DSSI FOR PILE SUPPORTED
ASYMMETRICAL BUILDING: A REVIEW

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ABSTRACT
The past earthquake study conducted on the foundation system (soil and foundation) reveals that the interaction of soil and foundation plays a major role in the response of superstructure. In this regard a literature survey has been carried out on frame structures supported on pile foundation which is in contact with more soil mass as compared to the other type of foundation system. In this research paper concept of dynamic soil-structure interaction is introduced, and the research methods were discussed. Based on several documents, a systematic summary of the history and status of soil structure interaction that considers pile soil structure interaction has been proposed as a reference for researchers. This study focuses on the complexity and excessive simplification of the model for foundation system and structures, and should be carried forward for its significance. The review is carried out including analytical, experimental and numerical approaches considered in the past study. The perusal of literature reveals that very few studies investigated on asymmetrical buildings supported on pile foundations. In this paper, an attempt is made to implement the prominent investigations on soil structure interaction analysis of framed structures supported on pile foundations.

KEYWORDS
Soil Structure Interaction; Asymmetrical building; Soil Pile interaction, Literature review

1. INTRODUCTION
Most of the building frames are supported on combined footings, isolated footings, raft, pile foundations depending on the amount of load and the nature of supporting sub soil. Generally the multi storied buildings constructed on weak strata are supported on pile foundation. The problem of interaction becomes more complex when soil, foundation and structure have to be modelled with equal rigour [70, 74]. The methods to solve the soil structure interaction problem can be grouped as direct approach, substructure approach. In dynamic analysis, the total interaction response is the combination of the two parts namely kinematic and inertial interaction. When the seismic wave passes through a soil mass, it vibrates and displaces due to distortion and dilation of waves through the solid media, such vibration in the supporting soil mass is called as the kinematic interaction. Once the excitation wave passes through soil and enters into the structure starts vibrating which exerts extra dynamic force to the soil mass, refers as the inertial interaction which depends up on the inertial forces produced by the structure [58,113].
1.1. **Direct Method**

Direct method is one in which the soil and structure are modelled together in a single step accounting for both inertial and kinematic interaction. Inertial interaction develops in structure due to own vibrations giving rise to base shear and base moment, which in turn causes displacements of the foundation relative to free field. While kinematic interaction develops due to presence of stiff foundation elements on or in soil causing foundation motion to deviate from free field motions [58,113]. Figure 1 shows building modelled with direct approach of SSI.

![Figure 1. Direct Method of Soil-Structure Interaction](image)

The response of the coupled system is calculated from the following governing equation given by Krammer (2003).

\[
[M]\dddot{U} + [C]\dot{U} +[K]U = -[M]\ddot{U}_g
\] (1)

Where, \( M, C \) and \( K \) are the mass, damping and stiffness matrices of the integrated system which includes the structure and foundation system.
\( \dddot{U}, \dot{U} \) and \( U \) are the acceleration, velocity and displacement of the system and \( \ddot{U}_g \) is the ground motion acceleration.

1.2. **Substructure or multistep method**

Substructure method is one in which the analysis has been broken down into several steps and the principal of superposition is used to isolate the two primary causes of soil structure interaction that is inability of foundation to match the free field deformation and the effect of dynamic response of structure foundation system on the movement of supporting soil.

Kinematic interaction is characterized as a motion of the superstructure due to rigid-body displacement of the ground surface [57,71]. The theory of kinematic interaction assumes that the building structure has no mass, the building foundation has no mass and the building foundation is completely rigid. During earthquakes, the seismic waves travel up through the soil and reflect the scatter off the rigid foundation. As the waves reach to the surface their motion will amplify. Thus the peak amplitude will observes at the surface. The motion of the massless structure does not change the response at the base. The foundation moves as a rigid body and scattering of a waves modifies the motion compared to the motion that would occur if the foundation was not present [86].
Thus the deformation due to kinematic interaction alone can be computed by assuming that foundation has stiffness, but no mass (Figure 2a).

![Diagram showing massless structure and structure with foundation](image)

**Figure 2. Interaction analysis using substructure method**

The equation of motion for this case is [86].

\[
[M_{\text{soil}}]\{\ddot{U}_{KI}\} + [C]\{\dot{U}_{KI}\} + [K*]\{U_{KI}\} = -[M_{\text{soil}}]\{\ddot{U}_g\} \tag{2}
\]

The structure and foundation (Fig. 2b) do have mass and this mass cause them to respond dynamically.

The deformation due to inertial interaction can be computed from the following equation of motion [86].

\[
[M]\{\ddot{U}_{II}\} + [C]\{\dot{U}_{II}\} + [K*]\{U_{II}\} = -[M_{\text{structure}}]\{\ddot{U}_{KI} + \ddot{U}_g\} \tag{3}
\]

Where, \([M] = [M_{\text{soil}}] + [M_{\text{structure}}]\) and \([M_{\text{structure}}]\) is the mass matrix assuming soil is mass less, \([K*]\) is stiffness of entire system, \([C]\) is damping matrix of entire system, \(\ddot{U}_g\) is input ground acceleration, \{\ddot{U}_{KI}\} displacement vector due to inertial interaction.

The right side of the above equation represents the inertial loading on the structure-foundation system. This inertial loading depends on the base motion and the foundation input motion, which reflects the effects of kinematic interaction. In the inertial interaction analysis, the inertial loading is applied only to the structure; the base of the soil deposit is stationary. The solution to the entire soil structure interaction problem is equal to the sum of the solutions of kinematic and inertial interaction analysis [113,62,65,105].

The amount of kinematic interaction in soil structure system depends largely on type, frequency content and angle of the incidence of the seismic waves, and embedment and flexibility of the foundation [87,90,92,102,106].

### 2. DAMAGES DURING EARTHQUAKES

Several damages have been evidenced during earthquakes due to incomprehension of soil structure interaction effect in design of structure and foundation system [80,91,107]. Some of these are captured in this review paper. In the 1985 Mexico earthquake where the damages on
10-12 stories buildings were observed with partial bearing capacity failure of foundation soil. It has been reported that this earthquake was particularly destructive to the unbraced buildings founded on soft soils, whose fundamental time period increased from about 1.0 s to nearly 2.0 s due to the interaction phenomenon. The 1995 Kobe earthquake (M=6.9) where the collapse and overturning of Hanshin expressway is observed because of sudden increase in natural period with interaction effects, also major collapse of Daikai station due to poor load transfer mechanisms due to interface effects [40]. In the 2010 Haiti earthquake (M=7), collapse of several buildings has observed because of deeper rotation failure due to movement of soils [37,41]. During 2001 Bhuj earthquake (Mw=7.6) caused extensive damage to life and property due to attenuation effect of the wave travelling through the soil layers with a high impedance contrast of the supporting soil layers [59].

3. FACTORS INFLUENCING SSI EFFECTS

Soil structure interaction is very complex phenomenon and its effect depends up on the many parameters including soil stratification, soil density, and wave propagation frequency. Few of these factors are discussed below.

3.1 Impedance contrast

Impedance contrast defined as the product of velocity and density of the material, thus varies the ground motion amplitude while travelling to the most heterogeneous soil media like soil [58]. Seismic waves travels faster in hard rocks as compare to softer rocks and sediments [31,60]. As the waves passes from harder to softer rocks waves become slower and must get bigger in amplitude to carry the same amount of energy [19]. Thus, shaking tends to be stronger at sites with softer surface layers, where seismic waves move more slowly [14]. Pisal (2006) carried out site response analysis using PSHA and study found that the impedance of soil layers plays important role in site response analysis [14,3,25].

3.2 Resonance

When the excitation frequency matches with the fundamental natural frequency of the system the phenomenon of resonance will takes place. This results in to tremendous increase in ground motion amplification. Perez and Rocha (1997) performed a shake table test to understand the effect of resonance in soil structure interaction for the different ground motions and study has been concluded that the system response is maximum for a ground motion in which frequency of the integrated system (structure + foundation system including soil) is nearest to the load frequency which proved that the soil have its own fundamental time period and that contributes in the structural response [34,86]. It has been observed that the thickness and velocities of the surface layer can be correlated with the different spectral peaks and resonance patterns for the different frequencies [45].

3.3 Damping in Soil

In dynamic analysis when the excitation/seismic waves travel through the soil mass the energy of the wave is dissipated due to the scattering the waves in to the infinite domain. Thus the
energy loss takes place in this phenomenon is called as the radiation damping. The energy of the input waves also can be used in deformations of the soil mass due to which the changes the soil material properties and referred as a material damping [28]. Absorption of energy occurs due to inelastic properties of medium in which the particle of a medium do not react perfectly elastically with their neighbour and a part of the energy in the waves is lost instead of being transferred through medium, after each cycle. This type of attenuation of the seismic wave is described by a parameter called as quality factor (Q) which is defined as the fractional loss of energy per cycle.

\[
\frac{Q}{\pi} = \frac{\Delta E}{E}
\]

where, \(\Delta E\) is the energy lost in one cycle and \(E\) is the total elastic energy stored in the wave. If we consider the damping of a seismic wave as a function of the distance and the amplitude of seismic wave, we have

\[
A = A_0 e^{-\alpha r}
\]

\[
A = A_0 e^{-Q \frac{r}{\alpha}}
\]

Where \(\alpha\) is called the absorption coefficient and is inversely proportional to quality factor \(Q\). Damping of soil mainly affects the amplitude of surface waves [26,58,70].

3.4 Basement Topography

Irregular basement topography when subjects to body wave incidence below, results in focusing and defocusing effects. This effects are strongly depends on the azimuth and angle of incident waves. The damage pattern caused by the Northridge earthquake reveals effect of basement topography very well [8,26,58].

3.5 Trapping of Waves

Due to the large impedance contrast between the soft sediments and underlying bedrock, seismic waves trapped over soft sediments. This results in increase in the duration of ground motion. When layers are horizontal this trapping affects only body waves. While in case of lateral heterogeneities this trapping also affects the surface waves. Interference of these waves also leads to resonance pattern. Kawase (1996) has brought in observation in the 1995 Hyogo-ken Nanbu earthquake which was the most destructive earthquake in Japan even though of moderate magnitude of 6 [8,26,30].

3.6 Lateral discontinuities

Lateral discontinuities where a softer material lies besides a more rigid one (for instance, ancient faults, anomalous contacts, debris zones, etc.) are best example of damage caused by strong lateral discontinuity (softer rock sandwiched between hard rock) was observed in the Bhatwari- Sonar village during the 1999 Chamoli earthquake. The village situated on a sloping
hill at the left bank of river Mandakini received greater damage. The hill mass is composed of rounded pebbles and young soil and is surrounded by hard older quartzite rocks. Amplitude amplification, generation of local surface waves in the softer medium and larger differential motion caused by shorter wavelength of the surface waves may be reason behind the greater structural damage [59].

Although numerous works have been done on interaction analysis of frame structure resting on combined footings, isolated footings, etc., not much of work has been done interaction analysis of frame structure resting on pile foundations [20,21,22,23] except a few studies as described in the following section.

In accordance with technical development, the methods for the study of SSI are categorized to analytical method, numerical method, and experiment and prototype observation. Several publications have featured the research status of SSI. Some of the studies which have been carried out to understand the effect of soil structure interaction are discussed in the following section.

4. LITERATURE REVIEW

4.1 Review on Experimental studies

Several researchers including Ward and Crawford (1964,1966), Ivanovic (1995,2000), Yano (2000), Kusama (2003), Dunand (2004), Kontani (2004), Jayalekshmi (2009), Hokmabadi (2014) etc. carried out a research on a experimental full scale and scaled down the models to understand the soil structure interaction effects for the buildings with the different types of the foundation type [23,24]. The response of structures to dynamic loads is often estimated using mathematical models as it represent some idealization of real structure and the behaviour of the system is the best evaluated by experiments on full scale structures such as ambient and forced vibration tests and recording of earthquake response [6]. These experimental models have been extended to the geotechnical applications to study the soil behaviour with the structure coupling under the dynamic load.

4.1.1 Ambient Vibration Tests

The ambient vibration tests describe the linear behaviour of the structures against the vibration produced by the sources including wind, microtremors, microseisms and various local random and periodic sources, since the vibration are small. It can also be used to obtain the linear response of the damaged structure and its components and can help in developing algorithm of structural health monitoring and structural control studies.

Ambient vibration tests are complete full scale experiments conducted at a large and dense set of points by placing the seismometers in strategic locations throughout the building on both the directions. The seismometers were usually located at a common point in a plan view but at different elevations, or floors, throughout the building. They measure the response of structures to micro tremors, microseisms, wind, vehicular traffic etc, which are 4 to 6 orders of magnitude smaller than the destructive strong earthquake motions. The apparatus associated with ambient vibration tests consists of a multi channel digital data acquisition system, a
microcomputer which has been programmed to perform various time and frequency domain functions. The instrumentation is chosen such that it covers amplitude and frequency range of interest and may vary from experiment to experiment. The results of ambient vibration tests can provide estimates of soil structure frequencies for smallest level of excitation. They are often used to estimate the frequencies of vibration, modal damping and mode shapes of full-scale structures, in the linear range of response. They can also be used extensively to identify and to monitor changes of system frequencies between small (ambient noise) and large (earthquake shaking) response amplitudes [27,36].

Crawford and Ward (1964) were among the first to show that the ambient vibrations test can be used to determine some of the lowest frequencies and modes of vibration of full scale structures [36]. For this purpose random wind excitation has been used to find the first three modes of vibration of a nineteen story building about the two major translational axes and the torsional axis of the building. Simultaneous recordings were obtained at floor levels 15, 11, 7, and 3 with the transducers, when the exciting force was a light wind. The relative power between the first three modes is obtained for each type of motion i.e. two lateral components and torsion. With this type of excitation it is seen that the power decreases rapidly with increasing mode. Also it has been found that the centre of the building is more suitable for obtaining information about the modes of one particular translational vibration. Also theoretical value of natural period of vibration was obtained by assuming the building as shear type building and using modal analysis and it has been shown that the some of the theoretical and experimental values are in good agreement [24,54,72].

An experimental analysis has been carried out to find the frequencies and modes of vibration of multi-storey buildings using wind induced vibrations (Figure 3). For these purpose three buildings of ten, thirty eight and forty seven stories were investigated. A simple theoretical model was used to calculate the frequencies of vibration of the buildings; the model was based on the assumption that the greatest percentage of the weight of the structure is concentrated at each floor level that is it is assumed that it is a lumped-mass system. With a comparison of the theoretical and measured values of the frequencies showed that this simple model was a realistic representation of only the smaller building. Power spectrum analysis of the vibration records were used to obtain an estimate of the damping characteristics of the buildings [24,54]. Several case studies including Kaprielian Hall building, Millikan Library building, 7-story reinforced concrete building in Van Nuys, California and many damaged building during earthquakes has been analysed by few researchers with the comparative study of modal frequencies of the building and concluded that reason for reduction of fundamental frequency of vibration may be the inducement of large strains following the strong shaking from earthquakes.

The study reveals that apparent frequencies of the soil foundation structure system appear to be influenced significantly by variations in the effective soil foundation stiffness. These variations can be monitored by a sequence of specialized ambient vibration tests [24,83].

Using the Ambient Vibration tests an empirical relation for damping values by studying a set of ambient vibration records of 26 different reinforced concrete buildings, all founded on thick alluvium. The ambient vibration records obtained at roof are used for the study and it has been observed that damping values exhibit some correlation with frequency and to a lesser extent with aspect ratio (L/H, L is horizontal dimension of building and H is height of building). By using a log linear least square fit the regression equation for damping has been derived and it comprises of frequency and L/H ratio as parameters [24,94].
To know the effect of SSI on damping and L/H, a single degree of freedom structural model with soil represented by cone model has been used. This model has been applied to set buildings taking into account their actual size and soil mechanical properties and it has been observed that the damping values derived under ambient vibrations cannot be extrapolated directly to the damping values under strong shaking as a lot of non-linear material degradation phenomena occur in both the structure and the soil, which should most generally increase the damping values of the whole (soil and structure) system at large strains. However, one may consider that the frequency values derived from ambient vibration recordings are an upper bound for the actual frequency values under stronger shaking, while, simultaneously, the ambient vibration damping values are a lower bound for the actual damping for strong motion.

4.1.2 Forced Vibration Tests

The force vibration requires a large scale shaking to simulate a earthquake loading. The source always mounted at the top of the structure to get the more prominent excitation and modes of vibration that have amplitudes at the higher levels. The test is generally complete full scale tests. Full-scale vibration tests using large shaking machines have proved to be one of the most effective methods for determining the dynamic characteristics of structures needed for understanding the effects of strong earthquake motions [47,51]. With these vibration generators it is possible to determine experimentally the most important periods and mode shapes of many actual structures, and to measure their energy dissipation properties. To excite the structure more efficiently, the source of forced vibration (e.g., shaker) is usually located on one of top floors of structure. The principal limitation of the vibration generators is that the testing range is generally limited to small vibrations. The apparatus associated with Forced vibration tests consists of Seismometers, a microcomputer which has been programmed to perform various time and frequency domain functions [51]. Initial work on Forced vibration tests followed by few applications of the same to SSI has been given below.

Paul (1968) conducted the forced vibration tests on Millikan library building. The vibration tests consist basically of determining the steady state response of the building to a sinusoidal exciting force produced by the eccentric masses of the vibration generators. The building was excited with two generators, installed on the ninth floor. The response of the building and nearby ground at selected locations was recorded with a 6 channel accelerometers amplifier recorder system. The soil structure interaction measurements showed that the
building responded very nearly as if fixed at the foundation; rocking contributed less than 1 percent to the total roof motions of the structure and foundation translation about 2 percent [81].

Forced vibration tests designed to isolate the effects of soil structure interaction are described and the results obtained for the nine storey reinforced concrete Millikan library building are analyzed and this study revealed the fact that the fixed base natural frequencies and modal damping ratios of the superstructure can be easily determined experimentally. These values may be significantly different from the resonant frequencies and damping ratios of the complete structure foundation soil system. It was also shown that forced vibration tests can be used to obtain estimates of the foundation impedance functions. It has been shown from the forced vibration tests that rigid body motion associated with translation and rocking of base accounts for more than 30% of total response at roof [84]. Also in an experiment conducted in 1974 the Millikan library building was forced to vibration by a vibration generator located at the roof. The basement slab and the roof were measured for shaking in both NS and EW directions. The observations indicate that for NS excitations each floor remains essentially plane experiencing an almost uniform translation and uniform rotation about EW axis. Also results of experiment indicate that interaction of structure and soil has a marked effect on the response during forced vibration tests [82,84].

A full scale experimental study has been carried out for Hollywood storage building Fig. 5 and the results the researcher has concluded that the interaction problem is so complex to summarize the dependent parameter and to simplify it is needed to neglected few of them. In the research the rocking effect of the wave propagation is neglected and the response of the building is estimated depending up on the ground motion transfer function for different ground motions (Figure 4).

![Figure 4. profile of transfer function for different ground motions considering soil structure interaction](image)

Few research has been carried out for estimating the significance of the SSI effects studied for both embedded and shallow foundation and revealed few facts like that the fundamental time period for due to SSI is a lengthen to 12% and 74% for the braced and unbraced structure, respectively [63,110].

A full scale vibration tests for HP 10x42 piles installed to a depth of 20 ft at a site containing soft clays using random vibration methods and predicted a interaction effect (Figure 5) [2,4].
Experimental simulation techniques for characterizing dynamic soil pile interaction concluded that the new experimental techniques has good agreement with the traditional forced vibration test using shaker or vibrator.\[2\] presented herein [50,54,83].

4.1.3 Shake Table Tests

Model tests are essential when the prototype behaviour is complex and difficult to understand. In model testing, usually the boundary conditions of a prototype problem are reproduced in a small scale model. Model tests are used to understand the effects of different parameters and the process leading to failure of prototype at a real time. The model tests can be divided into two categories, namely, those performed under gravitational field of earth (generally called shaking table tests) and those performed under higher gravitational field (centrifuge tests). Both shaking table and centrifuge model tests have certain advantages and limitations. Shaking table tests have the advantage of well controlled large amplitude, multi-axis input motions and easier experimental measurements and their use is justified if the purpose of the test is to validate the numerical model or to understand the basic failure mechanisms. The major work on in situ tests for SSI has been conducted to understand the behaviour of nuclear power plants at the time of dynamic loading. The two tests widely used for the purpose of understanding the SSI behaviour are discussed. The Nuclear Power Engineering Corporation (NUPEC 1998) had conducted extensive experimental studies on the SSI of the nuclear power plants. The following are series of tests conducted to verify the seismic analysis codes [10,89].

A model tests on dynamic soil structure interaction has been carried out on a series of forced vibration tests and earthquake observations were performed in the field to evaluate the SSI for rigid structures [115,38]. Three structural models representing reactor buildings and two concrete block specimens were used in the analysis. The effects of base mat size on dynamic soil stiffness, radiation damping and soil pressure distributions were investigated. A base mat uplift test of reactor building shaking table tests has been carried out in the laboratory and forced vibration tests in the field were conducted to investigate uplift phenomena of the rigid structures [11,9]. The soil was modelled with silicon rubber. The following are the conclusions of this study as the contact ratio decreased with increasing input motions, response amplification of the structure became low and resonance frequencies of the SSI system shifted toward longer periods. Horizontal motions with higher frequency were induced by uplift phenomena. The test has been extended for a embedment effects in which reactor building forced vibration tests with exciter and earthquake observation were performed in the field in order to investigate the embedment effects on SSI [38]. Shaking table tests using silicon rubber...
as soil model were also conducted to supplement field test. It has been concluded that the embedment of the building reduced response of structure and increased natural frequencies and damping factors of the SSI system [9,39]. Yano (2000) performed a model tests on dynamic cross interaction tests to investigate dynamic cross-interactions of structures. Forced vibration tests and earthquake observations were conducted in three different conditions as a single reactor building, two identical reactor buildings and two different reactor buildings [38]. It was found that the two identical building models showed lower amplification in the series direction and almost the same amplification in the parallel direction compared with the single building model [39].

Along with the above investigations some tests were also conducted to understand the dynamic cross interaction of adjacent buildings in nuclear power plants. For that a shake table test can be used to test the resistance of structures to seismic shaking. It can also be used to demonstrate the sensitivity of structures of different heights to the frequency of the ground motion. Nuclear Power Engineering Corporation (NUPEC) of Japan has conducted the model test to understand the dynamic cross interaction of adjacent buildings in nuclear power plants for 8 years from 1994 till 2001. This study consists of both field and laboratory tests on scaled models. The field tests include forced vibration and earthquake observation. The laboratory tests involve vibration tests using an exciter and a shaking table test that applies simulated earthquake ground motions [16]. The study reflected behaviour of reactor buildings in regards of the SSI influence when the building is isolated and adjacent with the other reactor building for both embedded and non embedded foundation system. The study has been concluded that the tendency that larger adjacent effects like displacements and rocking appear in the direction of parallel to the row of buildings [16].

The seismic vibration tests have been carried out to understand the nonlinear SSI behaviour of nuclear power plants during large earthquake motions. The influence of geometrical nonlinearity (uplift) of the base mat as well as the material nonlinearity of the soil under the base mat on structural responses is studied. The proposed vibration tests will be performed at a coal mine. Ground motions from large scale blasting operations will be used as excitation forces for the vibration tests. For conducting large scale model tests including SSI affects this type of experiments are important [98].

Pitilakis (2007) designed a shaking table to confirm the ability of the numerical substructure technique to simulate the SSI phenomenon. A model foundation–structure system with strong SSI potential is embedded in a dry bed of sand deposited within a purpose designed shaking-table soil container. The experimental system is subjected to a strong ground motion and simulated numerically to validate the result of the complete soil foundation structure system with linear viscoelastic domain using the substructure approach. Study found that the experimental and numerical responses in both frequency and in time domain were in good agreement [29,100].

The soil pile structure model has been tested on a shaking table subject to both sinusoidal wave and the acceleration time history of the scaled 1940 El Centro earthquake. In this analysis medium-size river sand is compacted into a 1.7m high lamina rectangular tank to form a loose fill with a relative density of 15% [10].

A single storey steel pile supported structure was tested for interaction performance. The experimental set up included the four end bearing piles with the pile cap and very distinct pounding phenomenon between soil and pile was observed. It has been noted that acceleration response of the pile cap was three times larger than that of the structural response. The pounding
observed due to the development of a gap between soil and pile which led to the extraordinary large inertia forces at the top of the pile and pile failure occurred due to the cracks in the pile volume. To explain this observed phenomenon, nonlinear finite element method (FEM) analyses with a nonlinear gap element have been carried out using SAP 2000. The spikes in the acceleration response of the pile cap caused by pounding can be modelled adequately by the FEM analyses. The present results suggest that one of the probable causes of pile damages is due to seismic pounding between the laterally compressed soil and the pile near the pile cap level [10,112].

Jayalekshmi (2009) studied the response behaviour of multistory structures with isolated or raft foundations, resting on a shallow soil stratum of homogeneous or layered soil, subjected to earthquake induced ground motions and to identify the structures in which the dynamic SSI effects are to be considered for a safe design. An experimental study has been carried out with the aid of a container box with structure embedded into the soil and accelerometers are placed in soil and building model for measuring the response to impact with impulse hammer [51]. The study concluded that the incorporation of soil flexibility in the analysis of low rise buildings is required for the realistic estimate of structural seismic response especially for single storey structures resting on very soft soil. Seismic base shear is found to decrease for the medium rise buildings, with raft foundation resting on soil as compared to fixed base due to longer natural period. It shows that the effect of SSI is advantageous to medium rise buildings on raft foundation. The investigations for low rise buildings with isolated footings resting on a shallow soil stratum on rock under transient loading reveal that the effect of SSI is to increase the seismic response of low rise buildings, up to three stories [51].

Madabhushi (2008) carried out a shake table test on a single pile in liquefiable soil strata. The results of this study provide information on performance criteria for seismic design of structures with pile foundations considering p-y relations for soil-pile interaction including the soil nonlinearity [48]. Pile soil interaction has been studied against the sinusoidal shaking to the shake table and the response is calculated with the sensors at the different pile lengths using 1g shaking to the shear box including the liquefaction effect [11] (Figure 6).

![Instrumented pile in the shear box apparatus](Figure 6)

The response is observed at different pile length and pile trajectory at the top (Figure 7). The study concluded lateral spreading displacements of the soil and pile behaviour were observed while soil liquefaction was triggered under shaking [11].
Li, Hou and Liu (2012) carried out a shake table test with 1/15\textsuperscript{th} scale down model on 3 by 3 pile group as a foundation type on a single symmetric building and the two adjacent building. The study concluded that an adjacent structures experiences more serious damage than that in single one. The SSSI effect has some influence on the soil frequency and the damping ratio of the SSSI system, but has little influence on the frequency and the characteristics of the vibration modes of the SSSI system [115].

Hokmabadi (2014) carried out a series of shake table tests for a mid rise symmetrical building supported by a shallow and deep foundation system in a homogenous soil condition. The response of the system is estimated for different ground motions and compared with the fixed base condition (Figure 8). The study concluded that the SSI effect is significantly high in shallow foundation than the deep foundation due to resistance soil and pile resistant [116].
### 4.1.4 Centrifugal Tests

The widespread technique of centrifuge modelling applied to geotechnical structures helps to investigate complex engineering problems. Dynamic loads generated by shocks and earthquakes are difficult to model in centrifuge, not much work has been reported in the literature. The behaviour of small-scale centrifuge models is representative of the behaviour of a full scale structure, named prototype. By increasing the mass forces, the centrifuge replicates the intensity of the prototype’s stress and strain fields in scaled earth structure models (Phillips, 1869). Many researchers outlined the principle aspects of centrifuge modelling in geotechnical sciences (e.g., Schofield 1980; Craig 1985; Corté 1989a, b; Taylor 1995; Garnier (2001, 2002), Hajialilue (2007). The similitude relations govern the scaling relationship between the model and the prototype. Garnier et al. (2007) and Ellis and Aslam (2009) compiled the principles, aspects, and uses of similitude relations in a state of the art. Briançon and Simon (2012) present the results of in situ experimental studies on rigid pile reinforced embankments (Okyay et. al 2014). Zelikson (1983) studied a scaled model of existing power station supported on its raft foundation and compared the response of the same model founded on anchor piles. Gosh (2007) conducted tests on different types of soil stratifications supporting a rigid containment structure. The results indicate that accelerations transmitted to structure base are dependent on stiffness degradation in supporting soil [117]. Chang (2006) studied the effectiveness of the commonly adopted retrofit strategy of adding a shear wall to a reinforced concrete frame through centrifugal modelling. The centrifuge tests reported here is the first model scale experiments that have included the simulations of building nonlinearity coupled with foundation nonlinearity. Data analyses of centrifuge tests indicate that frame wall systems have highly asymmetric hysteric loops due to asymmetry of lateral force resisting system (Shear wall is in asymmetrical position on one end of building) [12].

Kutter (2013) used a large geotechnical centrifuges to model realistic soil, foundation and super structures. In which special plastic hinge elements were attached at the end of beams in the super structure to accurately model beam stiffness and moment capacity (due to cold work and heat treatment process commercially available metallic elements often have behaviour that is scale dependent, thus it is not possible to find a small scale beam that has elastic and plastic properties (bending stiffness and moment) that are in accurate similarity with a large beam). Two models were tested a moment frame with shear wall building and soil pile bridge deck interaction. New techniques imposed in the centrifugal modelling give results that match with the existing systems [16].

Hajialilue (2007) established a test set up to find out the soil pile interaction effect in installation operations including the different installation procedures for the pile [99]. The study reveals that the interaction effect and pile response varies with the different installations procedures (Figure 9).
Ellis and Aslam (2009) performed centrifuge tests with both 6 and 16 vertical rigid piles under an embankment. In these tests, the embankment’s height varied between 35 and 210 mm within the scale of the model. In every test, the acceleration level ranged from 10-60 times g to simulate the different configurations of the prototype. They concluded that increasing the earth-platform’s height decreases the differential settlement at the surface of the embankment [1].

4.2 Review of Analytical studies

Piles are mainly used for coastal structures such as mooring and berthing piles, but usually formed in groups. However, tall buildings, offshore platforms, quays, viaducts, and bridge piers are generally built on pile groups. The difference between the behaviour of single piles and pile groups is that pile group response is influenced by the nonlinear pile - soil - pile interaction, the effect of the pile cap, the spacing of piles, and the arrangement of piles with respect to the direction of applied force [42]. So in order to have a good understanding on the group behaviour, first the single pile behaviour is discussed followed by group pile behaviour. Analytical methods to predict lateral deflections, rotations and stresses in single pile can be grouped under the following methods

1) Winkler Approach
2) P - Y Method
3) Elastic Continuum Approach
4) Finite Element Method

4.2.1 Winkler Approach

The Winkler approach (1867), also called the sub grade reaction theory, is the oldest method to predict pile deflections and bending moments. The approach uses a series of unconnected linear springs to model the soil with stiffness, $K_h$, expressed in units of force per length squared (FL$^{-2}$). The behaviour of a single pile can be analyzed using the equation of an elastic beam supported on an elastic foundation (Hetenyi 1946), which is represented by the 4th order differential beam bending equation.

$$\frac{E_p I_p}{d} \frac{d^4 u}{dz^4} + Q \frac{d^2 u}{dz^2} - w - pd = -K_h ud$$

(7)

Where
- $E_p$: modulus of elasticity of pile
- $Q$: Axial load on pile
- $u$: Lateral deflection of pile at point $x$ along the length of the pile
- $K_h$: Soil lateral subgrade reaction modulus
- $p$: Soil pressure over the pile
- $w$: Soil reaction per unit length over the pile (distributed load)
- $d$: Pile diameter
- $I_p$: Pile cross section moment of Inertia

Solutions to Eq (7) have been obtained by making assumptions simplification regarding the variation of $K_h$ with depth. The most common assumption is that $K_h$ is constant with depth for clays and $K_h$ varies linearly with depth for sands. Poulos and Davis (1980) and Prakash and Sharma (1990) provided tables and charts that can be used to determine pile deflections, slopes, and moments as a function of depth and non-dimensional coefficients for a constant value of $K_h$ with depth. Despite its frequent use, the method is often criticized because of its theoretical shortcomings and limitations. The primary shortcomings are the modulus of sub grade reaction that is not a unique property of the soil, but depends intrinsically on pile characteristics and the magnitude of deflection; and the method is semi empirical in nature; axial load effects are ignored and the soil model used in the technique is discontinuous. That is, the linearly elastic Winkler springs behave independently and thus displacements at a point are free from being influenced by displacements or stresses at other points along the pile.

4.2.2 p - y Method

McClelland and Focht (1956) augmented the sub grade reaction approach using finite difference techniques to solve the beam bending equation with nonlinear load versus deflection curves to model the soil. Their approach is known as the p-y method of analysis. This method has gained popularity in recent years with the availability of powerful personal computers and
commercial software such as COM624 and LPILE Plus3.0. A brief summary of the \( p \cdot y \) method of analysis is presented in the following section [7]. The \( p \cdot y \) approach to analysis of response of laterally loaded piles is essentially a modification of the basic Winkler model, where \( p \) is the soil pressure per unit length of pile and \( y \) is the pile deflection. The soil is represented by a series of nonlinear \( p \cdot y \) curves that vary with depth and soil type. The method is semi empirical in nature because the shape of the \( p \cdot y \) curves is determined from field load tests. Reese (1977) has developed a number of empirical curves for typical soil types based on the results of field measurements on fully instrumented piles. The most widely used analytical expression for \( p \cdot y \) curves is the cubic parabola, represented by the Eq. 8.

\[
\frac{P}{P_{ult}} = 0.5 \left( \frac{y}{y_{50}} \right)^{1/3}
\]  

Where; \( P_{ult} \) is ultimate pile resistant per unit length of pile. \( Y_{50} \) is deflection at one half of the ultimate soil resistance

The most widely used analytical expression for \( p \cdot y \) curves is the cubic parabola (Figure 10). The deflections, rotations, and bending moments in the pile are calculated by solving the beam bending equation using finite difference or finite element numerical techniques [87,52].

The method outperforms the sub grade reaction approach because it accounts for the nonlinear behaviour of most soils without the numerical limitations inherent in the sub grade reaction approach. However, the method has some limitations; such as the \( p \cdot y \) curves are independent of one another which concluded that the interaction will not be taken care by this method. Therefore, the continuous nature of soil along the length of the pile is not explicitly modelled. The acquisition of the appropriate \( p \cdot y \) curve is similar to the gain of the appropriate value of \( K_h \) and one must either perform full scale instrumented lateral load tests or adapt the existing available standard curves for use in untested conditions. These standard curves are limited to the soil types in which they are developed, but not universal.

4.2.3 Elastic Column Approach

Poulos (1971) presented the first systematic approach to analyze the behaviour of laterally loaded piles and pile groups by assuming the soil as a homogeneous elastic continuum. In this analysis, the soil is assumed to be a homogeneous, isotropic, semi - infinite elastic material
which is unaffected by presence of pile and also the soil at the back of the pile near the surface adheres to the pile [65,87].

In this model the pile is assumed to be a thin rectangular vertical strip divided into elements, and it is considered that each element is acted upon by uniform horizontal stresses (Figure 11) which are related to the element displacements through the integral solution of Mindlin’s problem [87].

![Figure 11. Continuum model for laterally loaded pile acting on (a) pile (b) soil adjacent to pile](attachment:image)

Finally, the soil pressures over each element are obtained by solving the differential equation of equilibrium of a beam element on a continuous soil with the Finite Difference Method (FDM). After the acquisition of the pressures, the displacements are found.

Novak (1974) presented an approximate continuum approach to account for soil pile interaction, in which it is assumed that the homogeneous soil layer is composed of a set of independent horizontal layers of infinitesimal thickness, extending to infinity. As each plane is considered independent, this model may be viewed as a generalized Winkler model. The planes are homogeneous, isotropic, and linearly elastic, and considered to be in a plane strain state.

The researcher presented the stiffness constants and constants of equivalent viscous damping for single, vertical piles in the form of tables and charts in which he gave it for two different cases like a constant soil shear modulus and shear modulus varies with depth according to a quadratic parabola. Elastic continuum approach was used by Madhav and Sarma (1982) to study the behaviour of overhang pile embedded in homogeneous soil mass subjected to both axial and lateral loads. The load displacement behaviour was found to be dependent on magnitude of axial load and also on pile and soil parameters (height of overhang, relative stiffness of pile and soil, undrained shear strength. The Continuum model has the advantage that it is able to take into account the continuous nature of soil, the semi infinite dimension of the half space, and the boundary conditions along the unloaded ground surface. Although yielding of soil may be introduced by varying the soil elastic modulus, this approach does not permit to consider local yielding and layered soil. One of the biggest limitations of the method (in addition to computational complexities) is the difficulty in determining an appropriate soil modulus, Kh [63].

### 4.2.4 Finite Element Method

The finite element method is a numerical approach based on elastic continuum theory that can be used to model pile - soil - pile interaction by considering the soil as a three - dimensional,
quasi- -elastic continuum. Finite element techniques have been used to analyze complicated loading conditions in which the soil is modelled as a continuum. Pile displacements and stresses are evaluated by solving the classic beam bending equation using one of the standard numerical methods such as Galerkin, Collocation, or Rayleigh Ritz. Various types of elements are used to represent the different structural components. Interface elements are often used to model the soil-pile interface. These elements provide for frictional behaviour when there is contact between pile and soil, and do not allow transmittal of forces across the interface when the pile is separated from the soil [51]. Salient features of this powerful method include the ability to apply any combination of axial, torsion, and lateral loads; the capability of considering the nonlinear behaviour of structure and soil; and the potential to model pile soil pile structure interactions. Time dependent results can be obtained and more intricate conditions such as battered piles, slopes, excavations, tie backs, and construction sequencing can be modelled. The method can be used with a variety of soil stress strain relationships, and is suitable to analyze pile group behaviour, as described in next Section. The implementation of three dimensional finite element analyses requires considerable engineering time to generate input and interpret results. For this reason, the finite element method has predominately been used for research on pile group behaviour, rarely for design.

4.3 Review of Numerical Studies

Soil structure interaction problem is a multidisciplinary subject which covers several areas of Civil Engineering. Virtually every structure is connected to the ground and the interaction between the artefact and the foundation medium may affect considerably both the superstructure and the foundation soil. The SSI problem has become an important feature of Structural Engineering with the advent of massive constructions on soft soils such as nuclear power plants, concrete and earth dams, buildings, bridges, tunnels and underground structures may also require particular attention to be given to the problems of SSI. The complexity of problem, due to its multidisciplinary nature and the fact of need of consideration of bounded and unbounded media of different mechanical characteristics, require a numerical treatment for any application of engineering significance. In the following sections we see the details of same.

4.3.1 Numerical Modelling of buildings

The widespread availability of powerful computers has brought about a great change in the computational aspect recently. Since the scope of numerical methods is incomparably wider than that of analytical methods, the use of general purpose numerical techniques has attained a sudden spurt to study the complex interactive behaviour. The methods are so general that it is possible to model many complex conditions with a high degree of realism, including nonlinear stress strain behaviour, non homogeneous material conditions, and changes in geometry and so on. A numerical model has been developed to estimate the response of the ground along with the pile foundation and concluded that pile experiences a mobility and large displacements in the direction of wave propagation (Figure 12) [14].
However, care must be taken about the possibilities of inaccuracy arising out of numerical limitations while Lehmann and Antes (2001) used the FEM BEM coupling model to investigate the structure soil structure phenomenon by giving a vertical load in the soil between the two structures. They found that this hybrid numerical model is suitable for analyzing the structure soil structure interaction problems. Emphasis was an application of FEM BEM coupling methods to SSI problems when more than one structure is present. But no such clarity is given in this study [32,60].

The attempt has been made to understand the seismic behaviour of tall buildings by considering the non-linear soil-pile interaction during strong earthquakes. In this study a 20 storey building is examined as a typical structure supported on a pile foundation for different conditions like rigid base, i.e. no deformation in the foundation; linear soil pile system and nonlinear soil pile system. The effects of pile foundation displacements on the behaviour of tall building are investigated, and compared with the behaviour of buildings supported on shallow foundation. The building was modelled as shear building and dynamic analysis is carried out using sub structure method. It has been concluded that the seismic behaviour of a tall building supported on a pile foundation is different from that on a shallow foundation or a rigid base. As Shallow foundation usually yields lower natural frequencies and much larger displacement amplitudes to both the superstructure and the foundation. The theoretical prediction for tall buildings fixed on a rigid base without soil structure interaction does not represent the real seismic response, since the stiffness is overestimated and the damping is underestimated [98].

The study has been extended for large embedded foundations in dams and tall buildings and observed that rocking and translation plays a major role in changing the response of system and it has been concluded that the rigid foundation doesn’t show any movements [96].

A combined Finite element based SSI model with consistent infinitesimal Finite Element Cell Method is used for modelling the soil region extending to infinity (far-field), and the standard Finite Element for the finite region (near-field) and the structure. By using this combined model, a computer program for harmonic and transient analyses of soil structure systems is coded. The model accuracy has been checked with various soil regions homogeneous, layered and top layer resting on a rigid bed rock. In order to decrease the computation time and achieve the solution of large scale problems, the model is parallelized. As a result of this parallel solution, significant time is saved for large scale problems [94,95,98].

Figure 12. Deviation of ground acceleration [14]
A parallel SSI model using a finite element based computer code has been proposed which contains finite and infinite elements for bounded and unbounded soil regions respectively. A sub structure method is applied to the soil structure system and the domain is represented by separate sub structures and interfaces. To check the accuracy of the model the results are compared with boundary element method. The study emphasized on validation of parallelized computer code by studying the already existing problems for which analytical solution is given. No significant comments about SSI phenomena have been given [87,100].

The seismic response of massive flexible strip foundations embedded in layered soils and subjected to seismic excitation has been formulated and the boundary element method (BEM) is employed to overcome the difficulties that arise from modelling the infinite soil domain, and the finite element method (FEM) is applied to model the embedded massive flexible strip foundation. The numerical solution for the soil foundation system is obtained by coupling the FEM with the BEM through compatibility and equilibrium conditions at the soil foundation and soil layer interfaces. A parametric study is conducted to investigate the effects of foundation stiffness and embedment on the seismic response. It has been concluded that SSI plays an important role and should be considered for both surface and embedded foundations when the difference of the stiffness between the foundation and the soil is large (81,74).

Gazetas (2004) studied the dynamic analysis of the rocking response of SSI problem by finite element discretization using ABAQUS. The response of shallow foundations subjected to strong earthquake shaking for nonlinear soil foundation effects associated with large deformations due to base uplifting and bearing capacity type soil failure were examined. Soil behaviour is represented with the elastoplastic Mohr-Coulomb model. It has been concluded that the initiation of uplifting and the mobilization of bearing capacity failure can be quite beneficial for the superstructure, under certain conditions related with the fundamental period of the structure and characteristics of ground shaking. In this study a nonlinear behaviour in the dynamic SSI analysis, sliding at the soil foundation interaction is not considered, but in reality this also incorporates nonlinear behaviour on soil foundation interaction [75,78].

Maheswari (2004) developed a numerical model for single pile and 2 x 2 symmetric pile group and soil nonlinearity taken in to account by HISS material model and the soil and pile interaction is achieved by Kelvin element. The study reveals the facts that for a harmonic excitation, the soil nonlinearity increases the pile head and structural responses at low frequencies (Figure 13, Figure 14)[5].

![Figure 13. Effect of nonlinearity on the response for a single pile model at different frequencies](image_url)
A new approach has been developed to carry out the analysis for separation causes at the pile head due to the inertia forces from the structure using existing time domain Winkler soil model (Hyperbolic soil constitutive model). The study observed that correction is necessary while dealing with separation of pile from soil domain during excitation. Effect of separation on the response depends very much on the level of nonlinearity, since accordingly various states i.e. separation, yielding and delinking are determined. Due to separation, there is increase in displacement while force is decreased which shows that stiffness of soil is decreased (Figure 15). Separation decreases the dynamic stiffness of the soil-pile system. As the level of nonlinearity increases, separation becomes more intense heading towards yielding and delinking and thus increasing the gap [5,17].

A procedure based on the viscous spring artificial boundary has been proposed and the modal superposition method, to analyze the dynamic SSI system in the time domain. The viscous spring artificial boundary introduced in this procedure transforms the infinite soil structure interaction system to an approximately finite system. A seismic wave input method is used to transform the wave scattering problem into the wave source problem. The modal superposition method is then applied to this approximate finite system. The solution procedure is realized in NASTRAN (developed by NASA), well known Finite element analysis software. Two examples are given to demonstrate the precision, stability, and computing efficiency. The first
example investigates a wave motion problem in a uniform semi infinite space. The second example analyzes the response of soil structure under seismic excitations. The results showed that proposed method with only a few modes can significantly reduce the computational time with almost the same precision as the traditional direct integration method. Followed by this Kham (2006) studied the site city interaction using 2 D boundary element method subjected to vertically incident wave. To investigate such phenomena, called site city interaction (SCI) herein, two simplified site city configurations are considered, one building configuration with same building and same spacing between them and other configuration in which different buildings with different spacing between them. These 2D boundary -element method models are subjected to a vertically incident plane SH waves. It has been observed that building density and city configuration play a major role in energy distribution inside the city [26,31,34]. A soil pile interaction using Winkler’s nonlinear model numerically and the response of the pile has been compared with the 3-D FEM model and centrifuge model [41].The study concluded that once the behaviour enters in plastic condition the p-y model shows large deviation from the experimental results whereas 2D FEM approach has good agreement with the experimental results (Figure 16).

![Figure 16. continuum model for laterally loaded pile acting on (a) pile (b) soil adjacent to pile](31]

Petropoulos (2008) studied the SSI problem by considering the source and path effects coupled with simulation of building response in the region of interest. To perform simulations of a sub-region the Domain reduction method is used and new parallel computing procedures have been developed for scalable computation. They have taken the data from the Great Los Angeles Basin area and the ground motion used to generate the seismic input is for a magnitude 7.1 rupture of the Puente Hills fault. It has been concluded that the multi scale simulation method using the domain reduction method provides an efficient approach for the simulation of site response and SSI effects [45].

Wegner (2009) studied structural response of a two way asymmetrical multi-storey building model subjected to bi directional harmonic and earthquake loadings. The time histories of the vertically and horizontal displacements and rotation of the roof are obtained using the scaled boundary finite-element method. The program Dynamic Soil Structure Interaction Analysis (DSSIA-3D, Wegner, 2009) which takes into account the soil structure interaction
effects is applied to study two way asymmetrical buildings. These results are compared with those of symmetrical buildings. It has been observed from this study that in case of asymmetrical buildings the lower to medium sized (up to 15 storey) buildings incurred the most impact from the earthquakes. The mass effect is not a major influential factor for tall buildings. It has been observed that asymmetrical building coupled with the two way asymmetrical earthquake loadings amplified the damages to the structure compared with symmetrical buildings [108].

Padron et al. (2009) studied the dynamic structure SSI of nearby piled buildings under seismic excitation by using BEM FEM model. From their study it has been concluded that SSI effects on group of structures with similar dynamic characteristics are important and also system response can be either amplified or attenuated according to the distance between adjacent buildings. Also it has been observed that when Rayleigh waves impinge in the same direction of alignment of structures, the first building to be hit suffers the largest displacements and at the same time shielding effect become apparent. Mao (2009), considered a real high rise frame shear-wall structure in Fujian province of China as an example to study the influences of soil-structure interaction on the super-structure using Finite element modelling. In this simulation, total 3 analysis steps are set gravity load, dead load and live load and seismic load are applied in the three sequence steps. The peak response of absolute acceleration, story drift, moments at beam ends, as well as inner force of columns and shear walls are analyzed under two orthogonal horizontal directions seismic excitations. Then the influences of field nonlinearity on seismic response of high-rise building are summarized and the rationality of reduction factor for soil-structure interaction calculation specified in Chinese seismic code is discussed. It is concluded that it’s usually safe for most stories of the high-rise frame shear-wall structure when the soil-structure interaction considered according to Chinese seismic code; however, the seismic response of structural member may be amplified in some stories, so it is unsafe in such regions [92,102,110,107]

Pitilakis (2010) proposed an equivalent linear substructure approximation of the soil–foundation–structure interaction system. Based on the inherent linearity of the approach, the solution of the structural and the soil domain is obtained simultaneously, incorporating the effects of the primary and secondary soil nonlinearities. A numerical code MISS3D has been developed to perform soil–foundation–structure interaction analyses in the three-dimensional linear elastic or viscoelastic domain, based on the substructure method. MISS3D is extended in order to model the nonlinear soil behaviour through an equivalent linear approach, resulting in a numerical tool named MISS3D-EqL. The proposed approximation is established theoretically and then validated against centrifuge benchmark soil–foundation–structure interaction tests [72,54,55].

Maheshwari (2011) carried out a soil pile interaction in liquefiable soil medium. Three dimensional soil pile-structure systems modelled with a finite-element code developed in MATLAB. Frequency dependent Kelvin elements (spring and dashpots) were used to model the radiation boundary conditions and soil nonlinearity was modelled by work-hardening plastic cap model. The study concluded that the bending moment owing to liquefaction is drastically increased at the transition zone between the liquefying and non-liquefying soil medium. Christoph Knellwort, Herve Peton and Lyesse Laloui (2011) discusses several is issues pertaining to heat exchanger piles. This paper presents a geotechnical numerical analysis
method based on the load-transfer approach that assesses the main effects of temperature change on pile behavior.

Mohmoud Ghazavi, Omid Tavasoli (2012) presented numerical analysis of pile driving for tapered piles. A three-dimensional finite difference analysis for tapered angle and geometry effects has been used on pile driving response of tapered piles. Generally speaking tapered and partially tapered piles offer better drivability performance than cylindrical piles of the same volume and length. A soil-pile system has been simulated for pile driving phenomenon using a three-dimensional model for non-uniform cross section piles using FLAC3D. Y. Xiao, L Chen(2012) discussed steel H shaped piles which are widely used in bridge foundation. The paper reports experimental results from monotonically loaded static tests on model steel H pile to pile-cap connections, in which the piles were subjected to tensile loading or horizontal loading with the bending in the strong or weak bending directions of the H pile. The tests indicate that H pile footing connections were effective in transferring vertical and lateral loads. The study also show that FEM analyses can capture the load and deformation relationship and load carrying capacity of the steel H pile to pile-cap connections satisfactorily. Yaru Lv, Hanlong Liu, Xuanming Ding and Ganpolang Kong F(2012) investigated the behaviour of X-section cast-in-situ concrete piles. A series of static load tests for piles foundations are conducted on the basis of a soft soil reinforcement engineering for a sewage treatment plant in the north of Nanjing, China. Comparative analysis between an XCC pile and a circular section concrete pile with the same cross sectional area indicates that XCC pile shows increasing pile-soil stress ratio and reduce settlement. It has been found that pile spacing is an important factor in XCC piles and the XCC pile should be considered as special friction file owing to high skin friction sharing. Above all, XCC can significantly increase ground-bearing capacity. Kampitsis et al (2013), developed a 3-D New-Beam approach based on the Boundary Element Method (BEM) to describe the phenomenon of soil pile structure interaction. The study explains the soil stratification with the soil interface as a Kelvin–Voigt element and soil nonlinearity captured by the means of a hybrid spring configuration consisting of a nonlinear (p–y) spring connected in series to an elastic spring damper model. The approach is validated with the existing numerical tool and found that the approach is efficient and accurate [48,66,76,85]. Varun et.al (2013) developed a macro element for soil structure interaction analyses of piles in liquefiable soils, which captures efficiently the fundamental mechanisms of saturated granular soil behaviour. He developed a mechanical model taking the base of a nonlinear Winkler-type for soil resistance acting along the circumference of the pile, and a coupled viscous damper that simulates changes in radiation damping with increasing material nonlinearity. Validation of the macroelement conducted using full-scale forced vibration test data from a blast-induced liquefaction test bed, and centrifuge data for seismic loading of piles with superstructure. It has been found that the macroelement parameters are estimated as a function of the measured soil properties and the level of effective stress. Predictions of bending moments and acceleration time histories at the top of pile and the superstructure are found to be in good agreement with both the full and the model scale data [105]. Hokmabadi (2014) carried out a 3-D nonlinear numerical analysis on the friction pile including the soil pile interaction for different ground motions and concluded that the base shear which will be the stability measure for the superstructure (Figure 17), will be more in friction piles as compared to the shallow foundations and frames supported with the frictions piles achieves a better life safety limit as compared to the other type of foundations (Figure 18) [2,116].
In all the above studies they have considered the buildings as shear type buildings and the soil as homogeneous, linear, elastic medium. But the dynamic structure soil structure interaction of nearby buildings has not been studied by considering fully framed structure with heterogeneous soil, material nonlinearity, nonlinearity in the super structure.

4.3.2 Numerical methods for efficient computation

4.3.2.1 Finite Element Method

FEM is an efficient common computing method widely used in civil engineering, discretizes a continuum into a series of elements with limited sizes to compute for the mechanics of continuum. FEM can simulate the mechanics of soil and structure better than other methods, deal with complicated geometry and applied loaded and determine non-linear phenomena. FEM is used frequently in the study of SSI and has produced some notable achievements in the field of SSSI. The development level of hardware and software has restricted the application of FEM in SSSI.
4.3.2.2 Boundary Element Method

A new numerical method developed after FEM only discretizes the boundary of the definition domain. It is different from the discretization of total continuum and uses functions satisfying the governing equation to approximate boundary conditions. The BEM is more advantageous compared to FEM because it requires only a surface discretization and satisfies automatically the radiation condition without any need for using special complicated non-reflecting boundaries as required by FEM by Wang S (1992). One disadvantage of BEM is its difficulty of application in the case of a heterogeneous medium [68,114].

4.3.2.3 Finite Element Method Boundary Element Method

Owing to respective disadvantages of FEM and BEM the coupling method of FEM and BEM was developed in the field of SSSI in 1990s. This method shows the advantages of both FEM and BEM. FEM is used for simulation of superstructures, foundations and near field soils whereas BEM is used for far field soil [67,117].

4.3.2.4 General Finite Element Program

At present there are a large number of available commercial finite element programs which have friendly interface and powerful nonlinear solver. They process well and are easy to master for users with great generality and therefore are very popular among SSI studies. When we are applying them to study SSSI, the biggest problem lies in how to solve huge calculations among brought by the large range of soil. Some common programs are ANSYS, ABAQUES, MSCMARC.

5. CONCLUSIONS

The review of current state of the art of the modelling of frame structures supported on pile foundations leads to the following broad conclusions.

1. To accurately estimate the response of structure, the effect of soil structure interaction is needed to be considered under the influence of both static and dynamic loading.
2. Finite element method has found to be very useful method to study the soil structure interaction effect with rigor. In fact, the technique becomes useful to incorporate the effect of material nonlinearity, no homogeneity and interface modelling of soil and foundation.
3. Although some attempts have been made to study the interaction effect of framed structures supported on pile foundations, still a detailed analysis considering the nonlinear soil model and gap separation between pile and soil has not been addressed.
4. From the study reviewed in above section it has been observed that in spite of acquisition of accurate results for representing soil as Winkler spring, the effect of passive resistance of soil (which comes from full scale soil pile model) also plays a major role in the response of system.
5. A very few research has been carried out on slender and Asymmetrical buildings with pile foundation. It has been observed that asymmetrical building with shallow foundation is been presented by few researchers but no attempt is made for deep foundation system.
6. Considering the present literature on pile soil interaction the research on complete three dimensional models representing the soil-pile-frame structure interaction system with nonlinear soil model is not carried out so far.

REFERENCES


