International Journal of Engineering

Journal Homepage: www.ije.ir

Aspects of Foundation-soil Interaction of Nuclear Structures under Seismic Conditions through the State-of-art Review

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PAPER INFO

Paper history:
Received 21 March 2022
Received in revised form 14 April 2022
Accepted 24 April 2022

Keywords:
Combined Pile Raft Foundation
Failure
Fragility
Nuclear Power Plant
Seismic Resistance
Soil Structure Interaction

ABSTRACT

This state-of-the-art review study emphasized the problem of failure of Nuclear Power Plants (NPP) due to earthquake forces. Soil-NPP interaction may lead to damage to these unique structures of the critical infrastructural system of any nation in demand to fulfill the energy requirement. So, the soil-structure interaction (SSI) is the key motivating factor to review the fundamentals of NPP with its base soil conditions. Moreover, the problems associated with NPP-SSI have been overcome with the application of an advanced foundation system called combined pile raft foundation (CPRF). This study checks the scope of the provision of CPRF to NPP through SSI. The approaches for analyzing the seismic behavior of NPP in CPRF are strategically reviewed in this study. According to the literature findings, SSI is the most significant factor in deciding the seismic resistance of NPP. The fragility analysis demonstrated the importance of SSI in the design of NPP earthquake behavior. CPRF plays an important role in NPP-SSI to minimize structural damage.

doi: *10.5829/ije.2022.35.09c.06*

1. INTRODUCTION

The dam sector, chemical sector, nuclear reactors, materials, waste sector etc., are the parts of any countries critical infrastructures (CISs). They are the spine of the development of a nation, and nuclear power industry is one of them. Worldwide, the strenuous growth in the development of the power plants has been observed [1, 2]. Nevertheless, due to the inseparable logic of natural calamities or by chance, these systems are highly susceptible to risky conditions [3-5]. Earthquake is one of the calamities affecting all type of structure, and NPP is no exception. While designing the reactor building (a component of NPP), tremor and break loss of coolant accidents are considered external and internal events [6-8]. Earthquakes of magnitude higher than that of design criteria often occur in the nearby vicinity of NPPs. Jin and Gong [9] studied the Fukushima Daiichi NPP incident (11th March 2011) in great east Japan was one of the example. Due to this Earthquake, Fukushima NPP bore severe destruction [7]. As a result of this situation, significant efforts were being made in many sectors such as geophysics, structural engineering, and nuclear safety engineering to recognize and assess the danger. Various active and passive approaches have been invented to reduce the seismic impact on the structure. The conventional methods suggest strengthening the structural elements to improve the seismic resistance of the structure. The practical solution is to protect the NPPs by considering the fragility analysis with and without soil structure interaction and combined pile raft foundation (CPRF) of the structure [7, 10]. Fragility analysis as well as SSI should be taken under consideration as it is the governing criteria for the seismic behaviour of the structure. The following sections consist of a preface of past literature and methodology enlightening the fragility analysis, and importance of SSI and CPRF on the response of NPP in earthquake situation.

2. LITERATURE PREFACE

CPRF, a raft supported by piles, is used to achieve desired loading strength. It helps to meet the ability

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Please cite this article as: B. Thakur, A. Desai, Aspects of Foundation-soil Interaction of Nuclear Structures under Seismic Conditions through the State-of-art Review, ***International Journal of Engineering, Transactions C: Aspects***, Vol. 35, No. 09, (2022) 1716-1722

requirements in an effective pattern than the conventional pile group foundation [11]. The reaction of the isolated piles differs from the piles in the group because of the pile-to-pile interaction factor. The pile-to-pile interaction factor is defined as the ratio of an unloaded receiver pile's displacement or rotations to those of a nearby loaded source pile owing to soil deformation [12]. From the last two decades, CPRF has been proven as a feasible and sustainable foundation as it decreases the settlement of structure, leading to massive financial savings without compromising the capacity of the foundation. Its primary application was for massive facilities. Design and construction guidelines for a vertically loaded piled raft in a range of subsoil conditions have also been established by the International Society for Soil Mechanical and Geotechnical Engineering (ISSMGE) [13]. Although the substructure of the building may face loading from all the sides simultaneously [14], the design of CPRF does not conventionally consider the combination of horizontal (H) and vertical (V) forces and moment (M). Attention is required while designing the CPRF for the load transfer process between the piles and the rafts. As the multi-directional interaction affects the structural response, the soil-structure interaction (SSI) and soil non-linearity must be considered for the design of the facility [15, 16]. The SSI is the interactivity between soil (ground) and a facility erected on it.

The analysis process of the SSI approach is to be done in a deterministic manner. Inertial, kinematic, free-field, and control motion are all stages in the SSI method [17]. The direct and substructure approaches are two general methods of analysis for SSI. The direct method involves assessing the combined soil-structure interaction in one step without superposition [18, 19]. The direct technique solves the SSI problem in both the time and frequency domains. The linear or nonlinear time-history analysis can be used to apply the direct approach. Analysis of SSI by the direct method shall consist of (1) model of structure, (2) model of foundation: geometry, stiffness, and interface, (3) model the soil: a) soil material properties (linear and nonlinear) and b) discretize the soil and locate the bottom and lateral boundaries of the soil structure model, (4) establish input motion to be applied at the boundaries, (5) perform SSI analysis, and (6) perform a second stage analysis for detailed structural response [20]. The substructuring method directly invokes superposition to solve the SSI problem in the frequency domain. Fourier transform techniques applied to the input motion are used to treat time variations in earthquake ground motion. Only linear analysis can be used to implement the substructuring method [20].

SSI is the mechanism through which the soil reaction controls the structure's motion alongside the structure influences the response of the soil. The structural model's fundamental period is determined by building height and the SSI. Raheem et al. [21] conducted a theoretical study on multi-storied frames with varying soil characteristics beneath the foundation and several stories to demonstrate the impact of SSI on the frames' dynamic properties. The findings were compared to the fixed-base structures. The SSI effect will enhance as the structural stiffness and the soil flexibility increase [21]. The stiffness properties using formuli derived by Gazetas [22] and AERB [23] are described in Table 1. Where ρ, G, ϑ represent the density of soil, shear modulus and Poisson's ratio, respectively;

L, B, and R denotes the half-length, half-width and R is A_b is the radius of a circular basement, respectively; Area of the base, I_{bx}, I_{by} and I_{bz} are the moment of inertia about x, y and z-direction, respectively.

The CPRF effectively governs the settlements and significantly escalates the strength of the whole structure [16]. In analyzing the CPRF behaviour pattern, a fragility analysis is important. Fragility analysis describes the risk of a specific structure being exposed to a seismic excitation above a damage limit state. Zentner et al. [24] used two types of methods for the fragility analysis of the nuclear industry; the numerical simulation method and the safety factor method. John and Robert [25] developed the safety factor method to develop the element of fragility functions. The ground motion measurements of the design-basis earthquake, several safety factors, and each element's ups and downs have been combined in this safety method. It was utilized to calculate the component's standard deviation and median capacity, which were then included in the fragility functions. At the same time, the numerical simulation method includes regression modelling [26], highest probability estimation [27, 28], and incremental dynamic analysis (IDA) [29], which were also applied to the NPPs case studies [9, 30]. Methodologies for fragility analysis available for CPRF are given in the methodology section.

TABLE 1. Rigid plate stiffness on a semi-infinite homogeneous elastic half-space [18]

Direction	Static stiffness [22]	Spring constant for circular base [24]
Vertical (z)	$K_z = \frac{2GL}{1-\vartheta}\left(0.73 + 1.54\right)\left(A_b/4L^2\right)^{0.75}$	$K_z = \frac{4GR}{1-\vartheta}$
Horizontal (y) lateral	$K_y = \frac{2GL}{1-\vartheta}\left(2.00 + 2.50\right)\left(A_b/4L^2\right)^{0.85}$	-
Horizontal (x) longitudinal	$K_x = K_y \frac{2GL}{0.75-\vartheta}\left(1 - \frac{B}{L}\right)$	$K_z = \frac{32(1-\vartheta)4GR}{7-8\vartheta}$
Rocking (r_x) about the x-axis	$K_{rx} = \frac{GI_{bx}^{0.75}}{1-\vartheta}\left(\frac{L}{B}\right)^{0.25}\left(2.4 + 0.5\frac{B}{L}\right)$	$K_{rx} = \frac{8GR^3}{3(1-\vartheta)}$
Rocking (r_y) about the y-axis	$K_{ry} = \frac{3GI_{bx}^{0.75}}{1-\vartheta}\left(\frac{L}{B}\right)^{0.15}$	$K_{ry} = \frac{8GR^3}{3(1-\vartheta)}$
Torsion	$K_t = 3.5GI_{bx}^{0.75}\left(\frac{B}{L}\right)^{0.4}\left(\frac{I_{bz}}{B^4}\right)^{0.2}$	$K_t = \frac{16GR^3}{3}$

Because of the haphazardness and uncertainty of earthquakes, several studies have focused on the seismic response and fragility evaluation of solitary buildings in recent decades. Burland [31] firstly introduced the concept of CPRF with unserviceability. Various numerical [32-35] and analytical research [14, 36, 37] have been performed to have deep insights into the nature of CPRF. The authors presented different ways to address the impacts of non-homogeneity of CPRF on horizontal and vertical response of structure. Choudhury and Kumar [38] have examined CPRF under V-M-H condition in sandy soil using 3D finite element (FE) analysis and evidence the results of improved performance of the structure with the CPRF over the traditional group pile foundation during earthquake loading.

The horizontal load and moment capacities of a piled-raft are determined by a number of factors, including pile-soil relative stiffness, raft-soil relative stiffness, pile spacing to diameter ratio, and foundation and pile head connection with the raft length to width ratio [42]. V-M-H interaction is also considered while developing failure and design envelopes [39]. A hysteresis-based model was utilized to investigate the bi-directional correspondence and the interaction between the soil, pile raft, and structure. The hysteresis model can accurately simulate the deformation in two primary directions. One of the analysis methods, the Square Root Sum Square (SRSS) method, was used for elastic analysis; however, it could not identify the inelastic interaction between both directions. The biaxial model achieves higher accuracy without many complex calculations and has been used for both steel and concrete structures.

Conventionally, one-directional approaches [40] are adopted in analysis that considers the hypothesis of a fixed base; SSI is neglected since it requires complex computing efforts. But studies show that the reflectance of SSI can damage the whole structure. In the seismic SSI of NPP, Abell et al. [41] evaluated the differences in response to 3-D, 3×1-D, and 1-D excitations. Furthermore, as multiple experts have indicated, the interaction between the soil, the pile foundation, and the structure is crucial factor in determining the seismic response of pile-supported buildings in a variety of soil types [40]. Different design standards like NEHRP [42] and ASCE 4-16 [20] have taken into account the relevance of SSI. The detailed methodology for the same has been elaborated in the following section.

2. 1. Methodology Some of the methods that have been experimented with in the past decade are discussed here. Kumar and Chaudhary [43] divided the CPRF system's settlement into two components: settlement caused by load-carrying by the raft and load-carrying by the piles. For stiffness, Fleming [44] solely evaluated the interaction between pile and raft and computed settlement appropriately. Clancy and Randolph [45] studied the small piled raft system, which has a raft width of 5 to 15 meters and is smaller than the length of the pile, while the large piled raft system has a raft width that is greater than the length of the pile.

The design model of the pile-raft system represents the piles and soil as equivalent constant spring [46, 47]. The ratio of induced load in a pile to the corresponding settlement near the raft pile junction was used to quantify the pile stiffness. Integrating the vertical stress in the top elements of the piles over a pile area yielded the induced load in a pile. The rigidity of the central pile corresponds to the pile in the rafts center. The edge pile stiffness refers to a pile close to the rafts edge. Different interactions regulate the behaviour of the piled raft, including pile-to-pile, pile-to-soil, raft-to-pile, and raft-to-soil interactions [48, 49]. The pile-to-pile contact caused by an adjacent-loaded pile causes more settling in a pile.

Poulos [50] provided a technique for determining the settling of a pile in a pile group by superimposing the additional settlement caused by each pile using the pile-to-pile interaction factor. The interaction factor is influenced by several variables. According to the work of two earlier researchers, Poulos [50] and Lee [51], these parameters are pile spacing, pile stiffness relative to the soil, and pile length to diameter ratio. The pile-to-pile interaction factor depends upon the distance between the two piles. Compared to the edge pile, the central pile is surrounded by piles all around it; hence the interaction impact will be greater for the central piles. As a result, the middle pile has been less stiff than the edge piles.

2. 2. Analysis of CPRF Loading Condition Pseudo-static load is an equivalent static horizontal load on the foundation unit replaced by the seismically induced load. To get the pseudo-static load, Attar [52] multiplied the seismic coefficient by a vertical load. Mali and Singh [53] considered the initial stage and loading stage for the finite element. Patil et al. [16] approached the analysis of safety related to the NPP structures resting on CPRF, simulating soil-pile interactions using the substructure method under static and dynamic loading conditions. Liu et al. [54] considered dynamic loading with four different types. Initially, the load carried by the piles at a particular displacement level was considered as the weight experienced by the piles at their top node, which was assumed to have transmitted from the raft. This is an example of the raft–soil interface; the raft load was estimated by summing the stresses encountered at all nodes lying on the Pasternak medium, as shown in Figure 1.

2. 3. Pile Dimensions The length, diameter and spacing of piles play an important role in the behaviour of CPRF. Kumar et al. [55] considered the spacing to diameter ratios of 2, 4 and 6. Kumar and Choudhury [43] computed the dimension of the pile as 0.5 m diameter and 15m length with the help of numerical methodology. Bhaduri and Chaudhury [15] also considered the length

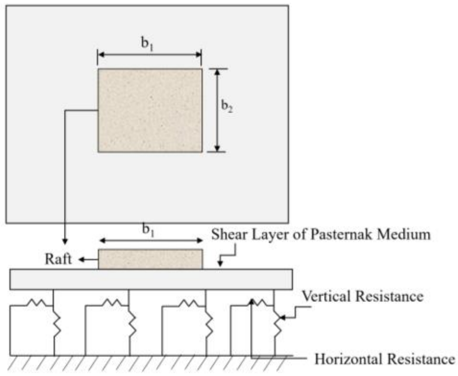

Figure 1. Raft on elastic medium with resistance at the bottom of the plate [15]

to diameter ratios to overcome vertical settlements of the pile. Mali and Singh [53] described the significant effect of the spacing up to 6m.

Unsever [34] and Bhaduri [15] reported how the pile raft elements share structure loading. From both the studies, it was noticed that the highest lateral shear would be borne by the raft initially, but as time permits, piles will resist the higher load. A systematic methodology must be adopted to analyze or simulate the seismic behaviour of the structure. Figure 2. shows the detailed methodology for the static analysis of CPRF.

3. DISCUSSIONS

The combined pile-raft foundation system has been identified as one of the most cost-effective and long-term foundations system for high-rise buildings, resulting in reduced settlements and provision of smaller piles than the pile group. The combined pile–raft foundation (CPRF) design concept may reduce the number, diameter of piles, and length used in a foundation structure. CPRFs are effective in lowering both average and differential settlement levels. The CPRF can be used for various types of soil. It should be designed according to the soil properties on which the construction is to be done. For that, soil-structure interaction is an important consideration. The SSI impact on the structure increased the fundamental period of vibration by 10.4% while reducing the base shear by 21.7 and 24% in longitudinal and lateral direction [56]. The hard rock foundation can neglect the influence of soil-structure interaction. However, for other soil types, it must not be neglected. For the purpose of determining the number of piles to be installed under the raft, the effect of the soil–pile–raft interaction factor is the most important aspect to be considered. When failure and design envelopes are established for each of the principal three (V-H-M) directions, it has been seen that piled-raft lateral capacity grows more as a result of combined loading than as a result of independent loading when combined and independent loading was considered.

The raft is critical in the distribution of the load, accounting for 23–31% of the total vertical load [58]. It shows the importance of the combined foundation compared to the traditional single raft of pile group foundation. The ISSMGE has developed design and construction guidelines for a vertically loaded pile raft for a variety of subsoil conditions. However, the traditional pile foundation design is still dominant in the engineering practice due to the guidelines and provisions

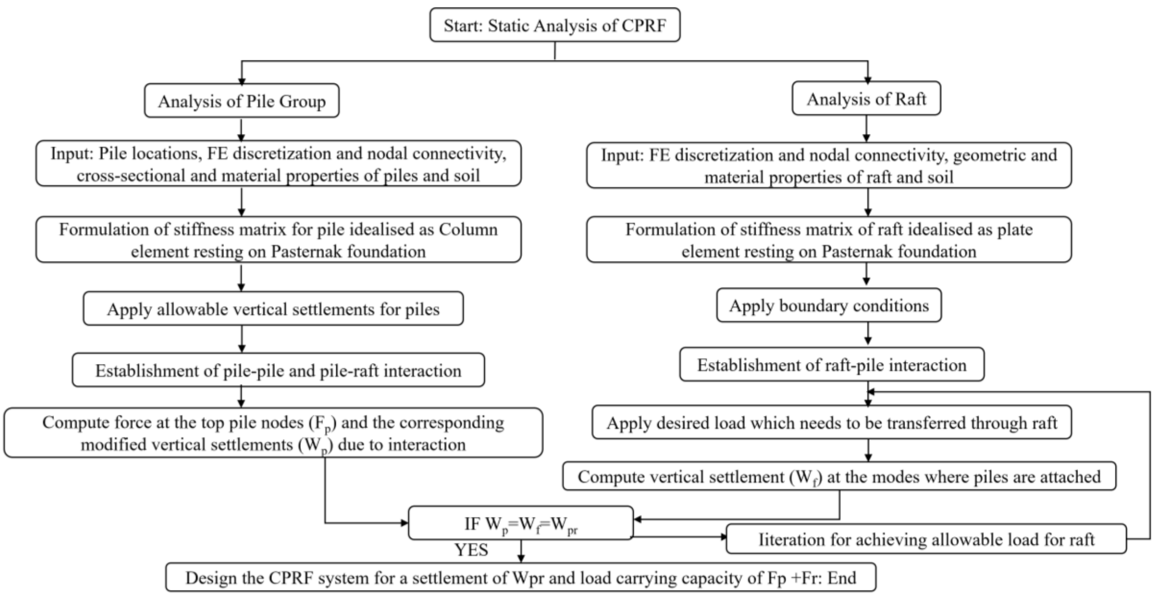

Figure 2. Methodology for static analysis of CPRF [15]

suggested by design codes. The reason may be due to the lack of confidence among the designers for incorporating load sharing advantage between rafts and piles to avoid conservatism through capacity-based design.

4. CONCLUSION

Nuclear energy is the only source to generate a tremendous amount of power with zero carbon footprints. NPP's do not emit the toxic gases that would be definitely generated if fossil fuels were used for power generation. It shows the importance of NPPs for any country. Nuclear reactors have the potential to release radioactive materials into the atmosphere and water that may be harmful to human health. Because of that, while designing and constructing, utmost care should be taken. Such structures are constructed considering the effects of an earthquake. This state-of-the-art review study emphasized the soil-structure interaction of nuclear power plant under the earthquake forces. The review study stated the following conclusions:

- The soil-structure interaction with its base soil conditions is the key factor to be included in the seismic design of NPP.
- The feasibility of an innovative foundation system called combined pile raft foundation (CPRF), which overcomes problems associated with NPP-SSI, is also checked.
- The approaches for analysis of the seismic behavior of NPP in CPRF are strategically reviewed in this study.
- According to the literature findings, compared to the findings obtained by fixed-base structure analysis, the inclusion of soil in the structural analysis yields results, stresses, and deformations that are closest to the real behavior of the structure.
- The fragility analysis demonstrated the importance of SSI in the design of NPP earthquake behavior. CPRF plays an important role in NPP-SSI to minimize structural damage.

5. ACKNOWLEDGEMENTS

The authors would like to acknowledge Department of Civil Engineering, Sardar Vallabhbhai National Institute of Technology, Surat, India for all kinds of support provided to facilitate this research.

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Persian Abstract

چکیده

این مطالعه مروری پیشرفته بر مشکل خرابی نیروگاه‌های هسته‌ای (NPP) در اثر نیروهای زلزله تأکید دارد. تعامل خاک و NPP ممکن است منجر به آسیب به این ساختارهای منحصر به فرد سیستم زیرساختی حیاتی هر کشوری شود که برای برآورده کردن نیاز انرژی مورد نیاز است. بنابراین، اندرکنش خاک-ساختار (SSI) عامل انگیزشی کلیدی برای بررسی اصول NPP با شرایط خاک پایه آن است. علاوه بر این، مشکلات مربوط به NPP-SSI با استفاده از یک سیستم فونداسیون پیشرفته به نام پایه رافت ترکیبی (CPRF) برطرف شده است. این مطالعه دامنه ارائه CPRF به NPP را از طریق SSI بررسی می کند. رویکردهای تجزیه و تحلیل رفتار لرزه ای NPP در CPRF به صورت استراتژیک در این مطالعه بررسی می شود. با توجه به یافته های ادبیات، SSI مهم ترین عامل در تصمیم گیری مقاومت لرزه ای NPP است. تجزیه و تحلیل شکنندگی اهمیت SSI را در طراحی رفتار زلزله NPP نشان داد. CPRF نقش مهمی در NPP-SSI برای به حداقل رساندن آسیب ساختاری ایفا می کند.