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Review article

Seismic soil-structure interaction in nuclear power plants: An extensive review

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ABSTRACT

The mutual behavior between the response of structure and soil, named soil-structure interaction (SSI) may become significantly important to be considered when structures are founded on deformable soil. In particular, critical infrastructures like nuclear power plants (NPPs) are particularly vulnerable to the consequences associated with the failure of any structural components because of the mutual interaction between the structure and the soil. In addition, soil mechanisms under strong earthquakes are highly non-linear and this reflects the discordance among the researchers for the selection of the most representative analysis model of nuclear structures. In this article, the role of SSI is assessed by presenting a critical discussion of the contemporary methods performed for the seismic analyses of NPPs. In particular, the paper proposes a discussion of the key issues that might facilitate the overall understanding of SSI phenomenon in case of NPPs.

1. Introduction

The quest for diminishing the dependency on fossil fuels has caused a rapid increase in the construction of nuclear power plants (NPPs) that are considered a valuable solution to produce a large amount of clean energy. However, their design process requires the maximum amount of safety considerations because of the consequences associated with any sort of damage of the structural components when subject to natural disasters such as earthquakes. In particular, soil-structure interaction (SSI) effects are necessary to be incorporated in the design process of NPPs when subjected to seismic ground motions. Previous investigations [1,2] on SSI have illustrated that the dynamic behavior of a structure founded on soil is quite different from that under the fixed base condition. In addition, as the interaction between the soil and nuclear structures are characterized as a critical seismic feature of NPP buildings, variation in such parameters eventually influences the responses of both that nuclear building and associated nonstructural components and raises concern regarding the safety of NPP establishments [3]. Therefore, the traditional design methods that consider fixed based conditions becomes non-conservative to consider the impacts of soil deformability on the structural performance.

The current study represents the industry-standard implementation method of seismic SSI in the case of NPPs adopted for the previous two decades. The paper describes the theoretical concepts behind these techniques pointing out the limitations, and highlighting the parameters influencing the SSI effects in NPPs based on the previous study findings. Unlike previous review studies [4,5], this research aims to provide a better understanding about the SSI mechanism in NPP structures from both experimental and numerical perspectives. This study starts with a compendium of the case studies of the nuclear plant structures throughout the years, followed by a discussion of the existing methodologies available for SSI analysis, and the contemporary progress of its modeling over the years.

2. Methodology

A systematic review is presented in this study by considering the Google Scholar database and by looking for several keywords. The keywords used for the selection of articles are “soil-structure interaction (SSI)”, “nuclear power plants (NPP)”, “nuclear structures”, “site effects”, “seismic SSI analysis”, “soil conditions”, and “structure-soil-structure interaction (SSSI)”. Many articles were written in other languages than English or inaccessible and thus it was necessary to filter the papers using year range and English language keywords, which led to the final selection of 170 articles.

Fig. 1(a) demonstrates the progression of the research on SSI from

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2000 to 2024 by pointing out that the growth of the SSI studies in the nuclear engineering field has grown consistently in between 2000 and 2014 before the conspicuous upsurge in 2015. The top countries contributing the most number of publications are illustrated in Fig. 1(b) and among the others, the United States takes the leading position, followed by South Korea and China. Fig. 1(c) exhibits the top journals that publish maximum number of articles. Fig. 1(d) indicates the contribution of various sources of the documents utilized in this review article.

3. Common NPP structures in soil-structure interaction (SSI) analysis

NPPs have been applied as electricity generators since 1954 and since then, several researches have been performed on the safety of NPP systems. The basic arrangement of an NPP structure is depicted through a flowchart in Fig. 2. Significantly, among the buildings in an NPP establishment, some of them are not generally analyzed, to shrink the computational time required for analyzing 3D FE models. Based on all the papers chosen for this research, the selection criteria of buildings in NPP establishments are classified into several categories as portrayed graphically in Fig. 3. According to the extensive literature survey, 9 types of structures were identified in the last 24 years, categorized as.

Type-1 Main Reactor/Containment building (with basemat/foundation),
Type-2 Other building (DGB, TB, SB, CPB) only,
Type-3 Two adjacent other building (DGB, TB, SB, CPB, FWS) on same basemat,
Type-4 Reactor and Auxiliary/Annex/Adjacent other building together,
Type-5 Main reactor complex (together with RB, EB, DB, and TB),
Type-6 Only Reactor building and basemat with isolator bearing/mat,
Type-7 Reactor building, Auxiliary building and basemat with isolator bearing/mat,
Type-8 Only substructure of NPP structure and
Type-9 Whole structure as per documentation (3D model); respectively.

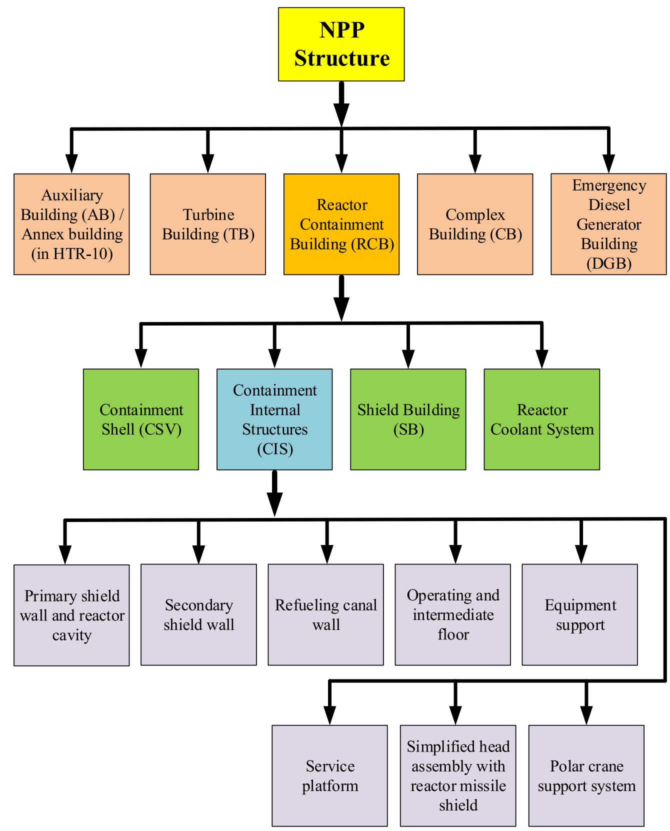
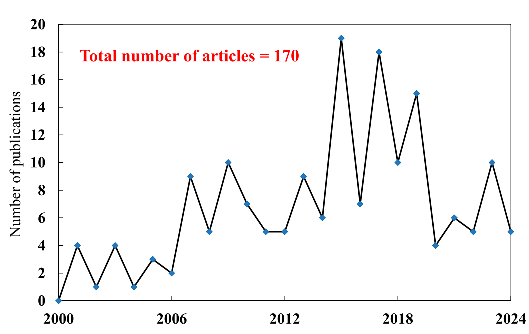
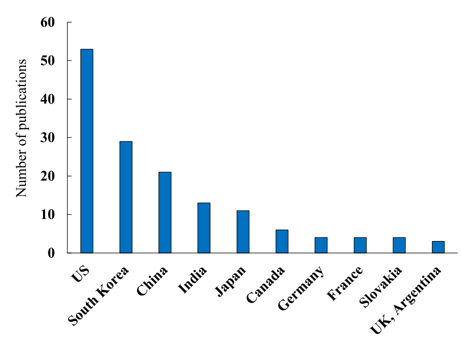


Fig. 2. Schematic representation of an NPP structure.

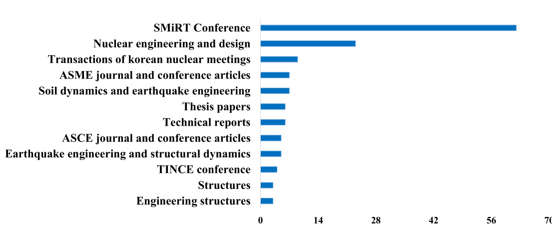
From the pie diagram (Fig. 3), it is evident that the majority of the preceding researches were concentrated on investigating the structural performance of Reactor building (RB) due to SSI as this building is considered to be the most crucial structure among other constructions.



(a) Year-wise breakdown of publications



(b) Number of publications from different countries



(c) Top journals with maximum number of publications

(d) Source-wise distribution of publication

Fig. 1. Statistical insights of publications used in this study.

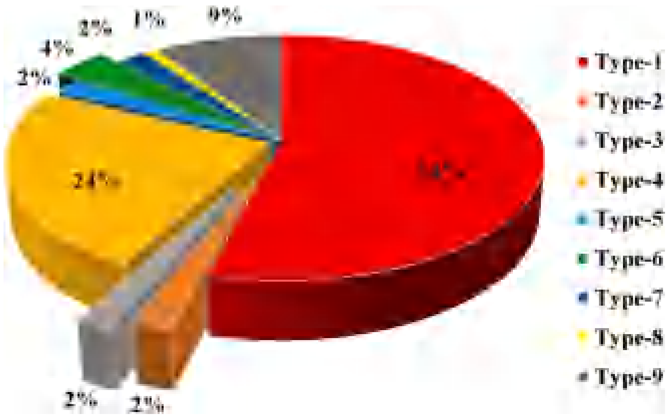


Fig. 3. Structures considered in previous studies.

4. Overview and significance of SSI analysis in NPP structures

During earthquakes, when the structures are constructed on soft soils, structural and soil behaviors are mutually dependent and SSI effects, as observed in the Loma Prieta earthquake in 1989 and the Kobe earthquake in 1995 [6]. In these cases, the assumption that the structure is fixed-based are non-conservative, as demonstrated by Forcellini [7,8] for several typologies of buildings due to two main effects.

(i) **Kinematic interaction:** It depends on the base-slab averaging (leading to increased rotation and decreased translation), embedment effects (spatial variation of earthquakes), alteration in the media of wave propagation, and kinematics of pile foundations.
(ii) **Inertial interaction:** It comes from the mass of the superstructure that distributes the inertial force to the soil and produces additional distortion and during stronger earthquakes, its effects become paramount. Inertial interaction causes the prolongation in time period and changes the damping properties.

In this background, many codes (ATC [9], ASCE [10], EN 1998-5 [11], FEMA [12], NEHRP [13], JSCE [14]) have suggested the implementation of SSI. From the comparison between different design codes (ASCE [15], FEMA [12]), Notably, a reduction in the total seismic coefficient is allowed due to the oversimplified belief of added flexibility, increased natural period, and embellishment of effective damping ratio (ζ) of the structure induced from the integration of SSI. In the cases of NPP, the impact of SSI is particularly important as observed from Fukushima Daiichi nuclear disaster in 2011 [16] and Kashiwazaki-Kariwa nuclear power station under Niigata-ken Chuetsu-oki earthquake (NOCE) in 2007 [17–19]. These investigations demonstrated that SSI effects are not conservative and need to be considered for the cases of flexible soil conditions.

In literature, there are many studies that have emphasized on the consideration of seismic SSI influences in the structural design of NPP structures.

Some studies have suggested that the integration of SSI in the seismic analysis of NPPs is quite beneficial as it, in some cases, reduces the seismic responses. For instance, El-Bahey et al. [20] discovered that including SSI effects in the fragility analysis of reactor buildings reduces the possibility of damage and increases seismic capacity under larger ground motions. Kumar et al. [21] stated that the fundamental vibration period of the structure rises by about 10 %, whereas the force demands decrease by up to 24 % by the consideration of SSI. Ali and Kim [22] evaluated the seismic response of a base-isolated NPP structure by applying the wavelet analysis and found that considering SSI effect induces significant dissipation in the total energy of the acceleration response of NPP structure, specifically for soft rock site, which evinces that, NPP structure is subjected to less acceleration when SSI effect was taken into account. Bhaumik and Raychowdhury [23] investigated the earthquake behavior of an internal shearwall of a nuclear reactor and found that considering SSI effects results in an escalation in force requirements while reducing displacement requirements of the shearwall-foundation-soil system. Their investigation also exposed that consideration of SSI significantly reduces the base shear and moment requirements while increasing the structural drift and ductility which tends to ascend when the nonlinear base condition is considered. Rangelow and Schütz [24] evaluated the effects of seismic SSI on a reactor building with a circular basemat with concrete piles to obtain internal structural loads for establishing a realistic seismic margin of the building and obtained that real-time assessment of SSI effects on NPP structures founded on large pile foundations can significantly mitigate the conservatism in the design calculations while identifying additional seismic margin.

However, several previous studies have presented the opposite hypothesis, which means overlooking the SSI effects may lead to the underestimation in force demands and result in hazardous consequences. For example, Kamagata and Takeqaki [25] demonstrated that one of the mechanisms behind the high acceleration levels in earthquake records comes from the interaction between a large building and the adjacent soil, leading to that increase in the local modes within the surface. Lee et al. [26] compared the conventionality of the fixed-base (FB) analysis to the SSI analysis for a base isolated NPP model in Korea. The findings of their study revealed that though the FB analysis provided conservative peak deformation for the base isolation, it was not quite over-estimated while considering the Floor response spectra (FRS) of the aboveground structure. However, they found smaller FRS under FB condition than that under SSI condition, which strengthens the hypothesis of underestimating structural responses when SSI condition is not considered. Kwag et al. [27] intended to examine SSI effects on the overall seismic fragility and total risk results of a PWR NPP containment building considering two failure modes: strength and displacement and discovered two opposing effects. A beneficial effect was found regarding the strength failure mode, but an adverse effect was exhibited considering the displacement failure mode. Their study findings suggested that ignoring SSI effects might cause serious damage to NPP structures. Furthermore, for the accurate prediction on the seismic behavior of NPP structures, the consideration of SSI is indispensable as suggested by the previous studies. Hoseyni et al. [28] declared that the influence of SSI should be integrated in the seismic probabilistic risk assessment (SPRA) and overlooking it may impose substantial uncertainties in the structural response. Jordanov et al. [30] and Jordanov and Karparov [29] found the SSI effects to be noteworthy and thus needed to be incorporated for realistic evaluation of the seismic performance of NPP structures while evaluating the seismic safety capacity of RBMK-1000 MW Main Building Complex. Kuldip et al. [31] also suggested that combining soil-structure interface helped to capture and calculate the response more precisely when they observed the seismic response of the 3D model of a RB considering SSI. Ghiocel [32] examined the influence of earthquake incoherency on the seismic responses of NPPs and the seismic structure-soil-structure interaction (SSSI) and found that these effects were amplified significantly by the motion incoherency for the soil sites which resulted in notable increase in the soil pressures, in-structure response spectra (ISRS), and bending moments in basement slabs and walls and therefore, overlooking SSI effects may lead to serious underestimation of seismic responses.

In addition, dynamic behavior of nuclear structures are heavily contingent on the characteristics of subsurface soil profiles. The seismic responses tend to alter significantly when SSI effects are taken into account. Wang et al. [33] designed a finite element (FE) model to evaluate the SSI influence on the NPP buildings under vertically incident seismic excitation. The results from the analysis depicted that the FRS found from the foundation level was decreased because of the soil flexibility while those at higher floor levels were remarkably changed when considering SSI, implying the fact that overlooking SSI might result in a risky design. Farahani et al. [34] examined the effects of subsurface profile on the seismic response of the Diesel Generator Building (DGB) when the building was experiencing earthquakes with significant spectral amplifications at higher frequencies. The results of the analysis revealed that the dynamic behavior of the DGB built on soil was largely contingent on the subsurface profile and the frequency of interest, recommending the necessity to consider the variability of SSI parameters in the seismic design and evaluation of NPP buildings by conducting thorough analyses or employing the simplified techniques outlined in this study. Kang and Lee [35] studied the influence of a hard-rock coherency model on the results of incoherent SSI analysis in the context of NPP structures and results hinted that the reduction in response due to wave incoherence was more apparent for embedded foundation compared to the foundation on the surface case. This phenomenon was anticipated to be observed in both hard-rock and medium-hard rock site conditions, which could not be obtained without the consideration of SSI.

Therefore, it can be drawn from the previous studies that the inclusion of SSI in the seismic analysis and design of NPP structures is crucial considering the huge expense and magnitude of associated disasters. In the next section, different methods of assessing the SSI effects are discussed.

5. Approaches for analyzing SSI

The overall process of assessing the SSI effects in NPP structures can be divided into experimental and numerical methods.

5.1. Experimental methods

Experimental methods are proven to be one of the most effective technique for assessing the effects of SSI when subjected to earthquakes. Even though laboratory tests may be not representative of the in-situ conditions of SSI due to the use of smaller-scale physical models [36], the experimental results are necessary for validating the reliability and accuracy of numerical methods.

In the past two decades, several studies were performed utilizing experimental techniques to probe the impacts of SSI in NPP establishments. For instance, NUPEC has established field and laboratory tests, labeled as ''Model Test on Dynamic Cross Interaction Effect of Adjacent Structures'', commissioned by the Ministry of International Trade and Industry of Japan (MITI) which took the benefit of modeling of nuclear buildings and adjacent structures during 1994 till 2002 [37]. Table 1 showcases the details of the influential parameters considered in past experimental tests conducted to investigate the effects of SSI in NPP structures throughout the last 24 years.

5.2. Numerical modeling

Even though experimental tests are necessary for understanding the most realistic physical phenomena of SSI system, they may be expensive and time-consuming. In addition, experimental facilities are not available all over the world due to the large expense associated with the installation, operation and maintenance of these equipment and thus, computational numerical analysis may be considered a valuable compromise. For the seismic SSI analysis of NPP structures, there are three available methods based on level of nonlinearity of the soil medium, which are termed linear, equivalent linear, and nonlinear analysis. Additionally, these analysis methods are further categorized as equivalent linear analysis in frequency domain (ELFD), and nonlinear analysis in time domain (NLTD). Though ELFD method is considered to be the prevalent technique in analyzing seismic SSI performance of NPP establishments when subjected to ground motions having small to moderate intensities, it has been proven to be inadequate in case of large seismic incidents. NLTD has an edge over the ELFD method in this sector as it possesses the ability to capture the nonlinear behaviors of the soil, and structure aptly. However, a combination of time domain and frequency domain analysis called boundary reaction method (BRM) is found to be quite efficient for NPPs having isolated bases [49]. A more sophisticated technique termed direct-hybrid-frequency-time-domain method (DHFTD) was proposed by Seo and Lee [50]. Based on the varied numerical modeling techniques used for the solution of SSI problems; the modeling methods can be categorized into two major sections: Direct method and Substructure method. These two approaches are extensively employed in the nuclear industry to deal with SSI-related issues of NPP structures.

5.2.1. Direct method

In the Direct SSI analysis method as illustrated in Fig. 4, soil, structure, foundation are modeled with a unified one and they are assessed simultaneously in a single process. To simulate the infinite boundaries of soil and represent the wave radiation to infinity, artificial boundaries are usually employed alongside the boundary of the truncated mesh to reduce the redundant degrees of freedom (DOF) as well as the computation time. Direct methods consist of finite element method (FEM) [51], boundary element method (BEM) [37], finite element method and boundary element coupling method (coupled FEM-BEM) [52], and finite difference method (FDM) [53].

SSI analysis by the direct method requires the modeling of the structure, the soil, soil-structure interface and the boundary by using numerical analysis software. There are several techniques to numerically model the structure, soil, soil-structure interface and boundary conditions, as described below.

• Structure: As NPP structures are quite large in dimension and complex in formation, choosing the appropriate structural model that illustrates the real behavior of the original establishment yet simple and computationally efficient is the foremost priority. As per the guidelines specified by ASCE [54], the structural model selected for single-step analysis should be capable of exhibiting the complete dynamic behavior of the NPP establishment while considering the structural discontinuities together. To evaluate the seismic performance of NPP structures considering SSI effects using the direct analysis method, FE modeling is the most popular and efficacious technique. There are several numerical approaches for modeling the structural components of NPP structures which are listed below and presented in Table 2.

Depending on the functionality, LMSM, and 3D FEM models are most widely used in simulating structural systems in SSI studies of NPP structures due to their advantages over the other modeling techniques. To model the structural components, the selection of the appropriate element type is crucial. For example, solid and shell elements are mostly used in 3D FEM models while beam elements developed based on Timoshenko beam theory [55] or Belytschko - Schwer beam theory [56] are utilized for LMSM models.

• Soil: several issues need to be considered: (i) selection of the properties of soil material (linear and nonlinear) and b) discretization of the soil along with the placement of the lateral and bottom boundaries of the SSI model. The soil profiles should be defined in terms of shear wave velocity (V_s), unit weight (γ), damping ratio (ξ) and relationships between shear modulus (G) and hysteretic damping (β) reduction to shear strain levels. These data should be attained from the site-specific laboratory and field experiments, complemented by practical knowledge, relevant empirical data, and published findings from tests of similar soil materials [57]. There are several soil modeling techniques which are described in Table 3 and pictorially represented in Fig. 5.

Coupled FEM-BEM method, another direct modeling technique, utilizes FEM for the simulation of structures and soil domain while BEM is applied at the far-field region [37,61]. This method facilitates the analysis process by introducing a truncated soil domain being meshed with a less expensive modeling cost. Clouteau et al. [61] presented the efficacy of coupled FEM-BEM methods in the SSI and SSSI analyses of NPPs. Firoj & Maheshwari [52] suggested combined BEM-FEM

Table 1
Description of earlier experimental approaches to observe SSI effects on NPP.

Author(s)	Year	Research Topic	Type of Experiment	Similarity ratio (Model: Prototype)	Shape and Dimension of Test Box	Considered Site Condition and model soil type	Input Motion	Important Findings
Choi et al. [38]	2001	To evaluate the results of the seismic analysis on a large-scale seismic test (LSST) structure using the results from forced vibration test (FVT)	FVT	1:4	–	Four types of soil (2 Sand, 2 gravel)	Artificial	The anticipated earthquake responses using the generated earthquakes and with the FVT-correlated model were identical with the observed responses
Ghosh and Madabhushi [39].	2007	To examine the foundation response of a typical nuclear power plant	DCT	1:50	Rectangular, 560 mm × 235 mm × 220 mm	Silica sand	Sinusoidal (at 50g centrifugal acceleration)	The base motion undergoes significant modification, leading to notable rocking within the structure due to the influence of kinematic interaction.
Bolisetti [40]	2010	To observe structure-soil-structure interaction effects on critical structures	DCT	1:55	Rectangular, 1651 mm × 787 mm × 584 mm	Dry Nevada sand	17 sets of excitations (at 55g)	In SSI system, increasing intensity of input motion leads to a de-amplification of acceleration at roof of the structure due to nonlinear behavior of the soil and structure.
Ha et al. [41]	2012	To replicate the seismic behavior of the Hualien Large-Scale Seismic Test (LSST) with SSI	DCT	1:50	Rectangular, 650 mm × 630 mm	Top sand layer, Mixture of residual soil and small size gravel (3 mm)	Chi-Chi (at 50g centrifugal acceleration)	The centrifuge test outcomes closely resembled the LSST data and shows the potential to observe proper soil– foundation- structure interaction (SFSI). Nonetheless, there was a slightly amplified response observed in the structure, primarily attributable to variations in material damping (concrete in the prototype and aluminum in the model).
Ha and Kim [18].	2014	To assess the seismic behavior of NPP structure incorporating SFSI	DCT	1:50	Rectangular, D_{ext} = 670 mm × 670 mm × 650 mm	Weathered soil with sand and backfill, sandy soil, weathered rock	Chi-Chi (at 50g centrifugal acceleration)	In terms of PGA, free-field ground motion typically exceeds foundation motion due to kinematic interaction, but this difference diminishes with increasing earthquake intensity due to inertia effects, and SFSI effects are minor in stiff soil conditions
Numanoglu et al. [42]	2017	To make comparisons between the results from element- level response of a new soil model (I-soil) from 3D nonlinear NPP SSI system and those derived from mcDSS and dynamic centrifuge tests, respectively	mcDSS and DCT	1:60	2D cylindrical LSB	I-Soil model, Sub-rounded, uniformly graded, fine-grained U.S. Silica Company Ottawa 40/70 sand	Chi-Chi, Landers, and Chile (at 60g centrifugal acceleration)	Shear stress- strain loop from the I-soil model overestimated the hysteretic energy dissipation under Masing un/reloading rules
Li et al. [43]		To understand the suitability and the SSI impacts on the structural response of a NPP on non- bedrock site under earthquakes	ST	–	Cylindrical (3D LSB), H = 1800 mm, ^{D}i = 4500 mm, ^{D}o = 4664 mm)	Non- bed rock; Sandy silt	Artificial (Three directions)	The structure exhibited a significant influence on the surrounding soil mass and the site's response spectrum within the mid and lower frequency limits under design basis safe-shutdown earthquake conditions
Cui and Fall [44].	2019	To clarify the mechanisms controlling SSI, associated factors, and the resultant seismic response of the SSI using the dynamic coupled elastoplastic-hydraulic model for soil behavior	DTT and ST	–	–	Loose sand foundation, Dry sand, Saturated sand, Stiff clay	Saguenay	The coupled visco-elastoplastic-hydraulic model showed the competency to illustrate the nonlinear behavior of soils
Numanoglu [45].		To propose a new, distributed element, plasticity-based constitutive model to measure settlements in dense to very dense sands in SSI analysis	DCT	1:60	2D circular laminar container, D_i^{594mm} and H = 400 mm	Medium dense to very dense sands, Ottawa 40/70 sand	Kobe, Northridge, Chi-Chi, Loma Prieta, Lotung, Landers, Chile (at 60g centrifugal acceleration)	The proposed soil model captured the responses in numerical models (uni- and bi-directional) in free-field and SSI in terms of PGAs, energy intensities, and depth-wise spectral acceleration
Xiaohui et al. [46]	2020	To observe the SSI effect of the site conditions on the SSI of NPP	ST	1:4	Cylindrical (3D LSB), H = 1800 mm, D_i = 4500 mm, D_o = 4664 mm)	Non- rock, Sandy soil	Artificial	Four crucial phenomena were observed: (i) significant nonlinear effects of non-rock site, (ii) magnification in the plastic deformation within the soil model, (iii) reduction in the natural vibration frequency of SSI system, and (iv) increase in the amount of damping ratio

(*continued on next page*)

Table 1 (*continued*)

Author(s)	Year	Research Topic	Type of Experiment	Similarity ratio (Model: Prototype)	Shape and Dimension of Test Box	Considered Site Condition and model soil type	Input Motion	Important Findings
Yang et al. [47]	2021	To evaluate the effects of earthquake intensity, frequency, soil-pile-structure interaction, and soil nonlinearity on the dynamic behavior of the NPP system	ST	1:25	Rectangular, 2000 mm × 2000 mm x 1300 mm (length x width x height)	Natural clay soil	1 artificial seismic wave and 2 natural ground motions	(i) The amplification ratios of the fixed-base superstructure are greater than that of the pile-raft foundation, (ii) acceleration at soil surface under the long-period motion is higher than that under short-period motions.
Zhao et al. [48]	2023	To observe SSI effects on the seismic behavior of a AP1000 NPP structure (base-isolated)	ST	1:40	Cylindrical, D = 3000 mm	Shanghai silty clay	RG 1.60, El Centro and Kobe	The structural self-weight and the interaction between the soil and foundation tend to manifest the rocking behavior in case of a non-isolated system while the deformation of isolators is lower in isolated models

* ST= Shake table, DCT = Dynamic centrifuge test, DTT = Dynamic triaxial test, mcDSS = Multi-directional cyclic direct simple shear test, FVT= Forced vibration test, LSB= Laminar shear box, H= Height, D_i = Internal diameter, D_o = Outer diameter, T = Layer thickness' D_{ext} = External dimension, L = Length, W= Width, PGA= Peak ground acceleration.

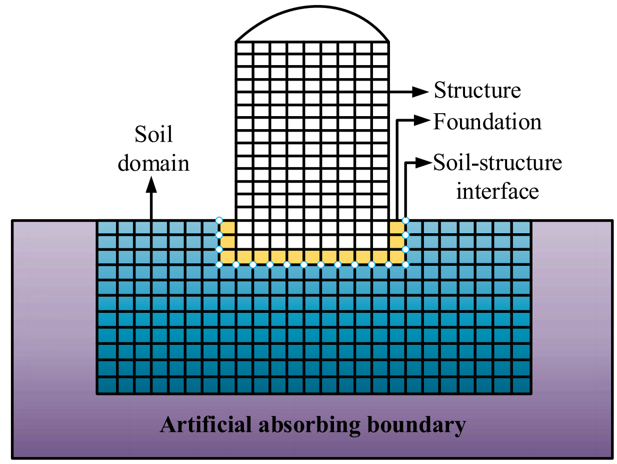


Fig. 4. Schematic illustration of direct analysis approach.

Table 2
Structural modeling idealizations used in numerical analyses.

Modeling approach	Key features
Lumped-mass stick model (LMSM)	• Simplest among all the structural models for numerical analysis and is computationally efficient. • Represents the original structure as a group of beam elements having masses lumped at element nodes. • Quite proficient in considering the global responses in linear analyses. • It cannot suitably approximate local behaviors and vertical responses in the case of nonlinear dynamic analyses.
Full three-dimensional finite element model (3D FEM)	• Most precise structural model for numerical analysis. • Capable of illustrating the whole structure with contact elements and detailed material properties with material nonlinearity. • The computational effort for such models while performing nonlinear dynamic analyses is quite expensive and extremely time-consuming.
Multiple layer shell model (MLSM)	• Relies on the concept of mechanics of composite materials and shell elements consisting of several layers. • Capable of depicting nonlinear characteristics of wall-type structures and reducing computational effort.
Beam-truss model (BTM)	• Divides the walls into beam and truss elements. • Still in the emergent stage which makes its utilization quite difficult due to the limited scope of verification and validation.

technique to solve SSI analysis of NPPs with CPRF. Li et al. [62] developed another coupled method termed FEM-SBFEM (Finite element method - Scaled boundary finite element method) to propose an efficient calculation technique for SSI analysis and showed its efficacy by applying it in the dynamic analysis of a base-isolated NPP structure.

DRM technique proposed by Bielak et al. [63] is a similar type of technique intended to reduce the big computational soil domain into a truncated size [16,64,65]. DRM method is adopted in Real ESSI simulator software [66] which is currently being extensively used for assessing seismic performance of nuclear facilities. LS-DYNA has an effective seismic input method module that is similar to DRM technique [67]. Abell et al. [68] utilized DRM layer in their study to connect seismic (near-field) simulations with local SSI response. Orbovic et al. [64] utilized DRM layer in their investigation of the use of nonlinear, time domain analysis in the seismic performance evaluation of NPPs. Sinha et al. [16] mention a framework for high-fidelity modeling of

Table 3
Summary of different soil domain modeling techniques.

Analysis Type	Modeling Type	Characteristics
Linear	Winkler's foundation	• The soil medium is illustrated as an arrangement of linearly elastic springs. • The springs around the loaded section are considered to be unaffected under partially distributed surface loading [58].
Nonlinear (also Linear)	Continuum (Micro-element)	• The soil medium is assumed as a semi- infinite and isotropic half-space continuum. • Capable of depicting the nonlinear performance of soil medium.
Nonlinear	Beam on Nonlinear Winkler Foundation (BNWF) [59]	• P-y curve approaches are utilized to obtain the stiffness of soil. • Widely used in seismic soil-pile-structure interaction (SSPSI) for its ability to simulate the rocking and sliding phenomena and the footing settlement for both linear and nonlinear soil.
	Plasticity Based Macro-element (PBM)	• Elasticity, plasticity, and uplift of the foundation are considered to illustrate the foundation behavior by incorporating an array of forces and displacements at the middle of the foundation. • An improved version (CIM) is proposed by Gajan & Kutter [60]. • Difficult to model and the amount of calibration required for the modeling parameters is very scarce.

seismic soil-foundation-structure (SFSI) interaction for a NPP prototype with shallow foundation where DRM layer was employed. Swetha and Justin [65] initiated a study to grasp the impact of the geometrically nonlinear interaction interface on the response of a surface-founded NPP structure under obliquely incident quasi-plane seismic waves and they used DRM technique to ameliorate computational efficiency. Wang et al. [33] proposed a new simulation framework for the dynamic response of Small Modular Reactors (SMRs) embedded inside soil where the realistic 3D motion was inserted into the high-fidelity SSI system through DRM. Boris et al. [69] recommended a framework and implementation technique for complete calculations of the flow of seismic energy for a SSI system of nuclear installations utilizing DRM layer. Solberg et al. [70] postulated a SSI analysis method in time-domain for the extension of DRM method to incorporate nonlinear materials. Fig. 6 illustrates the graphical representation of DRM.

• Soil-structure interface: For capturing the real-field SSI mechanism, the proper modeling of the interface where the foundation of the structure connects with the surrounding soil is quite important. There are two main types of soil-structure interface usually applied for SSI analysis of NPPs [71,72] which are explained below:

a) Tied/Bonded interface: This is the simplest form of interface characteristic which is generally applied when the soil behavior is elastic. This interaction does not permit any gapping and separation among the connected interfaces, indicating that no uplifting of foundation is allowed and that the behavior of foundation and soil is in sync under dynamic events.

b) Nonlinear/Unbonded interface: In reality, the soil behavior is inherently nonlinear during seismic events and this interface exhibits the similar field behavior of soil-structure interface. This interface allows gapping and sliding within the adjoined interfaces, which can simulate the rocking behavior of shallow foundations, an important SSI feature for estimating the seismic responses.

Even though it is conventionally believed that the nonlinear interface tends to reduce the earthquake responses of structures, it is not valid for all cases [71] and application of wrong interface characteristics may lead to inaccurate seismic demand estimation that could be hazardous for safety related structures like NPPs.

• Boundary conditions: In order to exclude the effects of spurious earthquake waves from the soil boundary, two types of boundary conditions are usually adopted in SSI analysis of NPP structures. The first typology of boundary condition, (named as non-transmitting boundary), considers the soil domain at a distance sufficiently large to remarkably abate the strength of reflected waves and increase the effective damping to incorporate the radiation damping [73]. This type of boundary condition requires high computational costs and thus transmitting boundary methods are frequently applied to model the boundary conditions. The latter one is called artificial boundary and it is of two types:

a) Approximate/local boundary: In approximate boundary models, the reflection of waves to the boundary can be circumvented. These boundaries are limited in space and time and the stiffness of the soil is modeled up to infinity. To inhibit the reverse propagation of waves into a computational domain, local boundaries (viscous damping, visco-elastic, transmitting) [74] are utilized. Elementary boundaries are generally employed in static analysis where stresses and displacement are assumed to be zero at the calculation domain boundaries. Tied degree-of-freedom (TDOF) is one of the most popular local boundary conditions used in SSI analyses due to its simplified application method. Another boundary type termed 'Kelvin element boundary' used by Maheshwari et al. [75] is also capable of absorbing the outgoing waves so that they cannot reflect back to the structure. Accurate result using these approximate boundary conditions is highly contingent on the selection of the soil domain size.

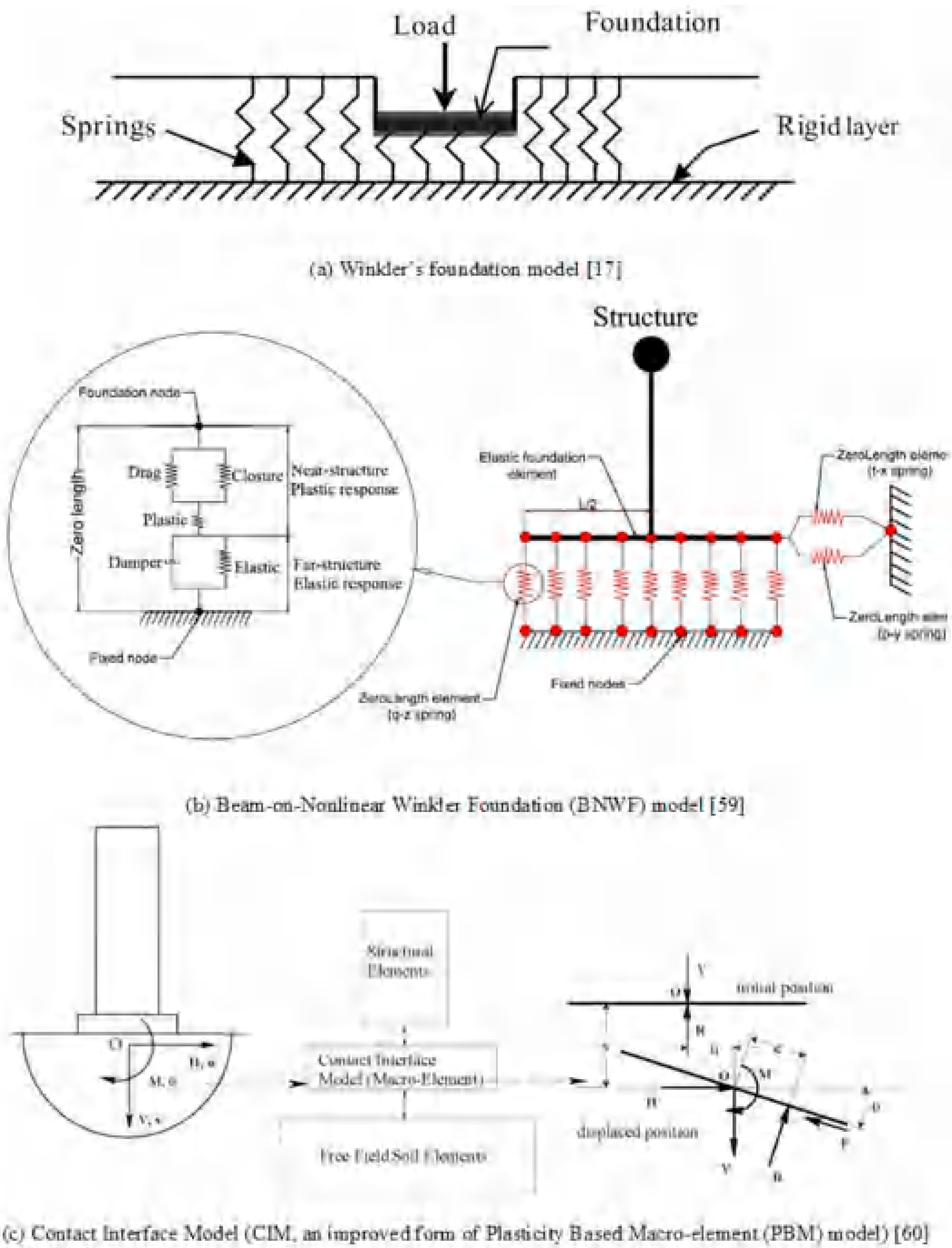
b) Rigorous/global Boundaries: Rigorous boundaries may simulate the far-field effect like infinite soil domain, and thus the unbounded soil domain is picked in a way that makes the near-field effects enclosed. These type of boundaries are global in space and time [4]. There are several methods for implementing rigorous boundaries. They are Infinite element method [24], Boundary Element Method (BEM) [4], Thin Layer Method (also known as consistent boundary) [4], Consistent Infinitesimal Finite Element Cell Method (CIFECM) [4], and Scaled Boundary Finite Element Method (SBFEM) [62]. Perfectly matched discrete layers (PMDL) [76] is another new type of absorbing boundary condition extensively used in the past decade due to its computational efficiency and accuracy in exhibiting nonlinear behavior of soil.

Table 4 illustrates the state-of-the-art of the direct SSI modeling of NPPs in the last 24 years.

5.2.2. Substructure method

The computational time is the biggest limitation of applying the direct method and thus the substructure method has been often used for solving SSI problems. In this approach, the SSI system is divided into a group of simpler substructures, solved separately and the solutions are superimposed to acquire the structural response. As the substructure approach can remarkably decrease the degrees of freedoms (DOFs) due to the decomposition of the SSI system into several subdivisions, the solution can be acquired by employing substructuring technique compared to the direct method. However, this method can strictly be applied by assuming the linear behavior of soil domain and thus its utilization is limited to linear elastic analyses or equivalent linear analyses. Therefore, it can be rigorously be applied only in preliminary assessments. In the case of sub-structuring method for embedded structures or structures with pile foundations is quite convoluted [24]. In the substructure approach, three steps are required to decompose the SSI system which are explained below.

1. Determination of Foundation Input Motion (FIM): When the structure and foundation are assumed massless, the motion on the base slab is termed the Foundation Input Motion (FIM). Only the kinematic interaction problems are solved to obtain FIM as it is assumed in substructure method that FIM tends to occur at the foundation level as a result of the variance in the rigidity between the soil and



(a) Winkler's foundation model [17]

(b) Beam-on-Nonlinear Winkler Foundation (BNWF) model [59]

(c) Contact Interface Model (CIM, an improved form of Plasticity Based Macro-element (PBM) model) [60]

Fig. 5. Different types of soil modeling methods.

structure. SSI's kinematic component is illustrated by transfer functions which is the ratio of FIM (u_{FIM}) to free-field motion (u_g). θ_{FIM} and u_{FIM} represent the rotational and translational constituents of the earthquake applied to the foundation (Fig. 7).

2. Estimation of foundation impedance function: The main purpose of obtaining impedance function is to obtain the damping and stiffness properties of soil-foundation interaction. These characteristics are analyzed either by utilizing complex impedance function models for rigid foundations or distributing simplified frequency-dependent springs (both translational and rotational) and dashpots around the foundation where the springs depict the soil stiffness and dashpots define the damping characteristics of soil, followed by the integration of SSI effects via dynamic impedance function and the application of FIM to the dynamic soil springs. The simple form of impedance functions can be illustrated by the below equation [6].

$$S\ (a_0) = K\ [k\ (a_0) + ia_0 c\ (a_0)]$$

Where, S= Function of dimensionless frequency, a_0
K= Static stiffness coefficients
k = Stiffness characteristics
c = Damping characteristics.

3. Investigation of structure on the compliant base under FIM: The response of the structure is derived in this final stage using the response spectra or time-history analysis of the superstructure on a compliant base being symbolized by soil springs and dashpots under

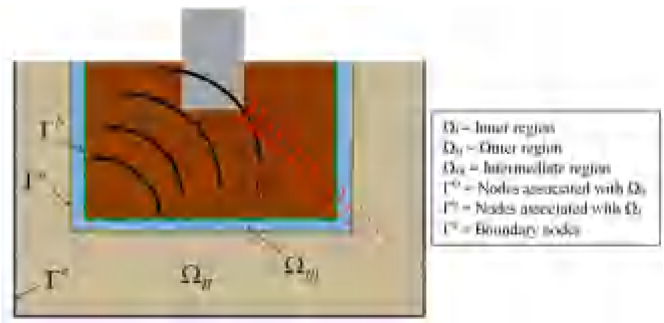


Fig. 6. Domain reduction method [70].

FIM as input earthquake. Fig. 7 shows the graphical representation of total substructure method.

Based on the solution process of SSI interaction problem, substructure method can be of four types (rigid boundary, flexible boundary, flexible volume, subtraction) [40]. Due to the reduced computational effort, Substructure method is a widely espoused method to solve SSI problems of NPP structures. However, outputs obtained from direct analysis approach provide more reliable results [120]. Several commercial software utilize substructure techniques for solving SSI problems. Table 5 showcases the compendium of all the seismic SSI studies on NPPs conducted during the last two decades employing Substructure method.

5.2.3. Commercial software packages for SSI analysis of NPPs

With the progress of technology, commercial FEM software packages have become available to perform FE models of NPPs. Since the various software applies different methods, former researches have proposed a selection based on the technique adopted for that particular study and computational efficiency. The most commonly used software packages include SASSI, CLASSI, LS-DYNA, ANSYS, ABAQUS, OpenSees, etc. Fig. 8 shows the percentage of different software used in preceding studies. Commercial computer codes SASSI and CLASSI utilizes the substructure method in the frequency domain [74]. Particularly, SASSI [164] is a preferred SSI analysis coding, specifically in nuclear and heavy industry, which uses flexible volume and substructure subtraction methods in frequency-domain, but it faces challenges while conducting nonlinear analysis as SASSI handles the nonlinearity of soil employing the equivalent linear method [97].

6. Relevant SSI studies on NPPs and discussion

With the progression in the field of numerical analysis, increased capability of commercial software, and availability of powerful computational components, significant advancement has been obtained in SSI-related research in the nuclear industry to date. Some of these earlier studies attempted to find some rationale behind the effects induced by SSI. Several researchers investigated the feasibility of different solving methods of SSI while some academics hypothesized various improved techniques to ameliorate the efficacy of the existing methods. This section presents an elaborate overview of previous studies regarding various SSI features and their influences in the seismic behavior of NPP structures.

6.1. Effects of soil medium

Researchers have been rigorously investigating the influence of different soil parameters on the overall SSI responses of NPPs during the previous decades. Differences in various soil factors like V_s, G, and ξ tend to heavily affect the seismic responses and eventually alter the response of the structure as well. Fig. 9 presents the response spectra of soil amplification in different soil conditions which was studied by Kwag et al. [27] who examined SSI effects on the overall seismic fragility and total risk results of a PWR NPP containment building. This section describes different aspects of soil factors and their impacts on the seismic SSI responses of NPPs based on the previous studies.

Nakaki et al. [141], Gila et al. [142], Cho et al. [138] found discrepancies in recorded field data and numerical results due to the difference in soil properties. Cho et al. [36] studied the fixed base (FB) condition in the SSI analysis of NPP structures and concluded that selecting the relative stiffness between the soil and structure is more apropos and logical rather than the ASCE 4–98 design code [10] stipulated criterion of choosing only shear wave velocity (V_s) despite the conservativism of the codal guideline. Ding et al. [83] observed that SSI effects, particularly in those NPP structures built on moderate hard soils, might amplify the structure responses. Sun et al. [117] found up to 28.87 % and 15.5 % increment in the peak acceleration and peak floor response spectrum, respectively, due to SSI impacts in sites with lower stiffness and no effects for highly stiff sites. Therefore, they recommended that SSI effects should be investigated for NPPs on non-bedrock sites. Tabatabaie et al. [136] evaluated the effect of embedment on the SSI response of EPR NPP structures and identified the strong correlation between the soil stiffness and the degrees of reduction in acceleration response spectra. Identical conclusion was also obtained by Chen [128] who found this effect to be significant in case of NPPs over shallow soil deposits. Xiaohui et al. [46] also discovered that the soil response accelerations were more affected by SSI effect under frequencies greater than 3 Hz and SSI effects also impacted the structural response, which clarifies the significant impact of the site soil conditions on the dynamic behavior of NPP structures. Liu et al. [107] found that the influence of the uncertainty of V_s is significant on the surface response spectra (SRS) after uncertainties in soil parameters were considered. From their observation, it is also clear that the reduction in G exhibits significant uncertainty under higher shear strain and thus the practice of considering a coefficient of variation (COV) of 0.5 as per the code [12] is not a feasible idea to address it. Wang et al. [165] conducted SSI analysis on HTR-10 NPP structures and concluded that the FRS at the foundation level was decreased while responses at higher floor levels were considerably changed after considering SSI. Both Desai and Choudhury [166] and Lee [167] evaluated the local site effects in the hazard assessment framework of NPPs and they both recommended that overlooking soil uncertainties may trigger the seismic risk. However, there are case scenarios where soil factors don't influence the SSI mechanism after a certain threshold limit. For instance, Subramanian et al. [168] revealed that the erraticism of soil factors up to a certain value of V_s does not affect the response and in fact, the response marginally reduces. All these research findings indicate that various uncertainties emerged from soil parameters need to be duly investigated while considering SSI effects in NPPs. Therefore, Králik and Simonovic [121] recommended that structural engineers and designers should be meticulous in gathering as much data as possible to describe the site properties upon which a proposed NPP structure is to be located.

Seismic SSI responses in homogenous soil are considerably different from that obtained from soil with multiple layers. The difference in the soil properties at each layer significantly changes the dynamic responses, which may lead to the underestimation of seismic demands if these layering effects are not properly considered. For instance, Amorosi et al. [87] investigated the seismic behavior of NPPs on layered soil medium and found that the fundamental frequency (f_n) of the SSI system declined considerably, and damping ratio (ζ) enlarged with ascending PGA, which shifts the structural sensitivity to a different frequency content range. Králik and Králik [169] illustrated that the impedance functions were not smooth for the layered subsoil with changing material properties than in case of the consistent subsoil. Politopoulos et al. [88] implied that the effects of SSI on NPPs are not the same for multi-layered soil compared to the homogenous one. However, Qadeer et al. [80] compared the seismic SSI results of an NPP with two sites in

Table 4
Overview of factors employed in earlier studies using direct analysis method.

Researcher (s)	Year	Analysis Type	Structural modeling		Soil modeling				Software
			Idealized model type	Used element type	Idealized model type	Used element type	Considered soil behavior	Boundary type	
Baušys et al. [77]	2005	ELFD	2D & 3D FEM	Shell, Solid	–	–	Nonlinear	Approximate (Viscous dashpot)	ABAQUS
Hiraki et al. [78]	2007	NLTD	LMSM	–	Axisymmetric	–	Linear	Approximate (Viscoelastic)	–
Tuñón-Sanjur et al. [79]		NLTD	LMSM, 3D FEM	Solid, Shell	Continuum (3D)	Solid	Nonlinear	–	ANSYS
Qadeer et al. [80]	2009	NLTD	LMSM	–	Soil spring - Damper	–	Nonlinear	–	SAP2000
Chen et al. [81]	2010	ELTD	3D FEM	Beam, Plate (Shell)	Soil spring - Damper	–	Linear	–	STAAD Pro
Saxena et al. [82]	2011	NLTD	2D FEM	Plane stress	Continuum (2D)	Plane stress	Linear (with nonlinear interface)	Approximate (TDOF)	–
Saxena and Paul [73]	2012	NLTD	2D FEM	Plane stress	Continuum (2D)	Plane stress	Linear (with nonlinear interface)	Approximate (TDOF)	NISA (to calculate natural period)
Bhaumik and Raychowdhury [23].	2013	NLTD	FEM	Fiber beam-column element	BNWF	Soil spring	Nonlinear	Approximate (Viscoelastic)	OpenSees
Seo and Lee [50].		DHFTD (Direct-hybrid-frequency-time-domain)	Computer code	Beam	–	–	Linear	Rigorous (Infinite element)	KIESSI
Ding et al. [83]		NLTD	LMSM	–	Soil spring - Damper	–	Nonlinear	–	OpenSees
Sayed et al. [84]		NLTD	LMSM	–	BNWF	–	Nonlinear	–	OpenSees
Rangelow et al. [85]		NLTD	3D FEM	Beam, Shell	–	–	Nonlinear	–	SOFiSTiK
Hoseyni et al. [28]	2014	NLTD	LMSM, 3D FEM	Brick (Solid), Plate (Shell)	–	–	Nonlinear	–	–
Orbovic et al. [64]	2015	NLTD	LMSM	–	Continuum (3D)	Brick (Solid)	Linear	DRM	Real ESSI Simulator
Bochert et al. [86]		ELFD, NLTD	3D FEM	Shell, Solid	Continuum (3D)	Solid	Nonlinear	Rigorous (Infinite element)	SASSI (Equivalent linear), ABAQUS (Nonlinear)
Amorosi et al. [87]		NLTD	3D FEM	Plate (Shell)	Continuum (3D)	Solid	Nonlinear	Approximate (TDOF)	PLAXIS 3D
Politopoulos et al. [88]		NLTD	Computer code	–	–	–	Linear	Approximate (Viscous dashpot)	CAST3M
Varma et al. [89]		NLTD	3D FEM	Beam, Shell, Solid	Continuum (3D)	Solid	Linear (Far-field), Nonlinear (Near-field)	Approximate (TDOF)	LS-DYNA
Kumar et al. [21]		NLTD	3D FEM	Beam, Shell	BNWF	–	Nonlinear	–	OpenSees
Lee et al. [26]	2016	NLTD (BRM)	LMSM	Beam	Continuum (3D)	Solid	Nonlinear	Approximate (Viscoelastic)	KIESSI-3D (ELFD), MIDAS/ Civil (NLTD)
Lee et al. [76]		NLTD	LMSM	Beam	Continuum (2D, 3D)	Shell (2D), Solid (3D)	Nonlinear	Rigorous (PMDL)	ABAQUS
Farahani et al. [34]		NLTD	3D FEM, Computer code	Shell	–	–	Nonlinear	–	SAP2000 (Fixed-base), SASSI (SSI)
Kim et al. [49]		NLTD (BRM)	3D FEM	–	–	–	Nonlinear	Approximate (Viscoelastic)	KIESSI-3D (ELFD), ANSYS (NLTD)
Sextos et al. [90]	2017	NLTD	3D FEM	Shell	Continuum (3D)	Solid	Nonlinear	Approximate (TDOF)	ABAQUS
Baltaji et al. [91]		NLTD	3D FEM	–	Continuum (3D)	–	Nonlinear	Approximate (TDOF)	MASTODON, LS-DYNA
Sinha et al. [16]		NLTD	3D FEM	Shell	Continuum (3D)	Brick (Solid)	Nonlinear	Rigorous	–
Chandran and Ratnagaran [92].		NLTD	3D FEM	Beam, Shell, Solid	Continuum (3D)	–	Nonlinear	–	SC-SASSI, ANSYS

(continued on next page)

Table 4 (*continued*)

Researcher (s)	Year	Analysis Type	Structural modeling		Soil modeling				Software
			Idealized model type	Used element type	Idealized model type	Used element type	Considered soil behavior	Boundary type	
Wang et al. [33]		NLTD	3D FEM	Brick (Solid)	Continuum (3D)	–	Nonlinear	DRM	Real ESSI Simulator
Tehrani et al. [93]		ELFD, NLTD	3D FEM	Shell	–	–	Nonlinear	Non-transmitting	–
Sextos et al. [94]		NLTD	3D FEM	Shell, Solid	Continuum (3D)	Solid	Nonlinear	–	ABAQUS
Rodari et al. [95]		NLTD	3D FEM	Beam, Shell, Solid	Continuum (3D)	Solid	Equivalent linear	Approximate (Viscous dashpot)	SAP2000
Lee [96]	2018	NLTD	3D FEM	Beam	Continuum	Shell	Nonlinear	Approximate (Viscous dashpot)	–
Zhu [97]		ELFD, NLTD	3D FEM	Beam, Shell	Continuum (3D)	Solid	Nonlinear	Approximate (Viscoelastic)	MSC. Patran/ Nastran, ABAQUS
Qu et al. [98]		NLTD	3D FEM	New interface element	Continuum (3D)	–	Nonlinear	–	GEODYNA
Bolisetti et al. [99]		ELFD, NLTD	3D FEM	Beam	Continuum (3D)	Solid	Nonlinear	Approximate (TDOF)	LS-DYNA
Kuldip et al. [31]	2019	NLTD	3D FEM	Shell	Continuum (3D)	Solid	Nonlinear	–	ABAQUS
Markou and Genco [100]	2019	NLTD	3D FEM	Shell	Continuum (3D)	–	Nonlinear	Approximate (TDOF)	SAP2000 (Linear), Reconan FEA (Nonlinear)
Swetha and Justin [65].		NLTD	2D FEM	Beam	Continuum (3D)	–	Linear	Rigorous	CLASSI
Qin et al. [101]		NLTD	3D FEM	Beam, Shell	–	–	Nonlinear	–	ANSYS, SASSI
Boris et al. [69]		NLTD	3D FEM	Shell	Continuum (3D)	Brick (Solid)	Nonlinear	DRM	Real ESSI Simulator
Králik and Králik [102].		NLTD	3D FEM	Shell	Continuum (3D)	Solid	Nonlinear	Non-transmitting	ANSYS
Bayudanto [103].		NLTD	3D FEM	Solid	Continuum (3D I-soil model)	Solid	Nonlinear	Approximate (TDOF)	LS-DYNA
Cui and Fall [44].		NLTD	3D FEM	–	Continuum (3D)	–	Nonlinear	–	COMSOL Multiphysics
De Borbón et al. [51]	2020	NLTD	3D FEM	Shell	Continuum (2D, 3D)	Shell (2D), Solid (3D)	Equivalent linear	Approximate (Viscous dashpot)	ANSYS
Van Nguyen et al. [72]		NLTD	LMSM	Beam	Continuum (3D)	Solid	Nonlinear	Approximate (Viscous dashpot)	ABAQUS
Ichihara et al. [104]	2021	NLTD	3D FEM	Beam, Shell	Continuum (3D)	Solid	Equivalent linear	Approximate (TDOF)	FINAS/STAR
Lee et al. [105]		ELFD (BRM)	3D FEM	–	Continuum (3D)	–	Nonlinear	Rigorous (Infinite element), Approximate (Viscoelastic, ANSYS)	KIESSI-3D (ELFD), ANSYS (NLTD)
Bahuguna and Firoj [106]		NLTD	3D FDM	Solid, Shell	Continuum (3D)	Solid	Nonlinear	Approximate (Kelvin element)	ABAQUS
Liu et al. [107]	2022	NLTD	3D FEM	Beam, Shell	Continuum (3D)	Solid	Nonlinear	Approximate (Viscous dashpot)	ANSYS
Firoj and Maheshwari [108].		NLTD	3D FEM	Beam, Shell, Solid	Continuum (3D)	Brick (Solid)	Nonlinear	Approximate (Viscous dashpot)	ABAQUS
Li et al. [109]		NLTD	3D FEM	Solid, Shell	Continuum (3D)	Solid	Equivalent linear	Approximate (Viscoelastic)	ABAQUS
Chen et al. [110]	2023	NLTD	3D FEM	Shell, Solid	Continuum (3D)	–	Nonlinear	Approximate (TDOF)	ABAQUS
Li et al. [62]		NLTD	3D FEM	Beam, Shell	Continuum (3D)	–	Nonlinear	Rigorous (SBFEM)	–
Firoj & Maheshwari [52].		NLTD	LMSM (Structure), 3D FEM	Beam, Solid	Continuum (3D)	Solid	Nonlinear	Approximate (Viscous dashpot)	ABAQUS
Sui et al. [111]		NLTD	3D FEM	Solid	Continuum (3D)	–	Nonlinear	Approximate (Viscous dashpot)	GEODYNA
Cheng et al. [112]		NLTD	3D FEM	Shell, Beam	Continuum (3D)	Solid	Nonlinear	Rigorous (PMDL)	LS-DYNA
Kumar & Kumari [113].		NLTD	2D FEM (Axisymmetric)	Shell (Plane strain)	Continuum (2D)	Shell (Plane strain)	Nonlinear	Approximate (Viscous dashpot, Kelvin element),	ABAQUS

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Table 4 (*continued*)

Researcher (s)	Year	Analysis Type	Structural modeling		Soil modeling				Software
			Idealized model type	Used element type	Idealized model type	Used element type	Considered soil behavior	Boundary type	
Lv & Chen [114].		LTD & NLTD	3D FEM	Shell, Beam	Continuum (3D)	Solid	Nonlinear	Rigorous (Infinite element) Approximate (Viscous dashpot)	ANSYS
Maheshwari & Firoj [53].		NLTD	3D FDM	Grid, Beam	Continuum	–	Nonlinear	Approximate (Kelvin element)	FLAC3D
Li et al. [115]		NLTD	3D FDM	Solid, Shell	Continuum (3D)	Solid	Nonlinear	Approximate (Viscoelastic)	ABAQUS
Sun et al. [116]	2024	NLTD	3D FEM	Solid, Shell	Continuum (3D)	Solid	Nonlinear	Approximate (Viscoelastic)	ABAQUS
Kanellopoulos et al. [71]		NLTD	3D FEM	Shell	Continuum (3D)	Brick (Solid)	Linear & Nonlinear	DRM	Real ESSI Simulator
Liu et al. [117]		NLTD	3D FEM	Shell	Continuum (3D)	Brick (Solid)	Equivalent linear	Approximate (Viscoelastic)	ANSYS
Wang et al. [118]		NLTD	3D FEM	Solid, Shell, Truss	Continuum (3D)	Solid	Equivalent linear	Approximate (Viscoelastic)	ABAQUS

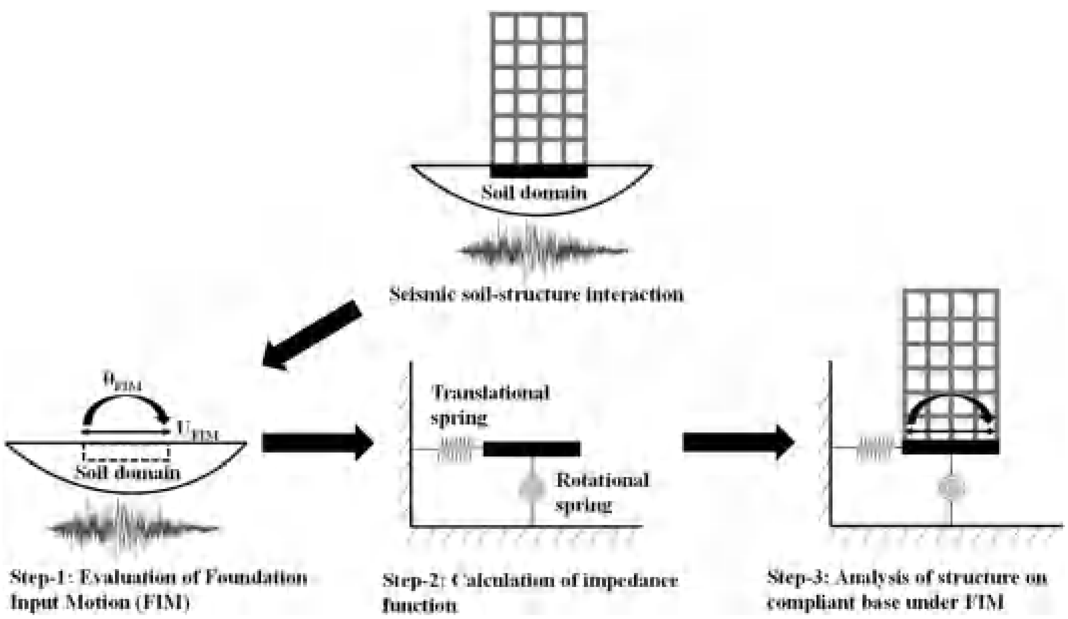

Fig. 7. Substructure analysis method [119].

China, and found that for the seismic assessment of existing NPPs, the layering effects of soil should not be mandatory, especially for surface foundations. A similar issue was studied by Králik and Králik jr [170], Králik and Králik [102] and Rieck and Houstons [124] where they observed the effects of the layered subsoil on seismic responses of NPP hall buildings. To sum up, the layering effects can be prominent or trivial depending on the foundation embedment and properties of individual soil layers.

6.2. Effects of foundation

Foundation characteristics (embedment, stiffness, soil-foundation interface etc.) are one of the important aspects to consider for SSI analysis. Chen et al. [81] considered deep embedment of building into soil, irregular shape of base slab, and application of soil springs at different elevations for the SSI analysis of an NPP facility. Their investigation presented that variations in peak structural response is occurred from foundation stiffness effects. Bahuguna and Firoj [106] investigated the dynamic behavior of a nuclear containment built on raft foundation considering SSI and geometric nonlinearity. Their study showed that the yielding force is decreased by up to 8.37 % with embedment while 2.37 % reduction is found without being embedded after incorporating SSI effects as compared to FB analysis (without SSI). Xu et al. [126] investigated the important issues potentially impacting the dynamic response of deeply embedded nuclear structures (DEB) NPP structures and the pressures on the embedded structures were found to be dependent on kinematic interaction loads. Jang et al. [123] showed significant embedment impact on the ISRS of APR1400 NPP structure due to SSI. However, there are cases which showed the opposite behavior. Frano and Forasassi [133] assessed the effect of variable depths of foundation (Superficial, Intermediate, and Full depths) on the seismic SSI behavior of NPP and found almost similar responses for last two cases where the superficial one exhibited large amplification, indicating that the embedment effect is beneficial for NPPs. Wang et al. [118] reported that the burial effect reduces the FRS of buried NPP structures compared to the surface-sited ones. Nakamura et al. [171] and Kumar & Kumari [113] also found the reduction in acceleration amplification due to embedment effects. Chen and Maslenikov [125] probed the effects of different foundation modeling techniques in the SSI analysis on NPP facilities and found it to be trivial. Hence, foundation characteristics are

Table 5
Overview of earlier NPP-SSI studies using Substructure method.

Researcher(s)	Year	Idealized structural model	Interaction solution method	Site/Soil condition
Jordanov et al. [30]	2001	3D FEM	Subtraction	6 layered soil
Králik and Simonovic [121].		3D FEM	Subtraction	Soft clay soil site
Varpasuo and Junttila [122].		3D FEM	–	7 layered soil
Jang et al. [123]	2002	LMSM	Flexible volume	3 layered soil
Jordanov and Karparov [29]	2003	3D FEM	Subtraction	6 layered soil
Rieck and Houstons [124].		LMSM	–	3 soil layers
Chen and Maslenikov [125].	2004	LMSM	–	Several layers (medium-to-very dense sands, compacted gravels, and hard silty clay; very dense sand and gravel; hard silty clay; dense sand; rock-like hard silty clay/sand mixtures)
Xu et al. [126]	2005	3D FEM	Subtraction	Homogenous soil with varying shear wave velocity (250–1000 m/s)
Xu et al. [127]	2006	3D FEM	Subtraction	Surface bedrock (2-layered)
Chen [128].		LMSM	Subtraction	Homogenous and layered soil
Pinto et al. [129]	2007	3D FEM	Subtraction	Homogenous soil with varying shear wave velocity (180–1500 m/s)
Tuñón-Sanjur et al. [79]		LMSM	Subtraction	3 sites (hard rock, firm rock site, and soft-to-medium soil)
Tinic et al. [130]		3D FEM	–	–
Johnson et al. [131]		LMSM	Flexible volume	Rock site
Kang and Lee [35].	2008	LMSM	Subtraction	2 sites (medium-hard rock and hard-rock)
Seo and Ryu [132].		LMSM	Rigid boundary	Horizontally layered soil medium with underlying half-space
Frano and Forasassi [133].		FEM	–	Soil site with loose sand zone
Nakamura [134].		LMSM	–	2 layered soil
Lee and Kang [135].	2009	LMSM	–	Homogenous soil with varying shear wave velocity
Tabatabaie et al. [136]		LMSM	–	10 different soil profiles
Alloety et al. [137]		LMSM	Subtraction	7 different soil profiles
Cho et al. [138]		3D FEM	–	7 different soil profiles
Xu and Samaddar [139].		LMSM	Subtraction	2 site conditions (rock and soil)
Chen et al. [140]		LMSM	–	Hard rock site
Nakaki et al. [141]	2010	3D FEM	Flexible volume	Soil overburden above rock
Gila et al. [142]		3D FEM	–	–
Johnson et al. [143]		LMSM	Flexible volume	Hard rock site
Ghiocel et al. [144]	2011	LMSM	Flexible volume	Rock subgrade with varying shear wave velocity
Bolisetti and Whittaker [145]		LMSM	–	14 horizontal layers
Ghiocel and Lee [146].		LMSM	–	2 site conditions (hard-rock and soft soil)
Lin et al. [147]	2012	LMSM	–	20 horizontal layers
Lee and Tseng [148].	2013	LMSM	Subtraction, Modified Subtraction	2 soil profiles
Yue and Ghiocel [149].	2013	3D FEM	Modified Subtraction	6 discrete layered soil profiles
Rangelow and Schütz [24].	2015	FEM	Subtraction	Alluvial soil layer (cohesion-less sand, cohesive clay, and mixtures)
Ghiocel [32].		FEM	–	2 sites (rock and soil)
Kabanda et al. [150]		3D FEM	Flexible volume	Sand layers on gravel layers
Drosos & Sitar [151]		LMSM, 3D FEM	–	9 soil profiles
Johnson et al. [152]		LMSM	–	3 site conditions (rock site, deep soil, and layered site)
Renault et al. [153]		LMSM	–	–
Bolisetti et al. [154]		LMSM	–	29 soil layers
Solberg et al. [70]	2016	LMSM	–	9 soil layers
Zhou & Wei [155]		LMSM, 3D FEM (Nonlinear)	Flexible volume	3 layers (medium soil, hard soil, and rock)
Seo et al. [156]	2017	LMSM, 3D FEM	–	Homogeneous halfspace
Watanabe et al. [157]		LMSM	–	4 layered hard rock
El-Bahey et al. [20]	2018	LMSM	Subtraction	Surface bedrock
Kwag et al. [27]	2018	LMSM, 3D FEM (Nonlinear)	–	3 types (rock, hard, and soft soil)
Tehrani et al. [158]		FEM	–	Gravels on solid limestone (with groundwater table)
Bolisetti et al. [99]		LMSM	–	Homogenous soil layer (shear wave velocity = 165 m/s)
Sunwoo et al. [159]	2019	FEM	–	–
James and Oleg [160]		FEM	Subtraction	2 soil profiles
Manuel et al. [161]		3D FEM	–	–
Iman et al. [162]		3D FEM	–	Gravel site on a solid limestone
Philip et al. [163]		LMSM	Subtraction	Soil spring and dashpot

case-specific and needs proper consideration depending on the investigation.

In addition, SSI effects may influence nonlinear effects such as slip and separation of the foundation in nuclear structures with embedded segments. Bhaumik and Raychowdhury [23] suggested that the sliding

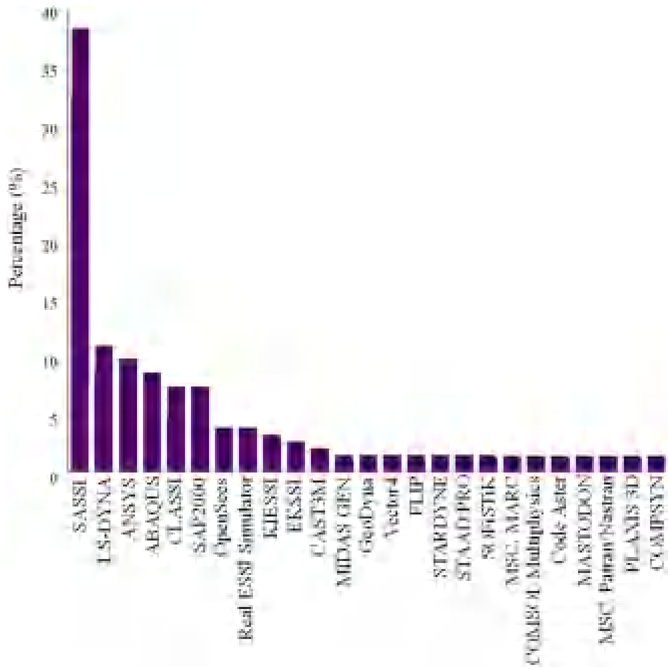

Fig. 8. Usage percentage of various commercial software in earlier studies.

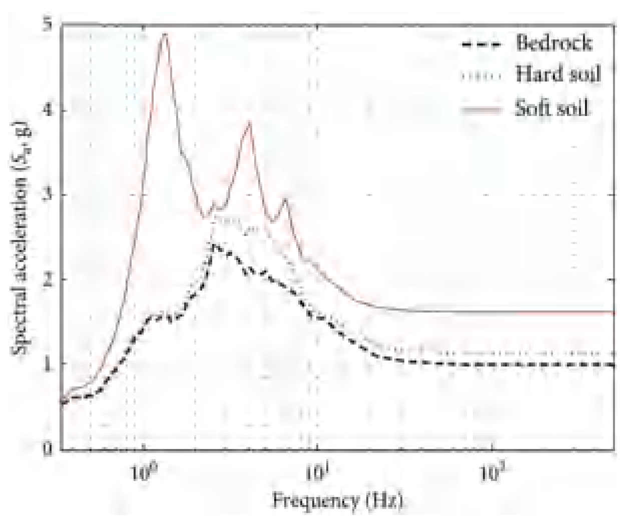

Fig. 9. Mean response spectra in different soil conditions (from site response analyses) [27].

and settlement of the foundation are found to be increased with increasing ground motion intensity for nonlinear base which should be rigorously contemplated for safe design of structures. Sextos et al. [90, 94] found that stiff containment structures founded on soft soils are more susceptible to foundation uplift and coupled nonlinear phenomena such as sliding and rocking at the foundation-soil interface induced from moderate (0.5–1.0 Hz) and significantly long period pulses. Saxena et al. [82] studied slip behavior under ascending static load at the reactor base and ended up with the conclusion that slip and separation at SSI interface develop greater stresses at several positions, which is reliant on the friction coefficient. Saxena and Paul [73] later studied embedment effects and found that both the horizontal slip and vertical separation reduced with the increase in the embedment, and significant reduction in the stress of the structure is observed, which illustrates the necessity of considering foundation embedment in the SSI analysis of embedded nuclear establishments. Based on these findings, it is vital to carefully consider nonlinear SSI effects, including slip, separation, and uplift, especially for embedded nuclear structures, to confirm safe design performance.

Apart from the shallow raft foundations, many NPP structures are also constructed on raft pile foundations in NPP structures and the seismic performance of piles is highly contingent on the SSI effects. Yang et al. [47] performed shaking table tests to observe seismic SSI responses of NPPs on pile-raft foundation and observed lower acceleration amplification ratio for the superstructure with a pile-raft foundation compared to the fixed-base superstructure, suggesting that this foundation type can extend the selection for probable NPP construction site. Firoj and Maheshwari [108] observed the nonlinear seismic responses of a NPP structure with combined piled –raft foundation (CPRF) by incorporating both material and geometrical nonlinearity and found that CPRF actually decreased the peak acceleration by 20.12 % and 33.1 % compared to the structure with pile group and raft foundation, respectively. Sayed et al. [84] numerically compared the seismic behavior of the fixed base isolated NPP reactor building with another model supported by deep pile foundation considering nonlinear SSI and found remarkable decrease in the peak acceleration. Sui et al. [111] performed nonlinear SSI analysis on a NPP structure with pile foundations and found that pile foundations can reduce the peak acceleration in the structure up to 26 %. Therefore, it is evident that pile-raft foundations significantly enhance the seismic performance of NPP structures through nonlinear SSI effects, making them a viable alternative to mat foundations.

6.3. Effects of structural aspects

Apart from the foundation and soil parameters, different structural factors also trigger the SSI effects during seismic events. SSI studies on NPPs during the past decades have mostly focused on the impact of SSI on structural damage and demand parameters. Bahuguna & Firoj [106] found from their study that the nonlinearity of the superstructure tends to increase the peak seismic response of NPP structure by 13.7 %. Moreover, Sunwoo et al. [159] averred that certain SSI factors, including concrete cracking, and SSSI on the seismic demand calculations of NPP structures produce significant increases in certain response quantities and thus they should be considered while evolving the design-basis seismic demand.

Research on the SSI analysis of NPP structures with upgraded earthquake-resistant systems has remarkably increased and base isolation technique is one of them. Hong et al. [172], Zhou & Wei [155], Han et al. [173] and Ding et al. [83] observed that the base isolation technique effectively mitigates the seismic vibration in NPP structures. In case of SSI analysis, properties of base isolation system tend to be affected by SSI which changes the dynamic response of the individual and unified SSI system components. SSI's tendency to lower the main frequencies of vibrations in heavy structures can reduce the effectiveness of isolation, which makes it a great area of interest especially in the seismic design of base-isolated structures in high seismicity zones [151]. Ashiquzzaman and Hong [174] marked the inclusion of rotational inertia of base isolator mass in the seismic design of containment buildings as a crucial factor as SSI impacts are more apparent in rigid squat/semi-squat buildings. Zhao et al. [48] declared that the seismic response at the structure bottom in the low-frequency range is significantly amplified by SSI effects along with the rocking phenomenon under operating basis earthquake (OBE) for the non-isolated model while in the isolated model, the vertical response increases due to the reduced hysteresis capacity of the isolation system by SSI effects. Drosos and Sitar [151] and Zhu [97] found similar results in case of vertical responses. Liu et al. [117] also discovered that SSI effects are important for the base-isolation design of NPPs as the isolation capacity depends on it. Ali and Kim [175] investigated seismic SSI effects of a base-isolated NPP, compared it with a fixed base model, and discovered that SSI plays a remarkable influence on the increasing rate of fundamental period (T_n). Thus, for the base-isolated design of NPPs, it is necessary to properly consider the SSI effects so that the rocking components don't reduce the isolation capacity. In this regard, Lee et al. [105] proposed a seminal technique for considering the rocking component of a base-isolated NPP structure with rigid basemat to illustrate the selection procedure of rocking input as per ASCE 4–16 [54].

6.4. Effects of SSSI

The effects coming from the mutual interaction between adjacent structures and surrounding soil is another important aspects of SSI analysis because the influences due to the presence of neighboring structures are not the same as SSI effects. In case of NPP structures, it is of utmost importance because NPP structures are usually surrounded by several auxiliary buildings and this issue has been addressed in many previous studies where SSSI effects in NPPs are rigorously investigated. Initially, the consideration of SSSI effects in the dynamic analysis of NPP buildings was highlighted due to their contiguous positioning by Lee & Wesley [3] as this phenomenon may significantly modify the seismic behavior of the entire NPP establishment. Bolisetti and Whittaker [145] investigated a pair of NPP structures by juxtaposing their responses with and without a neighboring structure and suggested that SSSI effects are necessary to be assessed. Their findings demonstrated that SSSI effects were found to be more severe at the rocking frequencies of the reactors and the behavior of the lighter structure was more impacted than the one of the heavier structure. Watanabe et al. [157], Seo et al. [156] and Chandran and Ratnagaran [92] also found that the dynamic SSSI responses of lighter buildings are likely to be influenced substantially, indicating the significance of combining SSSI effects into the design consideration of NPP structures. Yue and Ghiocel [149] examined SSSI effects for two NPP structures with large embedded foundations and found trivial impact on the reactor building exerted by the adjacent lighter turbine building structure, which re-strengthens the previous assumption that heavier NPP buildings are prone to impact the stability of contiguous lighter structures under seismic conditions. Anderson et al. [57] investigated the effect of structure, soil, and ground motion parameters on SSSI of large-scale nuclear structures. Their study discovered 33 % escalation in seismic demand vertically and 15 % increase in seismic demand in the perpendicular direction of the building due to the interaction with the larger adjacent structure and soil. Nevertheless, there are also studies which explored beneficial impact of SSSI on the seismic behavior of neighboring NPP buildings. For example, Chen et al. [110] examined SSSI effects on adjacent NPP structures and found it to be beneficial on the dynamic responses of NPP structures because of the mutual interaction of adjacent structures and surrounding soil. Li et al. [109] suggested that SSSI effects can be neglected for bedrock sites but should be considered for non-bedrock sites. However, all these findings indicate that SSSI mechanism between adjacent structures in NPPs are quite complex and its effects vary from case-by-case. Therefore, Kanellopoulos et al. [71] suggested that practicing engineers need to improve their modeling sophistication level for considering SSSI effects in NPPs as it can be either beneficial or detrimental based on the structural and site characteristics.

6.5. Effects of ground motion characteristics

Several ground motion features such as: ground motion incoherency (GMI), peak ground acceleration (PGA), frequency contents (FC) etc. have profound influence on the seismic response of NPP structures which makes them a significant concern to ponder while conducting SSI analysis.

Ground motion incoherency is an intricate phenomenon that stems from the random wave scattering and wave passage effects and leads to the spatial variation in seismic excitations [160]. The erratic influences exerted by the incoherency of earthquakes can be hazardous for the SSI of safety related critical structures, which necessitates its proper evaluation for seismic resilience of NPPs. Ghiocel and Ostadan [176] showed that incoherency effects trivially affect the low-frequency responses of the structure, but significantly impacts the high-frequency vibration modes and ISRS. Johnson et al. [131,143] assessed the incoherency impacts on NPP structures and found the incoherency effects on the structural response to be significant for frequencies larger than 10 Hz compared to coherent input. A similar result was obtained by Xu and Samaddar [139] while James and Oleg [160] stated that the motion incoherency effects on the dynamic response of NPP structures are minimum at frequencies lower than 10 Hz. The latter also identified significant effects on vertical responses by GMI in many instances, making it an important issue to consider for SSI analysis. Chen et al. [140] found significant influence of GMI on the seismic response of a NPP built on hard rock, especially in the high-frequency domain. Ding and Xia [177] researched to discover the motion incoherence impacts on a Nuclear Island (NI) built on a soft soil site and advocated that consideration of the wave incoherence reduces the redundant conservatism in the seismic analysis of nuclear projects. Ghiocel and Lee [146] found that the out-of-phase motion components induced by incoherency affects the wave scattering phenomenon. Wang and Feau [178] measured fragility curves of several plant equipments in Kashiwazaki-Kariwa NPP in Japan considering SSI and declared that the uncertainties in the input motion needs to be properly controlled to obtain correct results. Wang et al. [179] found significant changes in the peak acceleration and zero-period acceleration of in-structure response spectra due to the influence of motion incoherency on the SSSI of nuclear buildings. Both Aleshin and Seleznev [180] and Rangelow et al. [85] probed earthquake impacts at operating and beyond the design limit on the SSI behavior of NPPs. However, Ghiocel et al. [181] found minor impacts of incoherency on the SSSI between a NI complex and adjacent Annex Building (AB) structure. For the proper consideration of motion coherency effects, several researchers have demonstrated the feasibility of newly proposed techniques. Lee and Kang [135] described the effect of the newly proposed coherency function model for hard-rock sites by N. A. Abrahamson [182] for a typical NPP reactor building. Ghiocel [183] discussed the major features of stochastic modeling of wave incoherency and its implementation in the seismic design practice of nuclear constructions integrating SSI effects using a deterministic approach to compute motion incoherency effects. Boris et al. [69] illustrated a framework and implementation technique for complete calculations of the energy flow during seismic activities for a SSI system focused on nuclear installations. Cheng et al. [112] and Pinto et al. [129] showed the dissimilarities between the usage of real and spectrum matched motions in SSI analysis of NPPs. Hence, proper assessment of ground motion incoherency is crucial for the seismic resilience of NPP structures, as it significantly affects high-frequency vibration modes and can lead to substantial variations in seismic responses, particularly for frequencies above 10 Hz.

Intensities (PGA) and frequency contents of an earthquake are two of the important parameters for the seismic design of structures. Even though intensities are the fundamentals of seismic design and generally considered through the response spectrum, the effects of motion frequency contents are not properly considered in the seismic design of NPPs, which may exert significant influence on the long-period and inelastic structures [184]. Ghiocel et al. [144] observed the seismic SSI responses of a NPP building under earthquakes with higher FC and PGA and suggested that site-specific motion incoherency effects are more prominent in the high frequency range that might affect the high frequency sensitive NPP components. Van Nguyen et al. [72] found both SSI and FC of the input motion to be highly sensitive to the seismic performance of NPP reactor buildings under earthquakes. Alloety et al. [137] examined the SSI behavior of a Canadian NPP under two different design-basis motions and found that the earthquake with rich frequency contents governs in the seismic design. Ground motion components are also another important factor for SSI analysis of NPPs. Nakamura et al. [185] studied the combined effects of horizontal and vertical ground motions on a NPP and found trivial impact on horizontal responses. However, this may vary depending on the structural and site characteristics. To conclude, accounting for motion frequency content, alongside PGA, is essential for the effective seismic design of NPPs.

6.6. Comparison between existing analysis techniques

Numerous researchers in the nuclear industry have proposed various methods to upgrade the efficacy of the existing SSI analysis methods while several academics initiated studies to weigh the pros, and cons and assess the practicability of contemporary SSI analysis techniques for the seismic performance evaluation of NPPs. Prior studies on existing analysis approaches are explained in the following segments based on two analysis methodologies: frequency and time-domain analysis, and linear and nonlinear analysis.

6.6.1. Frequency and time-domain methods

Tehrani et al. [93] investigated a typical PWR containment building subjected to earthquake with different intensities, with ELFD, ELTD, and NLTD approaches. This work was further followed by Tehrani et al. [158] while observing the influence of both the single and unified impacts of nonlinear response of interaction interface, and structure on the ISRS of Gösgen NPP building in Switzerland under beyond-design-basis seismic events utilizing ELFD, ELTD and NLTD analyses and results indicated the pragmatic feasibility of time domain approaches for seismic SSI analysis in nucleaevaluated the effect of various SSI modeling methods. Fernandes et al. [186] evaluated the effect of various SSI modeling methods (Full FEM and Time-Laplace domain method considering nonlinear SSI) on the response of Kashiwasaki-Kariwa NPP reactor building and professed that both methods exhibited comparable results within the range of frequencies under consideration. However, Bolisetti et al. [154] and Bolisetti et al. [99] rigorously examined the feasibility of using frequency and time-domain methods in SSI analysis of NPP structures. Their investigation revealed significant differences in the results in presence of nonlinearity and the necessity of performing analysis in time-domain approach. To resolve the degree of uncertainty between two methods, Kim et al. [49] used BRM for NLTD SSI analysis under incident seismic waves to eliminate global iterations between frequency and time domain analyses and found it to be highly effective compared to ELFD method. A more sophisticated technique termed direct-hybrid-frequency-time-domain method (DHFTD) was proposed by Seo and Lee [50]. Orbovic et al. [64] suggested a methodology for NLTD SSI analysis of NPPs by modeling contact among the foundation slab and soil/rock employing contact element permitted for nonlinear response with a gap opening. Seo and Ryu [132] presented a 3D dynamic SSI analysis scheme in frequency domain by combining frequency-dependent infinite elements for increasing the accuracy level. Even though few studies [49,50] have shown the combination of frequency and time-domain analysis methods, no comparisons are made to the results from NLTD technique.

6.6.2. Linear and nonlinear approaches

The effects of SSI are different for linear and nonlinear conditions. In case of large structures like NPPs, both geometric and material nonlinearity emerge from numerous sources, which significantly influence SSI mechanism, marking it as one of the influential parameters to incorporate in the SSI analysis of NPP structures. Fig. 10 shows the difference between the linear and nonlinear soil responses studied by Lee [96] who studied the necessity of incorporating nonlinearity in the practical SSI analysis of NPPs.

Though ELFD method is used to be considered the standard SSI analysis technique in the nuclear industry due to the simplicity and computational efficiency [103], its inability to incorporate nonlinearity induced from soil, structure, and soil-structure interface under dynamic loading may cause serious underestimation of the seismic capacity of NPP structure which makes its ubiquitous adoption quite questionable.

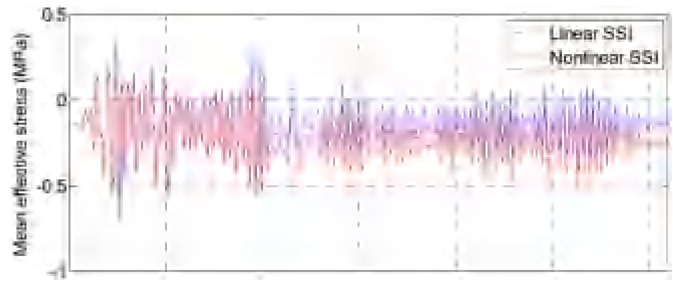

Fig. 10. Difference in mean effective stress generated in the soil due to linear and nonlinear SSI [96].

Researchers around the globe have been investigating the necessity and easy applicability of nonlinear analysis methods during the past decade. Inclusion of nonlinear behavior is also significant for obtaining the realistic evaluation of NPPs. Kabanda et al. [150] reported that NLTD analysis represents more accurate response and the distribution of frequency of recorded structural responses is better captured by this method than the ELFD method. It was obtained from the outcomes that the soil close to the NPP behaved largely in the inelastic range and the peak response from the ELFD analysis showed greater values than NLTD approach. Bolisetti et al. [187,188] studied the impact of adding nonlinear SSI on the seismic risk estimation of NPPs and noticed a significant reduction in risk resulting from the induction of NLSSI. While investigating NLSSI effects, Philip et al. [163] found the plastic energy absorption factor to be remarkably impacted by NLSSI effects which makes them necessary to be integrated into the SSI analysis. Wang et al. [33] found that the acceleration response of the NPP is diminished while the high-frequency acceleration constituent is damped out due to soil plastification considering NLSSI effects. Swetha and Justin [65] reported that the inclusion of geometrically nonlinear interface diminishes the structural response horizontally and the natural frequency of the system vertically under inclined seismic waves. Nakamura et al. [189] explored the suitability and effectiveness of a nonlinear 3D FEM in the fragility assessment and found it to be efficient for more accurate seismic probabilistic safety assessment (SPSA). Ichihara et al. [104], Kojima et al. [190] and Koyanagi et al. [191] utilized a FE model of Kashiwazaki-Kariwa NPP to assess the effect of the nonlinear and linear behavior of the interaction interface on the seismic response of the NPP building while Varma et al. [89] compared the numerical NLSSI analysis results utilizing the captured seismic motions at Fukushima Daichii (Great Tohuku) Earthquake. Lv & Chen [114] found higher values in the acceleration response spectrum of nonlinear case than linear case in rock sites. For the more efficacious incorporation of nonlinear effects in the existing analysis methods, several researchers have proposed newer NLSSI analysis techniques. For instance, Coleman et al. [192] represented a framework to perform NLSSI analysis for NPPs and high-hazard nuclear waste facilities whereas Seo and Lee [50] proposed an improved NLSSI method for a base-isolated NPP to achieve more realistic dynamic response. Sinha et al. [16] introduced a framework for high-fidelity modeling of seismic soil-foundation-structure (SFSI) interaction for an NPP prototype to reduce the modeling uncertainty. Lee [96] proposed a numerical approach based on mid-point integrated finite elements for the NLSSI analysis of an NPP containment building founded on poroelastic soil. However, some scholars' attempt for the improvisation of the existing technique did not exhibit any satisfactory results. For instance, Iman et al. [162] suggested a new method termed the enhanced equivalent linear (EELFD) technique and it was incompetent in simulating the physical behavior of the soil even after the suggested improvements because of its innate limitations to design the nonlinear and transient response of SSI systems like setting the properties of soil to constant values.

The disparity between the linear and nonlinear SSI responses is also of great concern in the context of numerical SSI investigations of NPPs.

As different commercial software utilize different analysis methods (linear, equivalent linear and nonlinear), scholars have been comparing their performances to select the best one that is capable of simulating the most realistic SSI scenario. Bolisetti et al. [193] assessed the safety of NPPs by examining the suitability of equivalent linear (SHAKE) and nonlinear (DEEPSOIL and LS-DYNA) programs over a wide spectrum of frequencies, shaking intensities, and four distinct sites varying from stiff sand to hard rock and found equivalent linear method to be inept of reproducing the high-frequency acceleration response. When the maximum strains were more than about 0.1 %, the equivalent linear responses tended to deviate from the nonlinear responses while this difference became acute from at strains larger than 1 %. Similar kind of difference in results was obtained by Lin et al. [147] who modeled the condensate storage tanks of NPP in Taiwan to evaluate SSI effects using SASSI and SAP2000. Bochert et al. [86] illustrated the compatibility and viability of computation of response spectra for a NPP building considering seismic SSI by employing different methods (direct and substructure, time and frequency domain) in SASSI and ABAQUS. Lee and Tseng [148] compared and analyzed how the different SASSI analysis methodologies, namely, Direct Method (DM), Subtraction Method (SM), and Modified Subtraction Method (MSM) provide similar seismic responses under the same SSI analysis model. Xu et al. [127] developed two FE models in SASSI and LS-DYNA programs to compute soil pressures on DEB nuclear structures and explored that results obtained from both software were identical even for varying depths of burial (DOB). Similar result was obtained from the investigations of Manuel et al. [161] and Markou and Genco [100]. Jang et al. [194] studied the pragmatism of utilizing 3D full model in the SSI analysis of NPP. Thus, different analysis methods for SSI, particularly nonlinear vs. linear, considerably affect the precision of seismic responses for NPP structures, highlighting the need for careful method selection.

6.7. Proposition of simplified analysis techniques

Several researchers have proposed several modeling and analysis methods for the improvement of the existing techniques in terms of computational efficiency and analytical costs in the SSI analysis of NPP constructions. For instance, Park et al. [195] proposed a simplified NPP model using beam element and verified it under various conditions to demonstrate its efficiency. Lee et al. [76] presented a 3D time-domain formulation of PMDL for truncating the modeling region for NLSSI analysis of NPPs whereas Chen et al. [196] and Lv & Chen [114]. invented an ingenious partitioned analysis method of SSI (PASSI) for ameliorating the computational effort by segregating the whole system into smaller subsystems. A simplified method termed Modified HK method was proposed by Huang et al. [197] while Tyapin [198] showed the application of another simplified analysis approach on a vent stack of NPP sample model. Li et al. [62] suggested a coupled FEM-SBFEM technique for SSI along with a comprehensive parallelized solution process to reduce the analysis duration. Qin et al. [101] presented a simplified framework for partially embedded NPPs on hard rock sites under seismic ground motion with high-frequency contents (HRHF site). Solberg et al. [70] proposed a time-domain method for SSI analysis of embedded NPP structures incorporating DRM. Both Nakamura [134] and Ogawa et al. [199] investigated on BWR NPP reactor building and proposed several practical methods for transforming the soil impedance from frequency domain to the impulse response in time domain and a MDOF parallel vertical modeling technique, respectively. Johnson et al. [152] proposed a technical tactic to investigate the positioning of seismic instrumentation placed in NPPs. Renault et al. [153] showed a practically implementable simplified approach for the hazard analysis of NPPs compared to the conventional approach. Qu et al. [98] introduced and exhibited the applicability of a 3D interface element to mitigate the intricacy in handling different scales between soil and structure. Baltaji et al. [91] obtained a significant match between the results from newly invented MASTODON software and those derived from universal software for site response analysis. Bayudanto [103] proposed a new soil model that incorporates pore water pressure and showed its accuracy in the NLSSI analysis of Kashiwazaki-Kariwa NPP. Abell et al. [200] and Abell et al. [68] introduced explicit modeling of their sources to consider the modeling uncertainty in the NLSSI analysis of NPPs. Hiraki et al. [78] proposed and illustrated the usability of an advanced lattice model in case of an embedded NPP building. Tinic et al. [130] recommended a novel methodology to incorporate the variability in the SSI modeling factors. However, all these suggested methods need to be verified in different SSI conditions in order to prove their accuracy and analytical efficiency.

7. Conclusion

Impacts of SSI consist of several distinctive mechanisms that may influence the performance of the system (structure, foundation and soil) that need to be considered in the design of critical safety-related systems like NPPs under earthquakes. The aim of this paper is to support the implementation of SSI analysis for NPPs by proposing a review on the state-of-the-art research in SSI analysis. Over the past 24 years, SSI has become an inevitable part of the seismic design and performance evaluation of NPP structures. With the increasing computational ability, FEM analysis has been demonstrated to be a reliable, efficacious, and pragmatic method in the site-specific SSI analysis of NPPs. The survey results presented by contemporary researchers was important to derive several considerations.

- Soil exhibits nonlinear behavior under seismic loading and the nonlinear impacts of structure, soil, and contact interface are site- and case-specific. In order to attain a realistic seismic response, nonlinearity should be considered in SSI analysis.
- Though newer SSI analysis techniques proposed by researchers manifest promising results, their applicability in different scenarios must be validated before adoption.
- Experimental approaches represent the approximate response pattern that is necessary for developing a reliable numerical model of NPP structures. Experimental data should be incorporated into the SSI problems for the verification and validation of results from numerical analysis.
- Although ELFD is extensively utilized for the SSI analysis of NPP structures, NLTD analysis illustrates a much more realistic behavior of the structure under earthquake loading. Moreover, nonlinear behavior cannot be properly captured in equivalent linear method. So, it is suggested to use the NLTD method instead of equivalent linear analysis methods for seismic strengthening of NPPs.
- Structural response of NPPs during earthquake events varies depending on the various soil parameters like Vs, G, and ζ of different soils. These soil data must be obtained from necessary field tests and incorporated into the numerical model.
- Material and geometric nonlinearities have a profound impact on the calculations of risk and potential losses of NPP structures. The effects induced by these phenomena should be properly considered.
- Considering the complexity and variability of SSSI effects on NPP structures, it is crucial for engineers to refine their modeling techniques to accurately evaluate these interactions, as they can considerably influence seismic behavior based on the characteristics of the structures and the site.
- For piled NPP structures, nonlinear SSI analysis of NPPs with CPRF should be conducted for the safety evaluation of these structures despite the complex analysis process.
- Based on the analysis type, the boundary condition should be modeled precisely. The espousal of wrong boundary conditions leads to erroneous and impractical results.
- Substructure technique is extensively utilized in the nuclear industry which is attributable to the reduced complexity and increased computational efficiency but its ineptitude to incorporate

nonlinearity is a red flag. However, the direct method is capable of exhibiting more realistic nonlinear effects but computationally inefficient. Moreover, there are several differences in the linear, equivalent linear and nonlinear analysis techniques and their effects vary depending on the system configuration. So, in order to get realistic responses from the numerical SSI analyses, a trade-off between accuracy and computational cost needs to be considered in the most efficient way.
- Finally, SSI effects cannot be generalized due to the contribution of numerous factors and correlations among them. The effects that deemed beneficial in one SSI system may be unfavorable in another system arrangement, therefore, it is suggested that engineers should consider as many factors as possible to properly incorporate SSI effects in the seismic design of NPPs.

In short, consideration of the impacts of SSI influences the structural behavior significantly. Since SSI may severely affect the seismic performance of critical infrastructures like NPPs, structural engineers need to incorporate additional precautionary factors in the seismic design and hazard evaluation of such critical infrastructures.

8. Future study scopes

Although significant improvements in the seismic SSI analysis of NPP structures have been made to date, there are still areas that are either left unfocused or have not been rigorously investigated yet. Future studies should put emphasis on analysis techniques that can poise between the accuracy and computational effort in the most efficient way. Some of the promising research topics include the consideration of the groundwater table in the soil media, and consideration of the combined effect of multi-hazard scenarios such as; tsunami and earthquake analysis, earthquake and fire analysis etc. Apart from these scenarios, the application of machine learning techniques in the seismic SSI investigation of NPPs should be rigorously probed. The usage of machine learning approaches might facilitate researchers in validating their numerical models more precisely to perform realistic parametric studies and also perform seismic hazard analysis considering different soil types and earthquake characteristics with minimal computational effort.

CRediT authorship contribution statement

Md. Rajibul Islam: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Sudeep Das Turja:** Writing – review & editing, Visualization, Software. **Dong Van Nguyen:** Writing – review & editing, Supervision, Methodology. **Davide Forcellini:** Writing – review & editing, Supervision. **Dookie Kim:** Writing – review & editing, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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