SSI Analysis of Framed Structure Supported on Pile Foundations - With and Without Interface Elements

by

Sushma Pulikanti, Pradeep Kumar Ramancharla

in

Frontiers in Geotechnical Engineering (FGE)

Report No: IIIT/TR/2014/-1

Centre for Earthquake Engineering
International Institute of Information Technology
Hyderabad - 500 032, INDIA
May 2014

SSI Analysis of Framed Structure Supported on Pile Foundations - With and Without Interface Elements

Dr. Sushma Pulikanti*1, Prof. Pradeep Kumar Ramancharla*2

Earthquake Engineering Research Center,
International Institute of Information Technology Hyderabad, Gachibowli, Hyderabad, India.

*1sushmapulikanti@gmail.com; *2ramancharla@research.iiit.ac.in

Abstract

In this paper an attempt has been made to understand the Soil Structure Interaction behavior of pile supported framed buildings under transient loading by taking the interface effects between the pile and soil. For this purpose a three dimensional Finite Element Method is used for modelling the soil-pile structure interaction using SAP 2000. A single bay five storey framed structure with a pile group foundation is modelled. First the significance of soil foundation structure interaction over fixed base analysis is studied, it has been observed that the presence of soil and foundation make a considerable change in response with a shift of natural period of the system. Next, a parametric study has been done to understand the significance of interface behaviour on soil foundation structure interaction. From the results it has been observed that under transient loading the acceleration response of top floor is reduced by two times, when contact between pile and soil has been modeled.

Keywords

Soil Structure Interaction; Framed Structures; Pile Foundations; Interface Elements

Introduction

Experiences from past earthquake disasters clearly shows that when a soil pile structure model is subjected to seismic excitations, the soil surrounding the pile may be compressed laterally such that a soil pile gap separation may develop. These soil pile gap separations have been observed in the past, both in field and laboratory tests. After 1995 Kobe earthquake, the soil pile gap was observed in reclaimed port Island and also in 1989 Loma Prieta earthquake, the soil pile gap developed along the Struve Slough crossing (Chau et al., 2009). In view of this there is a need to study the complex behavior of soil-pile interaction problems using numerical methods.

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 on interaction analysis of frame structure resting on pile foundations (Ingle and Chore 2007) 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 et al. in 1977. 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 (Cai, et al., 2000). Later Yingcai in 2002 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 et al., 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. 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 (Ingle and Chore (2007) , Chore and Ingle (2008 a, b)).

Later Chore et al. 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. Recently Deepa et al., 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 up to the characteristic depth and decreased when the frame has been treated for twelve storey RCC frame structure resting on pile foundations full depth.

Vivek et al., 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. More recently Sushma et al., 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 have considered the marginal effect of soil structure interaction. But to have a good understanding of the actual behaviour of the system there is a need to evaluate the effect of SSI on the response of high-rise structure.

Three Dimensional Finite Element Model

There are two approaches to perform SSI analysis. First is direct approach and the second is sub-structure approach. In this study, direct approach is used, where the pile, soil and frame system are modelled together in a single step accounting for both kinematic and inertial interaction. The resulting response of soil structure interaction system is computed from the following equation of motion

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

Steven L Kramer, (2003)

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

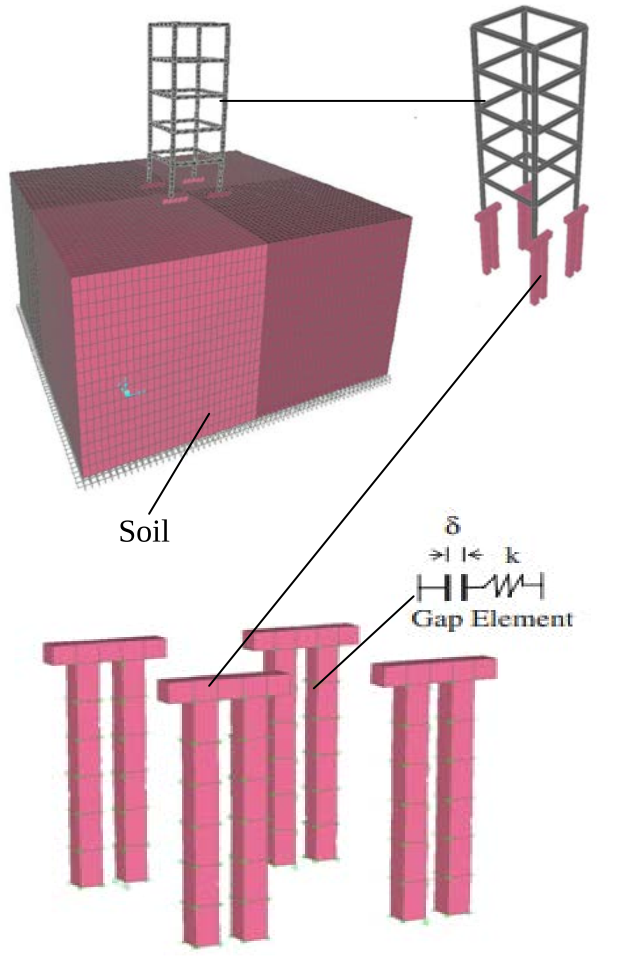
$\ddot{u}_{gs}$ *Input Acceleration*

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

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.

Model Formulation

The three dimensional finite element models of soil-pile frame system of width 30m, length 30m and height 18m as shown in Fig. 1 is considered and is modelled using SAP 2000. The soil and pile were modelled 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 modelled by using Frame element.



Pile with Link Elements

FIG. 1 3D FINITE ELEMENT MODEL OF SOIL PILE FRAME SYSTEM

The soil is assumed to be very soft clay and the piles are made of concrete and have square cross section with each side 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 modelled as elastic material. The material properties of the frame, pile and soil are given in Table1.

Boundary Condition

The bottom edge of the model is fully constrained in all three directions to model the rigid bed rock. The nodes along the top surface and four lateral surfaces of the mesh are free to move in all directions.

Pile – Soil Interface

In this study the effect of relative movement of soil and pile that is debonding / separation and rebonding of pile and soil is considered. To account for the discontinuous behavior at soil-structure interface many methods like use of thin continuum elements, linkage elements like discrete springs, special interface or joint elements, etc., are used generally (David et al., 1999).

SAP 2000 is used to model the separation / debonding of the pile, for that the "Gap element" in Link / Support properties is selected (Fig. 1). For the Gap element the force deformation relation as given in Eq. 2 is used. To model this gap element two input parameters have to be specified, one the spring constant and the other *d* the gap separation. The spring constant or contact stiffness *k* should be always 2 times stiffer than surrounding element, so the value has been taken as $50x10^3$ kN/m, with the gap separation of 0.01m.

$$f = \begin{cases} k\,(d+\delta)\ if\ \ d+\delta<0 \\ 0 \qquad\qquad\qquad otherwise \end{cases} \qquad (2)$$

Where δ *Intial gap seperation* $(\delta \geq 0)$;

k Contact Stiffness

Dynamic Analysis

The influence of Soil Foundation Structure Interaction (SFSI) on dynamic response of pile supported structure by taking interface modelling is addressed in this section by giving NS component of May 18, 1940 Elcentro earthquake as input. First the significance of SFSI over fixed base analysis is studied.

Significance of Soil Foundation Structure Interaction over Fixed base Analysis

To understand the significance of SFSI over the fixed based analysis (FBA), in this section SFSI results are compared with fixed based analysis results. For this purpose a pile supported framed structure as shown in Fig. 1 (without Interface Elemnts) is considered for the soil foundation structure interaction (SFSI) analysis and a framed structure as shown in Fig. 2 is considered for fixed base analysis. The dynamic analysis is carried out by giving NS component of Elcentro earthquake as input.

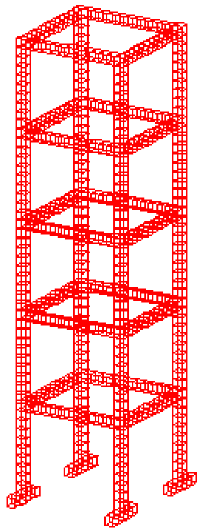


FIG. 2 3D FINITE ELEMENT MODEL OF FRAME STRUCTURE

First and foremost, a modal analysis is done for both the cases SFSI and FBA, to know the period of vibration corresponding to fundamental frequency, called characteristic site period. This provides a very useful indication of period of vibration at which the most significant amplification is expected. For FBA system the fundamental period is 0.6528 sec where as for SFSI system it is 1.238 sec. From this it has been clearly understood that by neglecting the interaction of soil, foundation and structure in the actual analysis, the fundamental period of the system is under estimated and so there will error in finding the significant amplification under strong ground motion.

Secondly, a dynamic analysis is carried out to find the response of the FBA and SFSI system. In order to relate the SFSI and FBA effects, the top floor response of FBA and the top floor response of the frame with SFSI are plotted as shown in Fig. 3. From the figure it has been observed that increase in response for SSI when compared to fixed base is because accounting for the kinematic and inertial interactions in later case. That is in this ground acceleration is getting altered before reaching the surface because of presence of soil that is site effect and also the presence of stiff foundation elements that is kinematic interaction.

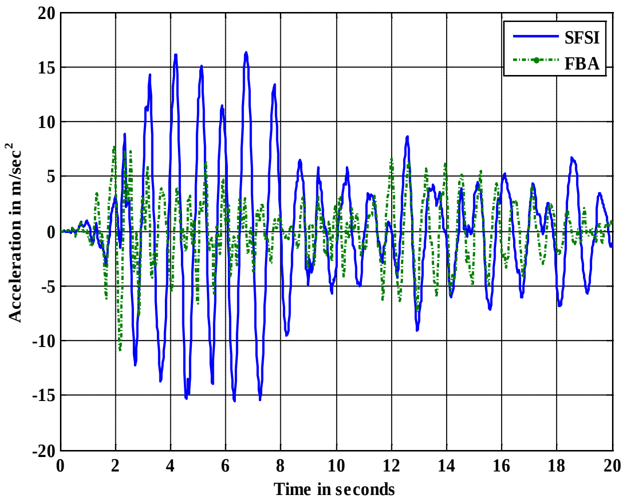


FIG. 3 COMPARISON OF ACCELERATION RESPONSE SFSI AND FBA SYSTEMS UNDER MAY 18, 1940 ELCENTRO EARTHQUAKE (NS)

Thirdly, in case of soil foundation structure interaction system the presence of soil and foundation making a considerable change in response with a shift of natural period of the system as shown in Fig. 4. This shift of period is observed as soil and foundation elements are playing a major role in the response. At the time of shaking there is a change in dynamic characteristics of the soil. The stiffness and damping characteristics of soil may change significantly because of the interaction effect. Also it has been observed that soil between the two piles is more stressed which is the reason for the increase in the response of structure.

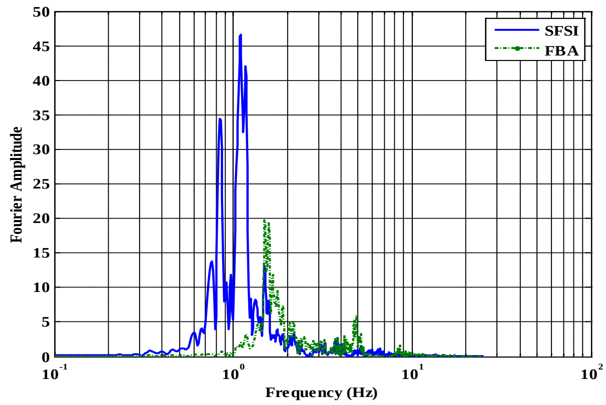


FIG. 4 COMPARISON OF FOURIER TRANSFORM OF SFSI AND FBA SYSTEMS UNDER MAY 18, 1940 ELCENTRO EARTHQUAKE (NS)

Significance of Interface Behaviour on Soil Foundation Structure Interaction

A pile supported framed structure as shown in Fig. 1 is considered for the soil foundation structure interaction (SFSI) analysis in this section. Fig. 5 and Fig. 6 show the response and Fourier Transform of the SFSI With and without link elements. From the response we can clearly see that there is an increase in response for the analysis without link elements. But in reality due to loss of contact between pile and soil during strong ground motion, there will be much decrease in response. So by considering all these effects in our analysis make our prediction close to reality.

To understand this complex behaviour in detail, a parametric study has been carried out for different soils namely very soft clay, soft clay, medium clay and hard clay with modulus of elasticity ranging from 15000 kN/m² to 100000 kN/m². Fig. 7 and Fig. 8 show the repose and Fourier Transform of SFSI system with link elements. From the Fourier amplitude spectrum we can clearly see that there is shift in frequency for very soft clay to hard clay. So to have a good understanding on the structural response for different clays for with and without interface elements, the responses and Fourier transform are plotted as shown in Figs. 9, 10, 11, 12.

From the responses it is very clear that for various soils considered in this study, the acceleration response of structure with Link elements is less when compared to acceleration response of structure without link elements except for hard clay. This reduction in response is because of formation of gap between pile and soil under dynamic loading. But in case of hard clay there is not much of gap separation

Between pile and soil under dynamic loding and the magnitude of response is the same. So depending on the type of soil, must take care in designing the building.

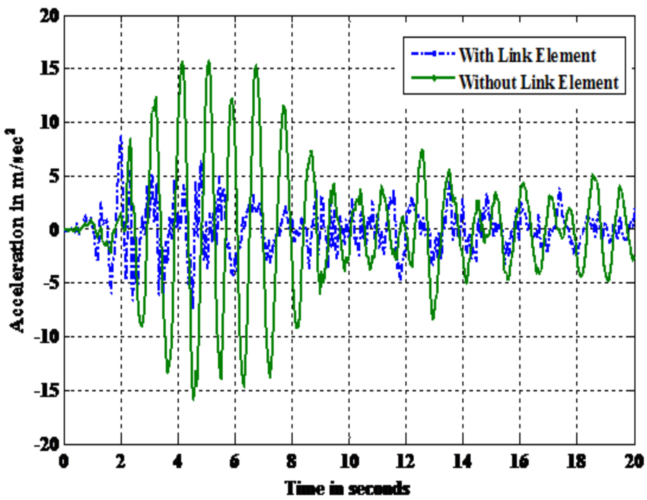


FIG. 5 COMPARISON OF ACCELERATION RESPONSE OF TOP FLOOR WITH AND WITHOUT LINK ELEMENTS UNDER MAY 18, 1940 ELCENTRO EARTHQUAKE (NS)

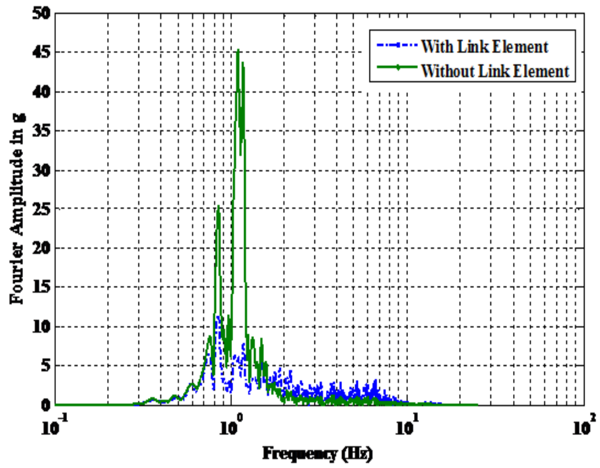


FIG. 6 COMPARISON OF FOURIER AMPLITUDE SPECTRUM OF TOP FLOOR WITH AND WITHOUT LINK ELEMENT UNDER MAY 18, 1940 ELCENTRO EARTHQUAKE (NS)

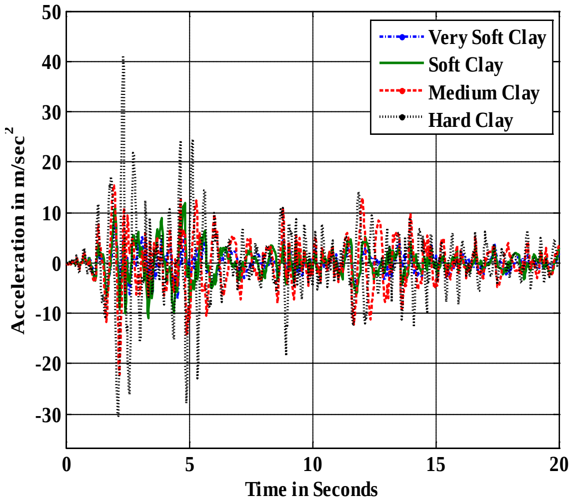


FIG. 7 ACCELERATION RESPONSE OF TOP FLOOR WITH LINK ELEMENTS UNDER MAY 18, 1940 ELCENTRO EARTHQUAKE (NS)

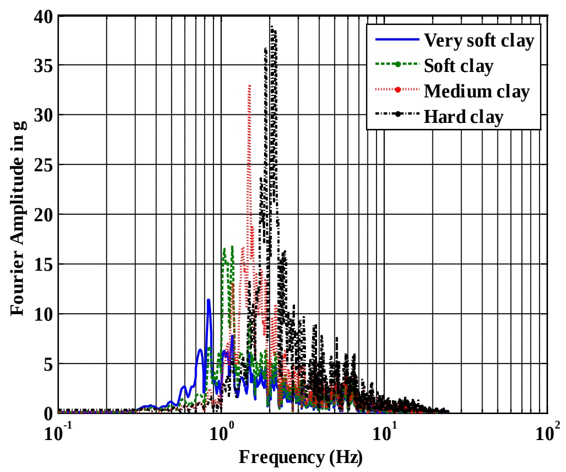


FIG. 8 FOURIER AMPLITUDE SPECTRUM OF TOP FLOOR WITH LINK ELEMENT UNDER MAY 18, 1940 ELCENTRO EARTHQUAKE (NS)

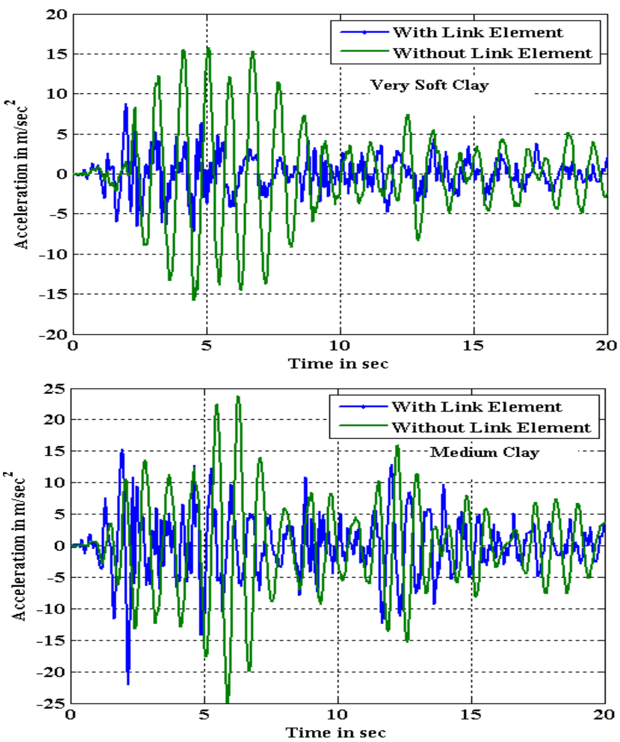


FIG. 9 COMPARISON OF ACCELERATION RESPONSE OF TOP FLOOR FOR VERY SOFT CLAY AND MEDIUM CLAY WITH AND WITHOUT LINK ELEMENTS UNDER MAY 18, 1940 ELCENTRO EARTHQUAKE (NS)

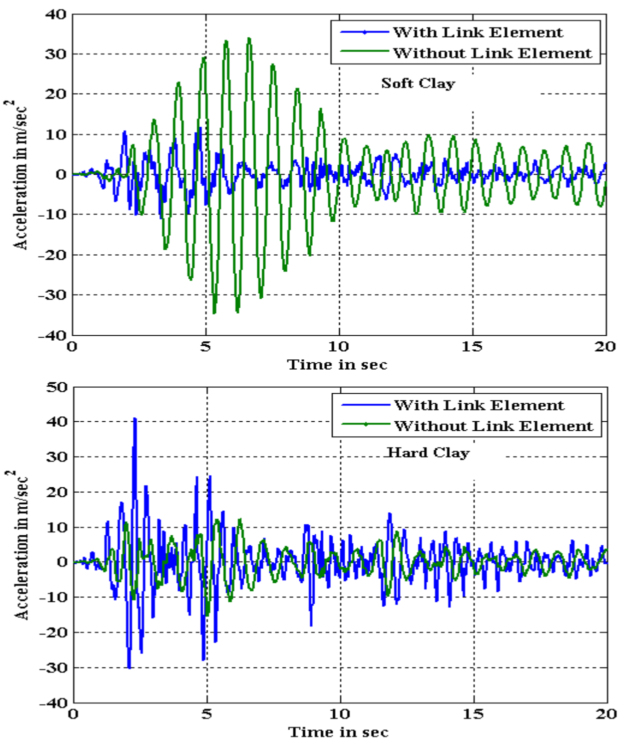


FIG. 10 COMPARISON OF ACCELERATION RESPONSE OF TOP FLOOR FOR SOFT CLAY AND HARD CLAY WITH AND WITHOUT LINK ELEMENTS UNDER MAY 18, 1940 ELCENTRO EARTHQUAKE (NS)

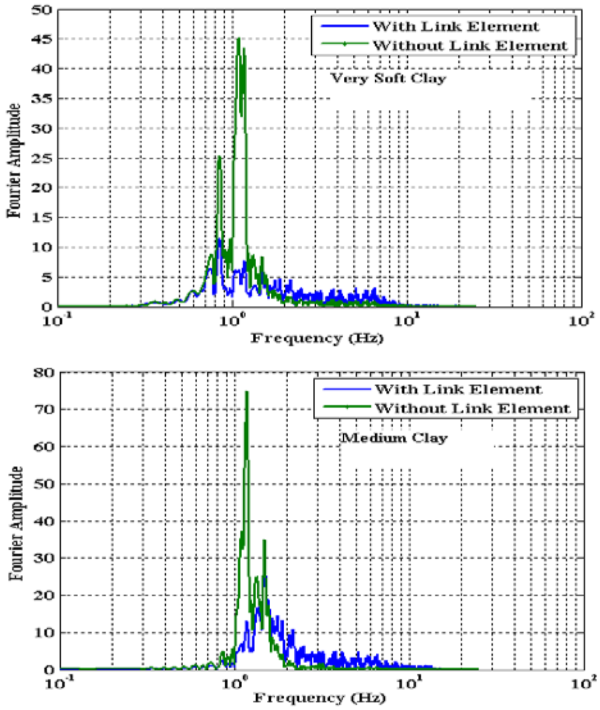


FIG. 11 COMPARISON OF FOURIER AMPLITUDE SPECTRUM OF TOP FLOOR FOR VERY SOFT CLAY AND MEDIUM CLAY WITH AND WITHOUT LINK ELEMENT UNDER MAY 18, 1940 ELCENTRO EARTHQUAKE (NS)

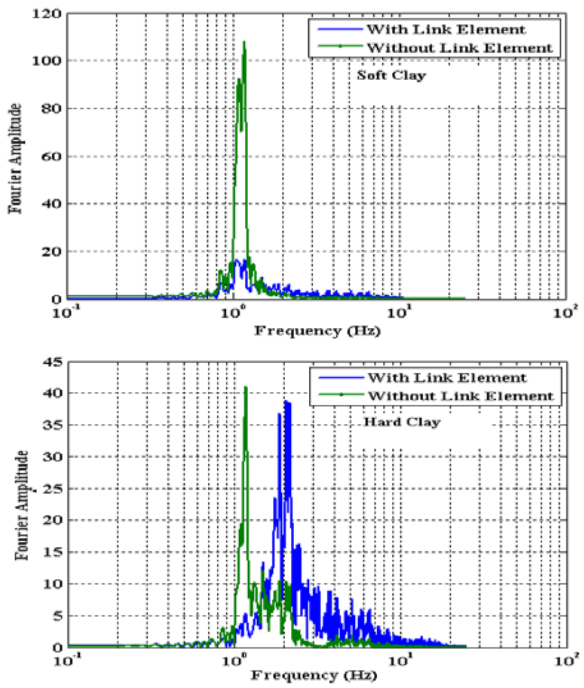


FIG. 12 COMPARISON OF FOURIER AMPLITUDE SPECTRUM OF TOP FLOOR FOR SOFT CLAY AND HARD CLAY WITH AND WITHOUT LINK ELEMENT UNDER MAY 18, 1940 ELCENTRO EARTHQUAKE (NS)

Conclusions

The seismic response of pile supported frame structure is studied by modelling the contact between pile and soil using Interface Element.

There is a two-time increase in the acceleration response of the top floor while considering the SFSI over fixed base analysis for nonlinear case. Also there is a clear shift in the natural period of the system of both. Which signifies that interaction is playing a major role in the response.

The acceleration response of the top floor has been reduced by two times, when contact between pile and soil has been modelled. Also there is an increase in Fourier amplitude by 4.5 times in case of response of top floor without link element.

There is a reduction in acceleration response of structure with link elements when compared to acceleration of structure without link elements for different soils, this is because loss of contact at foundation level the structure is not getting much dynamic force.

In case of hard clay the magnitude of acceleration response of structure for both cases are the same. This is because the dynamic force exerted is not enough to create a gap between pile and soil.

Therefore, to have a good understanding of SFSI behaviour under seismic loading a detailed analysis by modelling the contact between pile and soil has to be done. Neglecting this behavior makes the over estimation in assessing the strength of foundation.

REFERENCES

Buragohain, D. N. and Shah, V. L. "Curved interface elements for interaction problems." Proc. Int. Symposium on Soil-Structure Interaction, Roorkee, India, pp 197-202, 1977.

Cai, Y. X., Gould, P. L. and Desai, C. S. "Nonlinear analysis of 3D seismic interaction of soil-pile-structure systems and application." Engineering Structures 22, 191-199, 2000.

Chau, K.T, Shen, C.Y. and Guo, X.. “Nonlinear seismic soil-pile-structure interactions: Shaking table tests and FEM analysis”, Soil Dynamics and Earthquake Engineering 29, 300- 310, 2009.

Chore, H. S. and Ingle, R. K. "Interaction analysis of building frame supported on pile group." Indian Geotech. Journal, 38 (4), 483-501, 2008 a.

Chore, H. S. and Ingle, R.K. "Interactive analysis of building frame supported on pile group using simplified F.E. model." Journal of Structural Engineering, SERC, 34 (6), 460-464, 2008b.

Chore, H. S., Ingle, R. K. and Sawant, V. A. "Building frame-pile foundation-soil interaction analysis: A Parametric study." Interaction and Multi scale Mechanics, Vol. 3, No. 1, 55-79, 2010.

David, M. P. and Zdravkovic, L.. "Finite Element Analysis in Geotechnical Engineering", Thomas Telford Publishing, 1999.

Deepa B. S., Nandakumar C.G., "Seismic Soil Structure Interaction Studies on Multistorey Frames." International Journal of Applied Engineering Research and Development, Vol.2, Issue 1, 45-58, Mar 2012.

Ingle, R. K. and Chore, H. S. "Soil-structure interaction analysis of building frames: An overview." Journal of Structural engineering, Vol. 34, No. 5, Dec-Jan 08, pp. 360-368, 2007.

Lu, X., Chen, B., Li, P., and Chen, Y. "Numerical Analysis of Tall Buildings Considering Dynamic Soil-Structure Interaction." J. Asian Archit. Build., 2 (1), 1-8, 2003.

Sushma, P and Pradeep Kumar, R (2013) "Dynamic Analysis of Framed Structures Supported on Pile Foundations : A Review", Frontiers in Geotechnical Engineering, Volume 2, Issue 2, June.

Vivek, G., and Hora, M. S. "A review on interaction behaviour of structure- foundation- soil system." International Journal of Engineering Research and Applications, Vol. 2, Issue 6, November- December, pp.639-644, 2012.

Prof. Pradeep K. Ramancharla Worked in L&T-ECC for about a year (1997-98) and went to Tokyo, Japan for pursuing Ph.D. After receiving degree, he worked as a post-doctoral research fellow for one year (2001-02). He joined IIIT Hyderabad in September 2002 and started Earthquake Engineering Research Centre (EERC). He was also instrumental in initiating graduate program on Computer Aided Structural Engineering (CASE) at IIIT Hyderabad.

Prof. Ramancharla research interests are; i) macroseismo-tectonics of Indian plate, ii) large deformation analysis of faults, iii) non-linear structural response & damage estimation, iv) health diagnosis of historical and critical structures, v) sustainable construction technologies (with local & natural materials) and v) capacity building on disaster safety. In addition to the above, Dr. Ramancharla has keen interest in research on humanities and human values.

Prof. Ramancharla is a member of a few committees at both state and national level. He is Editor-in-Chief for Frontiers in Geotechnical Engineering. He is a member of Post Earthquake Reconnaissance Team (PERT) of NDMA, GoI. As a member of expert committee of NDMA; in addition, he has contributed to the preparation of National Disaster Management Policy and Guidelines for Earthquakes and Tsunamis as well as to the preparation of policy for restructuring of Fire and Emergency Services Department, Govt of AP. He is also a member of expert committees on Disaster Mitigation of Cyclones and Urban Floods. He is currently a BIS panel member of IS 456 & IS 1343 (CED2) and also a member of National Building Code of India (CED 46:P16).

Dr. Sushma Pulikanti Masters in Computer Aided Structural Engineering and Ph D in Civil Engineering from IIIT Hyderabad (2013), Hyderabad, India.

The main objective of the Ph D work is to contribute to the understanding of the seismic performance of superstructure considering the complex dynamic interaction among superstructure, the pile foundation and the soil. For this purpose, a numerical model has been developed using Finite Element Method with primary focus on the understanding of the behaviour of superstructure by modelling the nonlinearities of soil and the interface between soil and pile. She has worked as Teaching Assistant for courses like Earthquake Engineering, Advanced Structural Analysis, Geotechnical Earthquake Engineering, Foundation Engineering and Design.