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PERFORMANCE OF DRIVEN REINFORCED CONCRETE PILES UNDER THE EFFECT OF DYNAMIC LOADING

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Abstract: Dynamic analysis for reinforced concrete precast piles with (300x300 mm) in dimension and length (12 m) with different types of loading was carried out. The common precast pile in Iraq was adopted in this study. Finite element analysis by ANSYS software was adopted and dynamic loading was applied to check out the strength and performance of pile. The frequency range adopted is based on the low, medium and high frequency. The analysis consisted of single pile (without surrounding soil) and pile embedded in soil as nonlinear material (soil) analysis to evaluate the vertical and horizontal displacements at the location of applied load. According to the analysis of single pile without soil and when the model of pile embedded in the soil indicated that the soil – structure interaction represented the worst case that is mean the simulation of the pile must take into account the effects of soil on the behavior and performance of the precast pile. The applied static loading on the pile model and checking the results of pile strength capacity showed that the applied load equal to the value calculated as per ACI 543R-2000 suggested equation. Based on the finite elements analysis results in case of friction between the contact surface of soil and pile increased the strength capacity of the pile due to the forces developed along the pile so that these forces add to the bearing resistance of the pile. The displacements in case of low and medium frequency are tenth time more in case of soil-structure interaction as compared with the analysis results of single pile alone. It was concluded that the presence of friction between the contact surface of soil and pile increased the strength capacity of the pile due to the forces developed along the pile so that these forces add to the bearing resistance of the pile.

Keywords: *Dynamic loads, Harmonic, Finite element analysis, ANSYS, Driven pile, Precast.*

أداء ركائز الدق الخرسانية المسلحة المعرضة الى تأثير أحمال ديناميكية

الخلاصة: تم اجراء تحليل ديناميكي للركائز الخرسانية المسلحة المسبقة الصب بأبعاد (300x300 mm) وبطول (12 m) بانواع مختلفة من الاحمال الساكنة والديناميكية. في هذه الدراسة تم اعتماد الركيزة المسبقة الصب الشائعة في العراق. تم اعتماد طريقة تحليل العناصر المحددة باستخدام برنامج ANSYS لتقييم التحمل والأداء لهذا النوع من الركائز تحت تأثير الأحمال الديناميكية. مدى التردد المتبع يعتمد على نطاقات مختلفة واطئة، متوسطة و عالية. التحليل تضمن ركيزة منفردة (بدون تربة محيطة) وركيزة مغروزة في التربة كمادة غير خطية لتقييم الازاحات العمودية و الافقية عند موقع الحمل المسلط. نظراً لتحليل لحالة الركيزة المفردة بدون تربة و عندما يغرز نموذج الركيزة في التربة.فانها تشير الى ان تداخل المنشأ - التربة قد مثل الحالة الاسوء وهذا يعني ان محاكاة الركيزة يجب ان يأخذ بنظر الاعتبارتأثير التربة على تصرف واداء الركيزة المسبقة الصب.اظهر التحميل الساكن المسلط على نموذج الركيزة مع تدقيق نتائج قابلية تحمل الركيزة بأن الحمل المسلط يساوي القيمة المحسوبة تبعاً لمدونة ACI من المعادلة المقترحة. اعتماداً على نتائج تحليل العناصر المحددة في حالة وجود الاحتكاك بين سطح التماس للتربة والركيزة لذلك فان تلك القوى تضيف الى قوة التحمل للركيزة. ان الازاحات في حالة التردد الواطئ والمتوسط تكون اكثر من بعشر مرات من حالة تداخل التربة - المنشأ مقارنة بتحليل نتائج الركيزة بمفردها . تم استنتاج

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بان وجود الاحتكاك بين سطح التماس للتربة والركيزة زاد من قابلية تحمل الركيزة بسبب القوى المتولدة على طول الركيزة لذلك فان تلك القوى تضيف الى مقاومة عمل الركيزة.

1. Introduction

Piles are vertical structural element such as column element but settled into soil working as foundation which has the function of transferring the superstructure loading from weak compressible strata to less compressible soils or rock. A harmonic analysis is used to determine the response of the structure under a steady-state sinusoidal (harmonic) loading at a given frequency. A harmonic or frequency-response analysis considers loading at one frequency only. Loads may be out-of-phase with one another, but the excitation is at a known frequency [1].

In 2006, Wang and Sitar [2], studied the nonlinear performance of pile under static and dynamic loading. The nonlinear transient analysis based earthquake was adopted by finite elements approach. Analysis results concluded that the developed model is suitable for nonlinear analysis of soil-structure interaction as well as site-specific response analysis.

In 2008, Kanget et.al. [3], looked out on the relationship between soils and pile group based on numerical analysis under dynamic loading. The model was built using finite elements approach by the program FLIP (Finite Element Analysis Program for Liquefaction Process). The results from numerical analysis were compared with the full scale test and showed close results.

In 2010, Serdaroglu [4], studied the nonlinear analysis of driven pile under vibration. The finite elements analysis was adopted for analysis, they simulated pile models under the effect of dynamic loading and studied the factors that affect the stress wave propagation in the soil surrounding the pile.

In 2012, Jalalil et al. [5], studied the pile – structure interaction under impact loading. The models were built using finite elements approach by PLAXIS and ANSYS software. The applied impact loading on the pile - displacement was examined by applying Mohr-Coulomb as well as Hard-soil behavior laws. Analysis results indicated that the difference of velocity at the head or the bottom of the pile does not make a sufficiently great difference in the interface coefficient between pile and soil.

In 2012, Rahemi [6], looked out on the lateral deflection of pile under the effects of static and dynamic loading. The numerical analysis was adopted by performing three dimensional nonlinear analyses by ABAQUS. Analysis of results concluded that the most influencing parameters on lateral deflection of pile was slenderness ratio.

In 2013, Andersen et al. [7], studied the cyclic loading effects on the pile foundation and the geotechnical influences of cycling imposed by seasons, earthquakes, ice and machinery, so gave advised for type parameters that must considered in pile design in case of presence cyclic loading.

In 2013, Silva and Foray [8], investigated the effects of cyclic loading on the driven pile and presented a new cyclic stability diagram for the lateral friction. Test results indicated that applying large number of one direction low cycles cause concentration at the soil-pile interface which makes a turn to more marked interface expansion during further loading and shaft capacity gains for the piles.

In 2016, Rathod et al. [9], studied the dynamic response of pile under the effects of dynamic loading. Finite elements approach was adopted by PLAXIS 2D for simulating the pile and soil strata. Analysis results consisted of deformation and acceleration performance of pile with respect to time.

In 2016, Fattah et al. [10], conducted a series of laboratory tests to measure the response of pile foundation when subjected to dynamic loads. The accompanied measurements include vertical and horizontal displacement and settlement of pile cap, acceleration in three dimensions in both soil and cap and earth pressures. The model pile used has an outer diameter of 18 mm and inner diameter of 15 mm. A group of (2x2) piles was tested. It was concluded that for soil bed in dry state, the acceleration amplitudes increase with frequency for both soil relative densities (loose and medium).

In 2017, Fattah et al. [11], considered the dynamic response of pile foundation in dry sandy soil excited by two opposite rotary machines experimentally. A small scale physical model was manufactured to accomplish the experimental work in the laboratory. The test results revealed that, before machine operation, the pile tip load was approximately equal to the static load (machine and pile cap), whereas during machines' operation, the pile tip load decreased for all embedment depth ratios and operating frequencies.

The objectives of the present study are to evaluate the strength capacity and serviceability of precast driven pile that is widely adopted in Iraq under static and harmonic dynamic loading.

2. Pre-cast Reinforced Concrete Pile Characteristics

The full scale of precast pile was simulated with actual dimension as (300x300x12000 mm) with (8ϕ16 mm) represents the main reinforcements and (ϕ10 mm) as a ties (100 mm) center to center. The mechanical properties of the concrete and steel bar as cylinder compressive strength of concrete is (35 MPa) and yielding strength of reinforcement of (410 MPa), as shown in Fig. 1.

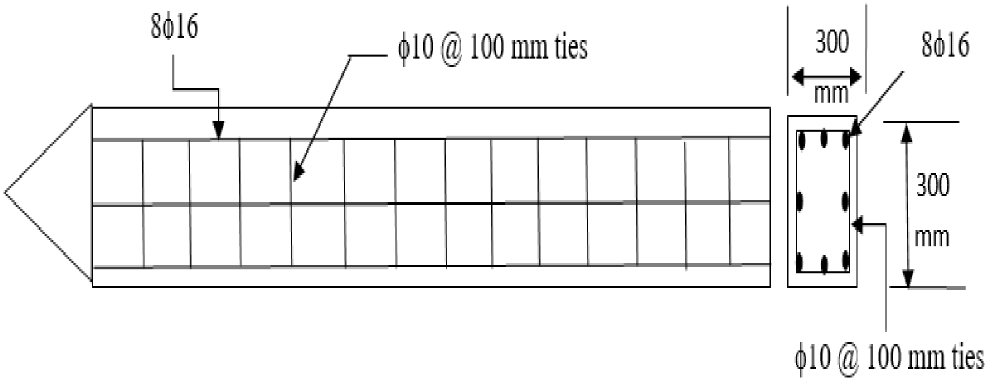


Figure 1. Pre-cast driven pile.

In the design of piles, the external load from the superstructure that included various types of loading must be considered such as live load that relay on the function of building according to ASCE –7– 2010 [10], dead load and others such as (wind, seismic if considered in that area zone of the building).

3. Pile Capacity

The allowable compressive capacity of pile was selected based on ACI 543R-2000 [13], in which the axial service loading capacity was based on eccentricity factors according to Portland Cement Association (PCA) [14]. The average load factor is (1.55) that represents the average factor for dead and live load according to ACI Code by assuming that the dead load is equal to the live load. The ACI 543R-2000 [13] suggested equation that relies on the assumption that the soil surrounding the pile gave holding as much lateral support and confines the pile, also, the applied forces cause no more than minor bending moments. The proposed equation for precast reinforced concrete is:

$$P_a = 0.33\, fc' A_c + 0.39\, f_y\, A_{st} \leq 0.4\, fc' A_c \quad (1)$$

In which, A_c: cross sectional area of pile,
f_c': compressive strength of concrete $\geq$ (35 MPa),
f_y: yield strength of main reinforced bars, and
A_{st}: total main reinforcement area embedded in concrete pile.

4. Numerical Study

The finite element approach (FEA) models have the same geometry and reinforcement of reinforced concrete precast square pile. The pile is assumed to be subjected to static and dynamic loading. The analysis was performed using finite element ANSYS 16.2 software. Throughout the FEA simulation, the influence of applied loading on the performance of pile is studied. Modal dynamic analysis is first used to determine the eigenvalues and eigenvectors. The eigenvalues are the frequency and eigenvectors are the modes where the first mode is the worst case assuming static behavior but under dynamic loading [15]. In ANSYS, model simulation SOLID65 is used for concrete while SOLID185 is used for soil and LINK180 for the reinforcement main and ties. Fig. 2 shows the stress – strain curve of concrete.

The nonlinear concrete is used for single pile and nonlinear of soil in case of pile embedded in soil with the effect of friction between the contact surfaces of soil and pile analyses were adopted in which the nonlinearity material were discussed in separate case. The compressive strength was assumed equal to (35 MPa) which is the minimum value required based into ACI 543R-2000 [13]. The stress-strain curve for concrete compressive strength is shown in Fig. 2.

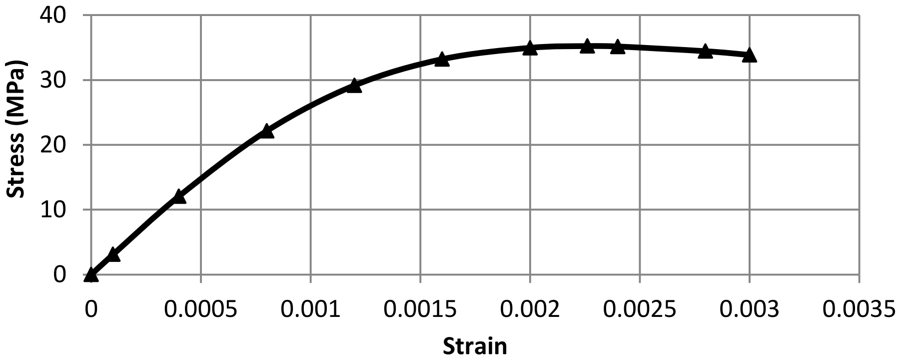


Figure (2). Stress – strain relationship of concrete [1].

The Drucker-Prager yield criterion with either associated or non-associated flow rule represents the nonlinearity of soil. The Drucker-Prager is used to simulate and model the nonlinearity of soil media applicable to granular (frictional) material such as soils, rock, and concrete, and uses the outer cone approximation to the Mohr-Coulomb law that is shown in Fig. 3.

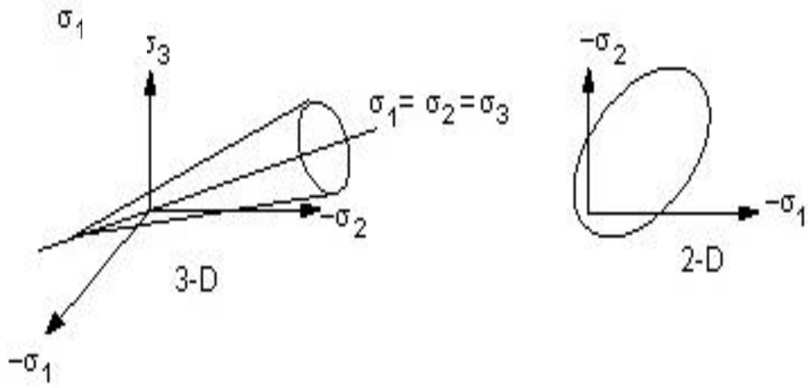


Figure 3. Yield criterion based on Drucker-Prager [15].

Where:-
σ_1 = Major principal stress,
σ_2 = Intermediate principal stresses, and
σ_3 = Minor principal stress.

A finite element modeling is done for single pile (without surrounding soil) and pile embedded in soil using finite element software by ANSYS. The material properties and constant models are defined using the material ANSYS for a different linear, nonlinear and contact material for the soil and pile.

The soil and pile are modeled integrally with interface element material as per meshing of foundation surface in contact with soil beneath and soil pile interaction including the friction effect between soil and pile with coefficient of friction (0.40) [6]. The soil in type of sandy soil with parameters lists in Table 1.

Table 1. Soil parameters.

Soil Type	Modulus of elasticity (kN/m^2)	Poisson's ratio (ν)	Internal friction angle (Φ) [6]
Sandy soil	20000	0.30	25

The dimensions of soil surrounding the pile are (2.30x2.30x12 m) and the base of the pile is assumed as rock, so that the boundary condition at the end of pile is fixed as simulated in the finite element model.

The selected soil dimensions based on that the center to center pile around three times the pile diameter on each side of the pile so that the equivalent pile diameter is (334 mm) and the dimension for each side of pile become (1000 mm). The applied loading is harmonic dynamic loading with frequency range between (0-40 Hz), (40-400 Hz) and (400-1500 Hz) for low, medium and high frequency range, respectively.

The pile section has the following properties: cross sectional area (90000 mm^2), moment of inertia ($7.2x10^8$ mm^4), and section modulus (16387 mm^3) with (12 m) in length.

The contact between pile and soil is represented in ANSYS by contact element that represents the relationship between two different materials that differ in the modulus of elasticity and Poisson's ratio to take into account soil – structure interaction. When two separate surfaces touch each other such that they become mutually tangent, so that the interface is dealt with as in contact.

The interface between soil and pile developed foresees transmit compressive normal forces and tangential friction forces. The two contact surfaces become free to separate and move away from each other. The stiffness of the system depends on the contact status, whether parts are touching or separated. The material properties of pile are listed in Table 2.

Table 2. Concrete properties

Concrete	Modulus of elasticity (MPa)	Compressive strength (MPa)	Tensile strength (MPa)	Poisson's ratio (ν_c)	Open shear (β_o)	Close shear(β_c)
	27800	35	4.2	0.15	0.2	0.7

Fig. 4 shows the profile of the pile (single) without surrounding soil, this pile was subjected to static and dynamic harmonic loading of low, medium and high frequency range.

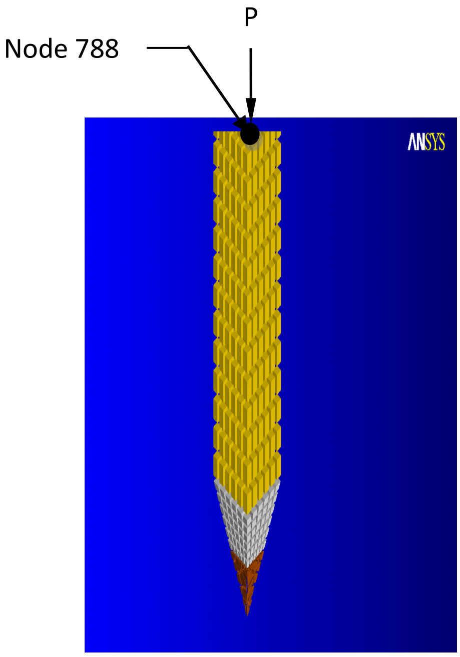


Figure 4. Driven pile (single) not embedded in soil.

5. Results and Discussion

The static load model results are presented in Fig. 5 and Fig 6 that represent the axial and lateral displacements under the effect of incremental applied loading up to ultimate pile capacity that was calculated based on equ.1. The static loading (1300 kN) was applied in steps at the top of pile and the displacements with stress along and transverse pile are calculated.

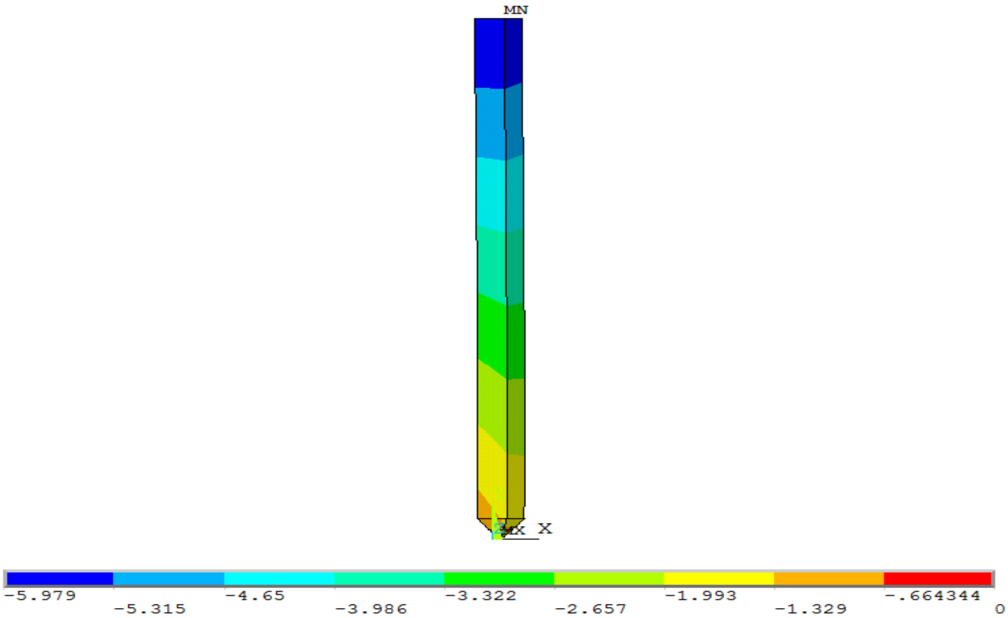


Figure 5. Vertical displacement along pile due to static loading "u_y".

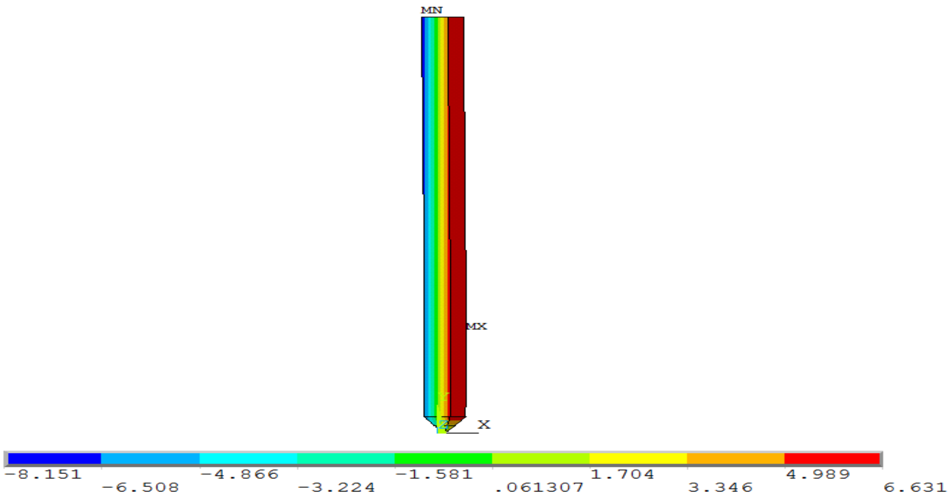


Figure 6. Horizontal displacement of pile due to static loading "u_x".

In the case of dynamic – harmonic loading for single pile, Figs. 7 to 15 show different cases of frequency range as low, medium and high for vertical, horizontal displacements and normal stress.

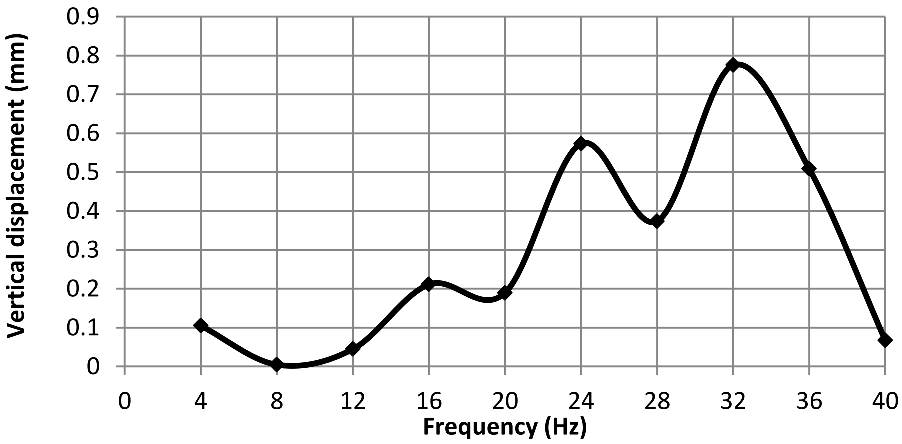


Figure 7. Vertical displacement (at the point of maximum displacement under static loading) due to low harmonic loading range.

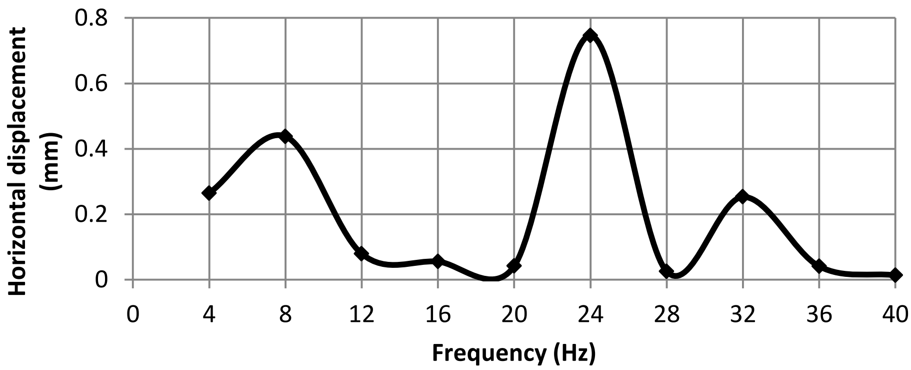


Figure 8. Horizontal displacement of the pile head (node 788) due to low harmonic loading range.

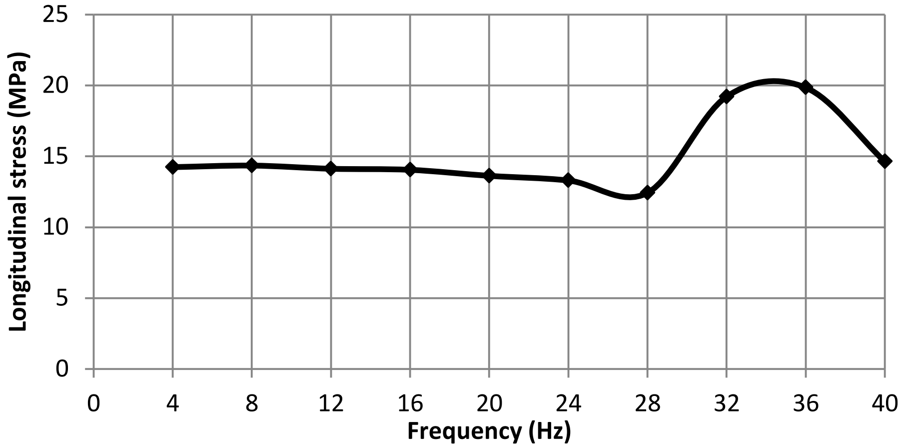


Figure 9. Longitudinal stress of the pile head (node 788) due to low harmonic loading range.

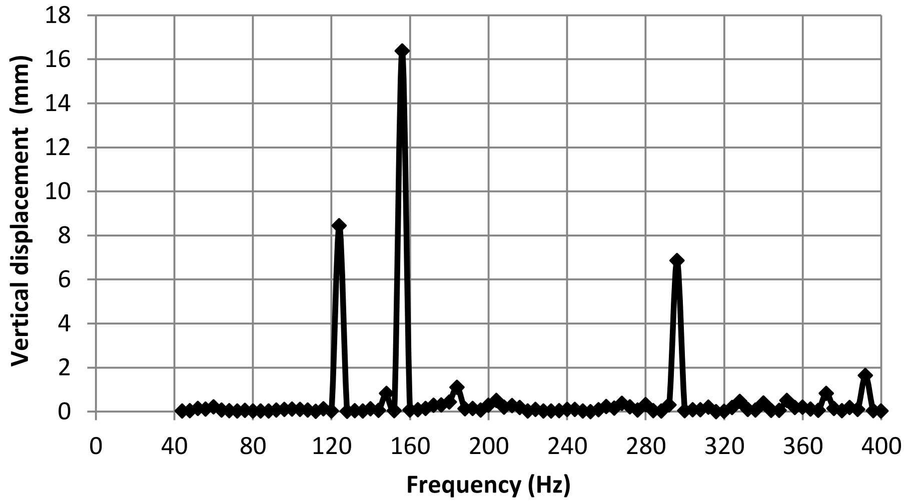


Figure 10. Vertical displacement (at the point of maximum displacement under static loading) due to medium harmonic loading range.

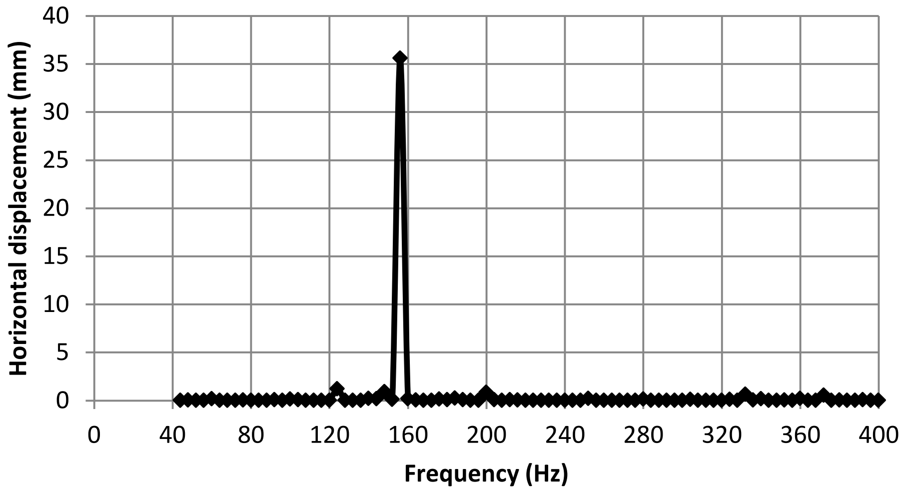


Figure 11. Horizontal displacement of the pile head (node 788) due to medium harmonic loading range.

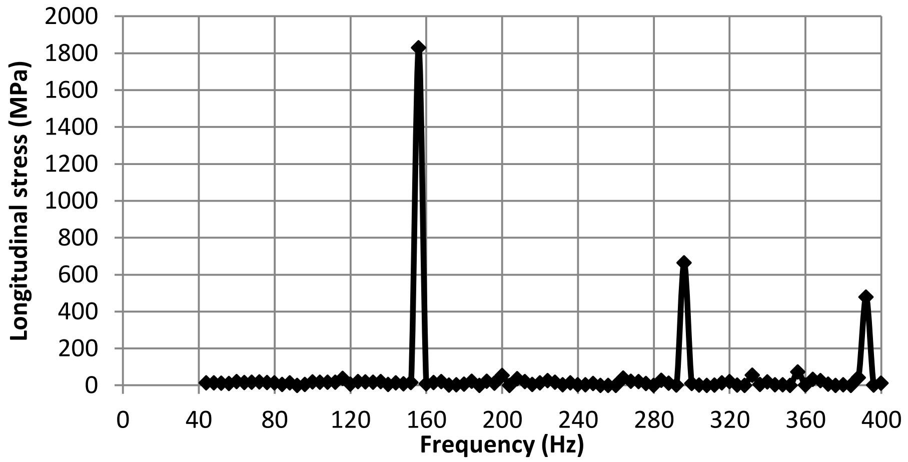


Figure 12. Longitudinal stress of the pile head (node 788) due to medium harmonic loading range.

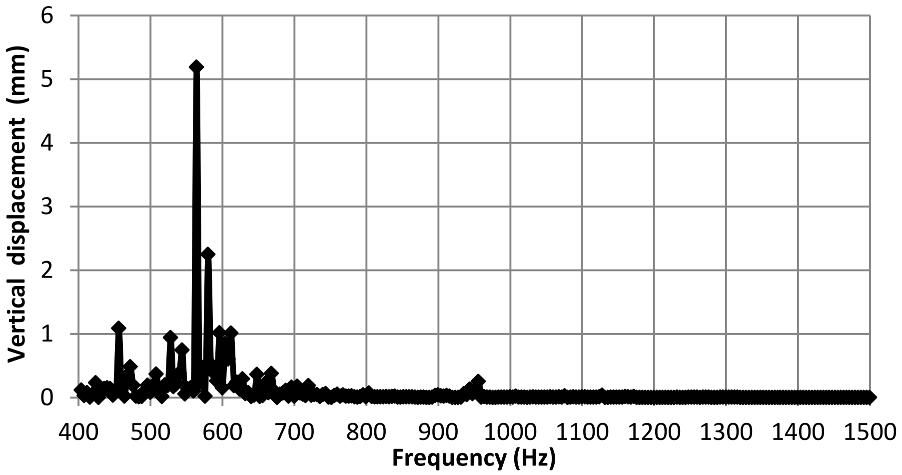


Figure 13. Vertical displacement (at the point of maximum displacement under static loading) due to high harmonic loading range.

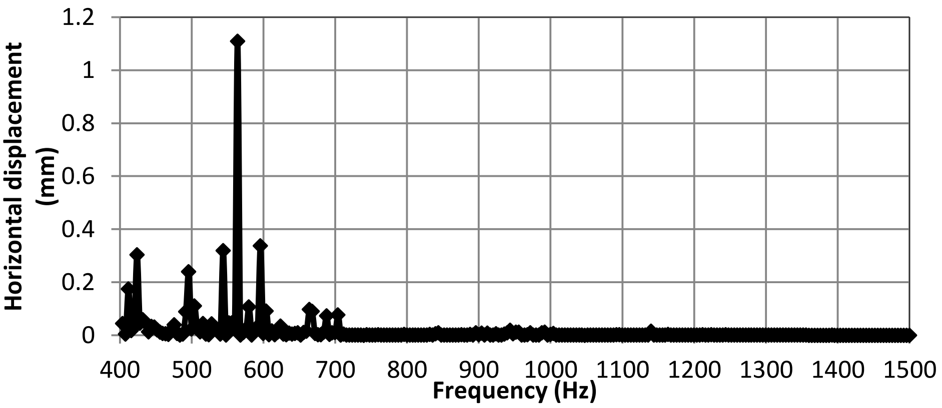


Figure 14. Horizontal displacement of the pile head (node 788) due to high harmonic loading range.

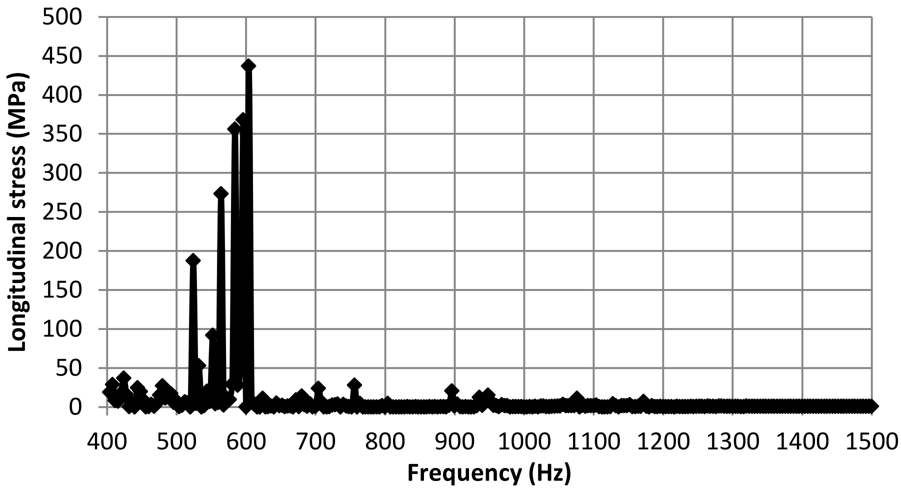


Figure 15. Longitudinal stress of the pile head (node 788) due to high harmonic loading range.

Fig. 16 and Fig .17 show the vertical and horizontal displacements through pile in case of the pile embedded in soil (soil-pile interaction).

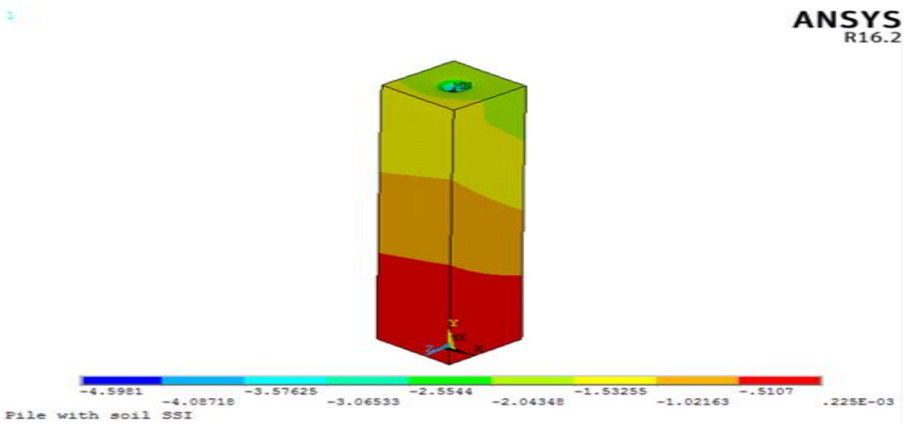


Figure 16. Longitudinal displacement along a pile embedded in soil due to maximum static loading.

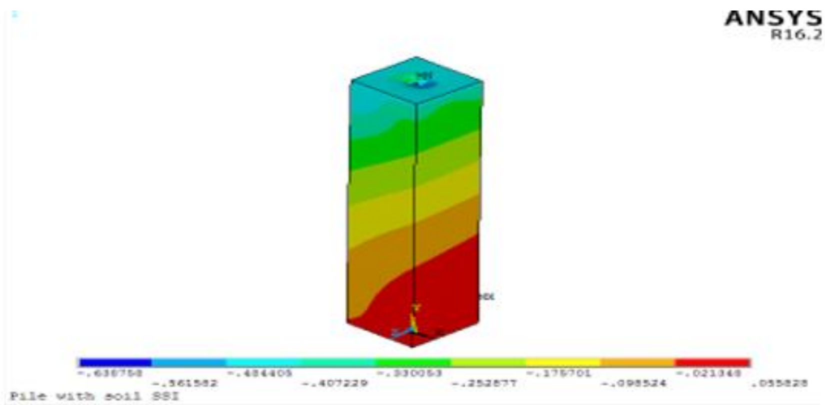


Figure 17. Lateral displacement along pile embedded in soil due to maximum static loading.

The maximum vertical displacements along the pile under the effects of ultimate static load and the frequency that caused maximum displacement in case of harmonic loading are shown in Table 3.

Table 3. Summary of analysis of results.

Status	Ultimate static loading (kN)	Dynamic loading		Displacement (mm)
Single pile (without surrounding soil)	1300			5.910
		Low frequency (Hz)	32	0.7751
		Medium frequency (Hz)	156	0.164
		High frequency (Hz)	564	5.18
Soil-pile interactions	1300			4.591
		Low frequency (Hz)	12	7.353
		Medium frequency (Hz)	320	1.6
		High frequency (Hz)	600	0.1

Figs. 18 through 23 represent the vertical and horizontal displacements in piles in case of soil-pile interaction for three cases of dynamic loading as low, medium and high frequency.

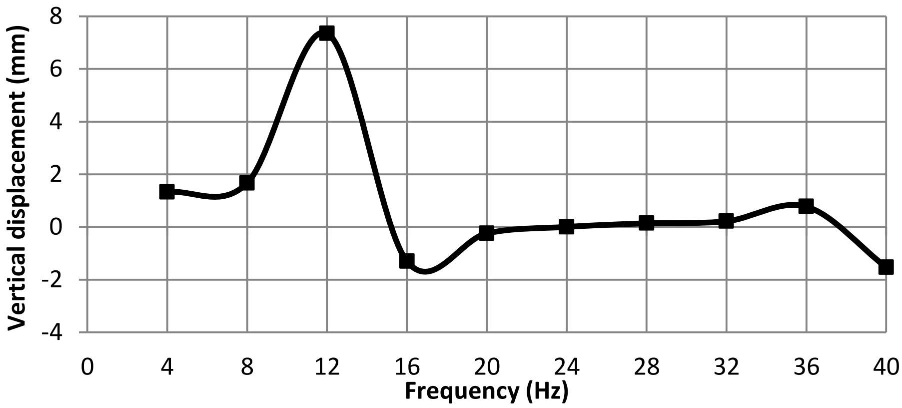


Figure 18. Vertical displacement (at the point of maximum displacement under static loading) embedded in soil due to low harmonic loading range.

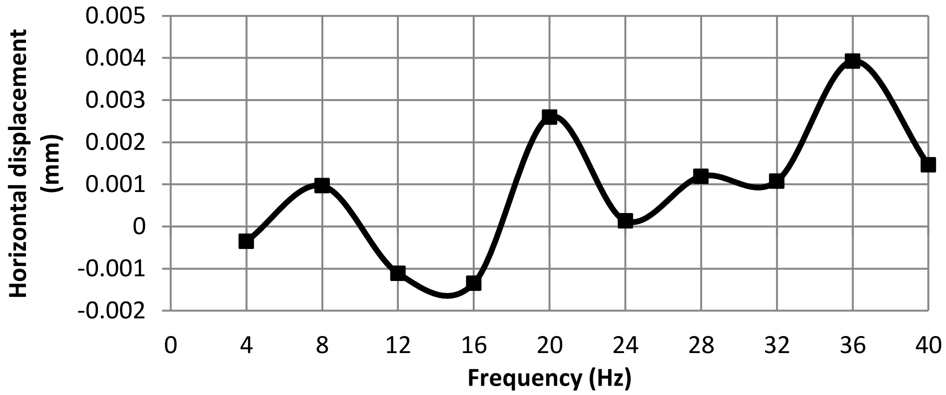
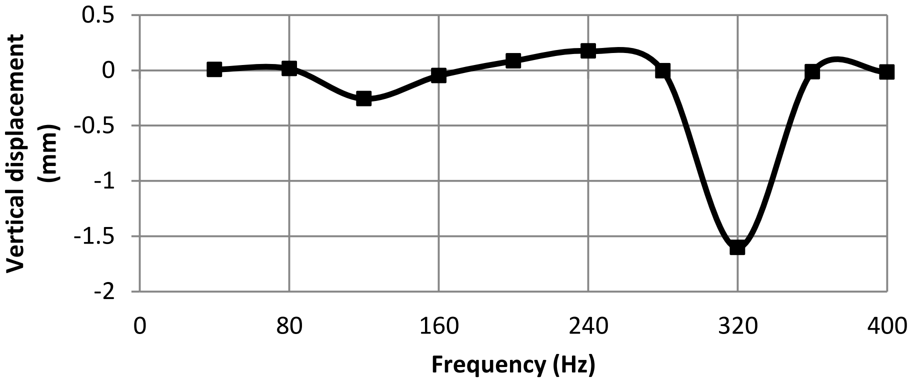


Figure 19. Horizontal displacement of the pile head (node 788) embedded in soil due to low harmonic



loading range.

Figure 20. Vertical displacement (at the point of maximum displacement under static loading) embedded in soil due to medium harmonic loading range.

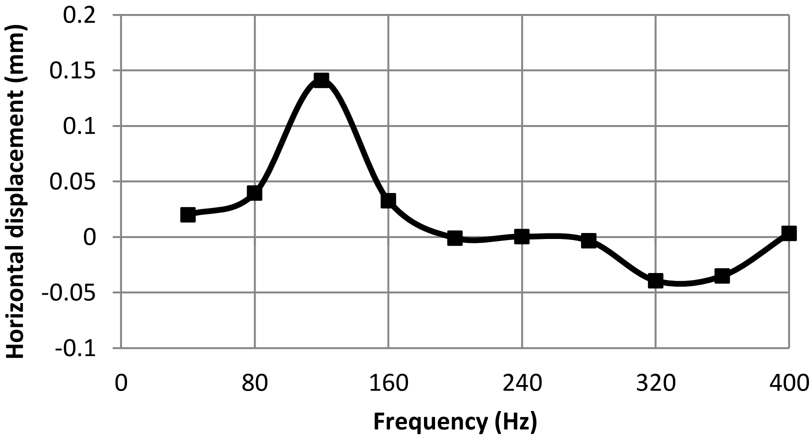


Figure 21. Horizontal displacement of the pile head (node 788) embedded in soil due to medium harmonic loading range.

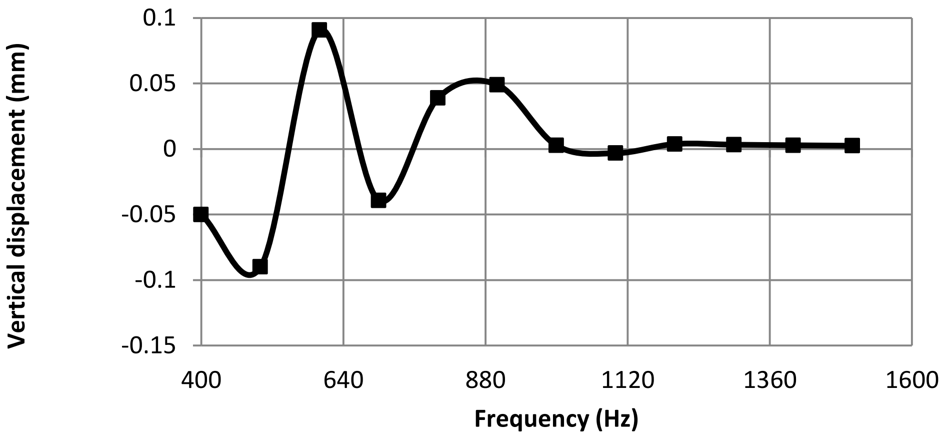


Figure 22. Vertical displacement (at the point of maximum displacement under static loading) embedded in soil due to high harmonic loading range.

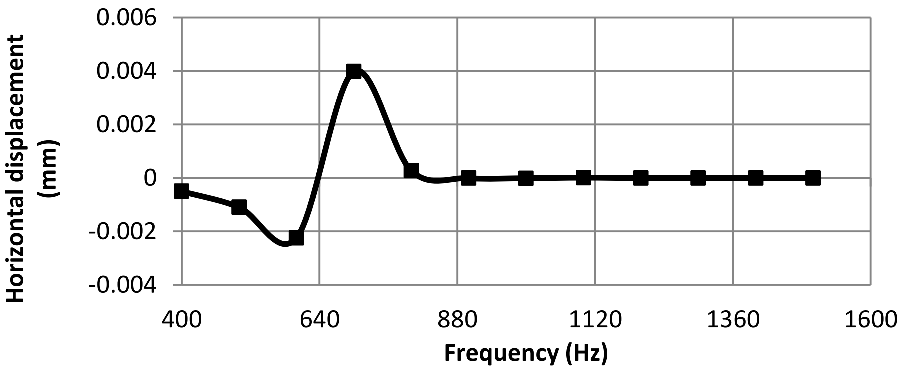


Figure 23. Horizontal displacement of the pile head (node 788) embedded in soil due to high harmonic loading range.

Figs. 24 to 28 show comparisons between the analysis results as displacements between single pile (without surrounding soil) and soil-pile interaction.

In case of harmonic loading, the maximum displacements along the longitudinal axis and transverse axis of the pile, the load was applied in different frequency ranges for full load, but the results are different in single pile than in case of soil-pile interaction. These different because of the different frequencies with constant applied loading (amplitude) and different time (sine wave) which make the applied force different as frequencies are different.

Figs. 24, 26 and 28 show that the frequency that causes maximum vertical displacement is not equal in case of single pile and soil-pile interaction. This is attributed to the soil contribution to some amount of displacements so that the maximum displacement is not equal.

Figs. 25, 27 and 29, show that the frequency that causes maximum horizontal displacement is not equal in case of single pile and soil-pile interaction. This is caused by the presence of soil which makes resistance in horizontal direction and the soil confines the pile around the surrounding surface area of pile, so that the transverse displacement becomes less in the presence of soil.

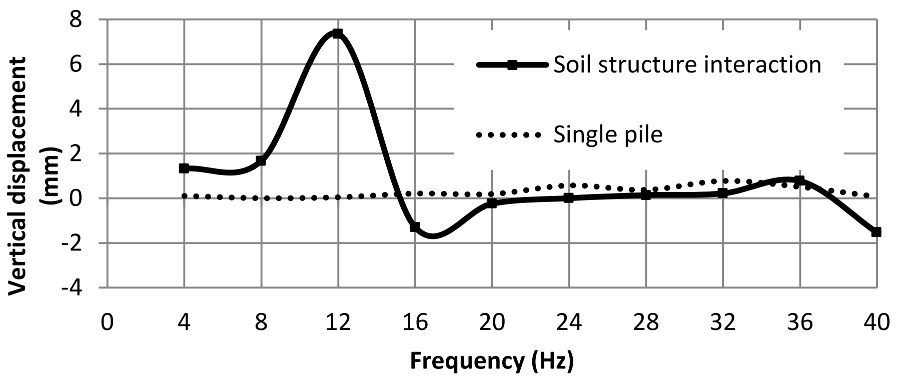


Figure 24. Vertical displacement (at the point of maximum displacement under static loading) embedded in soil compared with single pile due to low harmonic loading range.

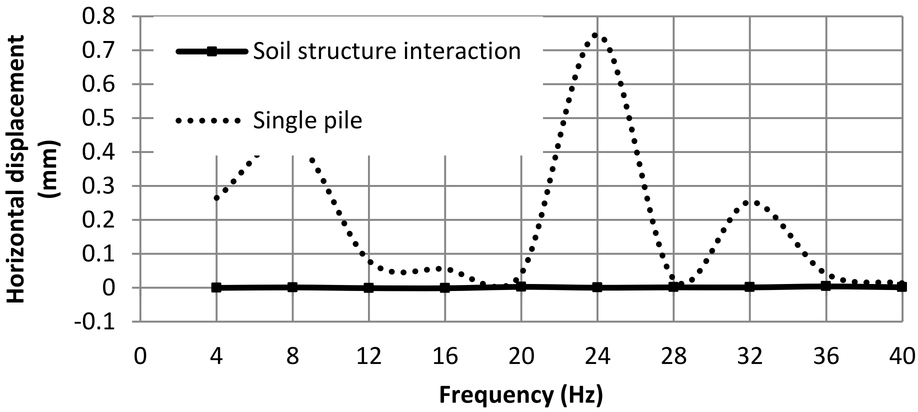


Figure 25. Horizontal displacement of the pile head (node 788) embedded in soil compared with single pile due to low harmonic loading range.

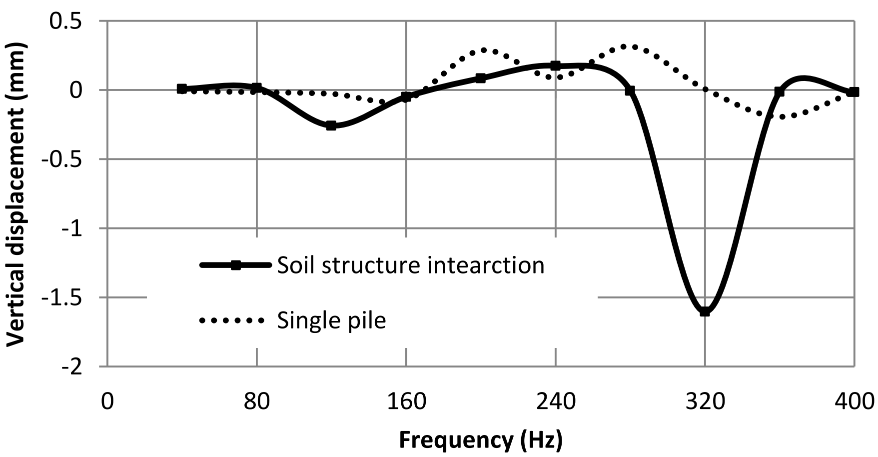


Figure 26. Vertical displacement (at the point of maximum displacement under static loading) embedded in soil compared with single pile due to medium harmonic loading range.

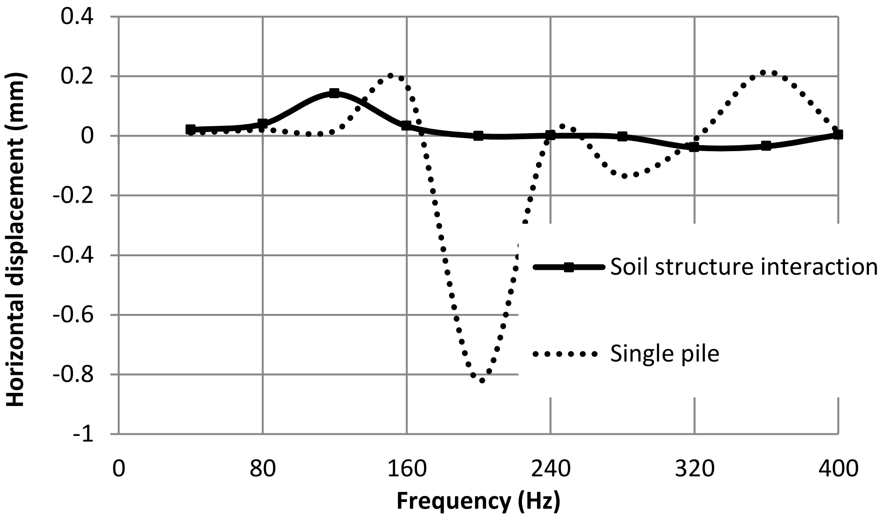


Figure 27. Horizontal displacement of the pile head (node 788) embedded in soil compared with single pile due to medium harmonic loading range.

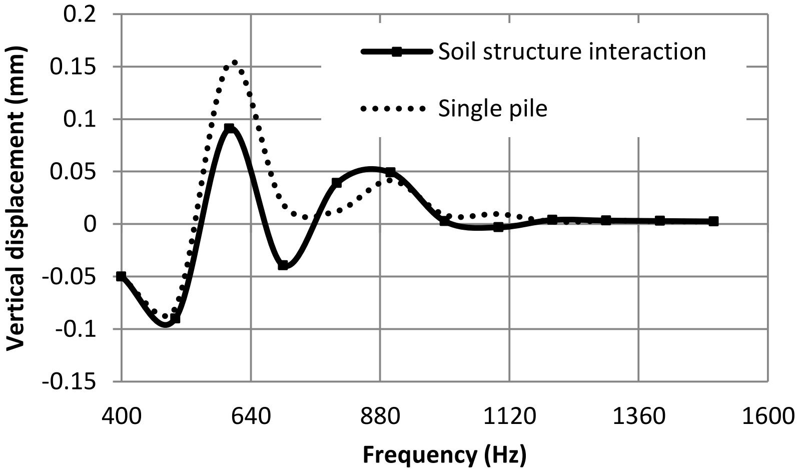


Figure 28. Vertical displacement (at the point of maximum displacement under static loading) embedded in soil compared with single pile due to high harmonic loading range.

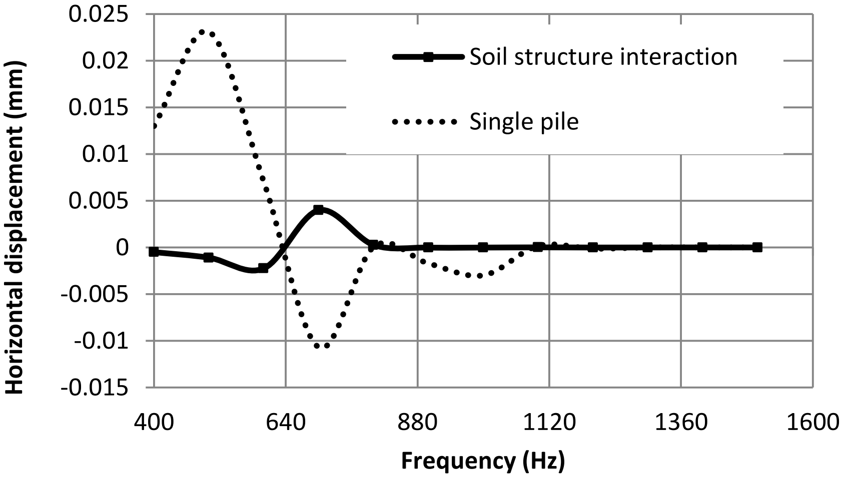


Figure 29. Horizontal displacement of the pile head (node 788) embedded in soil compared with single pile due to high harmonic loading range.

The pile capacity with (1300 kN) that is adopted in Iraq with safety factor ranged (2.5-3) is evaluated by applying equation "(1)"and by finite element analysis and it was shown that the pile capacity matched with strength requirement of ACI 543R-2000 [13] under static loading.

The displacement of single pile (without surrounding soil) within acceptable value of settlement (less than 10% of equivalent pile diameter around 42 mm). all the dynamic results at the point of maximum axial displacement due to static loading

6. Conclusions

Based on the results from numerical analysis, the following points are drawn:

1. The lateral displacement due to applied loading for single pile showed very small value (0.75 mm) indicating that stability is maintained and no buckling during pile driving can occur.
2. In the case of static loading, the static vertical displacement in case of pile embedded in soil is less than that for single pile because of presence of soil and the effect of soil-pile interaction that overcomes some of displacement.
3. The nonlinear analysis of soil as Drucker-Prager that deal with the granular materials like soil and taking into account the presence of the friction between the contact surfaces gave realistic results that are matching the site conditions.
4. The presence of friction between the contact surface of soil and pile increased the strength capacity of the pile due to the forces developed along the pile so that these forces add to the bearing resistance of the pile.
5. The displacements due to harmonic loading are little greater than the static analysis but still under the serviceability requirements.

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