Chapter 17
A State of Art: Seismic Soil–Structure Interaction for Nuclear Power Plants

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17.1 Introduction

Safety of lifelines structures when subjected to strong excitation is utmost important as their failure may lead to disasters. Soil–structure interaction (SSI) is a design issue which cannot be neglected for the structures founded on the soft or loose soils and subjected to the strong ground motion. Failures of many structures occurred during the 1994 Northridge, California, the 1995 Kobe, Japan, the 2001 Bhuj and 2011 Fukushima, Japan earthquakes due to SSI or a related issue. The safety of nuclear power plants (NPPs) is very important during earthquakes as the failure of these structures may cause disaster.

Due to the strong ground motion shaking, the nonlinearity of soil plays a big role and further if loose sand, it may be subjected to liquefaction. The seismic loading on foundation is resisted by the foundation–structure interaction, thus, the response depends on the dynamic properties of soil, foundation material, rigidity of the structure, type of loading, etc. Numerical modeling is a feasible solution to deal with this problem which is normally carried out using finite element method. However, soil–structure interaction plays a big role in such analyses and design.

In this paper, a state of art on soil–structure interaction during earthquakes for nuclear power plants is presented. A critical review on the available literature is made and key issues are discussed. The background literature also includes those published by first author and his research group at IIT Roorkee. Recent advances in SSI for NPPs have been discussed.

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17.2 Background of Study

There are several examples (Seed et al. 1989, 1992), which have clearly proved that buildings, bridges, dams, NPPs, offshore structures, pile foundations have been damaged in previous earthquakes due to unawareness of soil–structure interaction. The role of SSI was significant on the failure of Hanshin Expressway in 1995 Kobe Earthquake, Hanshin expressway having length of 630 m was collapsed and overturned (Maheshwari 2014). During 2001 Bhuj earthquake, the pier cap of a bridge was damaged due to SSI ignorance. During recent 2011 Fukushima, Japan earthquake, there was failure to nuclear power plants (NPPs) which were shut down. From these and other examples on damages in past earthquakes, a need to rationally incorporate soil–structure interaction in the design of structures was realized. Though research on SSI is in quite advanced stage, however, the importance of simplified analysis is not yet diminished as demonstrated by (Maheshwari 1997; Maheshwari and Watanabe 2006, 2009).

Seismic soil–structure interaction is very important for NPP like massive structures as compared to the building structures. Several researchers studied the numerical method for the soil-structure interaction problem (Spyrakos and Beskos 1986; Gazetas 1991; Wolf 1991; Kumar et al. 2015). The effects of SSI could be neglected at the hard rock condition having the average shear wave velocity greater than 1500 m/s (ASCE 2017). By considering the effect of soil–structure interaction, overall deformation demand of the structure may increase with the spectral displacement demand (Kwon and Einashai 2006). When the structure is embedded in a weak soil stratum, to reduce the structural deformation, the pile foundations are adopted to transfer the load from the structure to soil (Chore et al. 2012; Conte et al. 2013). In most of the earlier studies of SSI, a linear spring–dashpot model based on the rigid foundation on the half rigid space or 2D finite element method (plain strain) was considered (Firoj and Maheshwari 2018).

For the modeling of the unbounded soil domain, different boundary conditions are proposed by several researchers. In the direct method of SSI analysis, some of these boundaries are perfectly matched layers (Berenger 1994) and frequency-dependent Kelvin elements (Maheshwari 2003; Maheshwari et al. 2005; Maheshwari and Sarkar 2011; Sarkar and Maheshwari 2012a). In the substructure method of analysis, boundary used is consistent infinitesimal finite element cell method (Emani and Maheshwari 2009) and coupled FEM-SBFEM (Syed and Maheshwari 2014) for 3D SSI in time domain.

Wolf et al. (1981) studied the vertical and horizontal wave propagation seismic effect on pile of NPP structure. Wolf et al. (1983) studied the effect of horizontally propagating wave on the NPP structure resting on the very large basement of hard rock. Kumar (2013) studied the effect of embedment of NPP structure in the soil with three boundary conditions, i.e., elementary boundary, viscous boundary and Kelvin elements. Varma et al. (2015) studied the linear and nonlinear soil–structure interaction effect on the Fukushima Daichii nuclear power plant. They evaluate the source of nonlinearity and consider the gapping and sliding. Other nonlinear parameters were ignored for the simplicity. Kumar et al. (2015) studied the nonlinear soil–structure interaction behavior of NPP structure by applying the bidirectional ground motion. Wang et al. (2017) studied the NPP building of finite element model with transmitting boundary and subjected to vertically incident seismic forces. They consider the effect of dimension of soil domain and types of artificial boundary. They also investigate the 10 MW (HTR-10) reactor building to compare the floor response spectrum with the fixed base reactor building (Firoj and Maheshwari 2018).

17.3 Objectives, Approach and Effects of SSI

For dynamic soil–structure interaction, there are various issues which need to be incorporated accurately. These are listed as follows:

(a) Modeling of truncated soil mass so as to absorb the reflecting wave.
(b) For dynamic loading, the frequency of excitation affects the soil behavior, therefore it needs to be taken care. The analysis shall be performed in such a way that the effect of interaction forces between foundation sub-system and structure sub-system is fully accounted.
(c) Material nonlinearity of soil using advanced constitute model.
(d) Liquefaction modeling in SSI problem.

For SSI analyses, various approaches can be grouped in three categories:

(i) Continuum models: Correctly represent the geometrical damping as well as inertia effects. However, soil is assumed elastic, therefore, nonlinearity cannot be considered.
(ii) Discrete models: Lumped mass, spring and dashpot models. Geometrical damping is difficult to consider but nonlinearity can be considered.
(iii) Finite element method: Overcome the limitation of the above two models. However, the computation cost is high.

In this paper, both simplified and rigorous models to deal with SSI are considered. Soil is a semi-infinite half-space, and a major problem in dynamic SSI is the modeling of the boundary condition of truncated soil mass. The fundamental objective of the SSI analysis is that dynamic response of both the structure and soil is to be calculated, taking into the effect of material damping and radiation damping (Wolf 1985). The presence of soil will modify the control motion leading to free-field motion (FFM). Effect of foundation (neglecting its inertia) leads to kinematic interaction and resulting motion is different than FFM. Finally considering inertia of the superstructure will lead to inertial effects (Maheshwari 2014).

The stepwise procedure for performing the SSI includes control motion, free-field motion, kinematic interaction and inertial interaction. SSI effect will increase with the increase in flexibility of soil and stiffness of the structure.

The American seismic code for nuclear structures (ASCE 4–1998) indicates that fixed base conditions can be assumed to apply when $V_s > 1100$ m/s. This condition is generally satisfied in weak rocks. Dowrick (1987) indicated that the fixed base conditions can be assumed for structures when $V_s > 20\ fh$, where h and f are the height and fundamental fixed-based frequency of the structure, respectively.

17.4 Geological Background of Nuclear Power Plants in India

The first series of power reactors in India were constructed at Tarapur and in Rajasthan. The Tarapur reactor is on a basaltic formation while the Rajasthan one is on the quartzitic sandstone. The raft foundations were provided under the reactor buildings. Settlement of the foundation was not considered if resting on the rock. The Kudankulam NPP structure site at Kalpakkam in Tamil Nadu has about 8 m of sandy soils overlying rocky strata. Being on the sea coast, the ground table is also at reasonably high level at all the time. Lightly loaded structures were supported on soil on spread footings while the heavy structures were supported on the raft resting on the competent rock. The turbine and service building were supported on the bored piles. At the Kakrapar site, the basaltic rock is encountered.

The situation of Narora Atomic Power plant is challenging as it is founded on 'very poor ground' condition in a region of high seismic zone. Settlement under the static and dynamic loads was considered in the choice of the type of foundation. An examination of the liquefaction potential of soil was also carried out in view of the high seismic condition, a fairly high water table and cohesionless deposits. Some of the upcoming NPPs in India (e.g., in Gorakhpur village in Haryana) will be founded on soft or alluvium soils making SSI analysis necessary.

17.5 Review of Numerical Modeling of NPPs

As very few experimental data are available on the soil-structure interaction problem for the nuclear power plants, many researchers worked for numerical modeling of NPPs, some of these are briefly discussed here.

Wolf et al. (1981) studied the NPP structure at Angra dos Reis in Brazil (supported on pile foundation). One quarter of the foundation was considered for the analysis due to the symmetry. The pile was modeled as beam element and surrounding soil is modeled with the springs as Winkler-type foundation. The stiffness of spring along the pile length was distributed as per the dynamic shear modulus of the soil layer. The superstructure was modeled as lumped mass. It was found that the response spectrum at the top of the layer was amplified by 5 times in horizontal seismic motion while 3 times in vertical seismic motion. They studied the shear force, bending moment and axial force along the pile length and found inertial interaction forces were predominant as compared to the kinematic interaction. Further, it was reported by Wolf et al. (1981) that the dynamic stiffness of the group pile cannot be determined by a single group pile. For the vertical earthquake motion, it was found that boundary pile exhibits the more axial force (approximately 1.5 times) as compared to the central pile while the distribution of horizontal displacement, bending moment and shear force along the length of pile was hardly effected by the location of pile.

Xu and Samaddar (2009) studied the effects of SSI and incoherency on seismic response analyses of NPP structures. The SSI model includes the superstructure, represented by lumped mass and beams and foundation, represented by brick elements, same as Wolf et al. (1981). For this, software SASSI (2010) was used for the study considering a surface-founded structure.

Maheshwari (2011) reviewed the advances for soil–pile interaction with reference to nuclear structures. The effect of embedment of foundation into the soil of NPP structure considering the effect of the slip and separation is studied by Saxena and Paul (2012).

Kumar (2013) studied the dynamic behavior of NPP structure in 2D coordinate system assuming behavior of soil as linear as well as nonlinear. The elastic properties of soil were considered for the linear behavior while the nonlinear behavior is modeled using most commonly used constitutive Mohr–coulomb model. Author used three types of boundaries for the unbounded soil domain, i.e., elementary, viscous and Kelvin element boundaries. The structure was modeled using the shell element in ABAQUS (2011). It was reported that the response of the NPP structure is increased by 67% when the rock was replaced by the soil at the base of the structure. The effect of soil–structure interaction was decreased by a margin of 45% when the nonlinearity of the soil is considered. The peak acceleration at the top of the structure was found more in case of elementary boundary condition as compared to viscous and Kelvin element boundary condition.

Desai and Choudhury (2015) studied the site-specific analysis of the nuclear power plants and ports in Mumbai at the four locations, i.e., JNPT, Mumbai Port, BARC and TAPS. Compatible site-specific input acceleration time histories were developed from a wavelet-based target spectra matching technique.

Varma et al. (2015) considered solid element for the modeling of SSI for NPP. The boundary used at soil domain was transmitting boundary in LS-DYNA. To simulate the free-field condition, first seismic motion was applied at the base of the soil at the selected node without considering the structure effect. Then, the resulted motion is applied at the base of the structure to consider the SSI effect on the structure. A comparison of the linear and nonlinear soil–structure interaction was made using same soil domain, boundary condition, structure and loading condition. It was observed that the maximum acceleration in the model in which the structure was surrounded by the nonlinear soil is reduced up to 49.8% due to nonlinearity.

Kumar et al. (2015) studied the Kudankulam NPP structure (supported on raft foundation) located at north of Kanyakumari in the Tamil Nadu state. The structure was modeled using the 4-nodded quadrilateral shell element having 6-degree-of-freedom system at each node. The modeling of base slab and raft foundation was carried out using shell element. The nonlinearity of the soil is considered by modeling the soil–foundation interface using the spring–dashpot at the bottom and vertical side of the raft foundation. It was reported that the fundamental period of vibration was increased by 10.4% considering SSI effect on the structure while the base shear in longitudinal and lateral direction was reduced by 21.7 and 24%, respectively.

The seismically induced uplift effects on nuclear power plants were studied by Sextos et al. (2017). It was concluded that in the presence of soft soil formations, nonlinear soil-foundation–structure interaction and associated geometric effects are possible. Wang et al. (2017) also carried out analysis for seismic SSI for NPPs.

A simplified soil–structure interaction model of embedded foundation is developed by many researchers (Wolf 1985; Gazetas 1991; AERB 2005). All these approaches assume that the soil is an elastic semi-infinite medium. The effect of soil is represented by dashpots, effective masses and lumped springs, and foundation is assumed massless and rigid. The values of soil spring static stiffness coefficients for a rigid plate on a semi-infinite homogeneous elastic half-space as per Gazetas (1991) and AERB (2005) are given in Table 17.1.

Where G, ρ, v are shear modulus, density, Poisson's ratio; A_b—Area of base, B, L and R—half-width, half-length of the circumscribed rectangle and radius of circular basement; I_{bx}, I_{by} and I_{bz} are the moment of inertia about x-direction, y-direction and z-direction, respectively.

After the FE analysis of model, it was concluded by many researchers that there is no significant effect on the results of refinement of mesh after a certain limit. Researchers suggested the boundary should be approximately at a distance more than 3 times the length and width of the structure used for the earthquake excitation. The limitation of FE model was not considering wider range of earthquake excitation such as high PGA. In case of smaller dimension (viscous boundary) of the

Table 17.1 Stiffness for a rigid plate on a semi-infinite homogeneous elastic half-space

Force system	Static stiffness, Gazetas (1991)	Spring constant for circular base, AERB (2005)
Vertical (z)	$K_z = \frac{2GL}{1-\upsilon}\left(0.73 + 1.54\left(\frac{A_b}{4L^2}\right)^{0.75}\right)$	$K_z = \frac{4GR}{(1-v)}$
Horizontal (y) lateral	$K_y = \frac{2GL}{1-\upsilon}\left(2.00 + 2.50\left(\frac{A_b}{4L^2}\right)^{0.85}\right)$	–
Horizontal (x) longitudinal	$K_x = K_y - \frac{0.2GL}{0.75-\upsilon}\left(1 - \frac{B}{L}\right)$	$K_x = \frac{32(1-v)GR}{7-8v}$
Rocking (r_x) about x-axis	$K_{rx} = \frac{GI_{bx}^{0.75}}{1-\upsilon}\left(\frac{L}{B}\right)^{0.25}\left(2.4 + 05\frac{B}{L}\right)$	$K_{rx} = \frac{8GR^3}{3(1-v)}$
Rocking (r_y) about y-axis	$K_{ry} = \frac{3GI_{bx}^{0.75}}{1-\upsilon}\left(\frac{L}{B}\right)^{0.15}$	$K_{ry} = \frac{8GR^3}{3(1-v)}$
Torsion	$K_t = 3.5GI_{bz}^{0.75}\left(\frac{B}{L}\right)^{0.4}\left(\frac{I_{bz}}{B^4}\right)^{0.2}$	$K_t = \frac{16GR^3}{3}$

soil domain, the peak value of acceleration is about 52% less than the larger dimension (free boundary) of the soil domain. If the dimension of the soil domain (viscous boundary) is increased up to a certain level, then this model shows no difference in peak value as compared to extended free boundary model, Firoj and Maheshwari (2018).

17.6 Recent Advances in SSI

In the last three decades, there has been significant progress in SSI studies. With the advancement in computer technology, it is now possible to model and analyze large SSI problems such as NPPs and dams more rigorously. Most of these advancement are made on the two important issues. First, accurate modeling of the unbounded soil is a complex issue. Second, the soil behavior is highly nonlinear during the strong ground motion shaking and in saturated loose sand there may be a chance of liquefaction. The numerical modeling of these two issues further complicates the SSI problem. Recent studies have been carried out or going on these SSI problem. The first author and his Ph.D. students (Emani, Sarkar, Syed and Firoj) worked broadly in the area of SSI.

Maheshwari (2003) used Kelvin elements (combination of spring and dashpot) at the boundary of unbounded soil domain and HiSS soil model for the nonlinearity of soil. Emani (2008) carried out nonlinear dynamic SSI analysis using CIFECM for boundary and hybrid methods for computation. Sarkar (2009) considered liquefaction for SSI analysis. Syed (2014) used scaled boundary finite element method (SBFEM) to model the boundary for nonlinear seismic SSI. Firoj (2018) is working to study nonlinear SSI for NPPs. A number of research publications from these works are listed in references and further discussed in following sections.

17.6.1 Modeling of Boundary

There are many ways to model the unbounded soil domain which can be grouped into following two categories.

Approximate Boundaries. The approximate boundaries are limited in space and time. Besides modeling the soil's stiffness up to infinity, reflection of upcoming wave to the boundary is to be avoided. Elementary boundaries are usually applicable in static analysis in which stresses and displacement are considered zero at the boundaries of the calculation domain (Ghosh and Wilson 1969). Local boundaries or viscous boundary (Lysmer and Kuhlemeyer 1969) are used to prevent the back-propagation of waves into a calculating domain. Kelvin element boundary absorbs the outgoing waves and prevents them to reflect back to structure. In this boundary, outer node is attached with spring–dashpot, and this boundary is used by Maheshwari et al. (2005).

Liao and Wong (1984) proposed transmitting boundary for the numerical simulation elastic wave propagation. This boundary is applicable to 3D linear SSI problem with a time-stepping algorithm and convex artificial boundary. The accuracy of this boundary can be improved by decreasing the length of time steps. For higher transmitting orders, a local transmitting boundary was presented in a compact form, which can be directly incorporated into finite element analysis (Liao and Liu 1992). In addition, the deviation problem on high-order transmission has been removed.

Bettess (1977) gives the infinite element approach to incorporate the shape functions analogues to Lagrange polynomial including the exponential decay term. This infinite element can be used in both explicit and implicit analyses. Some researchers used to couple the finite element with the infinite element to solve the SSI problems (Godbole et al. 1990; Noorzaei 1991), subjected to static loading. Wolf and Song (1996) combine the advantage of doubly asymptotic and multidirectional formulation, and it is highly accurate for plane wave at the intermediate frequency. Even with these approximate boundary conditions, accurate result can be obtained if the soil domain size is selected large enough. But, these boundaries may lead to inaccurate results for the inclined waves. Wolf (1994) described various formulations for modeling the foundation vibrations using simple physical models.

Rigorous Boundaries. The rigorous boundaries are global in space and time. These boundaries can simulate the far field effect, and therefore the unbounded soil domain is chosen such that the near-field effects are just-enclosed. In the frequency domain, the rigorous boundaries or consistent boundaries are formulated in the form of dynamic stiffness matrices.

Boundary Element Methods: In the early stage of SSI, rigorous boundary element method is extensively used by the various researcher (Brebbia et al. 1984; Beskos 1987; Banerjee 1994). The two main advantages of BEM, namely the reduction of soil domain size and high accuracy of the method, are more pronounced in linear electrodynamic, especially when the domain is semi-infinite. Domain type of BEM, such as FEM and FDM, requires the discretization of surface and interior of domain.

Consistent Boundaries: The consistent boundaries, also called thin layer method (Lysmer and Wass 1972; Waas 1972; Kausel and Roesset 1975; Kausel et al. 1975), are developed for the analysis of footing on the layered soil mass. This limit uses precise displacement functions in the horizontal direction that satisfy the radiation conditions and are an extension in the vertical direction used for the finite element method. This consistent boundary is based on finite element techniques and thus does not need a separate fundamental explanation. This method is well suitable to analyze the horizontal layers with varying material properties in the vertical direction.

Consistent Infinitesimal Finite Element Cell Method (CIFECM): As an alternative to the BEM, which applies analytic solutions to incorporate radiation damping, Emani and Maheshwari (2009) used the CIFECM boundary (Fig. 17.1) for the SSI problem and its application in pile foundation.

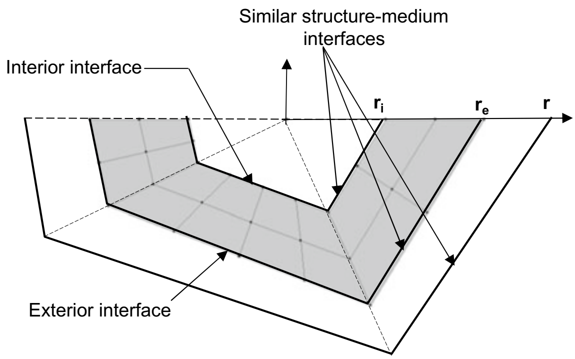

Fig. 17.1 Concept of CIFECM

Scaled Boundary Finite Element Method (SBFEM): This is an advanced version of CIFECM where spatial dimension at boundary is reduced by one, i.e., for a 3D problem only 2D boundary is required. This was used by Syed (2014) for nonlinear SSI as discussed later.

17.6.2 Nonlinearity of Soil

To analyze a nonlinear soil–pile interaction system in time domain, Matlock et al. (1978) have developed a unit load transfer curve also known as p-y curves. Various methods have been adopted to model the soil system in 1D such as Winkler models (Nogami and Konagai 1986, 1988; Nogami et al. 1992; Badoni and Makris 1996; El Naggar and Novak 1995, 1996), time-domain methods which are based on FEM formulations (Mylonakis and Gazetas 1999; Bentley and El Naggar 2000; Cai et al. 2000; Maheshwari et al. 2004a, b, 2005). However, in these methods, frequency dependence modeling of unbounded soil provided only approximate results, particularly in case of transient loading such as seismic loads. Nevertheless, the boundary conditions (local and transmitting) employed in these methods are not able to simulate the radiation boundary effects in case of oblique incidence of stress waves. However, these disadvantages of above methods can be improved using coupled finite element-boundary element (FE-BE) formulations.

Analytical analysis of linear and most equivalent linear systems using boundary integral methods (BIM) (Tajimi 1969; Kaynia and Kausel 1982; Mamoon et al. 1988; Fan et al. 1991; Miura et al. 1994; Maheshwari and Watanabe 2005) limited to steady-state response. To analyze a dynamic pile–soil interaction (DPSI), direct and transformed time-domain models have been proposed by Mamoon and Banerjee (1992). Cheung et al. (1995) have used boundary element method (BEM) in their model to evaluate the response of a single pile for horizontal excitation. Feng et al. (2003) employed time-domain BEM to evaluate the dynamic response of cylinder embedded in soil frictional slip at the interface. To capture the realistic nonlinear (3D inelastic) dynamic response of the frequency dependence of the numerical domain is to be accounted for, while considering the temporal and 3D spatial variations of numerical domain's response. To incorporate these requirements, coupled time–frequency domain and FE-BE coupling are employed. The authors have shown the advantages of FE-BE coupled model to evaluate the elastic (Emani and Maheshwari 2009) and cyclic nonlinear behaviors (Emani and Maheshwari 2008) of the 3D soil–pile systems.

Emani (2008) proposed and demonstrated a hybrid framework of analysis. This method is based on the hybrid frequency–time-domain (HFTD) formulation described by Wolf (1988). To satisfy the radiation conditions, the CIFECM (Wolf and Song 1996) is used and to account for material nonlinearity of soil, HISS model (Desai 2001) is employed (Maheshwari and Emani 2015).

Syed (2014) employed SBFEM to deal with boundary and used HiSS soil model for nonlinearity. Syed and Maheshwari (2017) and Maheshwari and Syed (2016) reported use of coupled FEM-SBFEM for nonlinear SSI for a soil–pile system. Syed and Maheshwari (2014, 2015) demonstrated the coupling and improvement in computational efficiency while using coupled FEM-SBFEM for nonlinear SSI analysis.

Firoj (2018) with nonlinear SSI for NPPs is reported by Firoj and Maheshwari (2018). The work is being extended for combined pile-raft foundation (CPRF) for NPPs as reported by Firoj and Maheshwari (2020).

17.6.3 SSI in Liquefiable Soil

Iida (1998) has used hypothetical Guerrero earthquake to analyze a 3D nonlinear soil–building interaction for various types of low to high-rise buildings and local sites effects are also incorporated. The results seem consistent with damage pattern observed in the Michoacan earthquake (1985). Wilson (1998) has evaluated the dynamic response of pile foundation in liquefying sand and soft clay for strong shaking in his doctoral thesis. Finn and Fujita (2002) reported the analysis and design result for pile foundations in liquefiable soils. Liyanapathirana and Poulos (2004) evaluated the effect of earthquake loading on liquefaction potential of soil deposits.

Liyanapathirana and Poulos (2005) have analyzed a piled system on Winkler foundation on liquefying soil with dynamically loaded beam. With the aid of Seed et al. (1976), Maheshwari et al. (2008) have reported response of pile foundation system for vertical loading with the effect of liquefaction phenomena. To evaluate the liquefaction potential of soil, Li et al. (2006) have performed shaking tests on the soil–pile–structure system. The experimental results compared with analytical solutions with equivalent linear soil model.

A five-story building that has tilted northeastward due to serious pile damage during the 1995 Kobe earthquake was studied by Uzuoka et al. (2007). Three-dimensional study was performed with elastoplastic soil medium. Soil–water coupled analysis was performed for soil–pile–building model. Sarkar (2009) investigated the three-dimensional soil–pile behavior under dynamic condition for the soil with liquefaction. The readers are referred to Maheshwari and Sarkar (2011, 2012), Sarkar and Maheshwari (2012a; b), Syed (2014), Syed and Maheshwari (2014, 2015), Maheshwari and Emani (2015), Maheshwari and Syed (2015).

17.7 Software Package for NPP Modeling

There is various software available for the finite element modeling of NPP structure on the soil.

17.7.1 SASSI

In many developed countries, System for Analysis of Soil-Structure Interaction (SASSI), a frequency-dependent program, is used to solve the 3D seismic SSI problem of NPPs. This enable the analyses of (a) wave propagation through the soil medium, (b) strain-dependent modulus reduction and damping property of soil and (c) input motion in free field using deconvolution procedure. Tabatabaie (2010) presents the recent development in the numerical modeling of NPP by considering the SSI effect using the SASSI (2010) program. The author presented the effect of foundation mesh refinement, effect of foundation embedment and effect of foundation flexibility.

17.7.2 LS-DYNA

LS-DYNA is a nonlinear dynamic analysis platform to solve the time-domain problem. LS-DYNA has a large number of martial library of soil (simulation of hysteretic behavior of soil), liquefaction soil model (pore pressure generation and loss of effective confining pressure) and geometrical nonlinearity (slip and separation). Various researcher (Wilford et al. 2010; Varma et al. 2015) used this software to deal with the SSI problem of NPP structures. Researcher concluded that the nonlinear soil–structure analysis has great effect on the seismic response of NPP structure.

17.7.3 ABAQUS

ABAQUS (2011) has the advantage over the LS-DYNA and SASSI in terms of efficient modeling of structural components (raft, piles and superstructure). Various researcher (Sextos et al. 2017; Firoj 2018) used this software for the modeling of NPP structure on CPRF and raft foundation. Researcher concluded that boundary condition, and geometrical and material nonlinearity has great effect on the seismic response of NPP structure.

17.8 Summary and Conclusions

A state of art on seismic soil–structure interaction for nuclear power plants is presented in this paper. It can be inferred that the soil–structure interaction is an important issue to be considered in the design of NPPs. Design may be unsafe if this effect is neglected. Some of the key conclusions are as follows.

1. The accurate modeling of boundary is very important for SSI during earthquakes. Both simplified and rigorous boundaries are available. Their application is case by case.
2. Interaction effects, e.g., soil–pile interaction (SPI) for a single pile and pile–soil–pile interaction (PSPI) for a pile group are must to be considered.
3. During seismic loading, the complex dynamic stiffness is frequency-dependent, and this characteristic needs to be modeled properly both in frequency and time domains.
4. During dynamic loading, the behavior of soil is nonlinear and this needs to be considered in the analysis.
5. For NPPs, recently combined pile-raft foundation (CPRF) is being used particularly for soft/alluvium soil conditions. The analysis of CPRF considering SSI is though complex but very important for safety of these structures.

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