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Dynamic Analysis of Soil Structure Interaction of Pile Supported Frame Structure

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Abstract— The Soil-pile-structure interaction is a complex phenomenon and which can affect the response of structure during dynamic excitation such as earthquake. To deal with such complexities, it is necessary to use numerical methods like Finite Elements for analyzing system behavior under dynamic excitation. In this paper, a five storied (G+4) two bay frame structures supported by pile group is considered for evaluation of structural response and soil structure interaction during transient event. The pile group is embedded in sandy soil mass. To simplify the full nonlinear transient dynamic problem, load time history is applied on edge of top structure beam in a lateral direction with triangular wave to predict structure response in one cycle. A Finite element method (FEM) based approach is used to model structure in ANSYS Mechanical using full transient method. The analysis load boundary conditions are derived from United States (US) Geological Survey for the creation of global shake map. This loads are typically observed high acceleration and damage levels during earth quake in past. The entire system is studied for five different peak loads with same frequency and structural responses are compared with and without soil effect under same dynamic load.

Index Terms— Dnamic Analysis, Finite Elements, Non-linear soil, Pile supported frame structure, Sandy Soil, Soil structure interaction, Superstructure deformation

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1 Introduction

The Civil engineering structures are always in contact with the ground to support the loads, as every structure is built to resist and transfer a combination of loads. The structural element that is in contact with the ground could sometimes be the structure itself or could be a structural component such as concrete footings, mat foundations, piles and drilled shafts. This resistance must be developed within serviceability and strength limits. There is mutual dependence of the structure and soil behavior during load transfer in time domain.

The influence of dynamic loads transfer on foundations is matter of concern as during earthquake there is massive damage to social eco-system. Thus the behavior of entire structural system during dynamic event is critical. To simplify SSI problem under dynamic event- generally, it is assumed the base of structure to be fixed, even in most of the situation foundation soil is flexible. This gross assumption is valid only when structure is established on relatively stiffer material than structure like solid rock. In all other cases, compliance of soil can induce two distinct effects on response of structure. There are mainly kinematic interaction and inertial interaction and entire process is referred as Soil-Structure Interaction (SSI). Kinematic interaction is all about modification of free field motion at the base of the structure and inertial interaction is the introduction of deformation from dynamic response of the structure into the supporting soil. Inertial interaction develops in structure due to own vibrations give 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.

Mainly two classical methods are adopted for dynamic analysis of soil-structure interaction: Direct Method and Substructure Method. Direct Method is one in which the soil and structure are modeled together in a single step accounting for both inertial and kinematic interaction. The response of the interacting system is computed from the following equation of motion [1]

$$[M]\{\ddot{u}\}+[C]\{\dot{u}\}+[K]]\{u\}=[M]\{\ddot{u}_{gs}\}$$

Where [M], [C], [K] are mass, damping and stiffness matrices; and u, $\dot{u}$, $\ddot{u}$ are displacement, velocity and acceleration of the system $\ddot{u}_{gs}$ input ground acceleration.

Sub-structure method is computationally more efficient, it allows the complicated soil-structure system is broken down into several steps that are the principal of superposition is used to isolate the two primary causes of soil-structure interaction, 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: The deformation of structure because of kinematic interaction only is calculated by considering only stiffness of foundation and effect due to it's mass is neglected. The equation of motion for this case is [1].

$$[M_{soil}]\{\ddot{u}_{KI}\}+[C]\{\dot{u}_{KI}\}+[K]]\{u_{KI}\}=[M_{soil}]\{\ddot{u}_{gs}\}$$

Inertial Interaction: The structure and foundation mass effect are considered during evaluation of deformations during dynamic event. The deformation due to inertial interaction is evaluated with following equation of motion [1].

$$[M\ ]\{\ddot{u}_{II}\}+[C]\{\dot{u}_{II}\}+[K]\{u_{II}\}=[M_{structure}]\{\ddot{u}_{KI}+\ddot{u}_{gs}\}$$

The solution to the entire soil-structure interaction problem is equal to the sum of the solutions of kinematic and inertial interaction analysis [2]. Smith [3] proposed the super position boundary condition to solve both the scalar and elastic wave propagation problems. The superposition boundary averages the solutions from two sets of boundary conditions corresponding to symmetry and anti-symmetry, which eliminate the reflected waves for a single boundary.

Pile Foundations: Pile foundation is the one of the best method of construction of foundation on soft soils. For simple structure, engineer is good to divide the design of major buildings into two components: structure and foundations. It is evident that the damage occurring at deeper part of piles is inherently difficult to detect and practically impossible to repair. Consequently, adequate provision in design is indispensable to make such damage as unlikely as possible.

2 Literature Review

Buragohain et al. [4] evaluated the space frames resting on pile foundation by means of the stiffness matrix method in order to quantify the effect of soil-structure interaction using simplified assumptions. On the similar lines, Cai, et al. [5] developed a three-dimensional nonlinear Finite element subsystem methodology to study the seismic soil–pile–structure interaction effects. In that study the plasticity and work hardening of soil have been considered by using δ* version of the HiSS modeling. Yingcai [6] studied the seismic behavior 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. Maheshwari [7] et al studied the 3D FEM nonlinear dynamic analysis for soil pile structure interaction. This model consists of two subsystems: a structure subsystem and a pile-foundation subsystem with material nonlinearity using HiSS model. Chore et al [8,9,10,11,12] reviewed the SSI analysis of framed structures and the problems related to pile foundations, and underscored the necessity of interactive analysis to build frames resting on pile foundations by more rational approach and realistic assumptions. They also 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. Later they also studied the effect of soil-structure interaction on a single-storey, two bay space frames resting on a pile group embedded in the cohesive soil (clay) with flexible cap. They have modeled actual interaction with the soil and foundation by replacing the foundation columns with springs. Deepa et al. [13] did a linear static analysis using commercial package NISA on a four bay frame. Sushma et al, [14] studied soil-structure analysis of framed structures supported on pile foundation with and without interface element in that she conclude that the acceleration response of the top floor has been reduced by two times, when contact between pile and soil has been modeled.

3 Scope of the Work

The objective of this work is to contribute to the understanding the static and dynamic performance of pile-supported structures and the sandy soil. The Finite Element Method is used to model soil structure interaction analysis of pile supported framed structures by programming in ANSYS.

3.1 FEM Model: A direct approach is used to model the soil structure interface (SSI) of five storied (G+4) space frame resting on pile foundation is considered for the purpose of the parametric study. The frame has total height of 15m, and is 10mX10m in plan with each bay of dimension 5mX5m. The height of each story is 3m. The slab is 200mm thick, is provided at the top as well as at the floor level. The slab at the top is supported by beams, 300mm wide and 400mm deep, which in turn rest on columns of size 350mm X350m. Below, Fig 1 shows plan and 3D view of structural system.

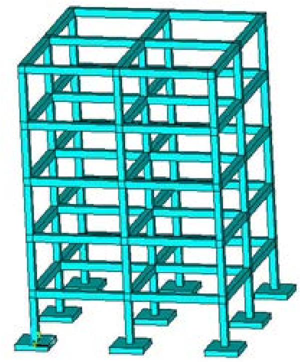

Fig. 1 –Structural System under Study

This design is governed based on **IS 456-2000** for building design. Each pile cap is supported by 4 square piles. A building frame is a three dimensional discrete structure consisting of a number of high rise bays in two directions at right angles to each other in the vertical plane. The vertical members are common to both sets of plane frames crossing each other. According to clause 6.1.5 of **IS1893** (part l) [22], for structures having lateral force resisting elements in the two orthogonal directions only, the design lateral force has to be considered along one direction at a time and not in both directions simultaneously.

Material Properties: Table 1 shows material properties used for FEM Analysis.

Table 1: Material Properties [5, 8]

Material Properties	**Corresponding Values**
Grade of Concrete used for the Frame Elements	M-20 (Ch Comp Strength: 20 MPa)
Young’s Modulus of Elasticity for Frame Elements	0.25491 × 108 kN/m2
Grade of Concrete Grade used for Pile	M-40
Young’s Modulus of Elasticity for Foundation Elements.	0.3605 × 108 kN/m2
Poisson’s Ratio (μc)	0.15
Modulus of Elasticity for soil Elements.	18050 kN/m²
Poisson’s ratio (μs)	0.3
Internal angle of friction (ϕ)	30

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4 Dynamic Analysis using Finite Element Analysis

The objective of this work is work is to understand the complex dynamic interaction between the soil, foundation and superstructure. In the similar lines of most of SSI analysis methodologies using FE approach, here author also simplified seismic analysis problem into inertia load problem. This is achieved by application of an Equivalent static load at the floor level.

Geometry and Boundary Condition: Fig 2 shows 3D FE model of large soil bin and structure along with pile and pile cap. The soil and pile were modeled using eight-node hexahedral elements. The soil is assumed to be sandy and the piles are made of concrete and have square cross section with each side 0.3m. The length of pile 5m with pile slenderness ration of 16.67. The numerical mesh size of all solid elements is taken 0.2m with total width of 19m and length of 19m with the height of 10m for soil bin.

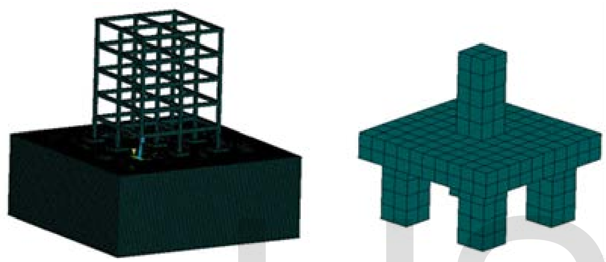

Fig 2: Finite Element Model Details

A nonlinear soil material model has been used to introduce the effect of plasticity. Soil model in this work is represented with Drucker-Prager yield criteria. Here, soil material model is represented with cohesion, angle of internal friction and dilatancy angle. In current work, soil considered is sandy soil and hence cohesion is taken as zero and angle of internal friction is considered as 30^{o} with dilatancy angle is zero. The piles and entire structure are assumed to behave as elastic material.

Load Intensity Derivation: Load intensity for analysis is derived based on seismic scale, which explains Peak Ground acceleration (PGA). PGA records the acceleration during earthquake. Generally, peak ground acceleration can be expressed in g's –acceleration due to gravity. Table 2 shows some of most damaging and high acceleration levels earthquake info and their PGA level.

For sensitivity analysis, 5 different analysis load cases are considered for dynamic anlyis of SSI. This acceleration levels are assumed from 0.7g to 1.1g to cover heavy earthquake conditions from table 2. From above information, load values are derived using Newton's second law as shows in table 3.

Table 2: Earthquake Detail Info

PGA	Mag	Depth	Fatalities	Earthquake
2.7g	9.0	30km	>1500	2011 Tōhoku earthquake & tsunami
2.2g	6.3	5km	185	Feb 2011 Christchurch earthquake
2.13g	6.4	6km	1	June 2011 Christchurch earthquake
1.7g	6.7	19kn	57	1994 Los Angeles earthquake
1.1g	7.3	8km	2415	1999 Jiji earthquake
0.8g	6.8	16km	6434	1995 Kobe earthquake

Table 3: Analysis Load Cases

Analysis case	Acceleration Level (g)	Beam total load (kN)
1	0.7	2000
2	0.8	2250
3	0.9	2500
4	1	2750
5	1.1	3000

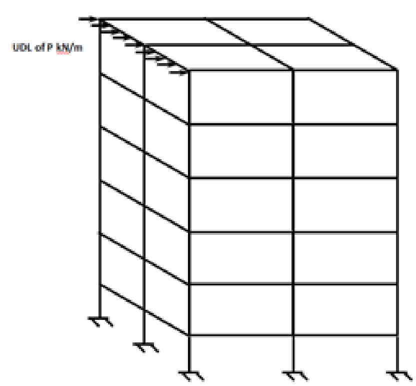

Fig 3: Load BC

This load intensity is applied as uniformly distributed load on entire face of top beam as shows in Fig3. Load Time History for Transient Analysis – In current techniques, solid element based approach is considered with displacement BC's remains same as explained earlier. Transient loads to beam surface is ap-

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plied as explained in following figure. All initial condition for analysis is set to ZERO and loads are applied in step as shows in Fig 4. An iterative (PCG Solver) approach is used to solve non-linear complex model in ANSYS.

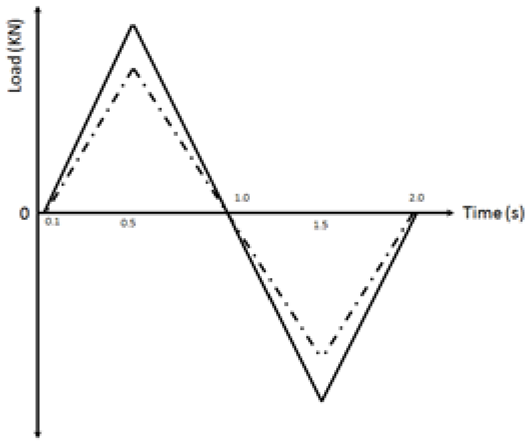

Fig 4: Lateral loads time history

5 Results and Discussion

Dynamic Analysis: Above mentioned FE model is run for total five analysis load cases to predict the effect of dynamic loading. This analysis is run for the model configuration of with soil and without soil effect.

Fig 5 shows load maximum displacement comparison of with SSI and without SSI Effect. It is observed that with SSI displacements are 16% higher than without SSI effect.

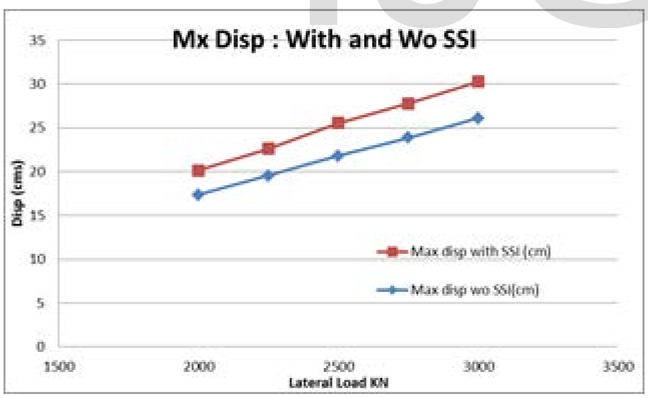

Fig 5: Comparison of Max disp with and without SSI Effect

Structure Response at all Floor Level: To compare structure response at all levels, peak load case (load of 3000kN) is considered. In the similar lines of above conclusion, displacement at all levels are higher in analysis with SSI but here % difference is higher is lower levels as compared to higher levels. The percentage increase in positive x- direction displacement due to consideration of the effect of SSI are 29.78%, 17.01%, 16.29%, 16.07%, 15.94% for the respective storeys. Fig 6 shows the displacement comparison at all levels with and without SSI.

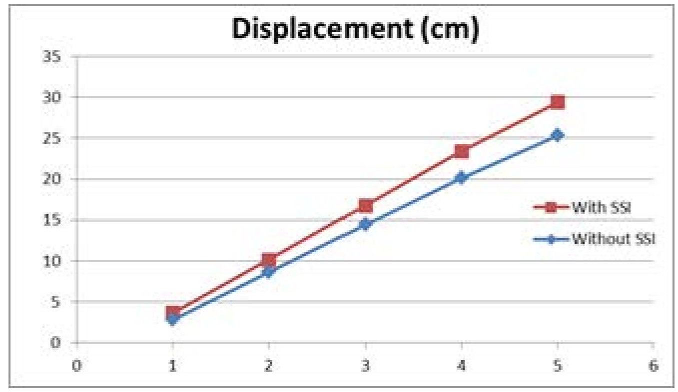

Fig 6: Comparison of displacement at all levels: with and without SSI

6 Conclusions

It is concluded from this analytical study, soil has significant contribution in structure response during dynamic events such as earthquake.

1) It is consistently observed that a displacement of structure for same loads increases around 16% for analysis with soil structure interaction in comparison with fixed base analysis.

2) For the same maximum load (3000kN), displacement at each level increases around 18% for the analysis with soil structure interaction as compared to fixed base analysis.

3) During dynamic simulation, displacements observed during loading in reverse (negative x direction) is consistently less that of forward (positive x direction) loading at peak force. This is due to inertia effect if structure.

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