Soil Structure Interaction Considering Near-field Earthquake - A Review

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Abstract: Rapid infrastructural development has led to a scenario where massive structures are being built in seismically active regions with less favourable geotechnical conditions. This has also increased the risk of damage and failure of these structures due to earthquakes. During an earthquake, the structure's response doesn't solely rely on the structure itself, but also on the ground motion characteristics and conditions of the subsoil. Earthquake-induced near-field ground motions, can cause significant structural damage by exposing structures to high input energy. A better understanding and design implication of soil structure interaction (SSI) considering near-field earthquake is needed to make future construction more resilient. In this paper, a concise review of the effects of SSI considering near-field earthquake has been provided. Studies related to the basic concept, analytical and computational approaches for SSI and characteristics of near-field ground motion have been presented along with the current status of researches on the topic of interest. The paper also highlights the areas that in earlier studies did not receive much attention.

***Keywords* - Soil Structure Interaction (SSI), Near-field Earthquake, Seismic Analysis**

I. INTRODUCTION

The engineering structure's seismic response is influenced by the medium on which it is resting. In general, rocks have very high stiffness and when a structure is built upon rock bed, owing to the stiffness of rock the structure's response is quite similar to the response observed in free-field motion. If the same structure is built over a soft soil deposit, the response would be different. "The process, in which the response of the soil influences the motion of the structure and the response of the structure influences the motion of the soil, is referred to as Soil-Structure Interaction (SSI)" [1]. The impacts of this process become more crucial on rigid and heavy structures resting on soft soils. Therefore, this problem of SSI has become a significant aspect of Structural Engineering, with rise in heavy construction on soft soils like bridges, tunnels, nuclear power plants, high-rise buildings, dams etc.

Ground motions resulting from an earthquake reflect the seismic source characteristics, the rupture process, the travel path from the source to the site and local conditions. Therefore, the characteristics of ground motion near an active fault can differ substantially from those of the far-field [2]. The distance is not defined clearly for the classification of a site as near or far-field. Comparing the source dimension to the distance from site may be a helpful criterion for defining the near-field region [3].

Various studies considering SSI have already been conducted by researchers. Roesset and Kausel had [4, 5] reviewed various developments, contributions and controversies that arose in early stages of SSI, whereas, the field has been significantly contributed by Wolf [6, 7, 8] continually. Gazetas and Mylonakis [9] analysed and provided the field evidences to describe the detrimental effects of SSI. The efforts have also been made by various researchers [10, 11, 12, 13, 14] in order to consider the effects of near-field earthquakes on seismic performance of various structures. However, the effect of SSI considering near-field ground motions has attracted much less attention.

The aim of this paper is to present a concise review of the numerous researches based on various effects of SSI on structural responses considering near-field earthquake. The review is arranged in sections covering various important elements highlighting the concept of SSI, the available analytical and computational techniques for SSI modelling, characteristics and effects of near-field ground motion in order to develop a fundamental knowledge of the subject, along with the recent researches on the topic of interest. The paper also highlights the aspects which are needed to give more attention.

II. SOIL-STRUCTURE INTERACTION

Mass of the structure, stiffness and damping characteristics of soil and structure are the major factors that affect the process of SSI. The SSI comprises of two interactions, i.e. "Kinematic Interaction" and "Inertial Interaction" [15].

Kinematic Interaction. If a foundation on or embedded in the surface of a soil is not able to follow the pattern of free-field deformation due to its stiffness, its motion is governed by kinematic interaction, even if the foundation has no mass. It only happens where the foundation system's stiffness impedes the development of free-field motion. Different modes of vibration in a structure can also be induced by kinematic interaction. For structures with no embedment, excited by vertically propagating shear waves, kinematic interaction could be neglected.

Inertial Interaction. It is induced mainly by the inertia forces produced during vibration in the structure owing to the motion of the structure's masses. If the supporting soil is compliant, the forces transmitted to the soil by the foundation will produce movement of the foundation that would not occur in a fixed base structure. This could be significant for stiff and massive structures. Wolf [6] suggested that kinematic and inertial components are prevalent at low and high ground shaking levels respectively.

According to technical advancements, the SSI modelling approaches come down to the analytical approach, numerical or simulation approach, and experimental approach. The following is just an outline of SSI based on the above-mentioned approaches.

2.1 Analytical Approach

The various approaches to analytical model and solve the SSI problems are discussed in the section on the basis of previous researches.

Discrete and Continuum Modelling. A review has been provided by Dutta and Roy [16] on different soil-foundation-structure system modelling methods and also attempted to compare their ability to solve practical problems with desired accuracy. Based on the elements used at soil structure interface, these methods can be categorised as discrete and continuum. Springs and dashpots are used as interface elements in discrete modelling. The soil medium is depicted as a system of springs that are discrete, identical, closely spaced but mutually independent and linearly elastic. As per this idealisation, the deformation in foundation due to applied load is restricted to loaded regions only. Whereas, continuum modelling is a conceptual approach of physical representation of the infinite soil media. It can be done using boundary element or finite element method. For the sake of simplicity, soil is usually considered to be semi-infinite and isotropic in the continuum idealisation. But, from mathematical point of view, the idealization of a semi-infinite elastic continuum contributes to multiple complexities.

In order to account for the limitations of both the fundamental approaches, some modified modelling approaches were suggested. The set of improved versions of discrete model include “Winkler model”, “Filonenko-Borodich foundation”, “Hetenyi’s foundation”, “Pasternak foundation”, “Generalized foundation”, “Kerr foundation”, “Beam column analogy model” and “Continuous Winkler model”. Improved continuum modelling methods include “Vlasov foundation” and “Reissner foundation”. Kucukarslan et al. [17] analysed the soil pile structure interaction using a proposed hybrid continuum numerical model. In the study, linear finite elements were used to model piles and other structural components and boundary elements were used for modelling of soil half-space, and the proposed algorithm is verified from experimental results conducted under static loads. This model can account for nonlinear behaviour of soil and also able to predict the pile group behaviour and pattern of pile settlement.

Linear and Nonlinear Analyses. Approaches can be categorised as linear and nonlinear based on the nature of elements used to model SSI. In SSI, nonlinearities include geometrical and material nonlinearities in soil, foundation, and superstructure. Among soil and structure, the properties of one has been considered as linear and other as nonlinear in most researches. “Continuum models”, “Beam on Nonlinear Winkler Foundation (BNWF)” models and “Plasticity Based Macro-element (PBM) models” are three main methods to consider foundation and soil’s nonlinearity. BNWF models were integrated by Raychowdhury and Hutchinson [18] in “Open System for Earthquake Engineering Simulation (OpenSEES)”. Later, to incorporate flexibility and energy dissipation both using single interface element, Nova and Montrasio [19] have introduced PBM models. Another model has been launched by Gajan and Kutter [20] called “Contact Interface Model (CIM)” worthy of incorporating gap geometry to account for the nonlinearity due to gapping in soil and foundation. A comparison has also been provided by Gajan et al. [21], between BNWF and CIM models and discovered that performance of CIM is more appropriate in cases of coupled moment, shear and axial responses and both models almost perform in similar manner in the case where one of the modes is dominant. For nonlinear SSI, Lee [22] has suggested a numerical approach by contemplating various finite element techniques for near-field and far-field areas.

Frequency Domain and Time Domain Analyses. Available analytical methods of SSI can also be classified as frequency domain and time domain analysis methods, on the basis of their calculation domain. Kaustell et al. [23] conducted a qualitative dynamic SSI analysis of a portal frame railway bridge to comprehend the effect on structure’s response and its dynamic properties due to high-speed load model (HSLM) of Eurocode. The equations of motion were solved in frequency domain and the solutions in time domain were found out using Fast Fourier Transform (FFT). Solutions required in the frequency domain are presumed to be linear and thus may not be appropriate for inelastic structures. Therefore, in frequency domain, assessment of damage and residual strength could not be accomplished. Nonlinear SSI analysis can only be performed in time domain; therefore, these analysis demand extensive computational effort, and for that various numerical tools have been developed lately. An assessment of the linear frequency-domain code, “SASSI”, and the time-domain commercial finite-element code, “LS-DYNA” has been presented by Bolisetti et al. [24]. The assessment comprised linear and nonlinear analyses of realistic soil-foundation-structure systems exhibiting nonlinear behavior. The findings indicated that in the presence of nonlinear behavior such as gapping and foundation sliding, the results of frequency- and time-domain codes vary substantially in spite of using same material properties.

Further efforts have been made to develop a hybrid approach having benefits of both frequency and time domain solutions. These hybrid approaches are classified as: “Hybrid Frequency-Time Domain (HFTD)” solutions and “Hybrid Time-Frequency Domain (HTFD)” solutions. For the first time, HFTD method was introduced by Kawamoto [25] to solve problems of structural dynamics. In that method, the equation of motion is solved in the frequency domain whereas non-linear effects because of cyclic loading can be applied to the system by pseudo-forces in time domain. Whereas, in HTFD approach like Bernal and Youssef [26], equations of motion can be solved in time domain considering non-linearities and the unbounded medium can be idealised as frequency-independent springs and dampers. The frequency dependency of impedance coefficients is considered at each iteration through pseudo-forces in frequency domain.

Direct and Substructure Approaches. The above-mentioned approaches could also be further categorised as, direct and substructure approach, based on the treatment of interactions of sub-domains in a system. In SSI analysis by direct approach, complete soil-structure system can be modelled and analysed together in a single step. The ground motion is specified as free field motion and is applied at all boundaries. The coupled system’s response is utilised in second stage analysis to get the response of structure. Whereas, the system is divided into various parts and solved separately, in substructure approach. Ultimately, all solutions are superimposed to obtain the structure's response. The benefit of substructure approach is that it divides the complex problem into various smaller problems for which an efficient modelling technique can easily be chosen. It could also be very useful when a parametric study is being carried out. Also, in this method, discretisation of semi-infinite soil medium is not needed, which makes it computationally efficient and faster than direct method. In the case of substructure method, kinematic and inertial components are accounted for individually using transfer and impedance functions respectively, which is not the case with direct approach. The substructure method is generally carried out in frequency domain because of the dependency of transfer and impedance functions on frequency. Although the substructure approach is commonly used to analyse SSI problems, Rahmani et al. [27] recently questioned its accuracy, noting that this approach consistently overestimates the basic structural responses such as design forces, bending moments and displacements, due to which the main SSI mechanisms are not recorded accurately. For quite some time, the benefits and drawbacks of the direct and substructure approach have been the subject of controversy. The benefits, drawbacks and limitations of the two methods have also been highlighted by Roesset [4] recently in his studies.

2.2 Numerical Approach

This portion describes the numerical approaches used in SSI researches, concentrating onto the three prevalent methods used to solve a typical problem of SSI, i.e. "Finite Element Method (FEM)", "Finite Difference Method (FDM)" and "Boundary Element Method (BEM)".

FEM has a wide spectrum of applicability and it could be used to solve any kind of problem since its use is not restricted by the nature of problem. This makes FEM an indispensable tool for numerical analysis. Although FEM has proven to be an appropriately effective technique, it needs a lot of time and computational effort to solve complicated problems. Therefore, researchers have attempted to develop more reliable and computationally affordable methods for SSI analysis. Stevens and Krauthammer [28] suggested a combined Finite Difference/ Finite Element (FD/FE) approach for dynamic SSI analysis of buried structures subjected to stress transients generated by earthquakes or nuclear explosions etc. FDM is compatible for analysing wave propagation in nonlinear continuous media and subjected to large deformations. Whereas, FEM is very suitable to analyse the structure and its response in different conditions. However, it is worth noting that the traditional finite element formulation cannot be used to model an infinite medium.

Apart from the FEM and FDM, the boundary element method (BEM) has also been extensively used and found to be an excellent method for handling a large soil continuum with elements required only on the boundaries making it attractive to researchers [29]. Wolf and Darbre [30] developed different BEMs i.e. "weighted-residual technique", "indirect boundary-element method" and "direct boundary-element method" for embedded foundations. In the first two methods, a weighting function is used whereas, in the third method the surface traction along the soil-structure interface is interpolated. Among different formulations, the indirect BEM resulted in relatively accurate results [31]. In addition, it also ensures the symmetry of soil's dynamic stiffness matrix and reduce computational effort for calculation of displacements due to applied loads. For finding the solution of governing differential equations of different SSI problems such as DSSI of nearby pile supported structures, Padron et. al [32] has used BEM in combination with FEM.

Chuhan et al. [33] presented a coupling model of finite element (FE)–boundary element (BE)–infinite element (IE)–infinite boundary elements (IBE). In this model, FE-IE coupling takes into account the radiation effects of infinite layered soil, whereas BE-IBE coupling discretise the underlying bed rock half-space. The coupled model enables the representation of the nonlinearity of the near-field soil by an equivalent linear approach which enables the system to be solved in frequency domain. The model can also incorporate the angular wave incidence from the far-field. The spatial dimension gets decreased by one due to the boundary elements used, thus decreasing the degrees of freedom compared to those that appear with finite elements; and hence ultimately reducing the computational energy and time. But, for inhomogeneous and anisotropic media, BEM is not very suitable [34]. Researchers, therefore, tried to develop a technique that would combine the benefits of both the technique i.e. FEM and BEM. This resulted to the development of a semi-analytical modelling technique, called as, "Scaled Border Finite Element Method (SBFEM)". In addition to above methods, Bielak et al. [35] introduced an efficient modelling approach, known as "Domain Reduction Method (DRM)". This method breaks the entire problem into two simpler parts. The first part incorporates the source of earthquake and the influence of path of propagation in a model that includes the source and a background structure from which the localized features are eliminated. Whereas, the second part models the effects of local site. Its input is a set of equivalent localised forces obtained from the first part. These forces operate only within a single layer of elements adjacent to the interface of exterior region and the geological components of concern. Hence, the size of analysis domain gets considerably reduced. DRM analysis also decreased computing time by 50 percent as compared to any of the conventional analyses [36].

2.3 Experimental Approach

There are lots of experimental studies conducted by various researchers to understand the process of SSI and its various effects. Gazetas and Stokoe [37] performed shake table tests and identified the reliability of impedance functions presented in Gazetas [38]. Boulanger et al. [39] evaluated dynamic beam on a nonlinear Winkler foundation (p-y analysis) against dynamic centrifuge model experiments and discovered a significant agreement in all nine earthquake shaking events considered in the study. Durante et al. [40] used shake table tests to explore the influence of different pile settings, with and without pile caps, and superstructure considering horizontal and vertical dynamic shaking. Hussien et al. [41] has reported the results of centrifuge tests to understand the seismic response of structures with single and grouped pile settings and recorded kinematic and inertial interaction effects. Martakis et al. [42] conducted a set of experiments in centrifuge facility to explore the effect of soil properties and structural parameters on SSI and therefore got hold of an experimental dataset that would function as a guideline in practical projects. Mostly experimental studies for SSI have been conducted using shake table and dynamic centrifuge model tests. Whereas, few full-scale dynamic tests have also been carried out, such as Zangeneh et al. [43] conducted for a portal frame railway bridge. Since such research is generally time-consuming and costly, scientists have been deeply involved in the development of modelling approaches to analyse the effects of SSI. So that, in design offices, these easy and economical modelling strategies could be used.

2.4 Computer Programs

The advancement in computer technology has given excellent assistance for SSI analysis and computing has, therefore, become a necessary tool. Lou et al. [44] have discussed the various computer programs available for SSI analysis and their advantages and disadvantages. The common programs for SSI analysis are "CLASSI", "FLUSH", "ALUSH", "SASSI" and "HASSI" etc. CLASSI, formulated by Wong and Luco, is based on the substructure analysis method and uses a frequency domain computing method that applies fast Fourier transform (FFT). FLUSH and ALUSH are based on 2D finite element that Prof. Lysmer designed to analyse SSI in the 1970s. These are also FFT-based frequency domain computing methods. Though, they cannot apply external dynamic loading. Prof. Lysmer has also developed SASSI which is again frequency domain computing method with FFT. This program could be used for structures with multiple, flexible or buried foundations.

The above-mentioned programs, though, have noticeable disadvantages such as they only analyse in frequency domain and are unable to perform nonlinear analysis. Nowadays, many commercial programs based on finite element (such as "ANSYS", "ABAQUS", "MSC.MARC") are available, with a convenient interface and strong nonlinear solver. They are user-friendly and computationally more efficient and hence are getting very popular amongst researchers.

III. NEAR-FIELD EARTHQUAKES

The earthquakes that occur in the nearby region of active fault are called near-field earthquakes. Researchers have conflicts about determining a definite distance as the near-field of fault. Therefore, they suggest that the near-field ranges from 10-60 Kms around the fault. UBC-97 Code, for instance, considers the near-field range to be less than 15 Kms from the epicentre [45]. In fact, as distance increases, near-field effects attenuate and are influenced by magnitude and site condition etc, hence it is quite difficult to make a quantitative distance. Therefore, it was considered as more reasonable to give a range of the distance. [46].

Factors affecting ground motions can merely be categorised with the magnitude, distance, and site condition for a particular earthquake. But in case of small distances, other factors may become dominant. In small distance areas, the variation of ground motion depends largely on the characteristics of earthquake source mechanism, rupture direction relative to the site, and slip direction of the rupture fault. All these aspects lead to the differences between near-field and usual far-field ground motions.

3.1 Characteristics of Near-field Earthquakes

There are certain factors which considerably affect the ground motion at a particular site in the near-field region, such as, rupture mechanism, slip direction relative to the site and permanent ground displacement at the site due to tectonic movement. Due to the first two factors, ground motions may have dynamic effects of “forward-directivity”, “neutral directivity”, or “backward-directivity” in the near-field region. Depending on the last factor, ground motions close to surface rupture may cause a considerable permanent static displacement, known as the “fling step”. In estimating ground motions for a project site in near-field region, these unique characteristics of near-field ground motions should be considered [47]. Forward-directivity pulses, which can best be distinguished in velocity time history, arise where the rupture propagation velocity is close to the shear-wave velocity. Because of the radiation pattern of fault, these pulses are primarily oriented in the fault-normal direction. However, the fault parallel direction can also contain strong pulses. Whereas, fling-step is generally defined by a one-sided large-amplitude velocity-pulse and a ramp-like step in the displacement time history [48].

There is usually a high vertical to horizontal response spectra (SV/SH) ratio and high PGV/PGA ratio in near-field ground motions. Ambraseys [49] researched the vertical to horizontal ratios of various ground motion parameters for different kinds of faults, such as peak ground acceleration, spectral acceleration, maximum absolute input energy, and given some useful conclusions. The PGV/PGA ratio is dependent on earthquake magnitudes and site conditions and in spite of larger than the values used in codes, the soft soil sites appear to have a higher ratio of PGV/PGA compared to other site conditions [50]. Elgamal [51] observed that in comparison to far field ground motion, the near field vertical ground motion displayed lesser energy over longer duration and also greater occurrence of high frequency component.

In response to realising the significance of near-field earthquakes on structural performance, several researches have been conducted on establishing predictive interactions for parameters that characterise the specific type of ground motion in the near-field region [52, 53, 54].

IV. RECENT RESEARCHES

Few recent pieces of research on SSI considering the near-field earthquake have been discussed in this section.

Davoodi et al. [55] addressed the effects of near-field ground motions with strong velocity pulse (forward directivity) and residual ground displacement (fling-step) characteristics and far-field ground motions on the dynamic response of SDOF system considering SSI. For directly analysing the soil-structure SDOF model in time domain, a numerical method is used that is based on interpolation of excitation. The SSI effects are studied by comparing the maximum displacement responses of equivalent SDOF systems. Findings of the research revealed that as compared to far-field, pulse-type near-field records usually generate higher responses particularly when the ratio of structure to soil stiffness is high. It has also been concluded that earthquakes with greater PGV/PGA ratio generate greater dynamic responses, with increase in structure to soil stiffness ratios.

Akehashi et al. [56] investigated non-linear response of a base-isolated building considering SSI under a double impulse as a replacement for near-field ground motions. The nonlinear base-isolated building model considering SSI was first modelled on a “swaying-rocking spring-dashpot system” as a 2DOF system (SDOF superstructure and base-isolation story). The 2DOF system was then converted into an SDOF system on a “swaying-rocking spring-dashpot system” by neglecting the mass on the base-isolation story. Ultimately, by neglecting the mass and moment of inertia of the base mat, the SDOF system on a “swaying-rocking spring-dashpot system” was further converted into an SDOF system. It also compared the results of time history analysis under the critical double impulse and the one-cycle sine wave as representation of the near-field ground motion, to examine the accuracy and reliability of the suggested methodology.

Shahbazi et al. [57] studied the seismic response of special moment frames (SMFs) considering SSI for near- and far-field records. In the study, steel buildings of 5 and 8 story configured with SMFs resting on type-II and III soils (according to the seismic code of Iran-Standard 2800) have been considered and the nonlinear time-history analysis was performed in the OpenSees software to model the systems and obtaining dynamic responses. The analysis results showed that the drift, displacement, base shear force, moment, and axial force of columns in both types of soil are greater than far-field earthquakes, under the effect of near-field earthquakes. Whereas, Tavakoli et al. [58] studied the response of reinforced concrete structures considering SSI for near-field and far-field earthquakes. The linear time history analysis was performed for a 3-story,7- story and a 15-story building using SAP2000.

Birzhandi et al. [59] studied the torsional effects and SSI simultaneously under near-field pulse-like earthquakes in a probabilistic context using incremental dynamic analysis (IDA) and fragility curves and also mentioned the need to develop approximate IDA and fragility curves for flexible base asymmetric structures to assess their probabilistic manner faster.

Masaeli et al. [60] conducted an extensive parametric study to focus on influences of near-field pulse characteristics on dynamic responses of soil-structure systems with regard to soil yielding and foundation uplifting. This research considers mid-to-high rise structures with broad range of slenderness ratio rested on mat foundations with various types of soil (i.e. soft to very dense). Results of the research showed that nonlinear SSI has the potential of amplifying structural responses when the soil-structure system is subjected to long-period pulses in case of fling and directivity pulses.

Zhang et al. [61] investigated and compared the nonlinear dynamic response and seismic damage of concrete gravity dams subjected to near-field and far-field earthquake, taking into consideration the effects of dam–reservoir–foundation interaction. The analysis was carried out in accordance with the “Concrete Damaged Plasticity (CDP)” model including the strain hardening or softening behavior. The analysis performed showed that for near-field earthquakes the responses (crest horizontal displacement) and accumulated damage of dams are observed to be considerably higher than those for far-field earthquakes.

Chaithra et al. [62] investigated the effect of flexibility of the soil on a tank filled with fluid. The tank, soil and fluid are simulated using finite elements to consider the impact of tank wall flexibility. Similar investigation has been conducted by Chaithra et al. [63] to study the impact of SSI for Chi-Chi earthquake. However, two types of earthquakes, one far field i.e. El Centro earthquake and one near field, i.e., Imperial Valley earthquakes, were considered in this research to know the effect of type of earthquakes on the SSI effect of the tank.

Pradhan et al. [64] conducted shake table tests to investigate the effects of density of soil on the bridge pier response considering soil-foundation-structure-interaction (SFSI). The model was tested for both near-field and far-field ground motion. The experimental findings indicated that the dominant frequency of induced vibration of bridge pier decreases with reduction in relative density of the soil during near-field motion. Though, this is not noted in the case of far-field motion.

Güllü et al. [65] studied the effects of near and far-field ground motions on dynamic responses of historic stone masonry building (125-years old Kurtulus Mosque, Gaziantep-Turkey) by SSI analysis (dashpot and elementary boundaries) as well as fixed base solution. To understand the effect of substructure's boundary type, dynamic SSI analysis was conducted using direct approach.

V. CONCLUSIONS AND FUTURE RESEARCH PROSPECTS

It is clear from the review that many studies that give an overall picture of SSI's effects have been conducted. However, for structures in near-field regions, there are few studies focusing on practical and reliable design methods. After carrying out the literature review, the authors of this paper believe that focusing research on ways to assess the effects and identify scenarios that lead to adverse effects of SSI on structures in near-field region is extremely important. The issues which demands attention and needs to be addressed are as follows:

1. Most of the works are limited to shallow foundations for simplification and calculability. Whereas, with increase in the height of the superstructure, deep foundations are required to be provided. Therefore, it is important to study the dynamic interaction of deep foundations.
2. In the modelling of structure and soil for the assessment of dynamic response, non-linearity has not been given due attention. In most cases, soil's behavior is highly nonlinear and the structure undoubtedly produces an inelastic response in case of major earthquakes. It is therefore important that modelling techniques be developed to include non-linearity in the analysis.
3. Many studies have been carried out to study the various characteristics and behaviour of near-field and far-field ground motions, and established that there is a considerable difference in the behaviour of vertical and horizontal components of both motions. Whereas, the rotational component also needs to be considered in studies to have a more comprehensive view of near-field ground motion.
4. The number of experimental studies based on SSI considering near-field earthquake are very limited. As the shaking table and centrifuge technique is becoming more and more mature, much experimental work in field and laboratories has yet to be performed.
5. Keeping in view the objective of providing guidance to real projects, the key criteria should be simplification and practical applicability of analytical and design techniques. In spite of latest advancements in this field, the existing FEM and BEM modelling methods are both time and resource exhaustive. Hence, simpler and resource efficient methods are need of the hour.
6. Indian standard codes do not provide specific guidelines for SSI and ground motion characteristics that can be used to design and analyse embedded foundation structures. There should be relevant provisions in the codes.
7. In previous studies, a limited number of records have generally been used to examine the characteristics of near-field earthquakes. The effects of SSI have also been considered by describing limited parameters of the soil structure that can be representative of rather limited situations. Therefore, it appears necessary to investigate the exceptional effects of near-field land.

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