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DYNAMIC INTERACTION BETWEEN TWO NEIGHBORING PILES UNDER HARMONIC LOAD

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ABSTRACT

The present work studies the effect of interaction between two neighboring piles. The piles considered in a soil half space. The effects of soil type, the distance between piles, the excitation frequency of the dynamic load and the size of soil half space investigated. The analysis performed using the finite element method utilizing in the Ansys 12.0 software and the dynamic analysis is considered. Two types of dynamic analysis adopt. The first is the free vibration analysis which is employed to predict the natural frequencies and their corresponding modes shapes in two cases. The first case for the pile alone with fixed boundary conditions along its base and for the whole system. system which include the piles and surrounding soil. The resulted effect of soil types, also distance between piles and the size of soil half space on the natural frequencies are investigated. The second is the forced vibration analysis (harmonic analysis) which is performed to predict the effect of the excitation which transmits by soil from the dynamic source (from the loaded pile – first pile which loaded with harmonic load at the head of pile) before interaction with the second pile also after the interaction between two piles due to applied harmonic load on the head of second pile have the same magnitude of the load applied at the head of first pile before interaction but in opposite direction (so we have two piles under equally harmonic load but in opposite direction). This type of analysis is utilized to study the effect of several factor such as soil type also the distance between pile the excitation frequency of dynamic load and the size of soil half space before and after interaction. Result showed that the dynamic response of embedded piles to vibration through the soil is highly dependent on the soil type where the response of embedded piles on the half space of soft silty clay is greater than those on half space of medium silty clay and dense sand-gravel soil respectively. The response of embedded piles on the half space of layered soil consist of soft silty clay above dense sand gravel is greater than layered half space consist of medium silty clay above dense sand gravel. The displacement of pile head decrease with increasing distance between piles before interaction but the displacement of pile head increase with increasing distance between piles after interaction. For all cases the response of piles in lager half space always greater as compare with smaller half space. Resulted showed that it is important to include the soil-structure interaction in the analysis of the system dynamic response in order to correctly simulate the dynamic problems for controlling on the resonance phenomena.

KEYWORDS: Dynamic Interaction, Piles, Harmonic Load

INTRODUCTION

In the world wide scope and because of the people are more aware of their life quality, comfort and safety, a special attention is recently given to study the effects of vibrations transmission through the ground to the neighboring structures. These vibrations are either generated by natural reasons like earthquake ground motion or by human made vibrations such as machine foundation, nearby roads or railway traffic, underground explosions and construction activities (such as pile driving and compaction of loose soil) (1). The ground vibrations induced from their sources and transmitted through the soil to the unsuitable place structures may cause noise, malfunctioning of sensitive equipments, and discomfort to people and even damage to structures (2,3). The ground vibrations cause disturbance to the soil and the adjacent structures depending on the energy transmitted to the soil (characterized sources of vibrations), soil conditions, the inherent structural strength and susceptibility of structures. This disturbance corresponding to high, medium and low levels of vibrations and different vibration frequencies. In strongly earthquake ground motion, the transmitted energy through the soil is high; therefore; the geotechnically unsuitable placed structures may suffer a great damages or even collapse while the vibrations of machine foundations and nearby road or railway traffic cause settlement, cracks to adjacent structures and a substantial annoyance to residents(4, 5). With rapid urbanization, high density development of housing, industrial and commercial areas are planned and zoned in urban cities and their skirts. This leads to buildings being constructed in close proximity to each other ; therefore; the study of ground motion and its effect on structures has largely concentrated on seismic and blast induced ground motions owing to their dramatic effects (4). The dynamic foundation-soil-foundation interaction phenomenon has long been recognized as an important factor in the seismic and machine vibration response of critical facilities and other closely spaced structures or portions of a structure(5). The study of ground vibrations must consider the frequency and time as well as amplitude of vibration. The frequency of a vibrating object described by particle position (displacement), particle velocity (change in displacement over time), or particle acceleration (change in velocity over time); each can be stated in time or frequency domain(6). The problem of predicting the transmission of vibrations through the ground is complex. Its complexity came from interaction of structural engineering, geotechnical engineering, and theory of vibration. The complexity include the lack of a comprehensive understanding of soil behavior, the difficulty of determining accurate values of soil properties, and the resulting near-and far-field behavior. However, in spite of these and other obstacles, it is possible to make reasonable assessments of ground-transmitted vibration through a judicious of the empirical and theoretical results(7). Vibration transmit through the soil in form of stress waves. The transmission characteristics of vibrations depend on the type of the generated waves which emanate from their sources to the soil and can be assessed by measuring particle motions. The amplitude of these waves diminishes with distance from the source (6). The attenuation of wave amplitude is due to two factors: expansion of wave front(geometrical damping) and dissipation of energy within the soil itself (material damping). The geometrical damping is the decrease in energy density or decrease in(displacement, velocity, and acceleration) amplitude when the wave transmission from source of excitation at certain distance and it depends upon the type of wave and the shape of the associated wave front. This damping depends primarily on nature of the vibration source whether it is surface or underground, the contact area between the source and the ground, and the mode of vibration such as rocking, twisting or translation. Material damping is the energy dissipation inherent to material behavior. In soil, the material damping is a function of many parameter, including soil type, moisture content and temperature(6). All real structures when subjected to loads which apply very slowly or shake the structures at roughly less than one-third of the lowest natural frequency of vibration, can be analyzed as statically even though loads vary with time. More rapid shaking makes inertia force (excitation generated by the mass in motion) very importance and the structures behave dynamically then the dynamic analysis becomes important (8). The dynamic analysis consist of two parts(9)

Free vibration analysis : this type of analysis uses to find the natural frequencies of the mode shapes that the structure undergo due to the motion by some disturbance at initial time equal to zero and there after no external dynamic force is applied. The determination of the structures natural frequencies is very useful to avoid the increasing of structures dynamic response due to resonance phenomena.

Forced vibration: the forced vibration analysis uses to determine the dynamic response of the structure such as the time-varying displacement, stresses and forces when the structure subjected to external dynamic force. The dynamic excitation that may be applied on the structures can be classified into two type (8): The first is the direct excitations where the load is applied directly on the structures. The second type is the indirect excitations where the load is transmitted to the structures through the soil in the form of stress waves. These waves emanate from source of dynamic excitation and spread through the soil then impinge the structures.

MODELING AND MATHEMATICAL FORMULATION

The finite element method is one of the numerical techniques that can be used to obtain theoretical analysis of these type of problems. In the finite element method, the actual continuum is represented as an assemblage of subdivision called elements. These elements are considered to be interconnected at specified joints called nodes or nodal points. The nodes usually lie on the element boundaries where adjacent elements are considered to be connected. Since the actual variation of the field variable (e.g., displacement, stress, temperature, pressure, or velocity) inside the continuum is not known, it can be assume that the variation of the field variable inside a finite element can be approximated by a simple function. These approximation functions (also called interpolation models or shape function) are defined in terms of the values of the field variables at the nodes(10). ANSYS is a finite elements program. This program contains several types of elements which can be used to formulate the structural problems. In the present study, two different types of elements are used (11). The first type of the elements is the BEAM4 element with tension, compression, torsion, and bending capabilities. The element has six degrees of freedom at each node, translation in nodal x, y and z. directions and rotations about nodal x, y and z axes. This element is used to represent the piles. In the present study the problem model consists of two piles in the half space of soil. The second type of elements is the SOLID45 element which is an eight-node cubic element with large deflection and large strain capabilities. The element has three degrees of freedom at each node: translation in the nodal x, y and z directions. This element is used to simulate soil. The soil surrounding the piles foundation is modeled using eight nodded brick elements (solid45) with perfect bonding between the soil and the piles. The common connected nodes between soil-pile foundation interaction have six degrees of freedom. The nodes of the BEAM4 (element of pile) coincided with SOLID45 (element of soil) and merged. The finite element modeling can be performed in two or three dimensions, it is realized that for problems with great variations in the geometric and material properties of the soil-structure system, a full three dimensions finite element modeling may still be necessary, in order to capture some of the local effects that may be hidden by two dimensional or other simplified models. In the present study, the three dimension finite element modeling is used (12).

PROBLEM DEFINITION

This search includes numerical application to study the dynamic interaction between two laterally loaded single pile under harmonic load. The whole system of the study that includes two piles and the surrounding soil. By using finite element method, the whole system is meshed to small element. The software Ansys12 program is used to perform the dynamic analysis of the cases studied. Two type of analysis are included in this study. The first is the free vibration which is performed by Block Lanczos iteration method to determine the natural frequencies and their mode shapes. The second type is the forced vibration analysis which is performed in frequency domain where the inputs are the amplitude and frequency of dynamic load and the output is the displacement. The Sparse Solver technique is used to solve the global matrix of forced vibration equation and determine the dynamic response (displacement) of piles

Description of the case study : The whole system is divided into two part, the piles and soil. All part are formulated by finite element method. The loading in the first case represent by applied dynamic harmonic load on the head of pile (1) in positive direction and measured the deformation at the head of pile (1) and pile (2). The loading in the second case represented by applied dynamic harmonic load on head of pile (1) in positive direction also applied dynamic harmonic load on the head of pile (2) in opposite direction as compare with direction of load applied on the head of pile (1). with various distance between them measured from C/C of piles. In this study we select three distance from C/C of piles (5m,10m, and 15m). also we select two half space of soil to study the size effect of half space on the response of piles before and after interaction respectively for various distance. The description of each part and the dynamic loads are as follow

Pile description : The pile used is a (0.5*0.5) meter square concrete pile. Length of the pile is (12m). Materials of piles assumed to behave as linear elastic. A structural damping of (ζ=0.02) is assumed. Properties of concrete used for constructing the piles are as follows. The elasticity modulus of concrete (Ec) is taken equal to (22.5*$\mathbf{10^3}$MPa) which is calculated from the following equation (based on the ACI318-08 formula for normal- weight concrete) (Ec=4700$\sqrt{\boldsymbol{f_c'}}$) where: f'_c is the cylinder ultimate compression strength of concrete which is assumed equal to 23Mpa in this study. The concrete density (ρ) is assumed equal to 2400Kg/$\boldsymbol{m^3}$. Poissons ratio of concrete is assumed to be 0.15. Soil description,The soil assumed as a half space of a homogenous, isotropic and damped viscoelastic material. The half space of soil is represented by using brick finite elements. Fixed boundary conditions are assumed along all external sides of soil half space except the top (ground surface) which is remained free. The bond between soil and piles are assumed perfect bond in all cases. Two size of soil half space are considered in this study and they are:

- Half space (1) with dimensions (30m length, 16m width, and 12m depth)
- Half space (2) with dimensions (35m length, 20m width, and 15m depth)

The boundaries of soil domain must be established at sufficient distance from the edge of pile. This distance should be large enough (13) not less than ten pile diameter while (14)indicate this distance must be out of the envelope load region as specified of ref (15) and set this distance equal to (2-6) pile diameter. In this work, the soil boundaries are taken at distance more than (10) pile diameter from outer pile edge. also in this study we use square pile so to obtain the diameter of pile by equally area of square pile and circular pile we obtained the required diameter.

Dynamic load description, In the first loading case the dynamic load is a concentrated harmonic load which is applied laterally at the head of the pile (1) in the positive direction. In the second loading case the same first loading case is used but we added a dynamic concentrated harmonic load which is applied laterally at the head of pile (2) in the opposite direction as compare with direction of first loading condition. The amplitude of the harmonic load is equal to (200KN) in the positive direction for all cases (first case and second case) which is applied at pile head (1) and also (-200KN) in the opposite direction for second case study only which is applied at pile head (2). Different load frequencies are considered within the range of 0.5 to 1.5 of the first natural frequency of the pile with fixed boundary condition.

RESULTS AND DISCUSSIONS

Free Vibration Analysis

This part of analysis is performed to predict the effect of the soil surrounding the piles on the natural frequencies and their mode shapes. The natural frequencies and mode shapes are determined for the following cases:

- Determination of the natural frequencies and mode shapes for pile only assuming fixed boundary condition at base.
- Determination of the natural frequencies and mode shapes for the whole system (the piles with surrounding soil).

Types of soils used in this study are as follows:

- Soft silty clay soil for the whole soil domain.
- Medium silty clay soil for the whole soil domain.
- Dense sand-gravel soil for the whole soil domain.
- Soft silty clay soil over dense sand-gravel soil(layered soil).
- Medium silty clay soil over dense sand-gravel soil(layered soil).

The depth of the upper layer of layered soil is (3m) in half space. Properties of each soil are listed in table 1. Comparing the results of natural frequencies in table 2 to table 8 clarifies that the natural frequencies values of the pile alone is higher than their respective values in soil half spaces and similarly the values of the natural frequencies of the piles in half space (1)(the smaller) are higher than their respective values in half space (2)(the larger) The reasons of the difference is due to the inclusion of the inertia (mass) of the soil in the model which lead to a reduction in the stiffness, and as more mass adds as more stiffness reduced(8). also it is clear that increasing the stiffness of the soil increases the natural frequencies of the piles. In the case of non-fixed boundary conditions of the pile, the stiffness of the pile and then the natural frequencies are inversely proportional to the relative stiffness at the boundary conditions (8). Research has shown that soil-structure interaction increase the time period in structural models(16). Also ($T=1/f$) from this relation we shown the period has inversely proportional with natural frequency this mean the increase of period lead to decrease in natural frequency or inversely(17). In this study we obtain increase in time period when we consider soil-structures interaction as compare with pile aloneas shown in table from 9 to 15. Also we obtained as distance increase between piles the natural frequencies of seven mode shapes will be increase for both cases of soil half space surrounding the piles. In the present study the analysis of seven natural frequencies of whole system piles and surrounding soil dose not show any significant difference for the same case with same distance between piles but as distance increase there are significant difference in natural frequencies. For the cases of layered soil, it is clear from the results of table from 3 to 8 that reducing the stiffness of the top soil leads to a little reduction in the natural frequencies which means that in the case of free vibration analysis, the major role is played by the lowest layer of the soil.

Forced Vibration Analysis

In this part, the dynamic response of the single pile due to ground vibrations which is transmitted from a nearby dynamically loaded pile is investigated. Also the dynamically interaction between two piles due to ground vibrations are investigated. Properties of the soil types are same as in the analysis of free vibration table 1. A concentrated harmonic load is applied on the pile head (on the two loading case) has the following characteristics :

F(t)= P cosώt (KN)

Where, P: is the amplitude of the forces (KN), ώ : is the excitation frequency (rad/sec). The effect of the following parameters on the response are considered :

- Type of soil (soil properties).
- Distances between the piles.
- Size of soil half space.
- Variation in the excitation frequency.

Effect of Soil Type

Three types of soils that are differed in properties are considered in this case study. These soils are soft silty clay soil, medium silty clay, and dense sandy gravel. Each type is used alone to form the half space, and then a combination of two soils (two layers of soil) are also used to form the half space, and these are (soft silty clay over a dense sandy gravel and a medium silty clay over dense sandy gravel). Soil properties are given in table 1. we discussed two case in this study first before interaction and second after interaction. Before interaction the harmonic load is applied on the head of first pile only. After interaction two harmonic loads equal in magnitude and opposite in direction are applied on the head of the first pile and second pile respectively. Three distance between the first pile and second pile are considered and they are (5,10 and 15 meters) The first natural frequency of pile alone with fixed boundaries is used as the exciting frequency and finally, the horizontal displacement in the x-direction of two piles head is used to represent the response of both piles to the exciting loads. Result showed that the response of the both piles is varying with soils types as shown in figure from (1) to (6). Also it is clear from the results of layered half space, that the response of both piles is closer to results of the case of a half space with top soil only. This clarifies that the main exciting energy is transmitted through the top soil. This condition is occurred in both half space size of soil before and after interaction. The effect of the size of the half space is clearly shown the response increase by increasing the size of the soil half space for all cases. This is due to the fact that increasing the size increase the masses included and thus reduces the stiffness of the system. Also the fixed boundaries of the half space behave as reflectors to the energy waves, the reflected waves interact with travelling waves and reduce it is effect (dissipate amplitudes of the travelling waves). therefore increasing the distances to the reflectors reduce the interaction between the two waves (the travelling and reflected) and thus increases the response of pile (8). Also it is clear as the soil modulus of elasticity increase the response of piles decrease before and after interaction respectively for both soil half space. The deflection at pile head (2) after interaction always in direction opposite to direction of applied load at pile head (1).

Effect of Distance between Piles

It is difficult to estimate to what degree the amplitude of vibration decreases at a certain distance, but generally, the attenuation of vibrations with distance is composed of two factors : geometric damping and material damping. The geometrical damping related to the type and the location of vibration source and the material damping is related to the ground properties and vibration amplitude (18).

The distance (5,10 and 15 meter)between the piles before and after interaction are considered in this case to study the effect of distance on the response. The harmonic load is applied with excitation frequency equal to the first natural frequency of the pile alone with fixed boundaries. analysis result showed that for both half spaces the behavior of the system are similar. It is well noticed from table 16 to table 19 as distance between piles increase the response decrease before interaction for both half spaces of soil. increasing the distance of the excitation from the pile head (2) leads to a reduction in the pile head (2) response and this is due to the decay in the excitation energy with distance (6,18). but after interaction the response increase due to the applied load at pile head which cause displacement at head in addition to displacement occur due to interaction between travelling wave from the source of excitation pile (1) and pile (2). this interaction between travelling wave lead to decrease the displacement occur at pile head (1) and (2) due to applied load on the pile head. Randolph(1981) has shown that the pattern of lateral movement at the soil surface around a laterally loaded pile can be related directly to value of $\boldsymbol{\alpha_{\rho F}}$ published by Poulos (1971). The attenuation function to be expressed approximately in the form (19).

$$\Psi(r,\boldsymbol{\theta})=0.34(1+\cos^2\boldsymbol{\theta})(\boldsymbol{E_p}/\boldsymbol{E_s})^{1/7}\ (\mathbf{s/d})^{-1} \quad (1)$$

The center-to-center spacing between the piles is (s) and the angle between the line joining the pile centers and the direction of loading is designated herein as the departure angle ($\boldsymbol{\theta}$). The values of a parametric study on the attenuation function are shown in tables from 20 to 23. All $\Psi(r,\boldsymbol{\theta})$ values decrease with increasing spacing between piles. In this study ($\boldsymbol{\theta}$=0).

Effect of Half Space Boundaries on the Displacement of the Piles

In the finite element analysis the boundary conditions represent constraints to the system. In this case the effects of the boundary conditions on the displacement of the piles are studied through changing the size of the half space which leads to different distances between the piles and the boundaries while the distances between the two piles remain constants. From figures (7-14) and for all types of soils it is clear that the maximum displacement of the pile head under the same load and same distance between piles is higher in the case of larger half space than the smaller, this is due to the constraint of the boundary conditions. As the distance between pile and soil boundaries increase the response of pile increase before interaction but this response decrease after interaction. Theoretically, the boundaries reflect the travelling energy, the reflected energy dissipates the travelling energy and reduces the effect of the load on pile(8).

Variation in the Excitation Frequency

It is commonly accepted that structures normally responded at their fundamental frequencies and low vibration modes as the energy required to deform the structures in their low modes is a minimum (8). To test the effect of the frequency of the applied load, the load case is repeated 7 times with a different frequency in each time. The frequency range used is from (0.5-1.5) times the first natural frequency of pile alone with fixed boundary condition. The values of the excitation frequencies are as following :

Lower limit of frequency range of excitation = 0.5 ($\boldsymbol{f_1}$) pile alone

= 0.5(0.017250)

= 8.625 e-3 Hz

Upper limit of frequency range of excitation = 1.5 (f_1) pile alone

= 1.5(0.017250)

= 0.025875 Hz

The values of the seven cases of excitation frequencies in Hz are listed in table 24 where:

$$f_i = \frac{\omega_i}{2\pi} \quad (2)$$

f_i = excitation frequency (Hz)

ω_i = excitation frequency (radian per second)

Each case of excitation frequency is applied as separate frequency and the equation of motion is solved for each case alone to determine the dynamic response of the whole system for different soil type that considered on this study. The effect of soil structure interaction lead to versus the frequency ratio (r) which is the ratio between excitation frequencies to the first natural frequency of pile alone with fixed boundary condition as following :

$$r = \frac{f_i}{f_1} \quad (3)$$

where :

f_i= excitation frequency for case in (Hz).

f_1= the first natural frequency of pile with fixed boundary condition.

The figure from (15) to (29) shows the variation of the horizontal response of whole system with frequency ratio (r) considering soil structure interaction effect.

It is well known from dynamic analysis that the response of a single degree of freedom structure to any excitation having frequency equal to the natural frequency of the structure will be in a resonance. for a multi degree of freedom structure,the effect of the excitation becomes a maximum when its frequency coincides with lowest frequency of the structure and usually in the design, the excitation frequency in the range of (0.5 to 1.5) of the lowest natural frequency of the structure is avoided(20,22) therefore this undesired range excitation frequency is considered in this study to determine the range of increase in the response of whole system. As shown in figures (15-29), the maximum response is occurred when the frequency ratio (r) equal to (1.5) this difference in (r) is depended on the soil type.

CONCLUSIONS

The following conclusions can be drawn from the present study:-

- As distance between piles in half space of soil increase the natural period should be increase.
- The response of both piles in half space of soil varying with soil type.
- The dynamic response of piles to vibrations through the soil is highly dependent on the soil type where the response of piles embedded on half space of soft silty clay soil is greater than those on half space of medium silty clay and dense sand-gravel respectively.

- The majority of the excitation energy is transmitted through the upper layer of the soil ; therefore; the upper layer of the soil has a significant influence on the dynamic response of a piles subjected to ground vibrations in the layered half space.
- In the finite element idealization of a soil half space problems, the size of soil half space affect the analysis results.
- The response of embedded piles on the half space of layered soil consist of soft silty clay above dense sand gravel is greater than layered half space consist of medium silty clay above dense sand gravel.
- The displacement of pile head decrease with increasing distance between piles before interaction but the displacement of pile head increase with increasing distance between piles after interaction.
- The frequency of the ground vibration has an influence effect on the response of existing structures especially when the excitation frequency is within the structure lower natural frequencies.

Table 1: Properties of Each Soil are Listed in Table

Type of Soil	Modulus of Elasticity (Es) (Map)	Density ((ρ_s) (Kg/M3)	Poison's Ratio (Ns)	Damping Ratio (ζ_s)
Soft	48	1600	0.4	0.02
Medium	98	1900	0.4	0.02
Dense	182	2200	0.3	0.02

Table 2: Natural Frequencies of Pile Alone with Fixed Boundaries along the Base

No. of Mode	Natural Frequency (f) (Hz)
1	0.017250
2	0.017250
3	0.16930
4	0.16930
5	0.46379
6	0.70337
7	0.70337

Table 3: Variation of the Natural Frequencies of the Piles with Soil Type. Perfect Bond (5m) Distance between Piles (Half Space 1)

No. of Mode	Natural Frequencies of the Whole System with Different Types of Soil (F) (Hz)				
	Softy Silty Clay	Medium Silty Clay	Dense Sandy Gravel	Soft Silty Clay over Dense Sand Gravel Soil	Medium Silty Clay over Dense Sand Gravel Soil
1	0.050014	0.065560	0.083385	0.058211	0.071288
2	0.058917	0.076910	0.088934	0.072341	0.085419
3	0.060115	0.078724	0.094537	0.073092	0.088429
4	0.065321	0.085618	0.098471	0.077679	0.090447
5	0.066172	0.086729	0.098860	0.079381	0.091908
6	0.066247	0.086839	0.098967	0.079984	0.097021
7	0.070471	0.091764	0.099479	0.080821	0.097747

Table 4: Variation of the Natural Frequencies of the Piles with Soil Type. Perfect Bond (10m) Distance between Piles (Half Space 1)

No. of Mode	Natural Frequencies of the Whole System With Different Types of Soil (*F*) (Hz)				
	Softy Silty Clay	Medium Silty Clay	Dense Sandy Gravel	Soft Silty Clay over Dense Sand Gravel Soil	Medium Silty Clay over Dense Sand Gravel Soil
1	0.050257	0.065852	0.083478	0.058319	0.071432
2	0.057881	0.075685	0.088271	0.072486	0.084711
3	0.061004	0.079788	0.096045	0.072981	0.089713
4	0.065350	0.085676	0.098688	0.076357	0.090708
5	0.066218	0.086755	0.0988	0.080380	0.091632
6	0.066429	0.087049	0.098856	0.080711	0.096449
7	0.070649	0.092275	0.099388	0.081036	0.097366

Table 5: Variation of the Natural Frequencies of the Piles with Soil Type. Perfect Bond (15m) Distance between Piles (Half Space 1)

No. of Mode	Natural Frequencies of the Whole System with Different Types of Soil (*F*) (Hz)				
	Softy Silty Clay	Medium Silty Clay	Dense Sandy Gravel	Soft Silty Clay over Dense Sand Gravel Soil	Medium Silty Clay over Dense Sand Gravel Soil
1	0.050415	0.066042	0.083567	0.058424	0.071556
2	0.056797	0.074419	0.087161	0.072596	0.083614
3	0.061111	0.079930	0.096602	0.072933	0.090076
4	0.065357	0.085696	0.098750	0.075309	0.090914
5	0.066197	0.086712	0.098755	0.080602	0.091531
6	0.067733	0.088577	0.098861	0.080695	0.096671
7	0.070748	0.092674	0.099123	0.080891	0.097496

Table 6: Variation of the Natural Frequencies of the Piles with Soil Type. Distance (5m) between Piles (Half Space 2)

No. of Mode	Natural Frequencies of the Whole System with Different Types of Soil (*F*) (Hz)				
	Softy Silty Clay	Medium Silty Clay	Dense Sandy Gravel	Soft Silty Clay over Dense Sand Gravel Soil	Medium Silty Clay over Dense Sand Gravel Soil
1	0	0	0	0	0
2	0	0	0	0	0
3	0.040913	0.052230	0.053090	0.050113	0.052806
4	0.0459	0.052842	0.053123	0.052367	0.052935
5	0.048326	0.052884	0.053146	0.052531	0.052973
6	0.051304	0.052949	0.053173	0.052647	0.053025
7	0.052075	0.054426	0.068528	0.053480	0.060486

Table 7: Variation of the Natural Frequencies of the Piles with Soil Type. Distance (10m) between Piles (Half Space 2)

No. of Mode	Natural Frequencies of the Whole System with Different Types of Soil (*F*) (Hz)				
	Softy Silty Clay	Medium Silty Clay	Dense Sandy Gravel	Soft Silty Clay over Dense Sand Gravel Soil	Medium Silty Clay over Dense Sand Gravel Soil
1	0	0	0	0	0
2	0	0	0	0	0
3	0.041008	0.052344	0.053113	0.050246	0.052858
4	0.045707	0.052878	0.053143	0.052469	0.052969
5	0.048499	0.052884	0.053146	0.052485	0.052970
6	0.051518	0.052916	0.053159	0.052575	0.052998
7	0.051809	0.054448	0.068550	0.053418	0.060493

Table 8: Variation of the Natural Frequencies of the Piles with Soil Type. Distance (15m) between Piles (Half Space 2)

No. of Mode	Natural Frequencies of the Whole System with Different Types of Soil (*F*) (Hz)				
	Softy Silty Clay	Medium Silty Clay	Dense Sandy Gravel	Soft Silty Clay over Dense Sand Gravel Soil	Medium Silty Clay over Dense Sand Gravel Soil
1	0	0	0	0	0
2	0	0	0	0	0
3	0.041123	0.052479	0.053128	0.050433	0.0529
4	0.045466	0.052882	0.053147	0.052478	0.052972
5	0.048623	0.052896	0.053149	0.052509	0.052979
6	0.051690	0.052909	0.053155	0.052551	0.052990
7	0.051750	0.054439	0.068568	0.053260	0.060504

Table 9: Period for Pile Alone

Mode	Period (Sec)
1	57.97
2	57.97
3	5.9
4	5.9
5	2.16
6	1.42
7	1.42

Table 10: Period of Whole System Piles and Surrounding Soil – Distance between Piles (5 M)- Perfect Bond (Half Space 1)

Mode	Period of the Whole System with Different Types of Soil (*Sec*)				
	Softy Silty Clay	Medium Silty Clay	Dense Sandy Gravel	Soft Silty Clay over Dense Sand Gravel Soil	Medium Silty Clay over Dense Sand Gravel Soil
1	19.99	15.25	11.99	17.18	14.03
2	16.97	13	11.24	13.82	11.7
3	16.63	12.7	10.57	13.68	11.31
4	15.31	11.68	10.15	12.87	11.05
5	15.11	11.53	10.11	12.6	10.88
6	15.09	11.51	10.10	12.5	10.3
7	14.19	10.89	10.05	12.37	10.23

Table 11: Period of Whole System Piles and Surrounding Soil – Distance between Piles (10 M)- Perfect Bond (Half Space 1)

Mode	Period of the Whole System with Different Types of Soil (*Sec*)				
	Softy Silty Clay	Medium Silty Clay	Dense Sandy Gravel	Soft Silty Clay over Dense Sand Gravel Soil	Medium Silty Clay over Dense Sand Gravel Soil
1	19.89	15.18	11.98	17.15	13.99
2	17.27	13.21	11.32	13.8	11.8
3	16.39	12.53	10.41	13.7	11.14
4	15.3	11.67	10.13	13.09	11
5	15.1	11.53	10.12	12.44	10.9
6	15	11.48	10.11	12.39	10.36
7	14.15	10.84	10.06	12.34	10.27

Table 12: Period of Whole System Piles and Surrounding Soil – Distance between Piles(15 M)- Perfect Bond (Half Space 1)

Mode	Period of the Whole System with Different Types of Soil (*Sec*)				
	Softy Silty Clay	Medium Silty Clay	Dense Sandy Gravel	Soft Silty Clay over Dense Sand Gravel Soil	Medium Silty Clay over Dense Sand Gravel Soil
1	19.83	15.14	11.966	17.116	13.975
2	17.6	13.44	11.47	13.77	11.96
3	16.36	12.51	10.35	13.7	11.1
4	15.3	11.669	10.127	13.278	10.99
5	15.1	11.53	10.126	12.4	10.925
6	14.76	11.29	10.11	12.39	10.344
7	14.13	10.79	10	12.36	10.25

Table 13: Period of Whole System Piles and Surrounding Soil – Distance between Piles (5 M)- Perfect Bond (Half Space 2)

Mode	Period of the Whole System with Different Types of Soil (*Sec*)				
	Softy Silty Clay	Medium Silty Clay	Dense Sandy Gravel	Soft Silty Clay over Dense Sand Gravel Soil	Medium Silty Clay over Dense Sand Gravel Soil
1	-----	------	------	-------	------
2	------	------	-------	-------	------
3	24.44	19.146	18.836	19.9	18.918
4	21.78	18.92	18.82	19.05	18.879
5	20.69	18.9	18.816	19	18.878
6	19.49	18.886	18.8	18.99	18.868
7	19.2	18.37	14.59	18.7	16.53

Table 14: Period of Whole System Piles and Surrounding Soil – Distance between Piles(10m) Perfect Bond (Half Space 2)

Mode	Period of the Whole System with Different Types of Soil (*Sec*)				
	Softy Silty Clay	Medium Silty Clay	Dense Sandy Gravel	Soft Silty Clay over Dense Sand Gravel Soil	Medium Silty Clay over Dense Sand Gravel Soil
1	-----	-----	------	------	------
2	-----	------	-------	------	------
3	24.385	19.1	18.827	19.9	18.918
4	21.878	18.91	18.817	19.059	18.879
5	20.619	18.9	18.816	19.053	18.878
6	19.41	18.89	18.811	19	18.868
7	19.3	18.366	14.588	18.72	16.53

Table 15: Period of Whole System Piles and Surrounding Soil – Distance between Piles (15m) Perfect Bond (Half Space 2)

Mode	Period of the Whole System with Different Types of Soil (*Sec*)				
	Softy Silty Clay	Medium Silty Clay	Dense Sandy Gravel	Soft Silty Clay over Dense Sand Gravel Soil	Medium Silty Clay over Dense Sand Gravel Soil
1	------	------	------	-------	-------
2	------	------	-------	--------	-------
3	24.317	19.06	18.822	19.828	18.9
4	21.99	18.91	18.816	19.05	18.877
5	20.566	18.9	18.815	19.04	18.875
6	19.34	18.9	18.813	19.02	18.87
7	19.32	18.369	14.584	18.77	16.528

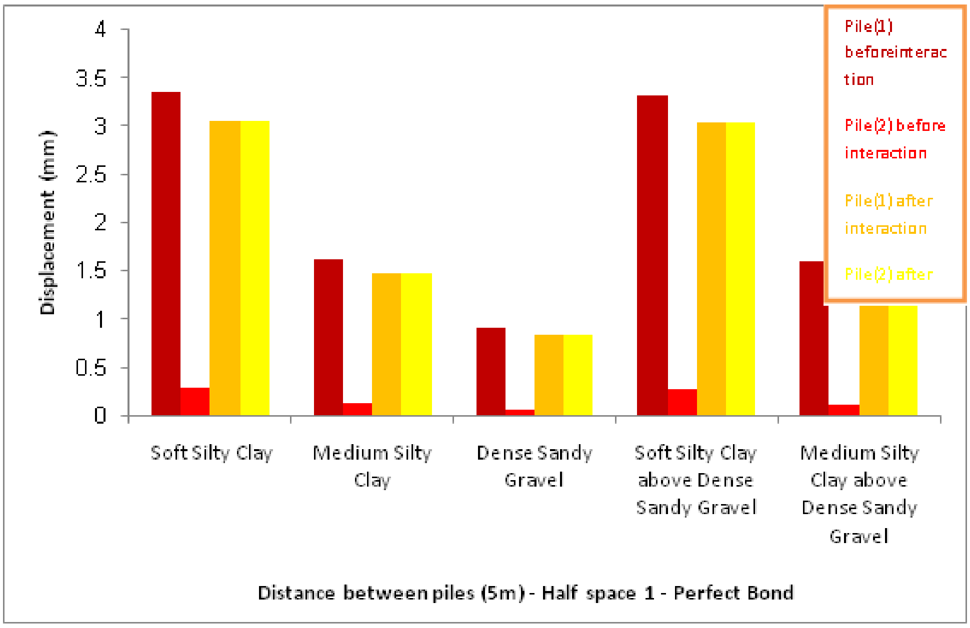

Figure 1: Variation of Displacement with Soil Type

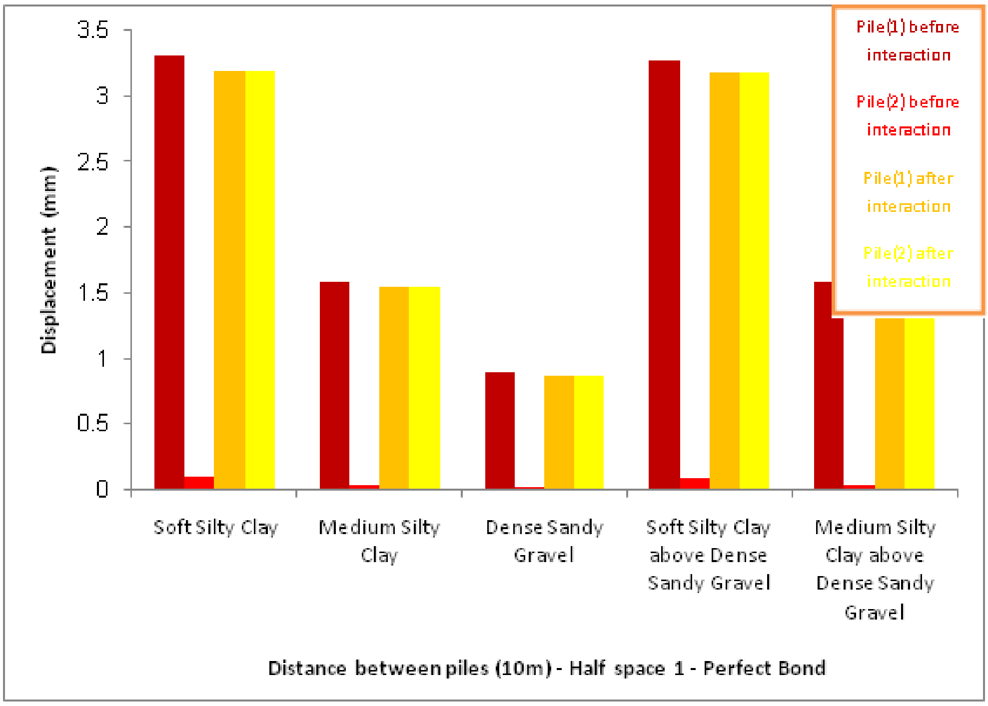

Figure 2: Variation of Displacement with Soil Type

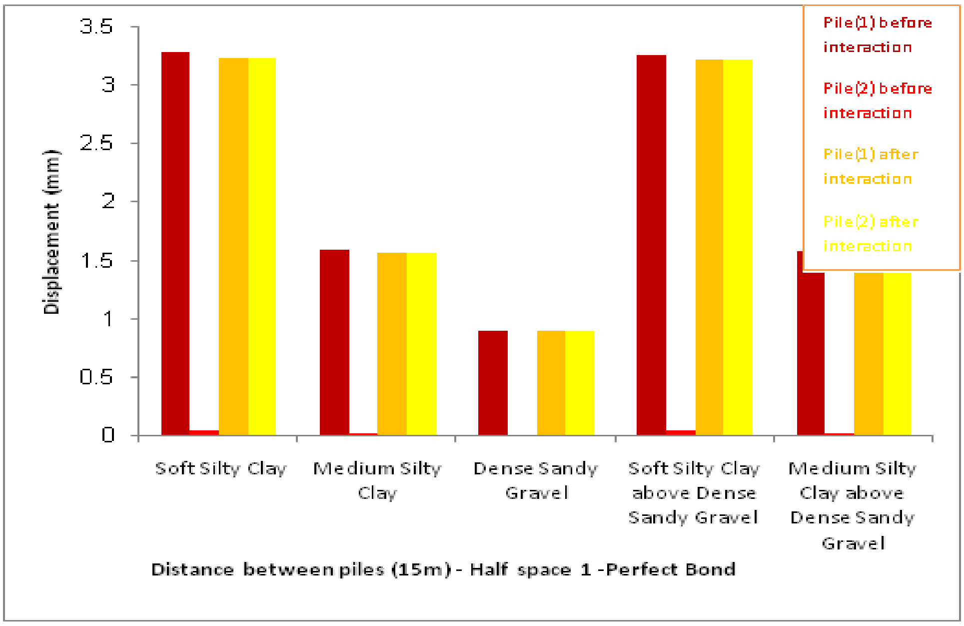

Figure 3: Variation of Displacement with Soil Type

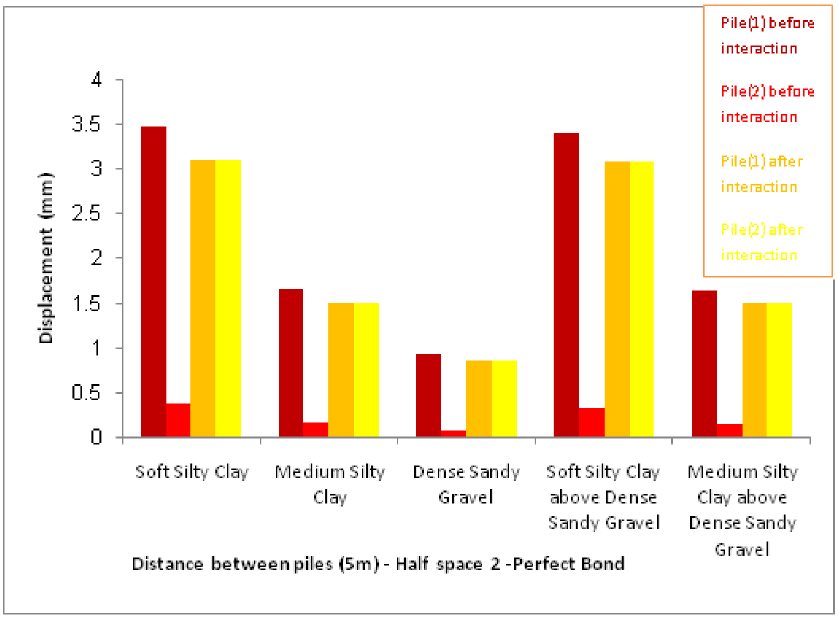

Figure 4: Variation of Displacement with Soil Type

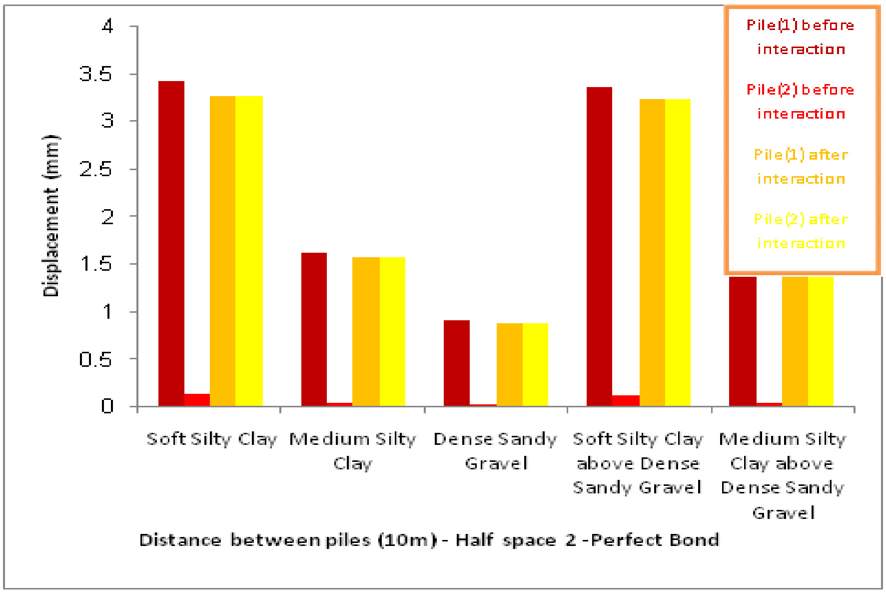

Figure 5: Variation of Displacement with Soil Type

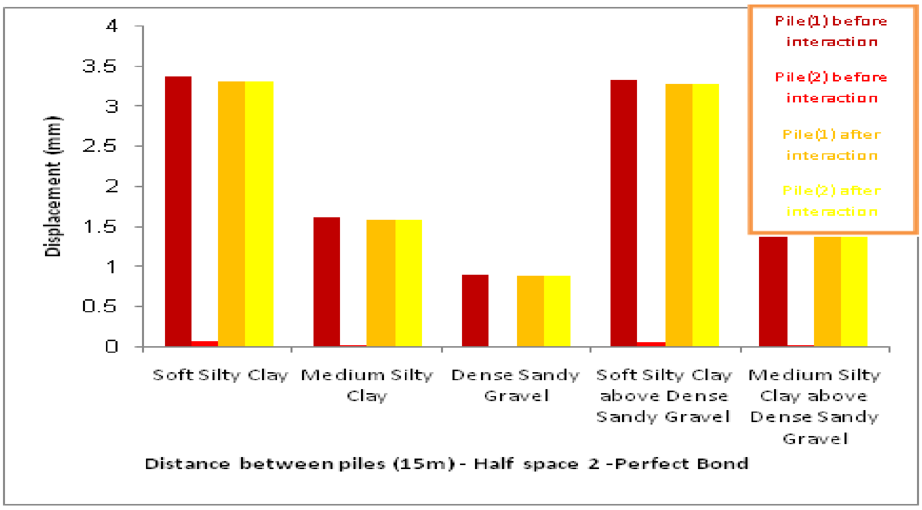

Figure 6: Variation of Displacement with Soil Type

Table 16: Variation of Displacement at Pile Head (1) with Increasing Distance for Half Space (1)

Distance (m)	Displacement (mm)									
	Soft Silty Clay		Medium Silty Clay		Dense Sandy Gravel		Soft Silty Clay over Dense Sandy Gravel		Medium Silty Clay over Dense Sandy Gravel	
	Before Int.	After Int.	Before Int.	After Int.	Before Int.	After Int.	Before Int.	After Int.	Before Int.	After Int.
5 m	3.369	3.063	1.621	1.488	0.915	0.853	3.329	3.05	1.614	1.484
10 m	3.31	3.201	1.594	1.55	0.9	0.881	3.274	3.176	1.588	1.545
15 m	3.289	3.239	1.587	1.568	0.899	0.891	3.26	3.218	1.582	1.564

Table 17: Variation of Displacement at Pile Head (2) with Increasing Distance for Half Space (1)

Distance (m)	Displacement (mm)									
	Soft Silty Clay		Medium Silty Clay		Dense Sandy Gravel		Soft Silty Clay over Dense Sandy Gravel		Medium Silty Clay over Dense Sandy Gravel	
	Before Int.	After Int.	Before Int.	After Int.	Before Int.	After Int.	Before Int.	After Int.	Before Int.	After Int.
5 m	0.305	3.063	0.133	1.488	0.062	0.853	0.28	3.05	0.129	1.484
10 m	0.108	3.201	0.044	1.55	0.02	0.881	0.098	3.176	0.043	1.545
15 m	0.05	3.239	0.02	1.568	0.008	0.891	0.042	3.218	0.018	1.564

Table 18: Variation of Displacement at Pile Head (1) with Increasing Distance for Half Space (2)

Distance (M)	Displacement (Mm)									
	Soft Silty Clay		Medium Silty Clay		Dense Sandy Gravel		Soft Silty Clay Over Dense Sandy Gravel		Medium Silty Clay Over Dense Sandy Gravel	
	Before Int.	After Int.	Before Int.	After Int.	Before Int.	After Int.	Before Int.	After Int.	Before Int.	After Int.
5 m	3.461	3.092	1.647	1.495	0.925	0.855	3.388	3.073	1.635	1.491
10 m	3.427	3.277	1.633	1.58	0.918	0.893	3.36	3.241	1.622	1.57
15 m	3.39	3.312	1.619	1.592	0.911	0.9	3.33	3.277	1.61	1.585

Table 19: Variation of Displacement at Pile Head (2) with Increasing Distance for Half Space (2)

Distance (M)	Displacement (Mm)									
	Soft Silty Clay		Medium Silty Clay		Dense Sandy Gravel		Soft Silty Clay Over Dense Sandy Gravel		Medium Silty Clay Over Dense Sandy Gravel	
	Before Int.	After Int.	Before Int.	After Int.	Before Int.	After Int.	Before Int.	After Int.	Before Int.	After Int.
5 m	0.369	3.092	0.152	1.495	0.07	0.855	0.315	3.073	0.144	1.491
10 m	0.15	3.277	0.055	1.58	0.025	0.893	0.119	3.241	0.052	1.57
15 m	0.078	3.312	0.027	1.592	0.01	0.9	0.06	3.277	0.024	1.585

Table 20: Variation of Attenuation Function With (E_p/E_s) for Half Space -1

E_p/E_s	Ψ / 0.34 (1 + cos²θ) (s / d)⁻¹		
	S = 5m	S = 10m	S = 15m
468.75	2.4	2.42	2.44
229.59	2.17	2.18	2.2
123.63	1.99	2	2.04
195.65	2.11	2.16	2.17
160.71	2.05	2.08	2.12

Table 21: Variation of Attenuation Function with (E_p /E_s) for Half Space -2

E_p/E_s	Ψ / 0.34 (1 + cos²θ) (s / d)⁻¹		
	S = 5m	S = 10m	S = 15m
468.75	2.4	2.42	2.44
229.59	2.17	2.18	2.2
123.63	1.99	2	2.04
195.65	2.08	2.11	2.12
160.71	2.04	2.07	2.08

Table 22: Variation of Attenuation Function with Spacing between Piles for Half Space – 1

Soil type	$\Psi / (E_p/E_s)^{1/7}$		
	S/d = 8.86	S/d = 17.72	S /d = 26.58
Soft silty clay	0.0768	0.0382	0.0253
Medium silty clay	0.0768	0.0381	0.0253
Dense sandy gravel	0.0769	0.038	0.0256
Soft clay above dense gravel	0.0767	0.0386	0.0254
Medium clay above dense gravel	0.0765	0.0382	0.0256

Table 23: Variation of Attenuation Function with Spacing between Piles for Half Space – 2

Soil type	$\Psi / (E_p/E_s)^{1/7}$		
	S/d = 8.86	S/d = 17.72	S /d = 26.58
Soft silty clay	0.0768	0.0382	0.0253
Medium silty clay	0.0768	0.0381	0.0253
Dense sandy gravel	0.0769	0.038	0.0256
Soft clay above dense gravel	0.0752	0.0376	0.0249
Medium clay above dense gravel	0.076	0.0382	0.0251

Table 24: Values of Excitation Frequency for Each Case and their Respective Frequency Ratio

Case No.	Excitation Frequency		Frequency Ratio (r)
	$f_i^{'}$ (Hz)	ω_i (Radian/Second)	
1	0.011089	0.0696	0.642
2	0.013554	0.0851	0.785
3	0.016018	0.1	0.922
4	0.018482	0.116	1.07
5	0.020946	0.1316	1.214
6	0.023411	0.147	1.356
7	0.025875	0.1626	1.5

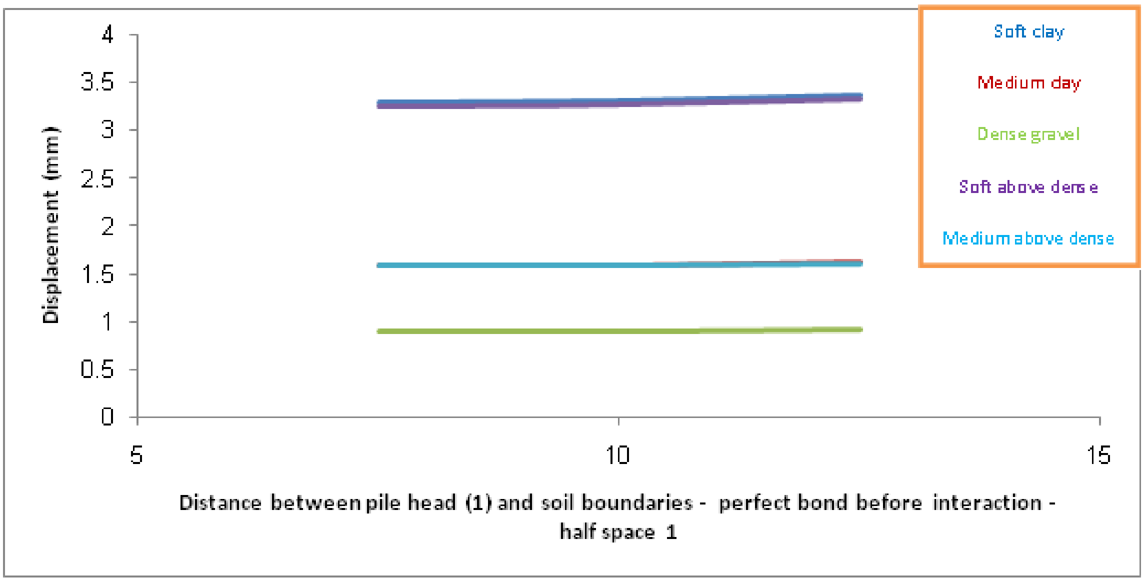

Figure 7: Variation of Pile Head Displacement with Distance between Pile and Soil Boundaries

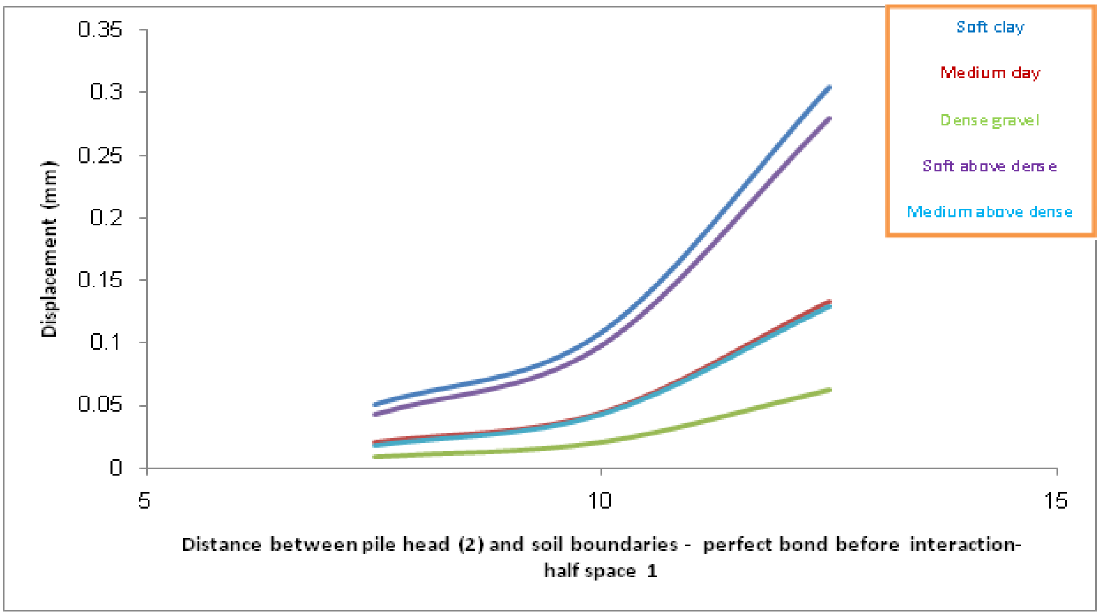

Figure 8: Variation of Pile Head Displacement with Distance between Pile and Soil Boundaries

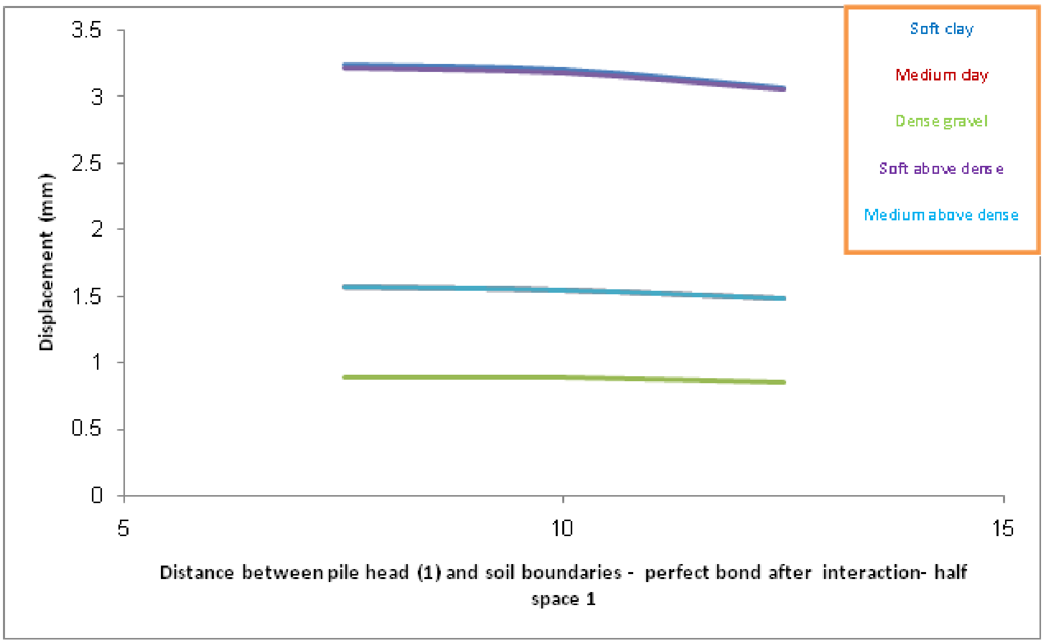

Figure 9: Variation of Pile Head Displacement with Distance between Pile and Soil Boundaries

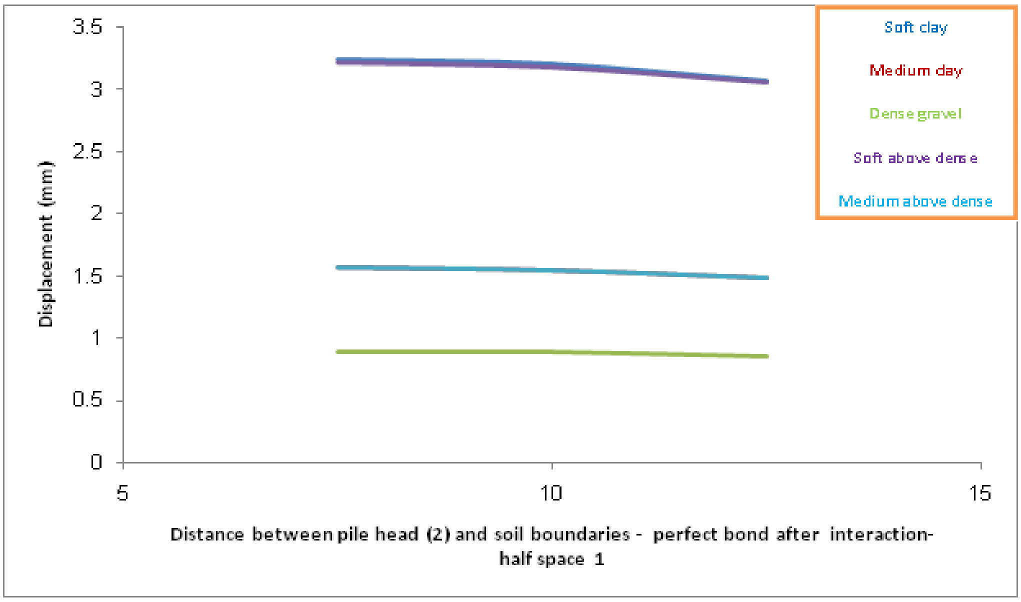

Figure 10: Variation of Pile Head Displacement with Distance between Pile and Soil Boundaries

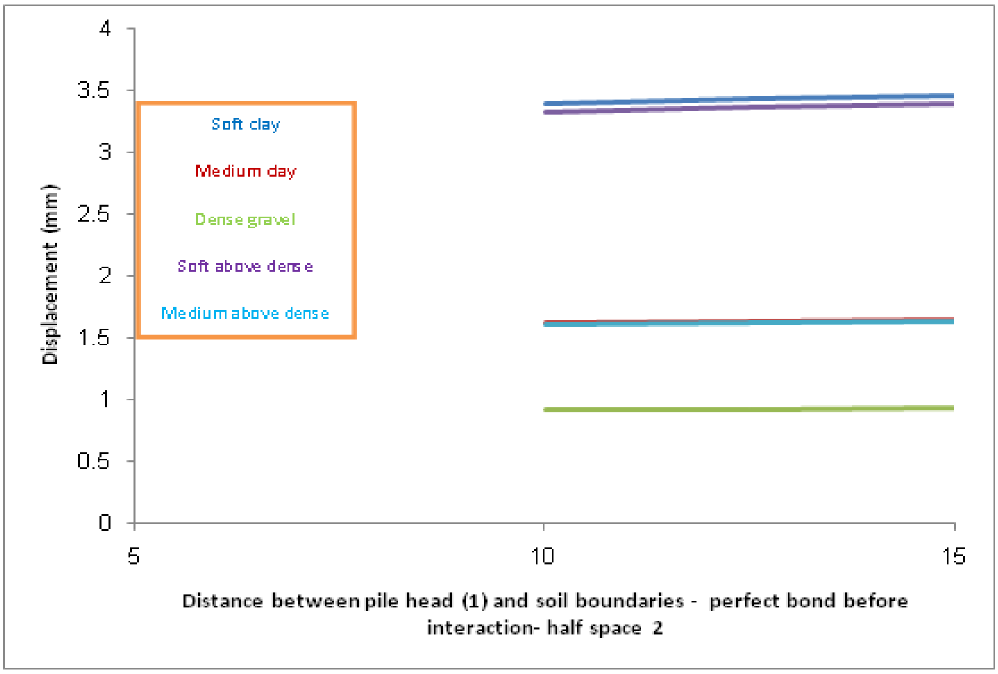

Figure 11: Variation of Pile Head Displacement with Distance between Pile and Soil Boundaries

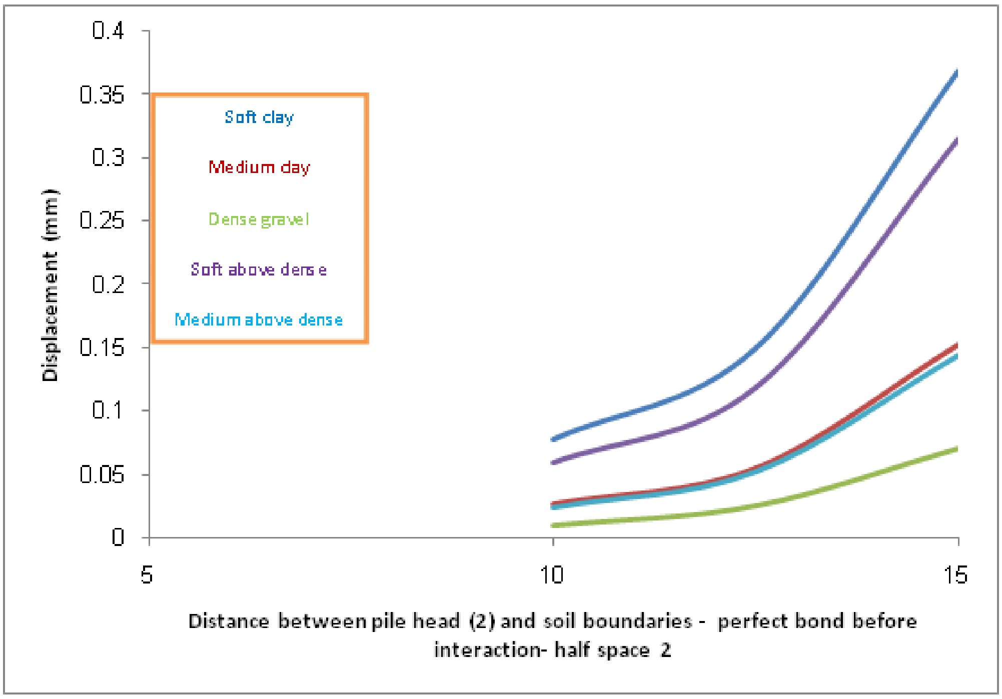

Figure 12: Variation of Pile Head Displacement with Distance between Pile and Soil Boundaries

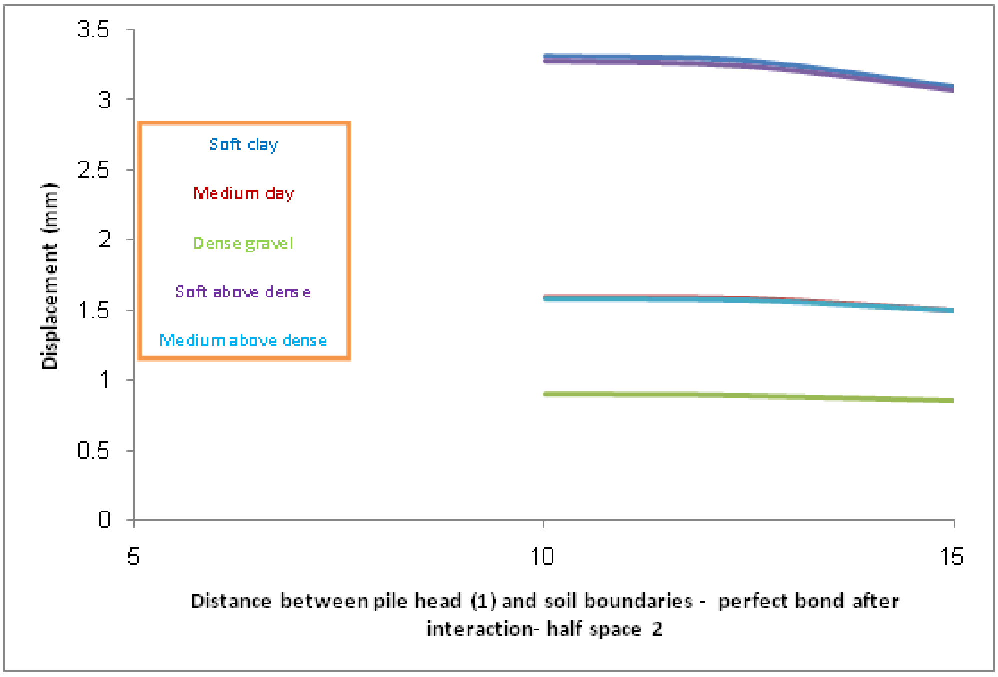

Figure 13: Variation of Pile Head Displacement with Distance between Pile and Soil Boundaries

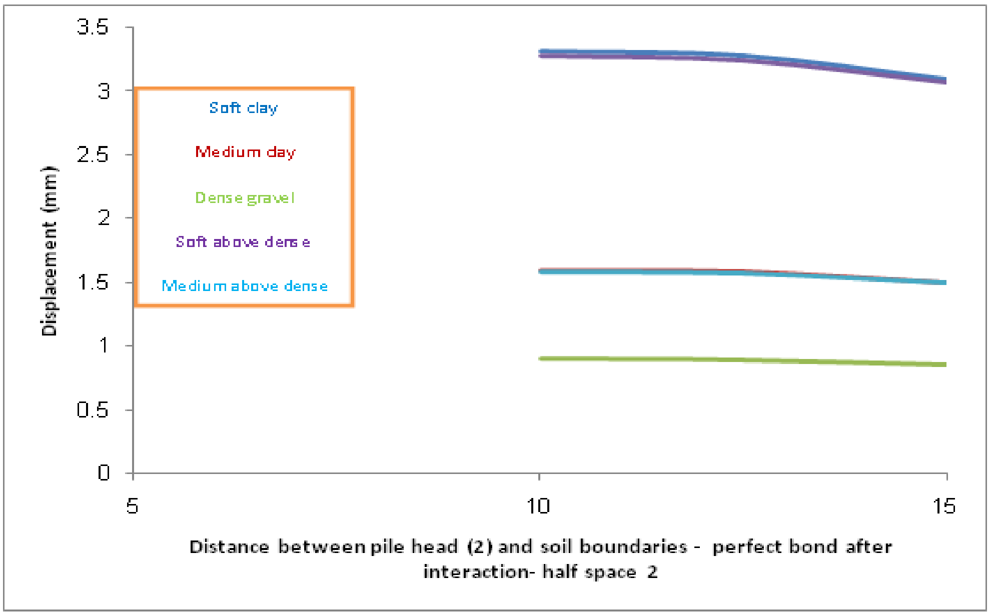

Figure 14: Variation of Pile Head Displacement with Distance between Pile and Soil Boundaries

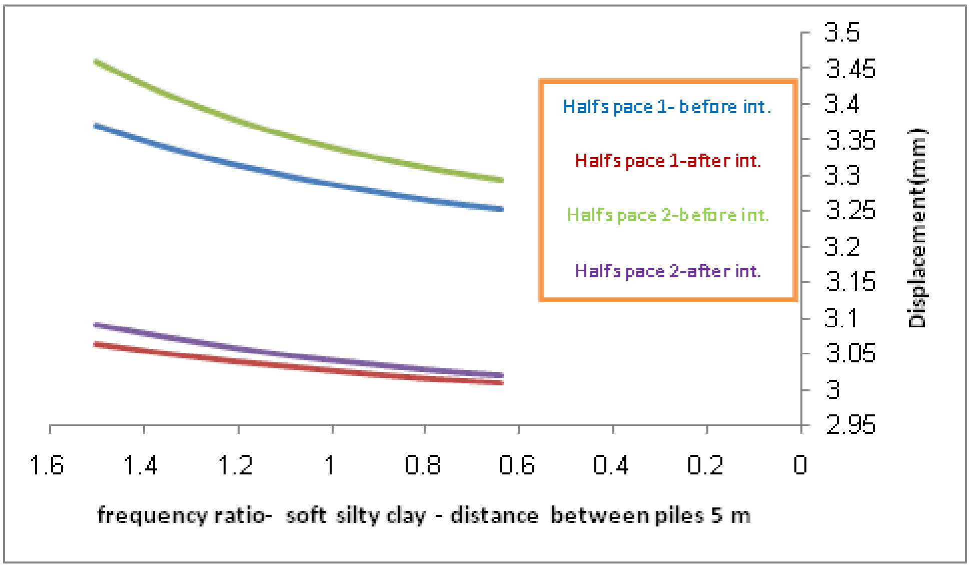

Figure 15: Variation of Response with Frequency Ratio

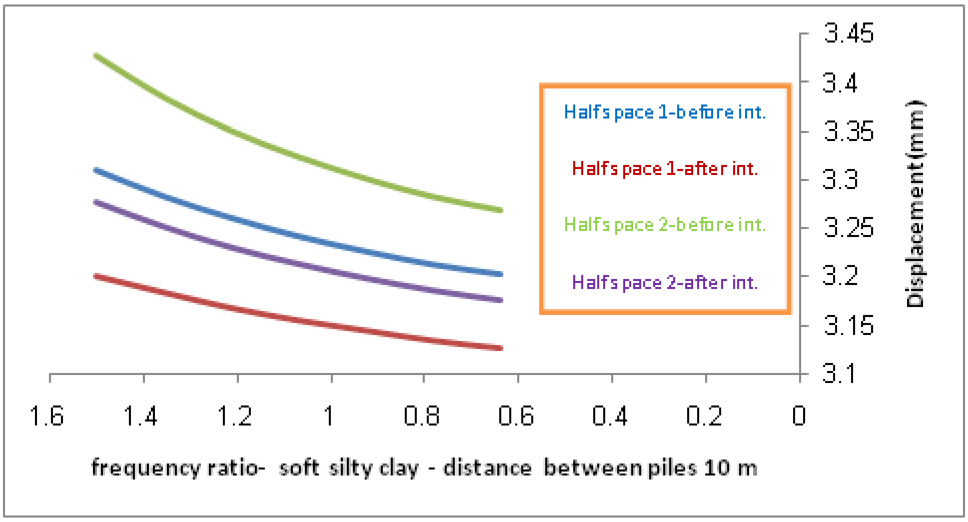

Figure 16: Variation of Response with Frequency Ratio

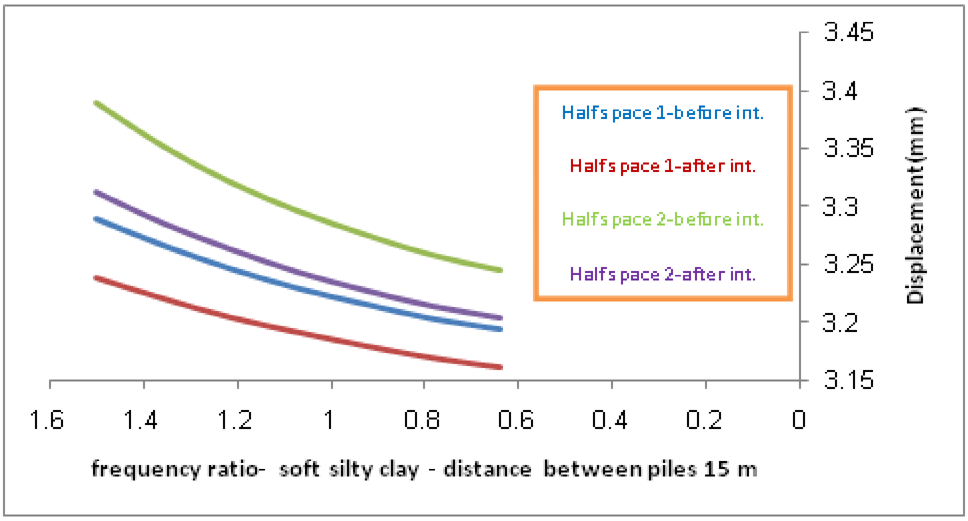

Figure 17: Variation of Response with Frequency Ratio

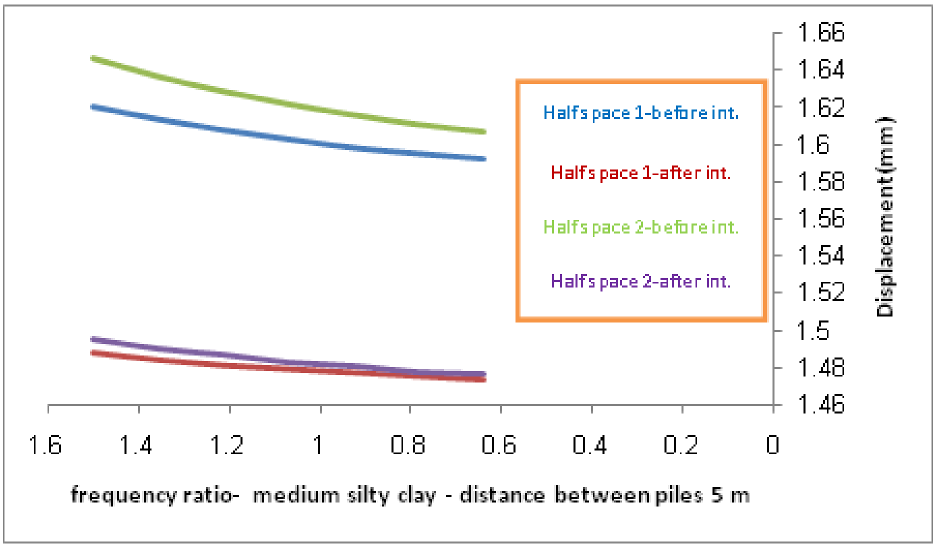

Figure 18: Variation of Response with Frequency Ratio

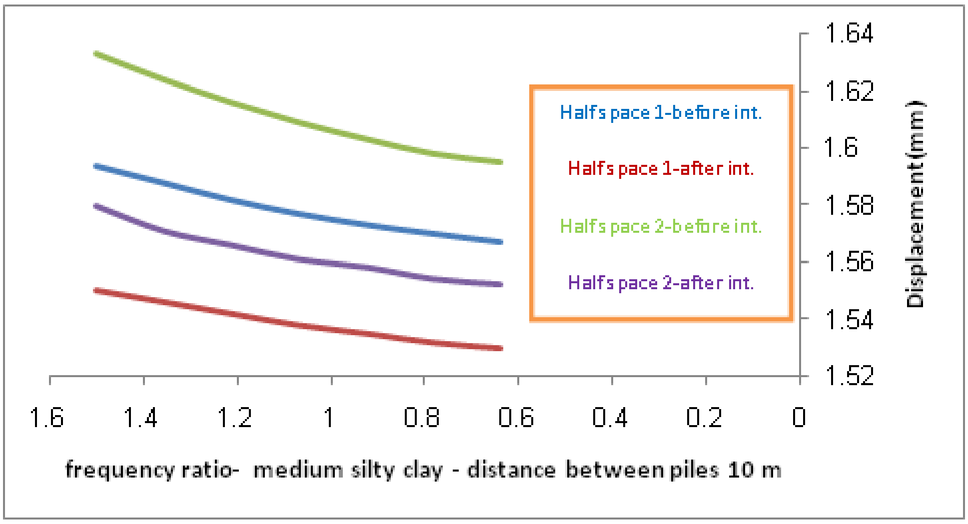

Figure 19: Variation of Response with Frequency Ratio

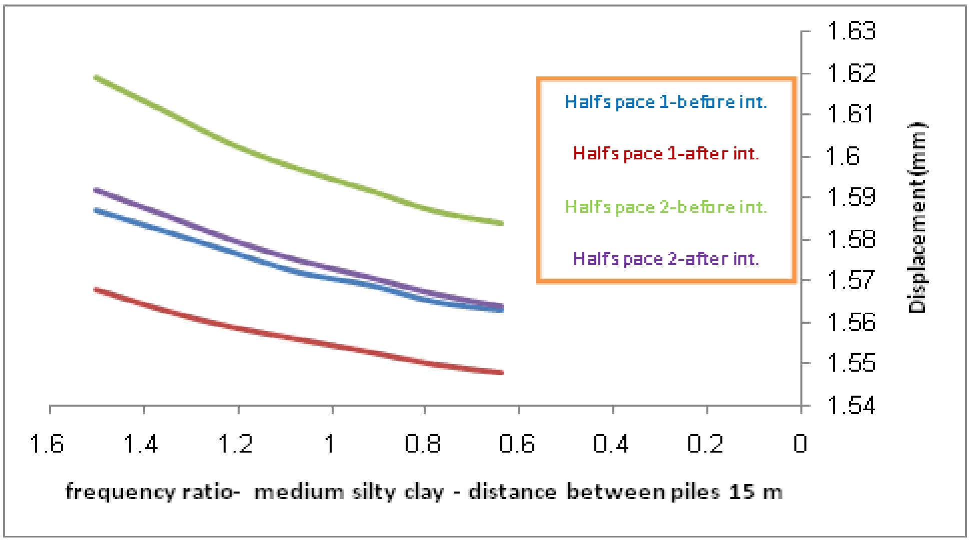

Figure 20: Variation of Response with Frequency Ratio

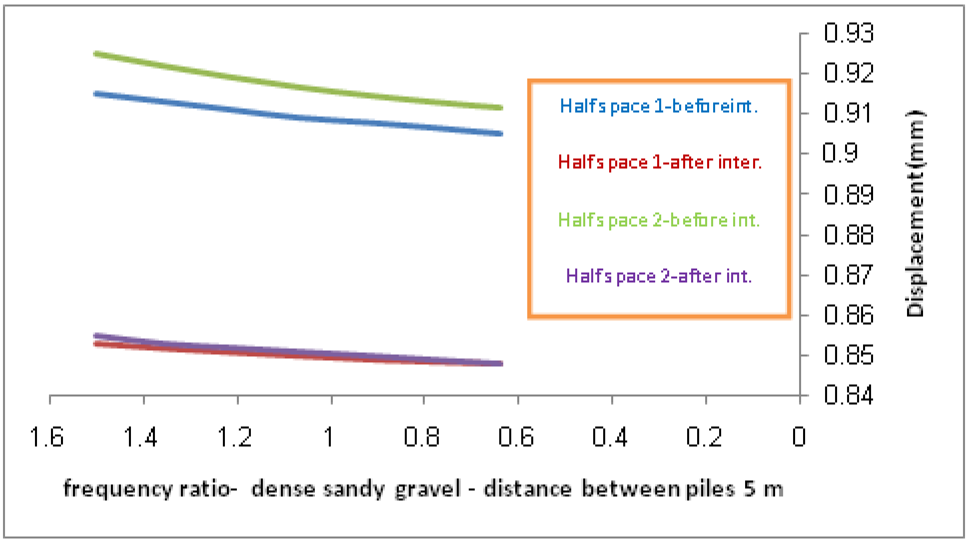

Figure 21: Variation of Response with Frequency Ratio

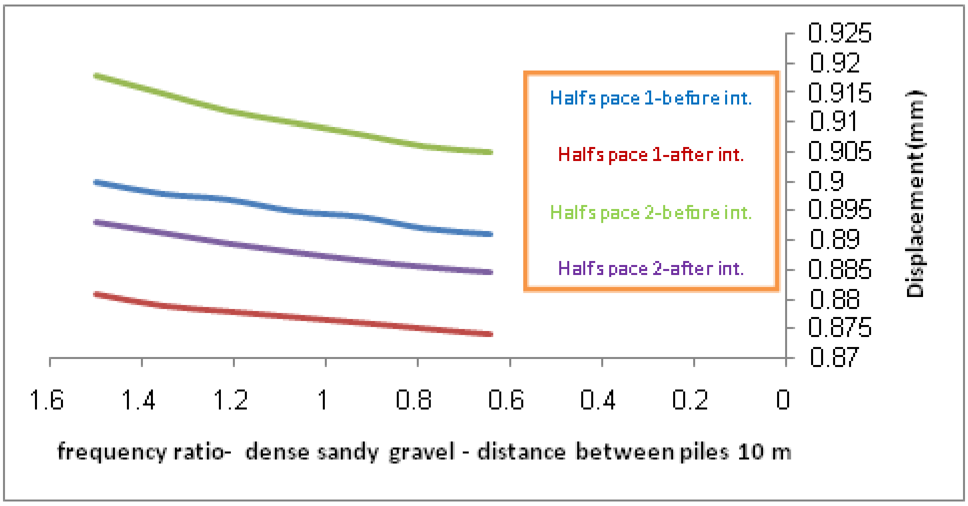

Figure 22: Variation of Response with Frequency Ratio

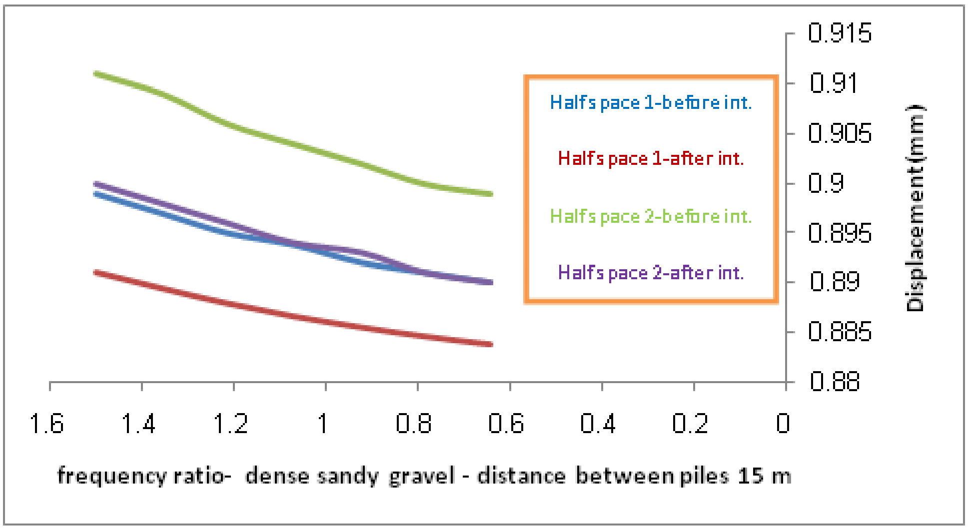

Figure 23: Variation of Response with Frequency Ratio

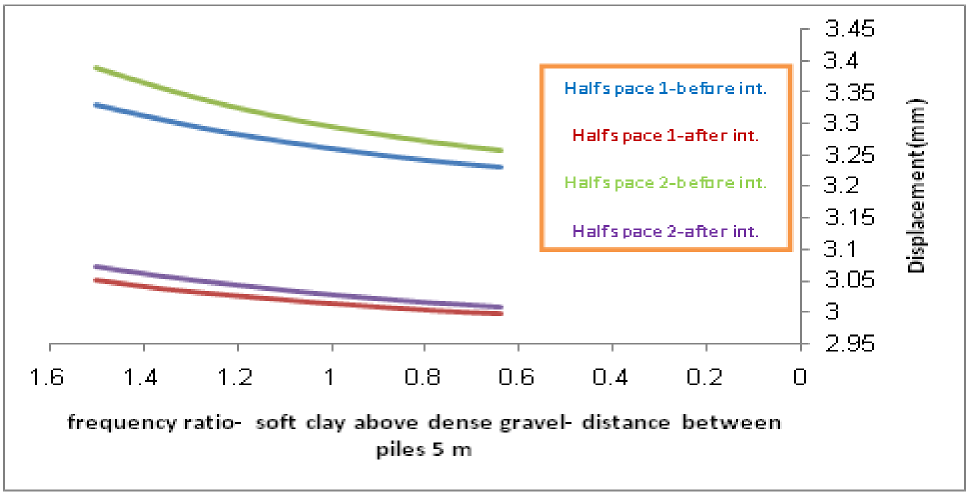

Figure 24: Variation of Response with Frequency Ratio

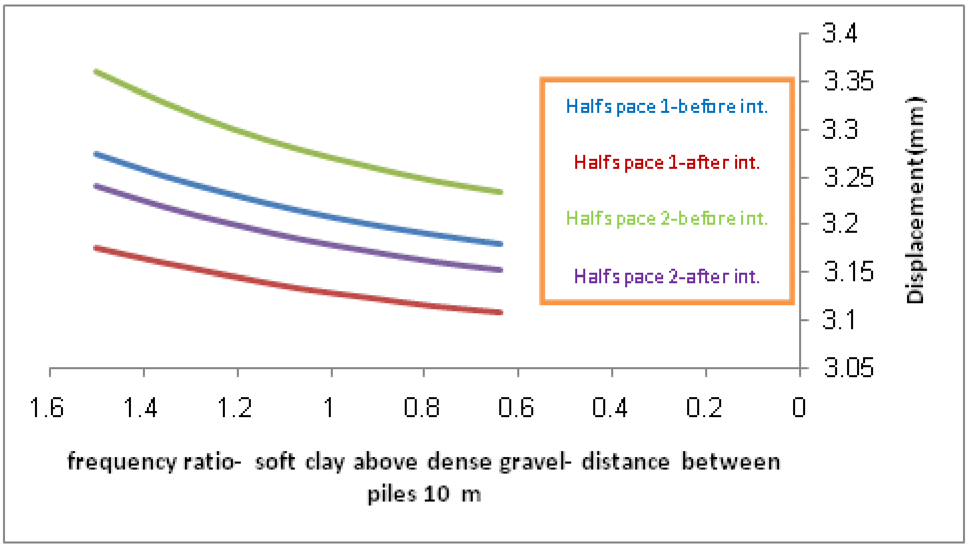

Figure 25: Variation of Response with Frequency Ratio

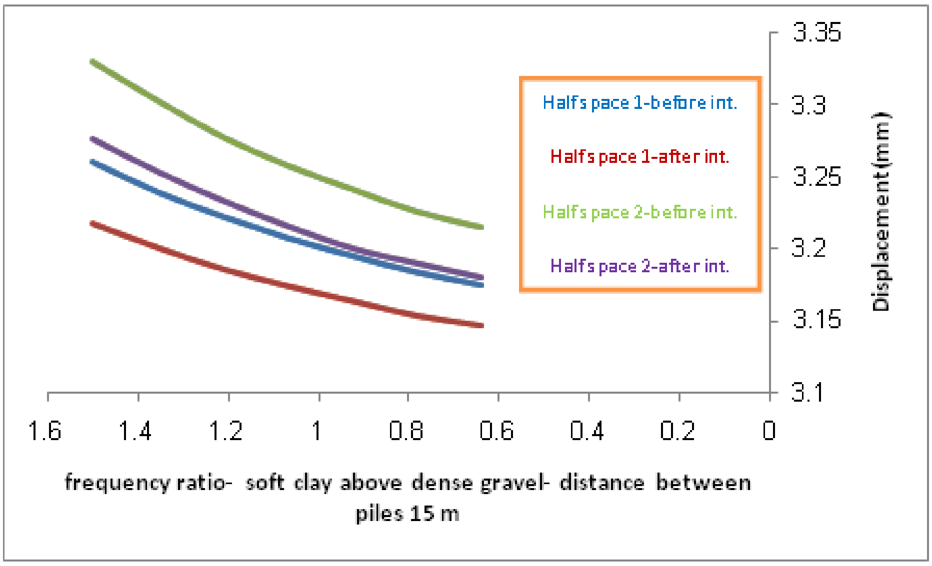

Figure 26: Variation of Response with Frequency Ratio

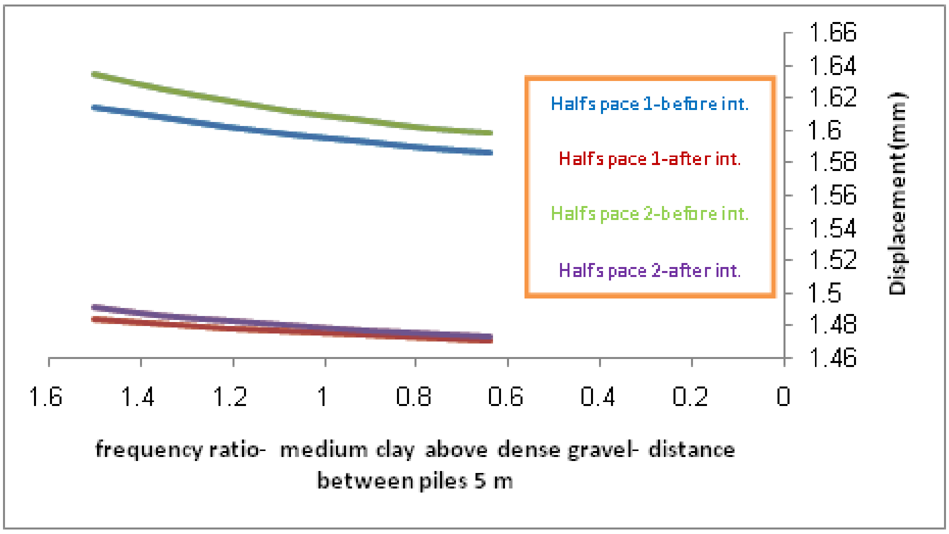

Figure 27: Variation of Response with Frequency Ratio

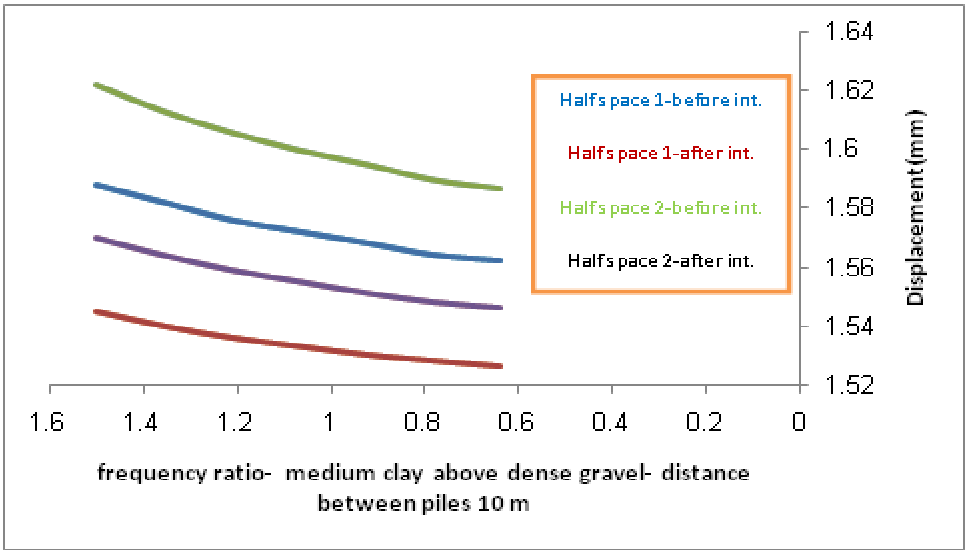

Figure 28: Variation of Response with Frequency Ratio

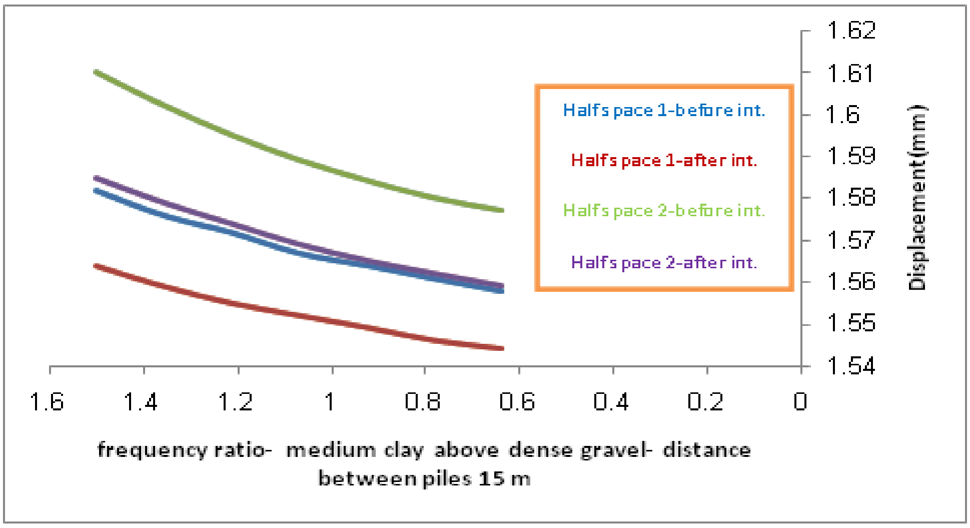

Figure 29: Variation of Response with Frequency Ratio

REFERENCES

1. Celebi E., Firat S. and Cankaya I. "The Evaluation of Impedance Function in the Analysis of Foundation Vibrations Using Boundary Element Method" Applied Mathematics and Computation, Vol.173, PP. (636-667), 2006.
2. Svinkin M. R. "Minimizing Construction Vibration Effects" ASCE, Vol. 9, NO. 2, 2004
3. Schevenels M., Badsar S. A., Lombaert G., and Degrande G.," Robust Ground Vibration Predictions Based on Saw test" Computational Method in Applied Sciences and Engineering" 2008.
4. Hao H., Ang T. C., and Shen J. "Building Vibration to traffic – induced Ground Motion" Building and Environmental. Vol. 36, PP(321-336), 2001
5. Sbarti B. and Boumekik A. "3-D Dynamic Interaction between Two Rigid Foundation Resting on layered soil part I: Homogenous Soil", Journal of Engineering and Applied Sciences, Vol. 1, NO. 4. PP(476-482).
6. Amic H., "A frequency-dependent soil propagation model" Present at SPIE Conference on Current Development in Vibration Control for Optomechanical System, 1999
7. Gutowski T. G and Dym C. L," Propagation of Ground Vibration" Journal of Sound and Vibration, Vol.49, NO.2, PP.(179-193), 1976.
8. Ahmed. R. Saber "Effect of a Lateral Dynamically Loaded Pile on a Nearby Multi-Storey Building" M.Sc. Thesis, Basrah University, 2010.
9. Arya S. C, O'Niell. And Pincus W. "Design of Structures and Foundations for Vibrating Machines", Gulf Publishing Company, Houston, Texas, 1979.
10. RaoS. S, "The Finite Element Method in Engineering" Elsevier Science and Technology Books, Four Edition, 2004.
11. Ansys 12.0 Help, SASIP, Inc., 2007.
12. Yang Y. B., and Hung H. H," Wave Propagation for Train-Induced Vibrations", World Scientific Publishing CO. Pte. Ltd, 2009.
13. Chaudhry A. R. "Static Pile-Soil-Pile Interaction in Offshore Pile Groups" Ph. D., thesis, University of Oxford, 1994.
14. Robert D. Cook "Finite Element Modeling for Stress Analysis" 1st, Ed, USA : John Wiley and Son, USA, 1995.
15. Jaffar. A. Kadim "Dynamic Analysis of Offshore Steel Structures Using Finite Element Method" Ph. D., thesis, University of Basrah, March, 2012.
16. Mahmoud Yahyai, MasoudMirtaheriMahoutian, Amir SaediDaryan and Mohammad Amin Assareh "Soil Structure Interaction between Two Adjacent Buildings under Earthquake Load" 1(2):121-125,2008.
17. Paz M., "Structural Dynamic Theory and Computation" Van Nostrand Reinhold Company, 1980.
18. Kim D. S., and Lee J. S., "Propagation and Attenuation Characteristics of Various Ground Vibration ", Soil

Dynamics and Earthquake Engineering, Vol.19, pp.(115-126), 2000.

19. M. Ghazavi and P. Ravanshenas "Pile-Soil-Pile Interaction under Horizontal Loading: A Simple Approach "International Association for Computer Methods and Advanced in Geomechanics, 1-6 October, 2008, Goa, India.