling strategies and evaluated the influence of removing components of Baseline Models parallel. Among various models, the best performance was obtained from the bathtub model.

### *4.2 Linear and non-linear analyses*

Based on the nature of structural elements used to represent SSI, approaches are categorised as linear and non-linear. Elasto-dynamic solutions are linear; solutions using t-z and p-y curves are non-linear. Nonlinearities involve material nonlinearities in buildings, soil, and foundation nonlinearities due to yielding structural elements, and contact loss among foundation and soil. In most of the cases, either soil or structure is considered as linear. Structural nonlinearity is considered by hysteretic laws and hardening. Bouman [25] considered three practical approaches for nonlinearity in foundation and soil, that are (1) Continuum models, (2) Beam on Nonlinear Winkler Foundation (BNWF) models, (3) Plasticity Based Macro-element (PBM) models. Raychowdhury and Hutchinson [26] integrated BNWF models for seismic Engineering Simulation. Thomas et al. [27] corroborated the concern model against centrifuge model tests. Montrasio and Nova [28] initiated PBM models for non-linear analysis. These models employ a single interface element to characterise flexibility and energy dissipation. [27] derived a modified PBM model termed as Contact Interface Model (CIM). This model has several advantages than BNWF models due to its capability of assessing the nonlinearity arising from gap geometry.

### *4.3 Frequency domain and time domain analyses*

Ticona Melo et al. [29] conducted a dynamic SSI analysis for the portal frame of the railway bridge with a high-speed load model (HSLM) of Eurocode. They analysed the use of Fast Fourier Transform (FFT) to find a solution in the time domain and equation of motion in the frequency domain. Solutions obtained in the frequency domain are not appropriate for inelastic structures due to inherently assumed linearity. Time-domain solutions are suitable in terms of computations as they rely on convolution integrals. Later efforts have been made to develop a hybrid strategy, advantageous for both frequency and time-domain solutions.

These mixed formulations are categorised as Hybrid Frequency-Time Domain (HFTD) solutions and Hybrid Time-Frequency Domain (HTFD) solutions. In HFTD approaches, a linear system is solved in the frequency domain, and pseudo-forces represent actual non-linear behavior. However, in HTFD, techniques such as equations of motion are solved in the time domain using frequency independent impedance functions.

### 4.4 *Impedance functions for SSI analysis*

The determination of impedance functions is the most complicated step in SSI analysis. They are used to represent inertial interaction effects. Equation no 3 shows a common form of impedance function, S as a function of dimensionless frequency, $a_0$ static stiffness coefficients, K. k, and c denote stiffness and damping characteristics.

$$S_{(a_0)} = K\,[k(a_0)] + i a_0 c(a_0)] \tag{3}$$

Computing impedance functions by using finite or boundary element methods were quite rigorous. Generally, foundation impedance functions of physical models are accurate and straightforward. Physical models are classified as cone models and lumped parameter models. Lumped parameter models represent a foundation as lumped stiffness, damping, and mass elements. In cone models, the load dissipation mechanism is described by the use of cones. Lumped models are mainly developed for shallow footings on homogeneous elastic half-space. Cone models were used to devise a computational tool Impedance Functions of Foundation. There are four significant steps involved: (i) numerical modelling of soil-structure system, (ii) identification of dynamic stiffness matrix of free-field, (iii) formulation of kinematic constraint matrices, and (iv) assessment of dynamic stiffness matrix of the soil-foundation system. Khoshnoudian et al.[30] analysed the use of cone models in SSI analysis. Cone models imply the foundation as a mass of rigid disks. The soil stratum beneath the foundation is discretized only at layer interfaces, and no rigid disks are used.

The lateral slopes were calculated by equating static stiffness coefficients of disk and cone. Once the SSI system is analytically modelled, displacements of various disk locations are obtained by the backbone cone. Nodal displacements of foundation elements are dependent on each other. This is characterized by kinematic constraint matrices, which eliminate dependent degrees of freedom. In the case of long piles, consideration must be given to the pile length for constructing these matrices.

## 5. Seismic protection systems for nuclear power plants

Seismic protection systems (SPS) are presently considered as a proven technology for reducing or eliminating seismic effects on structural components [1,31]; currently, only two NPPs are equipped with SPS that too designed 40 years ago [1]. In the design of NPP structures, seismic excitation must be considered. SPS was implemented in conventional structures, but still, the applications of SPS in NPPs are scarce. However, various researches piloted several investigations to include SPS in NPP design.

### 5.1 *Devices in seismic protection system for nuclear power plants*

Generally, three approaches are implemented for seismic protection they are (1) passive, (2) semi-active, and (3) active. Passive systems are devised in a structure to intensify the energy dissipation capacity of the structure. Passive systems cannot modify the dynamic properties during an earthquake and to produce active control forces by the system. A Semi-active system can monitor the response of the structure during seismic activity and change the dynamic properties of the reaction. Active systems are capable of modifying the dynamic properties of the real-time response of the structure. These systems required a pragmatic control strategy and used dynamic properties of seismic response to determining proper control signals for the actuators [32]. It is noticed that, in both theoretical and practical experimentation, passive systems are used because it is more valuable than the other control mechanisms. Active systems.

NPPs have unique requirements that differ from conventional structures. Therefore, seismic protections among the structures are quite different. The critical difference is indicated in Table 1. There are two issues considered in using SPS to suit the expected seismic performance in NPP. (1) Redundancy: In case of conventional building SPS depend on one set of traditional devices; but it is necessary to use two or more groups of traditional tools for NPPs (2) Spatial configuration: Generally isolation in the vertical direction is not considered for non-critical buildings regarding the implementation of SPS; but in future, advanced devices should able to deal with the vertical vibration as well as their location within the structure. Various SPS devices used in nuclear engineering is discussed briefly in the following sections.

Table 1 Key difference in seismic design of SPS: NPPs vs. Conventional structure

| *Factors* | *NPPs* | *Conventional structure* |
|---|---|---|
| Target performance for design basis event | Full structural integrity and the reactor's safe shutdown | Damage allowed provided life safety |
| Target performance for a beyond-design basis | SPS must remain functional (fail-safe system required) | No collapse |
| Isolation of vertical direction | Desired to reach full standardized seismic design | Not normally required |

### 5.2 *Passive devices*

#### *5.2.1 Elastomeric bearing*

Elastomeric-based bearings, generally known as laminated rubber bearings or seismic isolators. It consists of rubber layers or neoprene with alternate steel plates.

This device mostly used in seismic protection of non-critical buildings, and a wide range of research has been conducted to implement Elastomeric-based bearings in the nuclear industry. Based on the elastomer used, bearings can be classified as low-damping rubber bearings (LDRB) or HDRB [33]. Fig. 3 shows (a) images of an elastomeric bearing; (b) represents a typical hysteretic curve of an HDRB device.

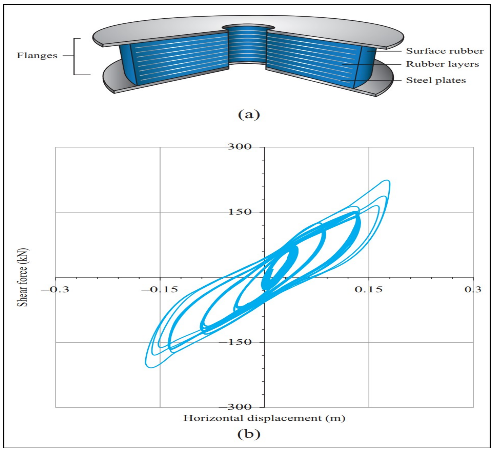

Fig. 3 Image and mechanical behavior of elastomeric bearings [33] (a). Schematic view; (b) hysteretic curve

### 5.2.2 *Lead-rubber bearings (LRB)*

LRBs are also elastomeric-based devices. These are generally made by low-damping natural rubber. The significant difference between LRBs and necessary elastomeric bearings is the presence of a lead plug. The provision of a lead plug improves the damping capacity of the bearing [34,35]. This device is preliminarily devised in New Zealand, and it is widely used for seismic protection of conventional buildings. Presently these devices are used for new-generation nuclear structures.

This device mostly used in seismic protection of non-critical buildings, and a wide range of research has been conducted to implement Elastomeric-based bearings in the nuclear industry. Based on the type of elastomer used, bearings can be classified as low-damping rubber bearings (LDRB) or HDRB [36]. Fig. 4 shows (a) images of LDRB; (b) represents a typical hysteretic curve of an LDRB device.

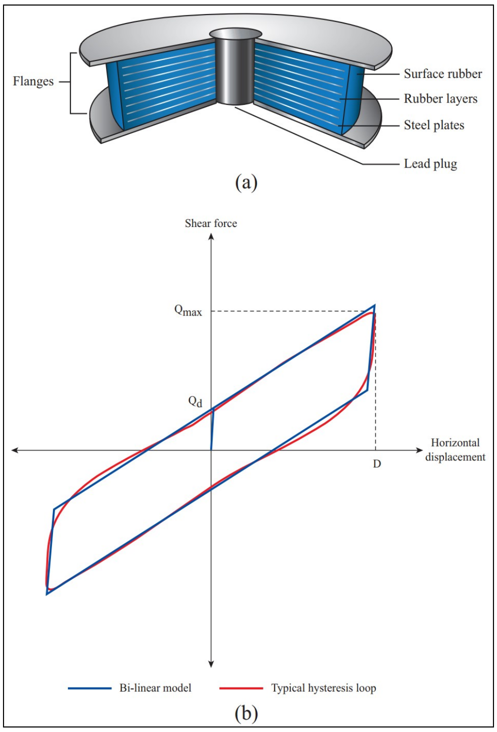

Fig. 4 Image and behavior of lead rubber bearings [33] (a). Schematic view; (b) hysteretic curve

### 5.2.3 *Steel spring*

(1) Steel springs generally provided to withstand the load transferred from the structure and to isolate the vertical direction of a structure to allow vibration in the vertical direction, (2) to be rigid in multiple degrees of freedom, and (3) to provide non-brittle failure mode during earthquakes [37]. Similarly, other devices like coned disk springs, helical springs, and metallic bellows are considered at the investigational level for nuclear deployment. Coned disk springs consist of high-tensile steel and considered as a versatile alternative for base isolation in the vertical direction. Hysteresis is developed due to friction between the disks stacked in series or single disks stacked in parallel. The effectual friction of these devices becomes critical in attaining higher energy dissipation levels [38].

Kitamura and Morishita [39] experimented with the potential of these devices in the nuclear engineering industry. Fig. 5 shows (a) the arrangement of coned disk springs for FBRs, (b) shows the hysteretic behavior of disks considered for potential nuclear applications.

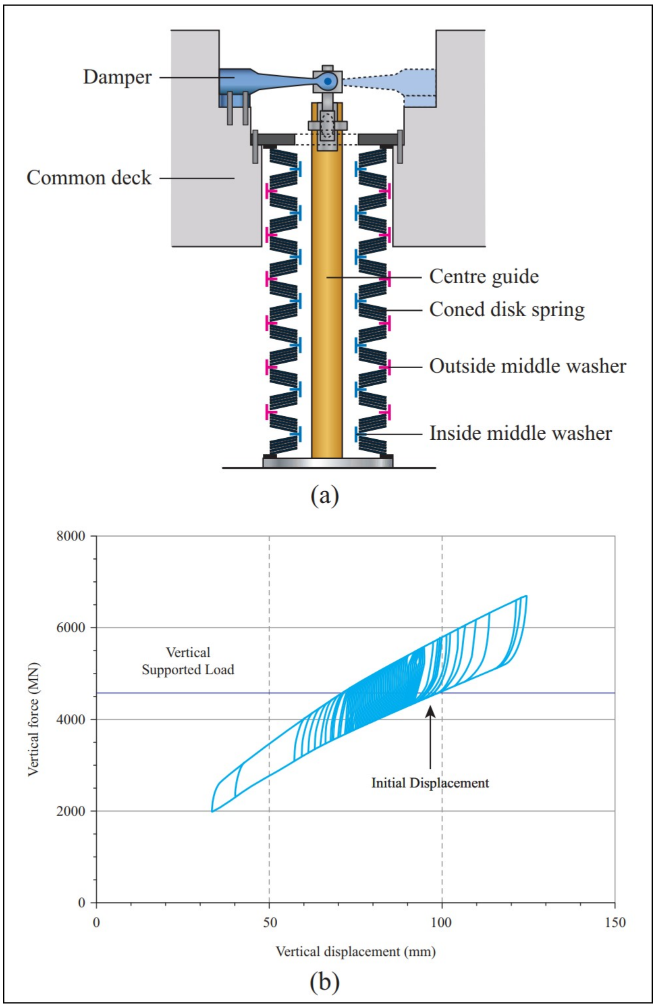

Fig. 5 Image and mechanical behaviour of coned disk springs [33] (a). Schematic view; (b) hysteretic curve

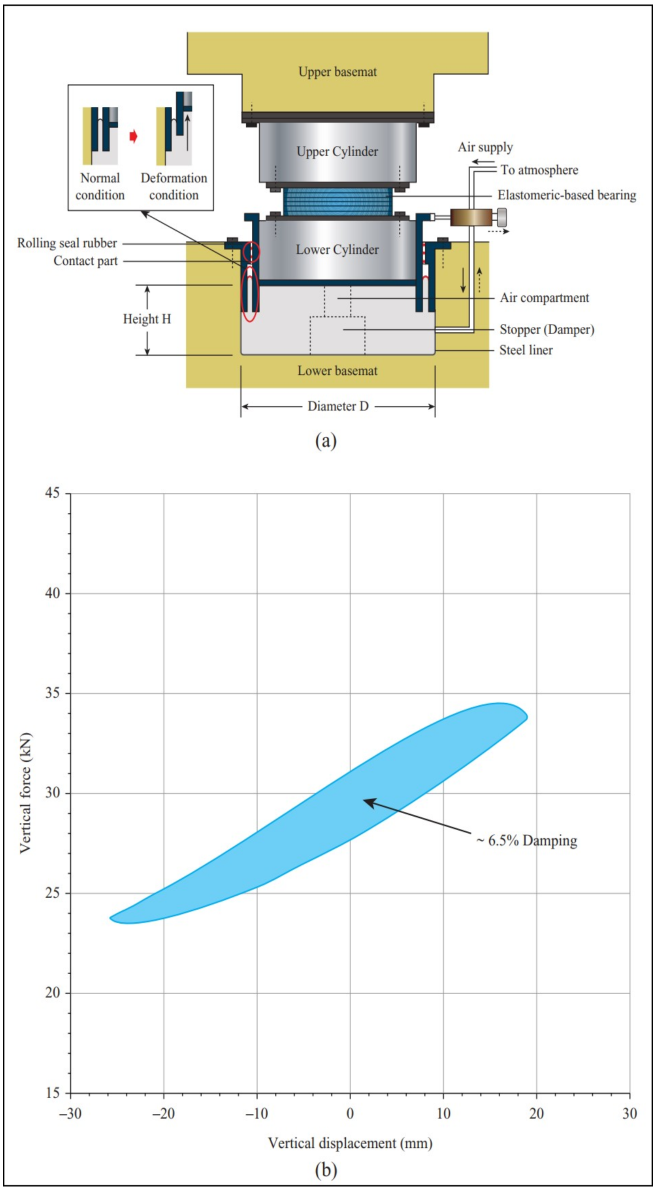

Fig. 6 Image and mechanical behaviour of vertical air springs [33] (a). Schematic view; (b) hysteretic curve

### 5.2.4 *Air spring*

Air springs are considered recently for deployment in nuclear engineering. Two types of air springs are studies such as (1) vertical air springs [40,41]; (2) 3D air spring [42]. Previously the devices were intended to isolate in the vertical direction of the structure. The latest devices were intended to isolate in the vertical direction of the structure. The latest devices were intended to isolate horizontal and vertical direction in one single device, considered as an innovative device for SPS. Fig. 6 shows (a) an experimental isolator based on arrangement of vertical air springs to isolate in the vertical direction, and (b) shows the hysteretic behaviour obtained experimentally in a 1/7 scaled model.

### 5.3 *Semi-active and active devices*

At present semi-active devices are not used for SPS in the nuclear industry; there is no result reported theoretically or experimentally. However, in recent years, few types of research have been considered on the use of semi-active devices in nuclear engineering. Umpteen efforts have been successfully made to implement semi-active tools in traditional structures, and positive results are also obtained. Symans and Constantinou [43] made a detailed review of semi-active devices for SPS. Very few attempts have been made to deploy active protection in the nuclear industry. [12] investigated the advantages of deploying dynamic control systems for SPS in NPP vessels.

Later, [44] reported the maiden attempt made on the application of the active control system in a low-risk building, though it has limited capacity to resist seismic loads. By then, no considerable research had been carried out, and the applications of active control systems in NPPs were restricted. Recently, [32] proposed an active control system for two NPPs in Bulgaria and provided its experimental performance.

In this system, active control forces were determined by sensors, and hydraulic actuators were distributed within the structure to resist seismic vibrations. This system was capable of reconfiguring the properties in real-time. The use of these systems with passive devices may have the potential for nuclear applications.

## 6. Conclusions

Based on the review of the literature, the following concluding remarks have been drawn for soil-structure interaction and seismic protection systems.

### 6.1 *(a) Semi-active and active devices*

- Based on the structure-to-soil stiffness, SSI during seismic activity may be constructive or detrimental to the structural response. However, in real-time applications, The structural response is a function of frequency, and it depends on the earthquake accelerogram. It is recognized that stable and massive structures present on soft soils may need the worst hit.
- Contemporary attempts contemplate the influence of SSI on the inelastic response of structures that have evidenced the importance of considering SSI in inelastic structural design. Currently, most of the structures are designed to reveal inelasticity during earthquakes by considering SSI in design.
- The sub-structure approach is expedient than a direct approach in SSI analysis. The determination of impedance functions is the most crucial step in substructure analysis. ASCE 7-16 gives clear guidelines on adopting SSI in the design of structures. Other standards propose few conditions for considering SSI in the design practice.
- Advanced research in the arena of SSI mainly focuses on identifying its effects on a particular structural type. Umpteen numbers of recent attempts have been made to study the impact of SSI

on structures with seismic resistant systems such as tuned mass dampers and seismic base isolators.

*6.1 (b) Seismic protection system (SPS)*

- SPS adopted in nuclear engineering is predominantly anticipated to give passive protection. The basic concepts remain the same for seismic safety of conventional and NPP structures; most probably, standard devices have utilized in both structures.
- However, NPPs require higher seismic performance, including isolation of the vertical direction, new devices need to be designed and test verified. Recently few valuable researches have been carried out to find vertical isolators suitable for NPPs.
- A spatial configuration may differ for SPS of NPPs, and that must be compared with conventional structures. Horizontal isolation alone not sufficient to reach acceptable seismic performances in NPPs.
- Considering vertical isolation is desired to meet standardised seismic design, two approaches have been reported to accommodate vertical isolation devices into NPPs, in most of the cases, space.

## Disclosures

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