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Soil-Pile Interaction in Deep Layered Marine Sediment subject to Seismic Excitation

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Abstract

Contrary to what is normally assumed, neither the response of the pile nor the response of the ground are independent of each other when subject to seismic loads. In the seismic design of buildings, dynamic response of a structure is determined by assuming a fixed base on sub-grade and neglecting the physical interaction between foundation and soil profile in which it is embedded. However, the seismic response of pile foundations in vibration sensitive soil profiles is significantly affected by the behaviour of supporting soil. This research uses validated finite element techniques to simulate the seismic behaviour of piled foundations embedded in multilayered vibration sensitive soils.

Keywords: soil-pile interaction, vibration sensitive soil, finite element technique.

1 Introduction

One of the reasons for the failure of a pile foundation during an earthquake is the inadequacy of piles to resist the induced moments and shears. Such failures can be prevented at design stage if the effects of inertial and kinematic forces induced by soil-pile interaction can be precisely calculated.

Generally, in designing structures, ground motion is applied directly to the base of the building without taking soil-pile interaction into account. This procedure is reasonable for structures on very stiff soil or ground, because in this case the displacement of the ground doesn't get modified. However, for structures on other types of soil, the base motion should be modified considering the soil-pile interaction effects.

There has been past research in the area of soil-pile interaction using different methods, but most of them are focused on homogeneous soil profiles and limited depths of piles [1,2]. The behaviour of pile foundations embedded in deep multilayered vibration sensitive soil profiles, which are typically found in estuaries, is still unknown. This emphasises the need for a detailed study to determine the soil-pile interaction for piles embedded in a vibration sensitive soil profile since the dynamic interaction between pile and soil governs the structural performance of the foundation system in relation to its strength and stability.

The aim of this research is to analyse pile foundations embedded in multilayered deep profiles soil strata comprising of soft soils when subjected to seismic excitation, to simulate the pile response and to determine the action effects for the design of the pile foundations.

This study will enhance the knowledge in dynamic soil-pile interaction behaviour and the research findings can prevent structural failure and provide cost effective designs under a credible earthquake.

2 Finite Element Modelling

The general purpose finite element software “ABAQUS” is used to model the three dimensional soil-pile system. The basic components of the finite element model are shown in figure 1 and are described in the following subsections.

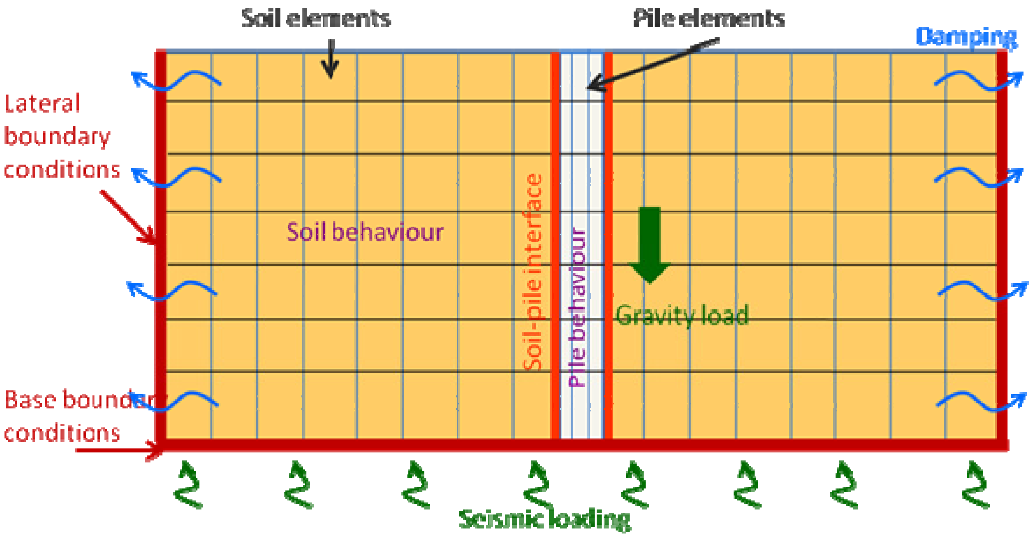


Figure 1: Components of the finite element model

2.1 Element types and size

Pile is modelled with eight node brick elements where as soil is modelled with eight node pore-pressure elements. These types of continuum elements in ABAQUS are capable of handling linear and complex nonlinear analyses involving contact, plasticity and large deformations [3].

In dynamic analysis, choosing of the right element size for the finite elements is essential to capture the motion of waves accurately. Since the vertically propagating S waves are considered in this study, the vertical direction subdivision is kept constant inside a soil layer to allow the distribution of waves evenly. The maximum element size in vertical direction has to be less than one-fifth to one-eighth of the wave length to ensure accuracy [4]. The common practice is to use the element length as one-sixth of the shear wave length [5].

In the horizontal directions, the mesh will be refined near to the pile with a gradual transition to a coarser mesh away from the pile.

2.2 Soil-pile interface

In ABAQUS, mechanical contact between two surfaces (bodies) can be modelled either as node based interaction or surface based interaction. In node based interaction, mechanical contact between two nodes is modelled using contact elements, whereas in surface based interaction surfaces are directly interacting with each other.

Surface based interaction has the advantage over the node based interaction, because of its capability to model both normal and tangential interaction behaviour whereas node based interaction facilitates only the normal interaction behaviour.

Surface based interaction has been successfully used to model soil-pile interface by researchers in the past [6] and will be used in this study. This type of interaction consists of the following steps.

1. Defining the surfaces which will be in contact
2. Defining the master and slave surfaces
3. Defining the mechanical (tangential and normal) properties of the surfaces

The two surfaces are to be defined based on their rigidities. The more deformable surface is defined as slave surface and the more rigid surface is defined as the master surface. The normal interaction behaviour is defined as hard contact behaviour. In this approach, when the surfaces are in contact, any contact pressure can be transmitted between them. The surfaces separate if the contact pressure reduces to zero. Separated surfaces come into contact when the clearance between them reduces to zero.

The tangential interaction behaviour is based on the Coulomb friction model. In this model, two contacting surfaces can carry shear stresses up to a certain magnitude across their interface before they start sliding relative to one another. The Coulomb friction model defines this critical shear stress τ_{crit}, at which the sliding of surfaces starts as a fraction of the contact pressure, P between the surfaces ($\tau_{crit} = \mu P$).

2.3 Analysis steps

The analysis of most structures begin with a complete mesh of stress-free undeformed elements and subsequently apply the specified loads to obtain the desired stress state. However, the response of buried structures depend on the history of the loading, i.e. in-situ state of stress in the ground. Therefore it is important to apply initial conditions before applying any external loads such as seismic loads.

This analysis of soil-pile interaction consists of two consecutive steps, where in the first step (Geostatic) in-situ stress conditions are achieved and in the next step, seismic load is applied.

In the geostatic step, gravity load is applied together with a user defined stress field for the soil mesh. ABAQUS then calculates stresses which are in equilibrium with the external loading (in this case gravity) and boundary conditions. If modelled correctly, the vertical effective stresses should be closer (or equal) to what the user defined at the initial conditions and also the contours should be parallel. Furthermore, vertical displacements should be very small.

In the consecutive dynamic step, the seismic loads are applied as displacement-time history at the base of the model. Since the most critical type of earthquake shaking is “S” wave that creates horizontal movements in ground, this research is focused on “S” waves. Here, vertically propagating “S” waves are created, in which motion is perpendicular to the direction of wave propagation (horizontal in this case) by giving a horizontal base displacement.

2.4 Boundary conditions

Base of the soil-pile model is kept fixed in all directions during the geostatic step. However, in the dynamic step, where seismic waves are induced, it is kept fixed in the vertical direction, and released in the horizontal direction.

The lateral boundaries are set free to move in the horizontal direction and restricted in the vertical direction. Static active failure of the vertical boundaries is prevented by applying the earth pressure in the horizontal direction [7].

2.5 Material models

During the analysis, pile is assumed to behave linear elastically.

Even though, the soil is modelled as a linear elastic material in literature, elastic-plastic models provide a better representation of the real soil behaviour. They require a yield function which separates elastic from elastic-plastic behaviour and a plastic potential (or flow rule) which prescribes the direction of plastic straining.

In this research, Mohr-Coulomb model is used to model the elastic-plastic behaviour of the soil. The model suggests that the yielding begins as long as the shear stress and normal stress satisfy the following equation;

$$\tau = C + \sigma_n . tan\emptyset \qquad (1)$$

Where, C is the cohesion and $\emptyset$ is the friction angle. The Mohr-Coulomb model is based on plotting of Mohr's circle for state of stress at failure in the plane of maximum and minimum principal stresses.
The yield criterion of the Mohr-Coulomb model can be defined as:

$$\mathrm{f} = (\sigma_1 - \sigma_3) - (\sigma_1 + \sigma_3).\sin\emptyset - 2\mathrm{C}.\cos\emptyset = 0 \text{ for } \sigma_1 \geq \sigma_2 \geq \sigma_3 \qquad (2)$$

Where, σ_1, σ_2 and σ_3 are principal stresses and σ_1 and σ_3 are maximum and minimum principal stresses (positive in tension).

2.6 Damping

Damping of the system is achieved through stiffness proportional material damping and it is assumed to be constant throughout the analysis. The damping matrix is given from the equation (3),

$$[C] = \beta[K] \qquad (3)$$

Where, [C]= damping matrix, [K]=stiffness matrix and β=damping coefficient
In this case, $\beta = 2\xi/\omega_0$
where, ω_0 is the predominant frequency of loading and ξ is the material damping ration which is assumed to be 5%.

3 Model validation

Model validation was carried out to ensure the proper behaviour of the pile itself, wave propagation in free field and well the combined behaviour of the soil-pile system under static and dynamic loading.

For the validation purpose, pile was considered as a homogeneous linear elastic material with density of 2300 kg/m^3, young's modulus of 20GPa and Poisson's ratio of 0.25. Soil was also considered as a linear elastic material with a density of 1203kg/m^3.
First, pile behaviour was validated with different mesh sizes. In this case pile was considered as a cantilever without the surrounding soil. A horizontal load was applied at the free end and the pile deflections were obtained at different locations and those were compared with the theoretical values (figure 2). The mesh that gave the deflections closest to the theoretical values was used in the present analysis.

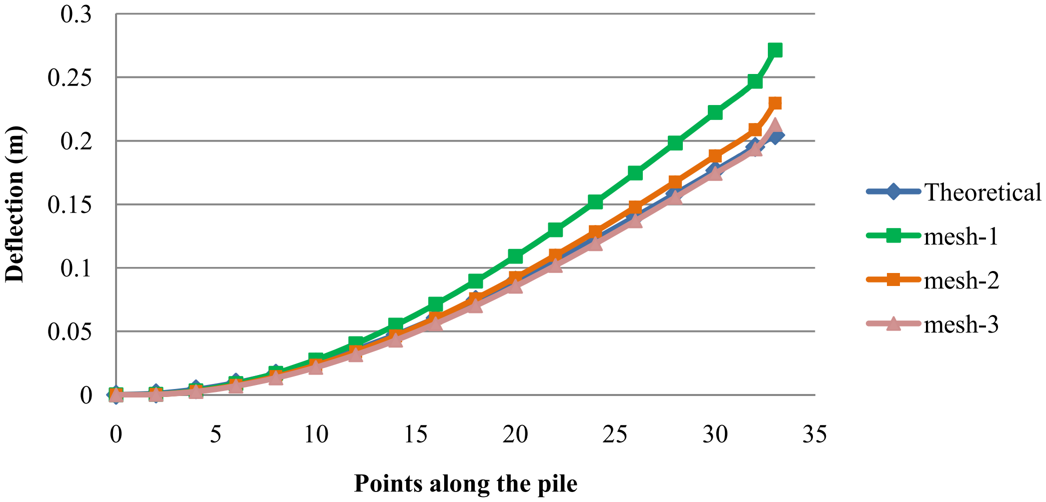
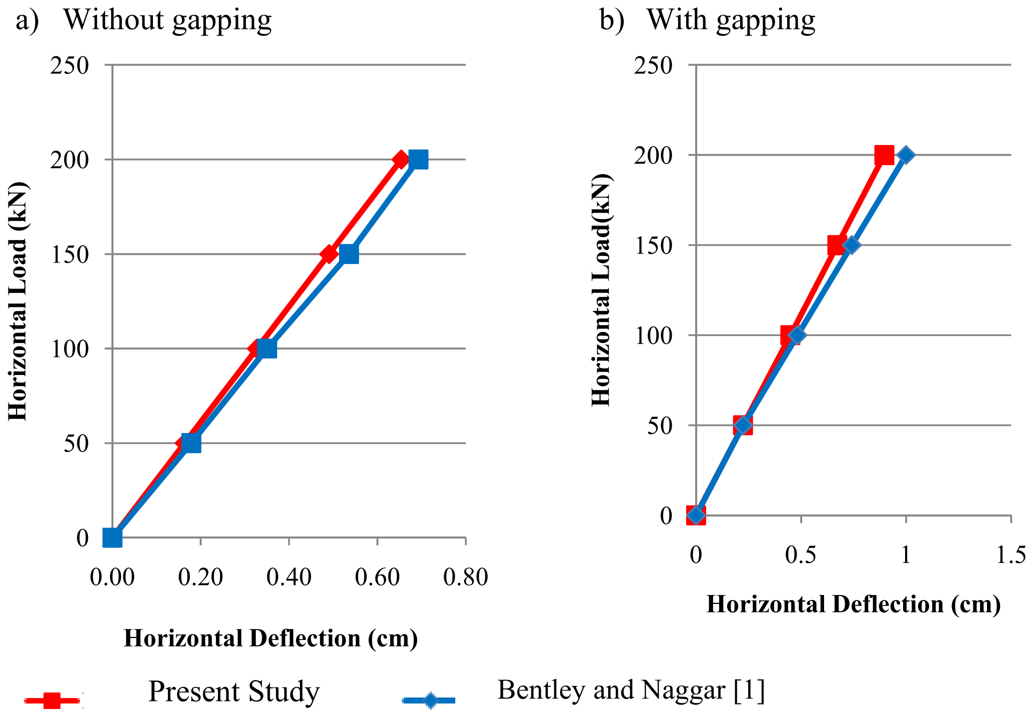


Figure 2: Pile mesh validation

The soil-pile system was validated under different static loads applied at the top of the pile. The two cases consider for this analysis are; a) without gapping: gapping between soil and pile is not allowed, b) with gapping: gapping between soil and pile are allowed.

The pile responses obtained from the present analysis for both cases were compared with the work done by Bently and Naggar [1] as shown in figure 3. Present analysis shows a very good agreement with the results of Bently and Naggar [1] for both cases. Therefore it is apparent that the soil-pile system gives the expected behaviour under static loading.


a) Without gapping

b) With gapping

Figure 3: Validation of pile response under static loading

In the next step, free field response (ground response without pile) was validated. For this, the seismic wave for El-Centro earthquake was given as displacement-time history at the base of the model. The obtained results from the developed ABAQUAS model was compared with the results obtained from the commercial geotechnical software “GeoStudio” (Figure 4).

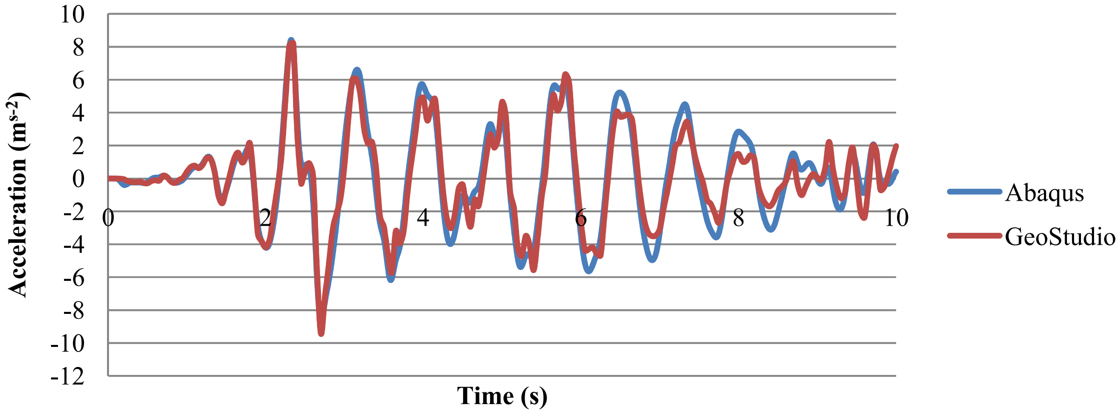
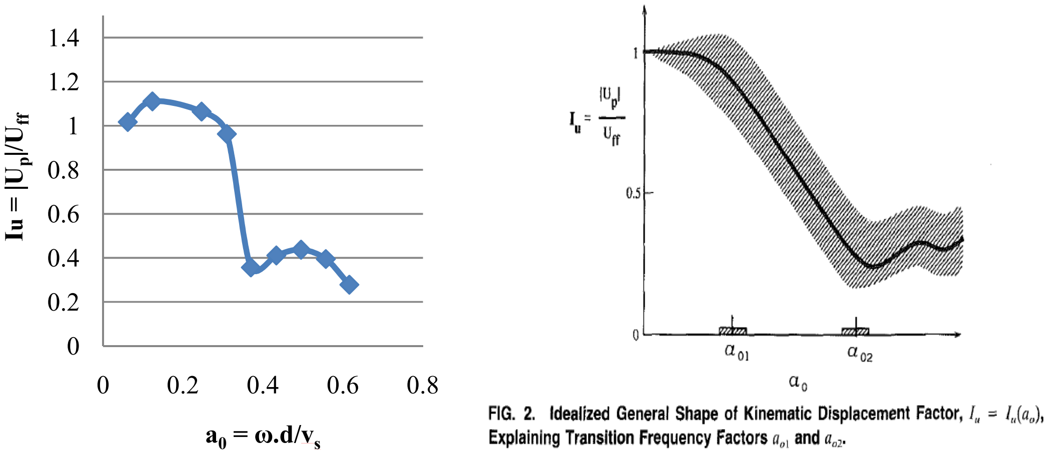


Figure 4: Validation of free-field motion

In the final validation step, the soil-pile system was validated for the dynamic loading. In this step, base of the model was excited at different frequencies to produce vertically propagating harmonic shear waves which produced horizontal ground motions. To investigate the soil-pile interaction effects, a factor I_u was defined as $|U_p|/U_{ff}$, where, U_p=pile response at top and U_{ff}= amplitude of free field motion. Then the present analysis results were compared with the work done by, Fan et al [8] as shown in figure 5.



a) Present study

b) Study by Fan et. al [8]

FIG. 2. Idealized General Shape of Kinematic Displacement Factor, $I_u = I_u(a_o)$, Explaining Transition Frequency Factors a_{o1} and a_{o2}.

Figure 5: Validation of pile response under dynamic loading

Where, dimensionless frequency a_0 is defined as $\omega.d/V_s$, where ω=circular frequency of loading, d=pile diameter (width in this case), V_s=shear wave velocity of soil. According to the figure 5, it is evident that the present analysis, follows the work of Fan et al. As observed by Fan et al [8], in the present analysis also three distinct regions can be identified in the I_u vs a_0 graph as described below.

1. A low frequency region in which $I_u \approx 1$
2. An intermediate frequency region, where I_u declines rapidly
3. A relatively high frequency in which I_u fluctuates around a constant value of about 0.2-0.4

4 Example

To test the soil-pile interaction behaviour in a deep multilayered soil profile, that has vibration sensitive soils, a 33m deep soil profile was selected and the properties were obtained from Cone Penetration Test Values. Table 1 shows the soil properties of the respective soil layers and their layer thicknesses. In this example, the soft most layer is located at the top of the layer and the soil stiffness increases as go down in the profile.

For this example, single pile embedded in that soil profile subjected to a seismic load (El-Centro) is considered here.

The modelling of soil pile system was carried out as described in section 2. To see the difference in pile response in each layer, midpoint of the pile were selected for each layer.

	Layer Thickness (m)	Density (kg/m^3)	Young's Modulus (MPa)	Poisson's Ratio	Cohesion (kN/m^3)	Internal Friction Angle (^{0})
Layer-1	16	1631	10	0.4	39	0
Layer-2	6	1835	15	0.4	59	0
Layer-3	2	1886	21	0.4	83	0
Layer-4	2	1937	63	0.4	0	35
Layer-5	7	1937	248	0.3	0	50

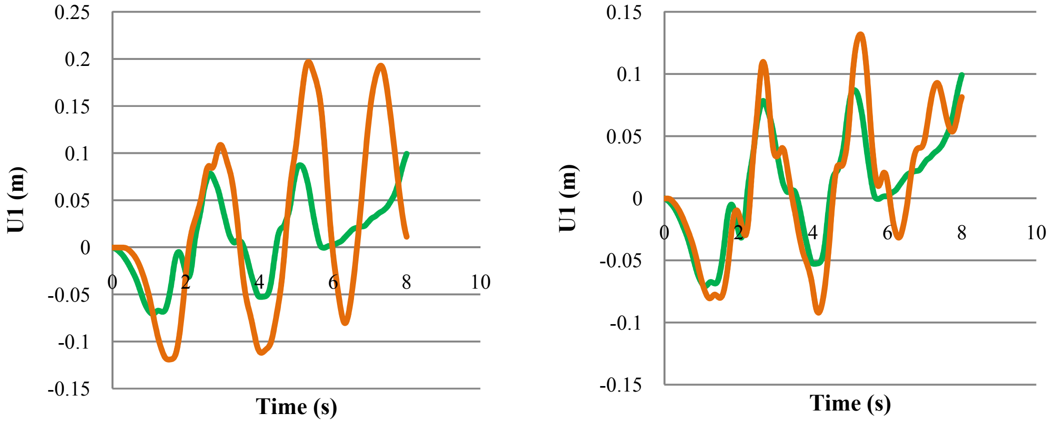
Table 1: Soil layer properties

From figure 6 it is evident that the pile response in case of a seismic excitation depends on the properties of surrounding soil. In the presence of stiff layers pile response strictly follows the base motion as it doesn't get amplified. However as the soil layers get less rigid, pile response become greater than the input motion given at the base as it gets amplified when propagating through the soft layers.

Also piles embedded in a layered soil profile can have different mode shapes during a seismic excitation as shown in figure 7. Therefore it is important to investigate their behaviour for the proper design of such pile foundations.

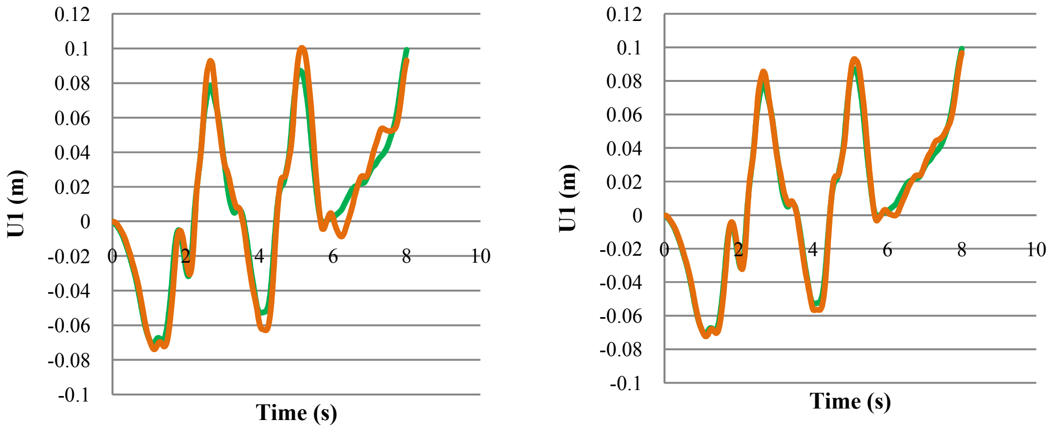
a) Pile response at mid depth of layer -1

b) Pile response at mid depth of layer -2



c) Pile response at mid depth of layer -3

d) Pile response at mid depth of layer -4



e) Pile response at mid depth of layer -5

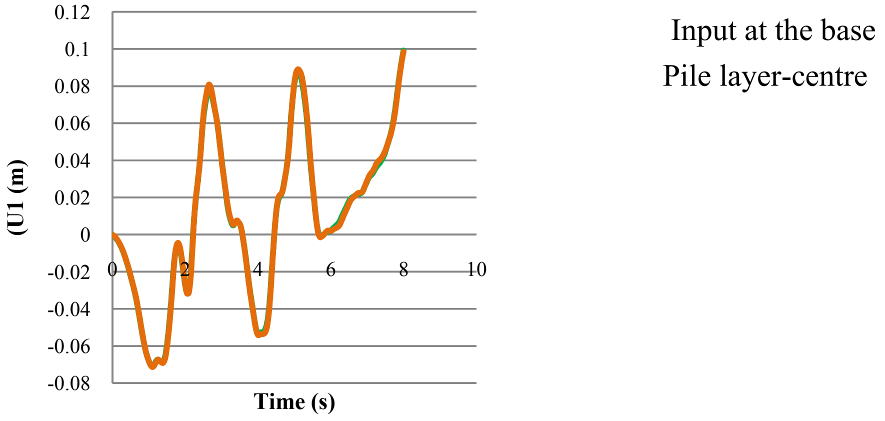


Figure 6: Pile response at mid depth of different layers

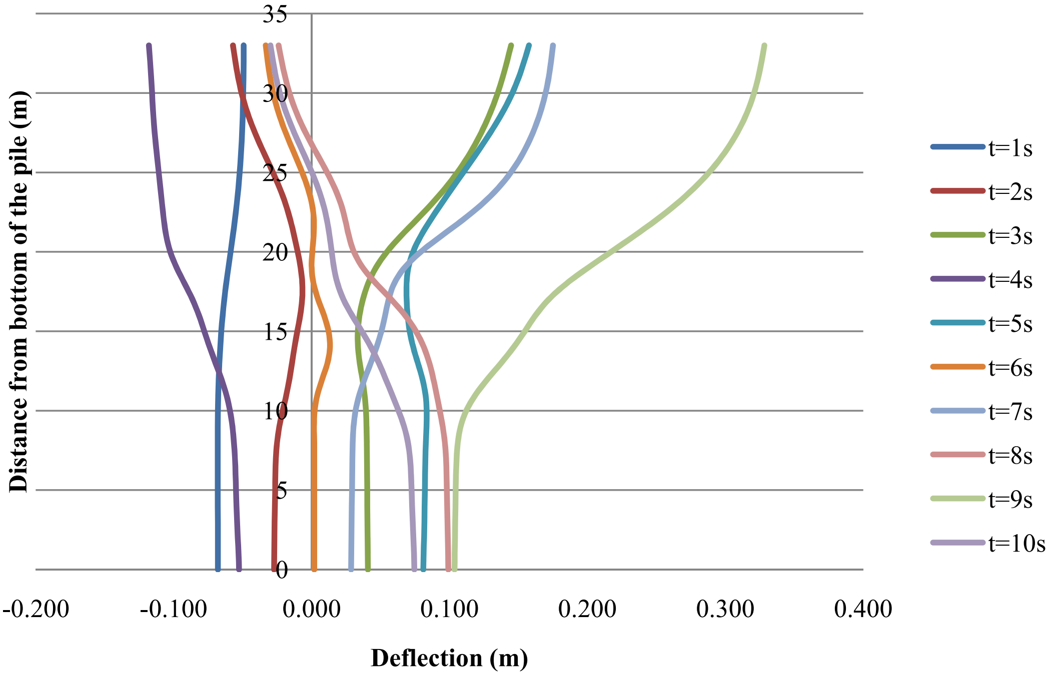


Figure 7: Pile mode shapes during the excitation

5 Conclusion

The response of a piled foundation subjected to a seismic excitation depends on the properties of the soil surrounding the pile. The pile response is very much different in vibration sensitive soft soil layers, even though it follows the input motion which is given at the base of the model in stiff soils. Therefore it is not suitable for the analysis of a super structure with the seismic input at the base of the structure because the actual input that transmits through the pile foundations can be different depending on the soil layers present.

Also when embedded in layered soil, piles can have different modes of deflections under seismic excitation. Therefore it is important to investigate the behaviour of pile foundations embedded in multilayered deep soil strata with soft soils under a seismic excitation to determine the action effects for the pile design.

A detailed analysis of this study will be carried out in the future considering different soil profiles with soft layers at intermediate levels in the soil profile, group effects and the loads transferred from the super structure to the pile foundations. Finally a rationale method will be developed to determine the action effects arising from soil-pile interaction in the time domain for the design of foundation system.

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