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STATE OF STRESS OF A SFSI SYSTEM OF PILE SUPPORTED FRAME STRUCTURE - LINEAR AND NONLINEAR ANALYSIS

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Abstract

Experiences from past earthquake disasters clearly shows that the ground motion was responsible for majority of property and life loss. Among the collapsed structures during the 1964 Niigata earthquake, the 1995 Kobe earthquake, the 1999 Koceli earthquake, the 2001 Bhuj earthquake and the 2004 Sumatra earthquake, excessive damage was occurred to pile supported bridges, towers, chimneys, high rise structures, etc. In view of this, there is a need to study the complex behaviour of soil-pile-structure interaction problems.

In this research paper, a numerical study is carried out to understand the dynamic soil Foundation structure interaction (SFSI) of a framed structure supported on a pile foundation. For that purpose a 5 storey pile supported framed structure is modeled and the behaviour under strong earthquake excitations associated with nonlinear material behaviour is studied. A peculiar behaviour in the stress state of pile in the SFSI system is observed. This behaviour is because of Soil resistance acting downward along the pile shaft because of an applied transient load. Also, the comparison of linear and nonlinear stress states and the effect/significance of soil plasticity on the stress states are commented.

Keywords: Soil Foundation Structure Interaction; Soil Plasticity; Pile Foundations; Fame Structure; Stress States.

1. Introduction

In the past, in the analysis and design of engineered structures, it was assumed that the foundation of structure was fixed to a rigid underlying medium [1,2]. However from the investigations following the major earthquakes in the past, it has been evidenced that response of soil to dynamic loads is playing a role in the damage. The behaviour of it becomes much complex, when it interacts with the structure and substructure, making the soil-structure interaction analysis as an important factor in dynamic analysis.

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 [3] except a few studies as described in the following section. The work on Soil structure Interaction analysis of frame structures supported on pile foundations has been started by Buragohain in 1977 [4]. After that hardly any work was reported on the same till 2000, when Cai, et al. developed a three-dimensional nonlinear Finite element subsystem methodology for studying the seismic soil–pile–structure interaction effects. In which the plasticity and work hardening of soil are considered by using δ* version of the HiSS modelling [5]. Later Yingcai in 2002 [6] studied the seismic behaviour of tall building by considering the non-linear soil-pile interaction, in which a 20-storey building is examined as a typical structure supported on a pile foundation using DYNAN computer program, leading to the conclusion that the theoretical prediction for tall buildings fixed on a rigid base without soil-structure interaction fails to represent the real seismic response, since the stiffness is overestimated and the damping is underestimated.

Besides, in 2003 Lu studied the dynamic soil structure interaction of a twelve storey framed structure supported on raft pile foundations using ANSYS, in which the influence of the following parameters soil property, rigidity of structure, buried depth, dynamic characteristics on SSI is studied [7]. Along these lines Chore and Ingle reviewed and presented a methodology for the comprehensive analysis of building frames supported by pile groups embedded in soft marine clay using the 3-D finite element method. The effect of various foundation parameters, such as the configuration of the pile group, spacing and number of piles, and pile diameter, has been evaluated on the response of the frame [8].

Later Chore in 2010 developed a Finite Element model to study the effect of soil-structure interaction on a single-storey, two-bay space frame resting on a pile group embedded in the cohesive soil (clay) with flexible cap [9]. Recently Deepa in 2012 did a Linear static analysis using commercial package NISA on a four bay frame, from which it has been observed that SSI effects increased the responses in the frame upto the characteristic depth and decreased when the frame has been treated for twelve storey RCC frame structure resting on pile foundations full depth [10].

Vivek in 2012 presented a review on interaction behaviour of structure-foundation-soil system. In which he gave a brief description of research done by various researchers on linear, nonlinear, elasto-plastic, plastic soil structure interaction effects under static and dynamic loading conditions [11]. Recently Sushma in 2013 presented a literature pertaining to SSI analysis of framed structure supported on pile foundations, from which it has been concluded that most of studies reported till now has considered the marginal effect of soil structure interaction. But to have a good understanding on the actual behaviour of the system there is a need to evaluate the effect of SSI on the response of high-rise structure by considering soil plasticity and interface effects [12].

More recently in 2015, Aamidala et al., proposed a simplified method to study the effect of soil structure interaction on rigid framed structure. In which they have observed that instead of using expensive 3D models to understand the effect of SSI, simplified methods can also efficiently analyze them [13]. Also Aslan et al., in 2015 conducted shake table tests on 5, 10 and 15 story structures with real earthquake events for two different cases fixed base analysis and structure supported by end bearing pile on soft soils. From the test results it is observed that the rocking component plays an important role in increasing the lateral deflection of the superstructures, by shifting the performance level of the structures to near collapse there by signifying the importance of seismic SPSI in the seismic design of buildings resting on soft soils [14].

In this paper a numerical study is carried out to understand the seismic performance of super structure by considering the complex dynamic interaction between Super structure, the Pile Foundation and the Soil. For this purpose a commercially available Finite Element program is used to model soil structure interaction analysis of pile supported frame structures [15]. The main objective of this paper is to focus on the Stress state of the SFSI system by modeling the nonlinearities of soil.

2. Model Description

The system under consideration comprises of framed structure supported on pile groups embedded on a visco elastic half space. A plane sketch of the problem is given in Fig. 1, with geometric properties of building and piles labeled. The pile groups are defined by length l and sectional diameter d of the pile and L be the width of pile cap. The structural height is given by h.

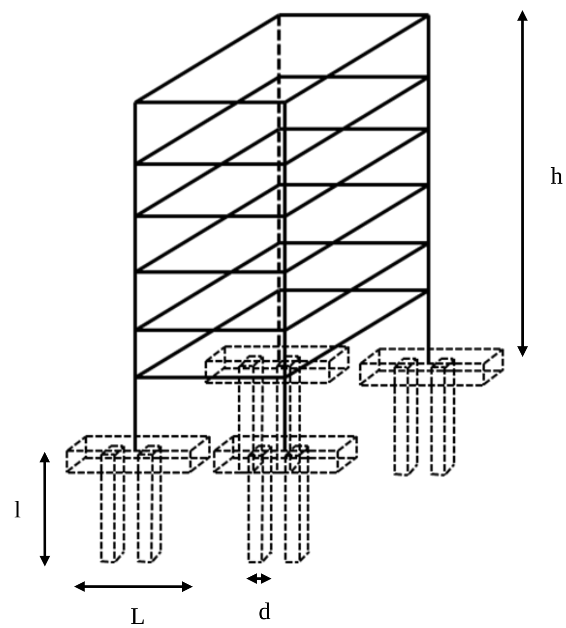


Fig. 1 – Schematic diagram showing the Pile supported Frame Structure

3. Numerical Modeling of Soil Pile Structure System

A three dimensional finite element model of soil-pile frame system of width 30m, length 30m and height 18m as shown in Fig. 2 is considered and is modeled using commercially availabe Finite element program. The soil and pile were modeled using eight-node hexahedral elements called brick element. Each node has three degrees of freedom that is translation u_x in x, translation u_y in y direction and translation u_z in z direction. Frame has been modeled by using Frame element.

Generally SSI analysis procedures include direct approaches in which the soil and structure are modeled together and analyzed in a single step and substructure approaches where the analysis is broken down into several steps. In this study direct approach is used, where the pile, soil and frame system are modeled together in a single step accounting for both kinematic and inertial interaction. Inertial interaction develops in structure due to own vibrations gives rise to base shear and base moment, which in turn cause displacements of the foundation relative to free field. Kinematic interaction develops due to presence of stiff foundation elements on or in soil cause foundation motion to deviate from free field motions. The seismic loading is applied as transient loading

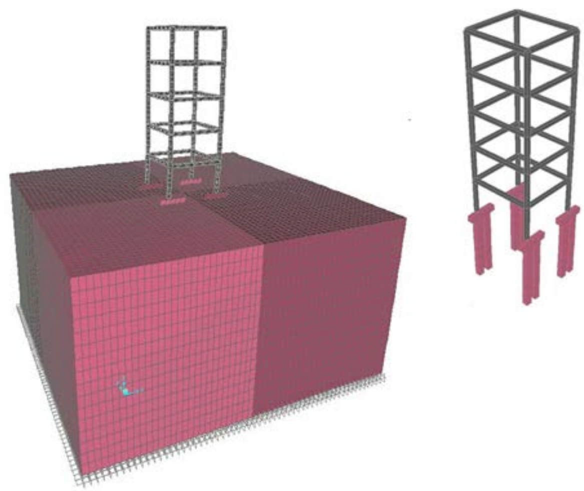


Fig. 2 – Finite Element Model of Soil Pile Frame System

accelerating the whole system. The resulting response of soil structure interaction system is computed from the following equation of motion

$$[M]\left\{\ddot{u}\right\} + [c]\left\{\dot{u}\right\} + [k]\left\{u\right\} = -[M]\left\{\ddot{u}_{gs}\right\} \tag{1}$$

Where $[M],[C],[K]$ *are mass, damping and stiffness matrices*

$\ddot{u}_{as}$ *Acceleration inside the soil*

$u, \dot{u}, \ddot{u}$ *are displacement, velocity and acceleration of the system* [16]

In dynamic analysis the above Eq. (1) is constructed in incremental form using the Newmark average acceleration method which is unconditionally stable for any time step Δt.

3.1. Boundary Conditions

The pile is completely embedded in the soil and it is assumed that soil and pile are perfectly bonded, so separation between soil and pile is not considered. For dynamic analysis, the bottom edge is fully constrained in all directions to model the rigid bed rock and the nodes along the top surface and two lateral surfaces of the mesh are free to move in all directions.

3.2. Model Parameters

The material properties of soil, pile and frame are given in Table 1. It is assumed that pile is made up of concrete and has a square cross section with each side equal to 0.5 m. Four pile groups of 2X1 piles of length 6m and spacing of 0.5 m is considered. The length of the pile cap is taken as 2.5m. The frame considered is regular one which is widely used in constructions with one bay 5 stories with beam size 0.3m, column size 0.3m and storey height equal to 3m and it is modeled as elastic material.

Only nonlinearity of soil is considered in this study and the yield strength in compression is taken as 25 kN/m^2 and yield strength in tension is taken as 10% of yield strength in compression. To account for nonlinear material behaviour Mohr Coulomb yield function is used. This function, which has units of stress, depends on the material strength and invariant combinations of the stress components. The function is defined such that it is negative within the yield or failure surface and zero on the yield or failure surface. Positive values of F imply

Table 1 – Material Properties

Material	Youngs Modulus (kN/m^2)	Density (t/m^3)	Poisson's Ratio
Very Soft Clay	15 x 10^3	1.8	0.4
Concrete Pile	25 x 10^6	2.4	0.2
Concrete Frame	25 x 10^6	2.4	0.2

stresses lying outside the yield or failure surface (that is soil yield) which are undefined and which must be redistributed via the iterative process / increment analysis.

3.3 Seismic Loading

Earthquakes induce two components of motion one in the horizontal and one in the vertical plane, the amplitude of the later usually being considerably less and Since the two horizontal components are usually similar, the earthquake motion is applied in the form of a prescribed horizontal acceleration. For the transient motion, the NS component of 1940 Elcentro Earthquake, with peak ground acceleration equal to 2.93 m/sec^2 has been used.

For the transient loads the relationship type which indicates material nonlinearity is the hysteretic cycle, where the F-D relationship is developed for a system subjected to cyclic loading. Stiffness and response are evaluated at each time step. Between each displacement step, stiffness may change due to nonlinear material behavior, in which performance incorporates inelastic response. The nonlinear equations are solved iteratively in each time step and iterations are carried out until the solution converges.

4. Dynamic Analysis

The influence of SFSI on dynamic response of pile supported structure is addressed in this section. To have a good understanding on SFSI behaviour first the behaviour of Soil and Soil Foundation Interaction is studied.

4. 1. Free Field Soil

As a first case, the state of stress in the middle of free field soil along the depth is measured by giving NS component of May 18, 1940 Elcentro earthquake record as input to the soil system shown in Fig. 3. In order to be able to relate the effect of plasticity on free field response, the state of stress of linear and nonlinear systems are plotted as shown in Fig. 4a and Fig. 4b respectively. From the figures, it has been clearly observed that because of the consideration of soil yielding effects there is a considerable increase in the stress, which signifies that soil plasticity plays a major role in dynamic analysis.

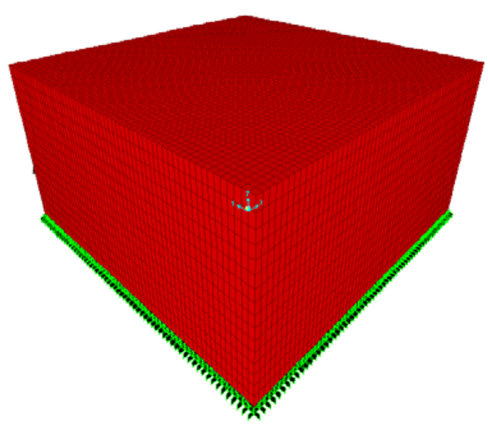
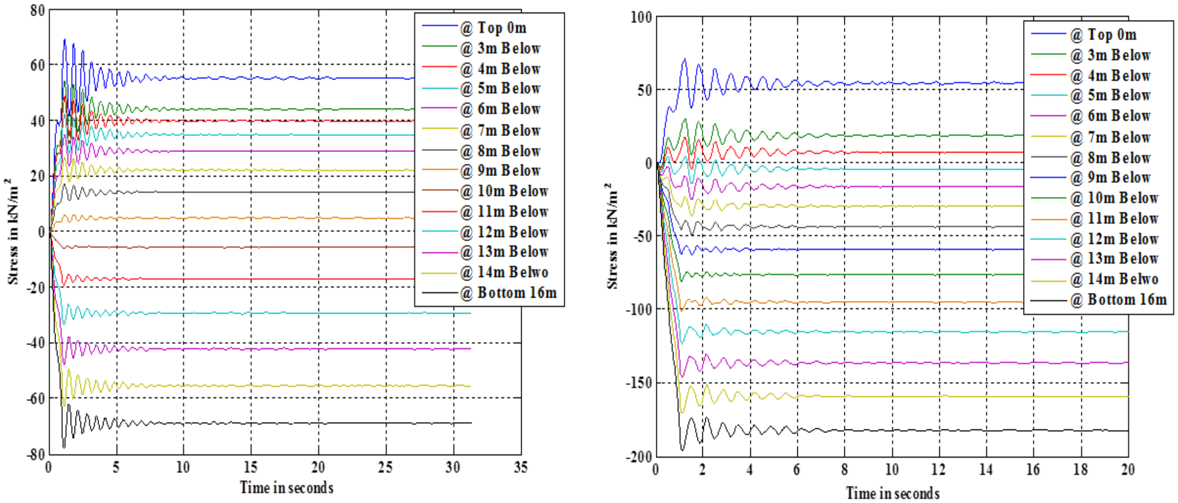


Fig. 3 – Finite Element model of Free Field Soil



(a) (b)

Fig. 4 – Variation of stress in the middle of Free Field Soil along the depth under May 18, 1940 Elcentro Earthquake (NS) a. Linear Case b. Nonlinear Case

4.2. Soil Foundation Interaction

Before finding the complex state of stress of the actual Soil Foundation Interaction (SFI) model (Fig. 5), first the state of stress of SFI of a single pile and soil (Fig. 6) is considered. Fig. 7a shows the state of stress of SFI of Single pile and soil for linear case. From the figure it has been observed that stress is maximum at bottom of the pile that is at the pile tip, with decreasing order of stresses in the rest of pile. Also at 1m above the bottom (pile tip) the stresses are tensile. This is due to resistance offered by the soil through skin friction, which acts downward along the pile under couple effect. Fig. 7b show the variation of stress along the length of pile for nonlinear case. The behavior of stress state is same as discussed for linear case except the change in magnitude of stress. This change in magnitude for nonlinear case is purely because of the effect of soil plasticity.

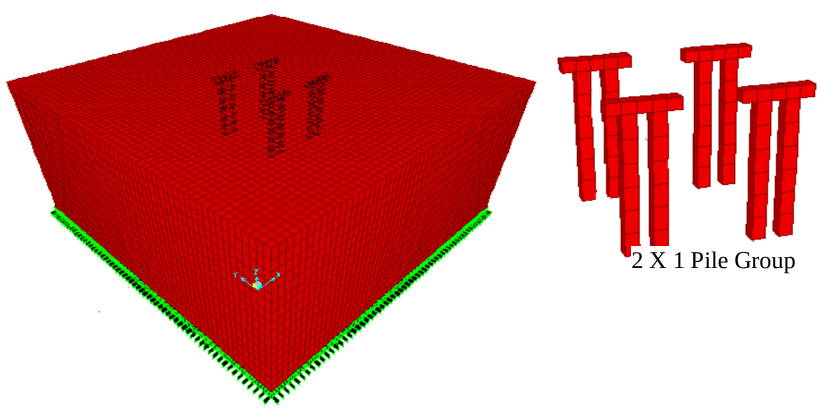


Fig. 5 – Finite Element Model of Soil Foundation Interaction Model

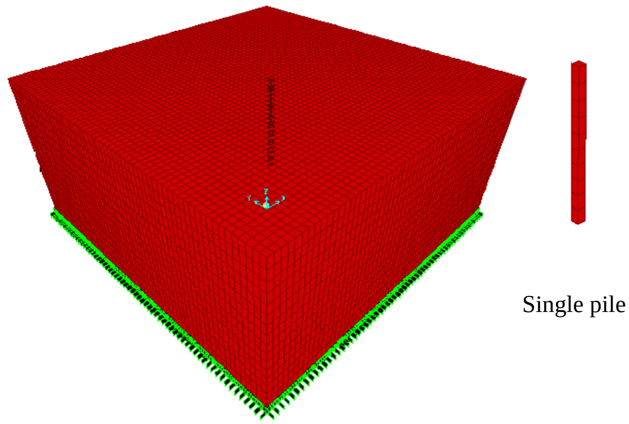


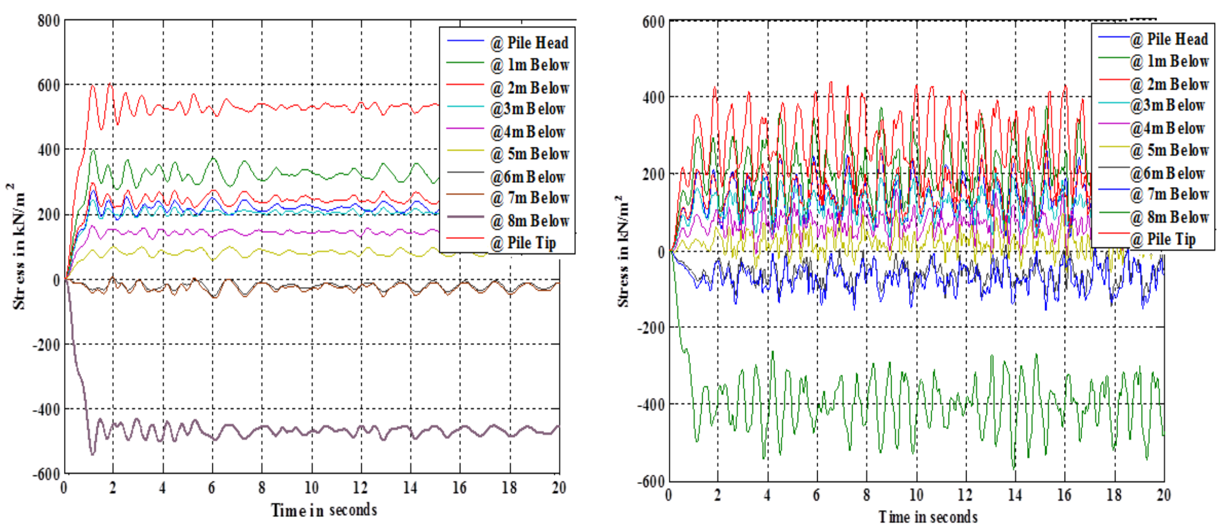
Fig. 6 – Finite Element Model of Soil Foundation Interaction Model of Single Pile

The effect of SFI of a pile group as shown in Fig. 5 is considered. Fig. 8a shows the variation of stress along the length of pile for linear case. The behavior on the state of stress, which has been observed in SFI of single pile, has been observed hear also (Fig. 7). That is stress is maximum at the bottom of the pile which is at the pile tip, with decreasing order of stresses in the rest of pile. Also at about 1m above the bottom (pile tip) the stresses are tensile. Fig. 8b shows the stress state of pile 2 under pile cap 1, this behavior is little different from the later behavior as here along with the soil resistance, the group interaction of pile with adjacent piles (piles under cap2) is also effecting the stress state.

Fig. 9 shows the variation of stress along the length of pile for nonlinear case. The behavior of stress state is same as discussed for linear case except the change in magnitude of stress. This change in magnitude for nonlinear case is purely because of the effect of soil plasticity.

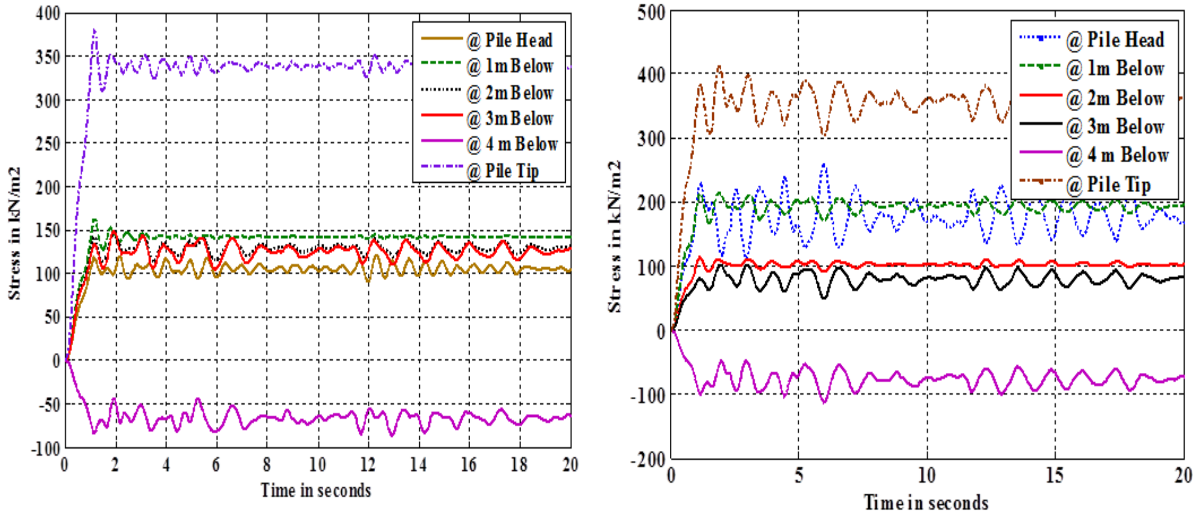
4.3 Soil Foundation Structure Interaction

A pile supported framed structure as shown in Fig. 2 is considered for the soil foundation structure interaction (SFSI) analysis. The NS component of May 18, 1940 Elcentro earthquake is given as input for the transient analysis. The behavior on the state of stress, which has been observed in SFI section, has been observed hear also (Fig. 8). But while comparing the stress states for SFI and SFSI, the stress levels are more for FI when compared to SFSI in both linear and nonlinear analysis (Fig. 10a and Fig. 10b). This decrease is because of the combined effects of inertial and kinematic interaction in later case.



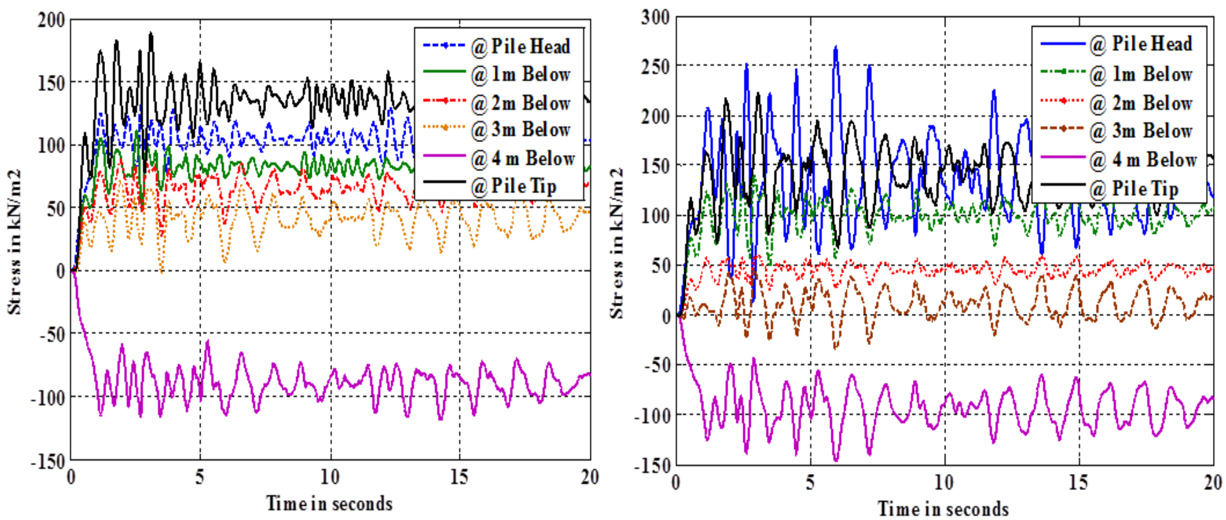
(a) (b)

Fig. 7 – Variation of stress along the length of pile under May 18, 1940 Elcentro Earthquake (NS) (Single Pile Soil) a. Linear Case b. Nonlinear Case



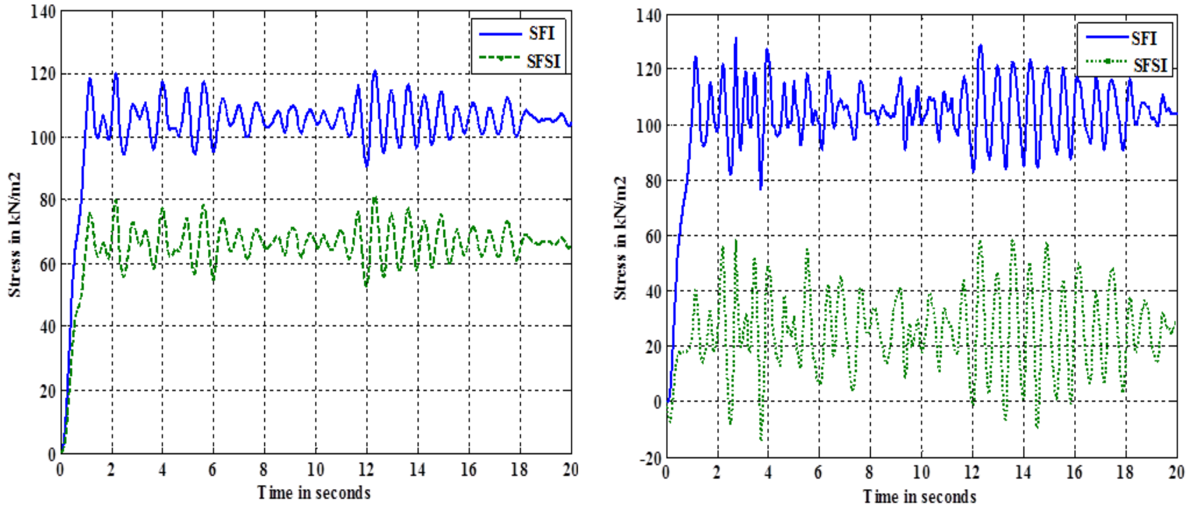
(a) (b)

Fig. 8 – Variation of stress along the length of pile under May 18, 1940 Elcentro Earthquake (NS) (2 X 1 Pile Group and Soil) a. Pile 1 under Cap 1 b. Pile 2 under Cap 2 (Linear Case)



(a) (b)

Fig. 9 – Variation of stress along the length of pile under May 18, 1940 Elcentro Earthquake (NS) (2 X 1 Pile Group and Soil) a. Pile 1 under Cap 1 b. Pile 2 under Cap 2 (Nonlinear Case)



(a) (b)

Fig. 10 – Comparison of stress at the pile head for SFI and SFSI under May 18, 1940 Elcentro Earthquake (NS) a. Linear Case b. Nonlinear Case

5. Summary and Conclusions

In this paper a numerical study is carried out to understand the dynamic soil Foundation structure interaction of a framed structure supported on a pile foundation. The primary focus is on the understanding the state of stress of the pile by considering Soil structure Interaction.

To understand the complex behaviour of state of stress of the piles by considering Soil Foundation Structure Interaction, First the state of stress of free field soil, single pile soil and group piles soil is studied.

In case of free field soil, because of the consideration of soil yielding effects there is a considerable increase in the stress values, which signifies that soil plasticity plays a major role in dynamic analysis.

In case of SFI of Single pile, a distinct behaviour of stress state has been observed. That is stress is maximum at the bottom of the pile that is at the pile tip, with decreasing order of stresses in the rest of pile. Also at about 1m above the bottom (pile tip) the stresses are tensile. This behavior may be because of Soil resistance acting downward along the pile shaft because of an applied transient load.

In case of SFI of a Pile group, the behavior on the state of stress, which has been observed in SFI of single pile, has been observed hear also. But when comparing the stress states of pile 1 under cap 1 and pile 2 under pile cap 1, the behavior is little different from the later behavior as here along with the soil resistance, the group interaction of pile with adjacent piles (piles under cap2) is also effecting the stress state.

While comparing the state of stress of linear and nonlinear cases, the change magnitude for nonlinear case is purely because of the effect of soil plasticity as under strong excitations the soil goes to nonlinear state.

While comparing the stress states for SFI and SFSI, the stress levels are more for FI when compared to SFSI in both linear and nonlinear analysis. This decrease is because of the combined effects of inertial and kinematic interaction in later case.

To produce a safe and economic design, there is a great need to find the structural response by considering the Soil Foundation and Structure Interaction.

Also while designing the piles care must be taken in designing the pile tip as suddenly above the pile tip level the stresses are becoming tensile.

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