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EFFECT OF SOIL-PILE CAP INTERACTION ON THE DYNAMIC RESPONSE OF ROTARY-MACHINE FOUNDATIONS

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ABSTRACT

This paper investigates the effect of soil-pile cap interaction on the dynamic behavior of the soil-pile system under vibrations. Vertical vibration tests were conducted using experimental models of pile footings embedded in a finite dry sand layer. The pile footings consist of two groups of circular piles with spacing/diameter (S/d) ratio equals to 5; the length/diameter (L/d) ratio for first group was 13.3 and for the second was 20. Each group includes models with different number of piles. A physical model made of steel box of dimensions of 700 × 700 mm and 800 mm in height was used for accommodation the test model. In order to study the effect of cap interaction, the first tests were conducted where a gap was left between the caps and sand surface as reference, and the second tests all caps in contact with sand surface. The maximum displacement amplitudes and the corresponding resonant frequencies of the experimental system were measured using vibration meter and accelometer fixed on the top of the pile cap. The results of both groups indicated that the pile cap interaction significantly increases the vertical amplitudes and increases slightly the resonant frequencies in different proportions.

تأثير تداخل قبعة الركائز مع التربة على الاستجابة الديناميكية لأسس المكائن الدواره

الخلاصه

يدرس هذا البحث تأثيرَ تداخل قبّعةِ الركيزة مع التربةِ على سلوكِ نظامِ الركيزة والتربةَ تحت تأثي الأهتزازات. تم اجراء تجارب مختبرية لاسس الركائز تحت تاثير الإهتزازِ العمودي والمطمورة داخل طبقةِ محدودة من الرملِ الجافِّ. تتالف النماذج المختبرية من مجموعتين من الاسس المستندة على ركائز دائرية بنسبة المسافة بين الركائز على القطر (S/d) مساوية إلى 5 و نسبة طول الركيزة على القطر (L/d) للمجموعةِ الأولى كانت 13.3 وللثانيةُ كانت 20. تتكون كُلّ مجموعة من نماذج مختبرية تحتوي على عددِ مختلفِ مِنْ الركائز. النموذج الفيزيائي تم صنعه من الصفائح الفولاذيةِ على شكل صندوق بابعادِ تتالف من طولِ وعرضِ (700 × 700) مليمتر و بأرتفاع 800 مليمتر. لدراسة تأثيرَ قبّعةِ الركائزِ، الإختبارات الأولى أجريتْ لنماذج مختبرية بحيث كانَ هنالك فراغ بين سطحِ الرملَ والقبّعاتَ والتي تم اعتبارها كنقطة دالة بينما الاختباراتُ الثانيةَ تم اجرائها بحيث كُلّ القبعات كَانتْ بتماس مع سطحِ الرملِ. إنّ الإزاحات القصوى و تردد الرنين المسلطةِ على النماذج المختبرية تم قياسهاً باستعمال مقياس الاهتزازات ومقياس السرعة والذين تم تثبيتهما على الوجه العلوي لقبّعةِ الركائز. ان نَتائِج الفحوصات لكلتا المجموعتين أشارتْ إلى ان تداخل قبعة الركائز مع التربه يزيد الإزاحات العموديةَ بشكل ملحوظ ويَزِيدُ بعض الشّيء ترددات الرنين بنسب مختلفه.

الكلمات المفتاحية

سعة الازاحه العمودية، تردد الرنين، نسبة طول الركيزه و القطر (L/d)، نسبة المسافة بين الركائز الى القطر (S/d)، و مجموعة الركائز

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Introduction

The design of a machine foundation subjected to dynamic loading should satisfy the usual requirements of safety and stability, and in addition, must satisfy certain design criteria relating to the presentation of excessive dynamic movement of the foundation and structure. The design criteria most often encountered is related to the dynamic response of the foundation. Criteria are expressed in terms of the limiting amplitude of vibration at a particular frequency or a limiting value of peak velocity or peak acceleration [1].

There are different dynamic loads that can act on piles such as earthquake forces, wave forces, wind forces, machine unbalances, etc. These dynamic loads cause damage to piles due to the vibration effects, liquefaction, and embankment movements [2].

The response of pile foundations is greatly affected by the behavior of soil media, in which piles are embedded. Many researchers conducted studies for the dynamic response of pile groups (e.g., Novak [3] and [2], Gazetas [4], Maheshwari and Watanabe [5] and Halabian and Maleki [6]).

Novak and Sheta [7] studied the dynamic response of single and grouped piles depending on the comparison of theory with experiments considering the pile-soil-pile interaction. The study briefly concluded that the dynamic response of pile groups is affected by interaction of the piles with soil and also by the interaction between individual piles in the group with soil.

Han and Wang [8] presented a study of nonlinear soil-pile-structure interaction in dynamic or seismic response. The measurements of vibration were carried out in the field for a revamped project, and the measured data were matched with the results calculated by the computer program. They concluded that soil-pile interaction is an significant factor which affects the stiffness and damping of the foundation.

Embedded pile caps usually have a favorable effect on the response of the group and should be adapted wherever possible. It would be realistic to assume that the embedment effect generates only the side friction between the cap and the soil and that to only when dense granular backfill is used. The soil below the pile cap which is likely to be of inferior quality can settle away from the cap for non-cohesive soil; similarly for cohesive soil this can shrink away from the sides of the pile cap and can become ineffective [9].

This work aimed to study the effect of pile cap-soil interaction on the dynamic response of grouped piles under different frequencies as well as the effect of length and number of piles on the vertical amplitude and resonant frequencies not covered in previous works.

Experimental Model

1. Test Tank

A steel tank with dimensions of (0.7 × 0.7 × 0.8) m was fabricated and assembled to be used as a model of the experimental work. The size of the test tank was optimized in order to minimize the boundary reflections. Also the internal sides of the tank were covered with 25 mm polystyrene sheets as an absorbing boundary as shown in Figure (1). The absorbing boundaries minimize the reflection of generated waves from the machine operation [10].

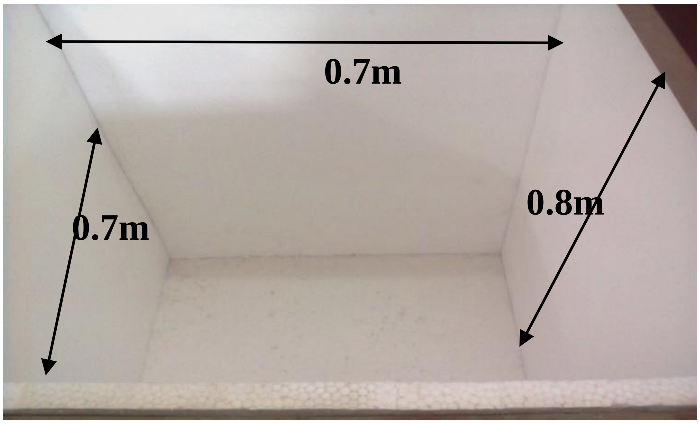


Figure (1): Soil Tank with Isolated Boundaries.

2. Piles and Caps.

Two series of piles footings which represent experimental models of deep foundations are used. All models include caps with dimensions of (250 length, 250 width, and 30 height) mm and circular piles of 30 mm in diameter. The first series involve models of piles with L/d of 13.33, while the second series involve models of piles with L/d of 20. Each group has three models consisting of cap comprising of 2, 3 and 4 piles with S/d ratio equals to 5. A steel plate was fabricated to form molds of the caps and iron tubes were used to form molds of the piles. The reinforcement for the piles and cap are of 3 mm steel bars as shown in Figure (2). The piles and cap were casted monolithically to be rigid mass.

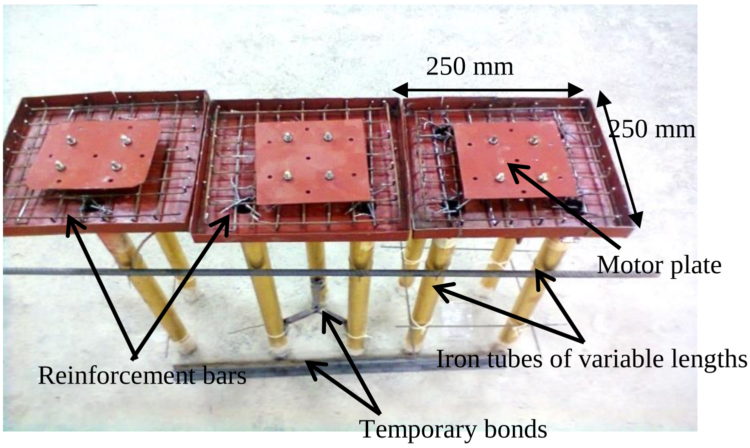


Figure (2): Molds of Deep Footing Model.

3. Concrete

Gravel which passes from sieve No.5 (smaller than 4mm) was used in a mixture of concrete with w/c ratio of 0.45. An additive (flocrete SP42) was used in the concrete mixture, which enables the water content in the concrete to perform more workability and increase the compressive strength. All properties of concrete were specified according to ACI-Code 2008 [11]. The two series of experimental deep footings are shown in figure (3).

4. Soil

Dry clean sand has a particle size restricted between sieve No.18 (1.0 mm) and sieve No.200 (0.075 mm) was used as soil in this study. Its grain size distribution curve shown in figure (4). According to Unified Soil Classification System (USCS), the sand is classified as poorly graded (SP). The dry density of the sand was obtained using sand raining method. The sand was rained through a mesh of 4 × 4 mm openings using different heights of drop, which produce different values of relative density. The relative densities with heights of drop were drawn , Fig. (5). A 51% relative density soil filled the tank. Figure (6) shows the raining method of filling the steel tank by soil.

(a)

(b)

Figure (3): Two Series of Pile Models (a) Models with L/d of 20 (b) Models with L/d of 13.3.

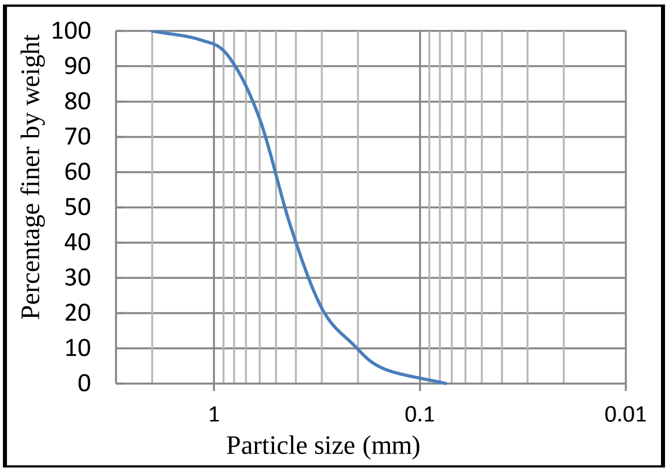


Figure (4): Grain Size Distribution.

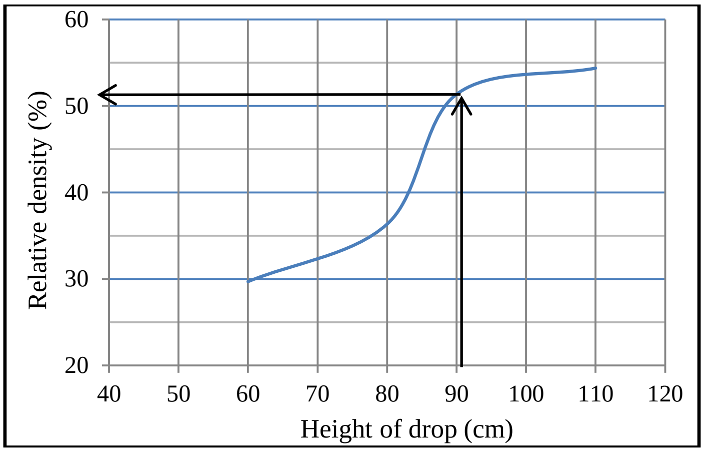


Figure (5): Relative Density versus Heights of Drop in Sand Raining Method.

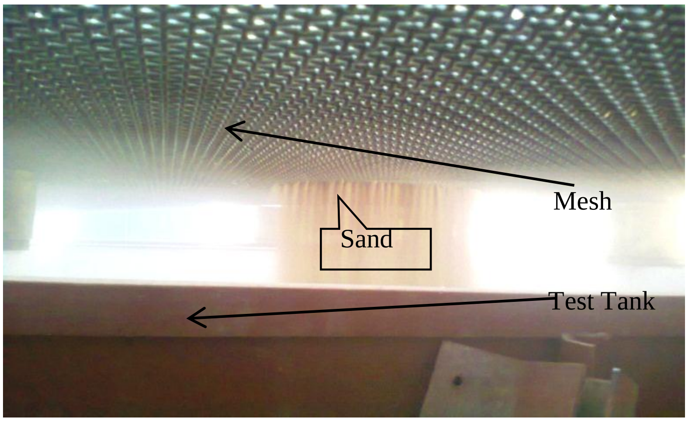


Figure (6): Filling the Tank Using Sand Raining Method.

The standard tests were performed to determine the physical properties of the soil as shown in Table (1). The obtained dry unit weight and the void ratio of the soil for the relative density (51%) were 15.5 kN/m^3 and 0.759, respectively.

Table (1) Physical Properties of the Used Sand [10]

Parameters	Value	Units
Maximum dry unit weight, from procter test. ($\gamma_{dry\ max}$)	19.4	kN/m^3
Maximum dry unit weight (raining method), $\gamma_{dry\ max.}$	17.64	kN/m^3
Minimum dry unit weight (raining method), $\gamma_{dry\ min.}$	14.23	kN/m^3
Optimum moisture content.	8.5	(%)
Relative density (%)	51	(%)
Specific gravity, Gs	2.78	-

Methodology

1. Dynamic Load and Measurement

An electrical rotary-motor with a maximum rated speed of 9500 rpm through a shaft was modified to be used as a mechanical oscillator. A rotating disc was connected to the

rotating shaft (manufactured from steel with diameter 80 mm and a thickness 5 mm). A single mass (m_e) is placed on the rotating disc at an eccentricity (e) of 30 mm from the axis of rotation as shown in figure (7). The centrifugal forces due to mass unbalance are considered to act at the center of gravity of the rotating part and vary harmonically. The speed of the machine in the two orthogonal directions is perpendicular to the shaft. The forces in the two orthogonal directions are equal in magnitude and 90 degrees out of phase, and transmitted to the foundation through the bearings [12].

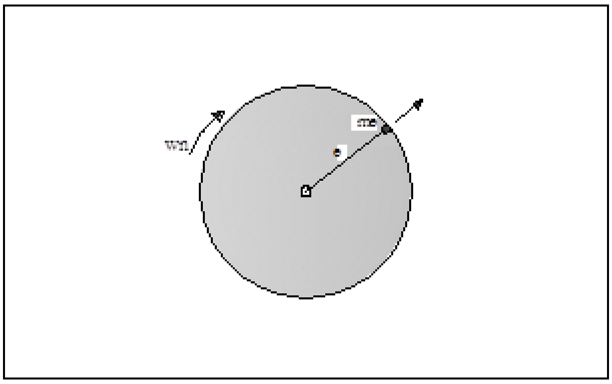


Figure (7): Rotating Mass Type Oscillator with Single Shaft [13].

The maximum dynamic force (F_o) can be calculated as the following: [14].

$$F_o = m_e\, e\, \omega^2 \qquad (1)$$

Where: ω is the circular frequency of the system. The applied dynamic force at any time (t) is given by:

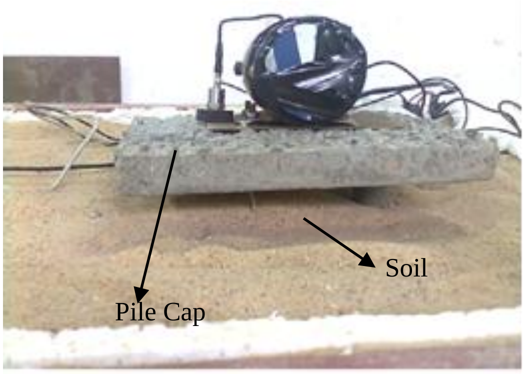
$$F_{(t)} = F_o \sin \omega_t \qquad (2)$$

To control the speed of the electrical motor, a speed control was attached to induce vibration unit. With the help of the speed control unit and by varying the voltage supplied to the motor, the speed of the motor and hence the oscillator can be varied, which in turn, cause a change in frequency of vibration induced by the oscillator. The speed of the motor was measured using tachometer which was fixed with constant distance from the steel disc of the motor. The vibration was measured by fixing vibration pick-up on the top face of the foundation connected to the vibration meter by wire. The vibration meter is connected to the computer and the information of time versus displacements were recorded in an excel sheets.

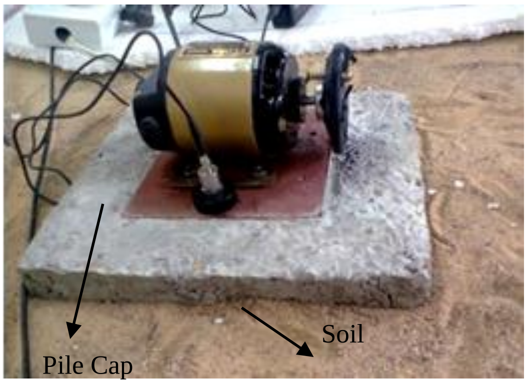
2. Program of the Work

To study the effect of soil-cap interaction all models were tested in two conditions. The condition with non-interacted model was considered as a reference condition. This reference condition was conducted where the pile cap was lifted about 5cm from ground level as shown in Fig.(8a). The second condition employs the same configuration of the above model except the pile cap was in contact with the soil surface (interacted model), Fig.(8b).

The systems of soil-pile-cap were subjected to the dynamic forces and the response of the pile cap was evaluated as a vertical displacements. Many frequencies (started from zero to 140 Hz.) were applied on the top face of pile caps to find out the resonance frequency. At each frequency the time-displacement graphs at center and corner of the caps were drawn; these graphs represents the response of the pile group. The effect of two parameters are investigated (Number and length of piles), while the remaining parameters are kept constant and the piles are assumed to be floating piles. The overall system of pile-soil model, oscillator, tachometer, vibration meter and control of speed are shown in figure (9).



(a)



(b)

Figure (8): Two Conditions of Pile Caps (a) Pile Cap without Interaction with Soil (b) Pile Cap Contacted with Soil (Interaction Model).

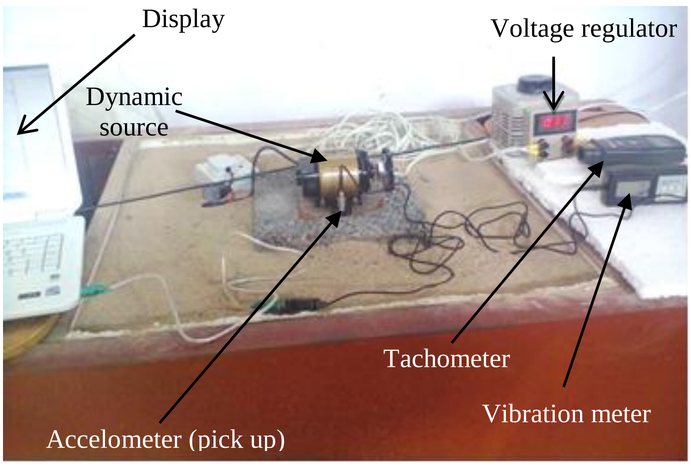


Figure (9): View of the Overall System of Rotary Machine Foundation and Vibration Meter.

Results and Discussion

The main aim of this study is to find out the effect of pile cap interaction on the dynamic response of rotary machine foundation resting on pile group. The accelometer (pick up) was fixed on the top pile cap and the vertical displacements were measured. The historic time versus displacements were considered for each frequency.

Figures (10) through (12) show some examples of the historic time versus displacement at the center or corner of two piles with L/d ratios of (13.3 and 20) for interacted and non-interacted pile caps. It can be seen that the oscillation is decreased or vanished with increasing the frequency. In low frequency, the values of displacements are variants, while in high frequency the displacements are stable and approximately have constant values.

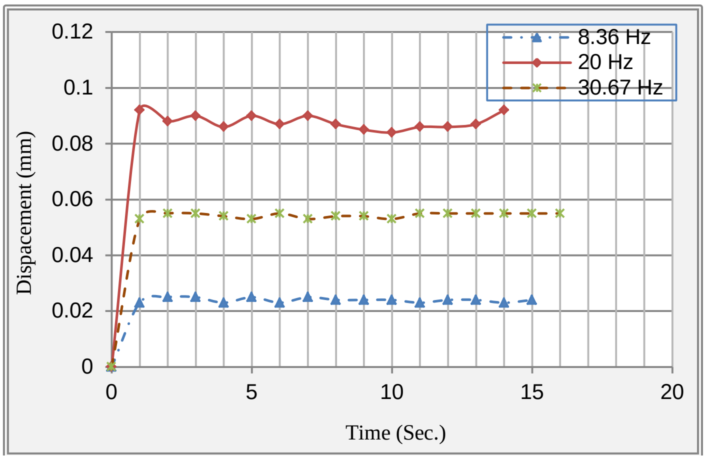


Figure (10): Vertical Displacement versus Time at the Center of Two Piles with L/d Ratio of (13.33) for Non-interacted Pile Caps.

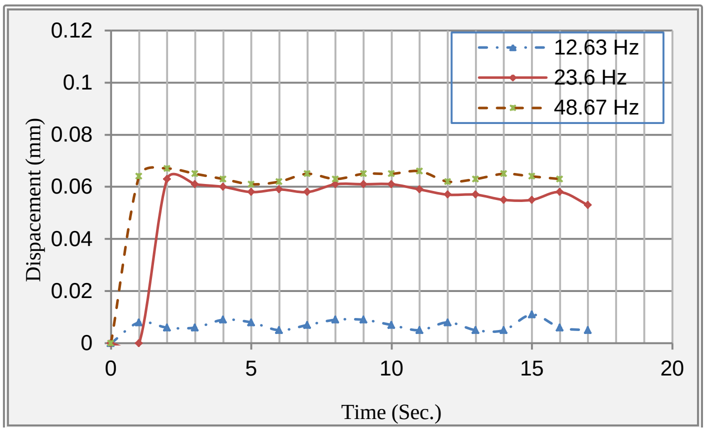


Figure (11): Vertical Displacement versus Time at the Center of Two Piles with L/d Ratio of (13.33) for Interacted Pile Caps.

Figures (13) through (16) are examples of the displacement amplitude as a function of the frequency for concrete pile with length/diameter (L/d) ratio of 13.3 and 20. Two peaks of frequency resonance were observed; the first peak is due to the low inducing frequency and the second peak is due to high inducing frequency. This conclusion was verified by Gazetas [4], Prells [15], and Ladhane [16].

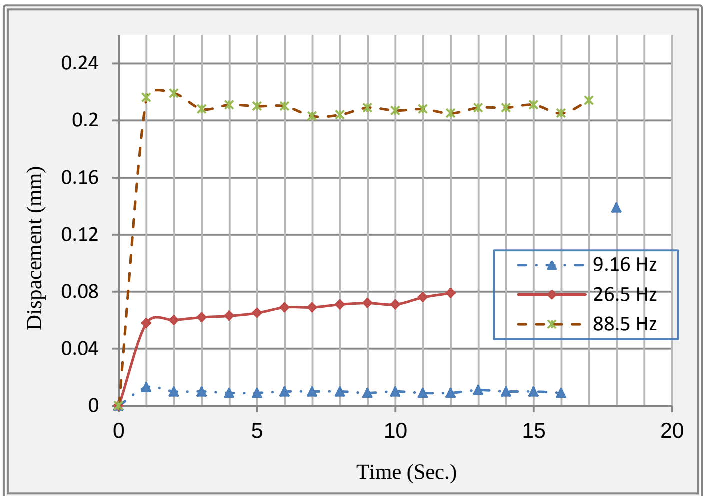


Figure (12): Vertical Displacement versus Time at Corner of Two Piles with L/d Ratio of (20) for Non-interacted Pile Caps.

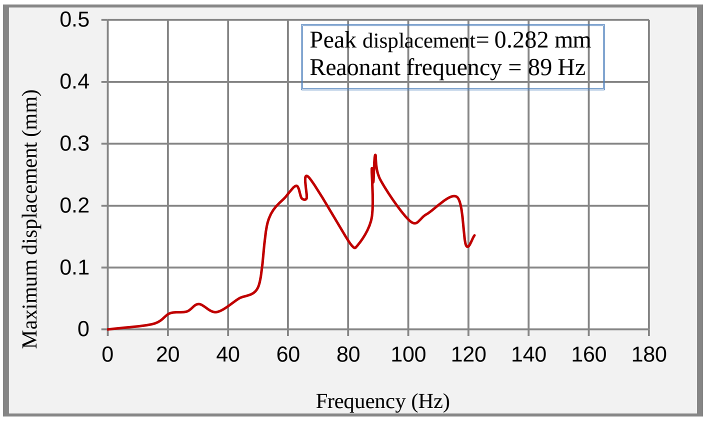


Figure (13): Vertical Displacement versus Frequency at Center of Two Piles for Non-interacted with L/d ratio of (20).

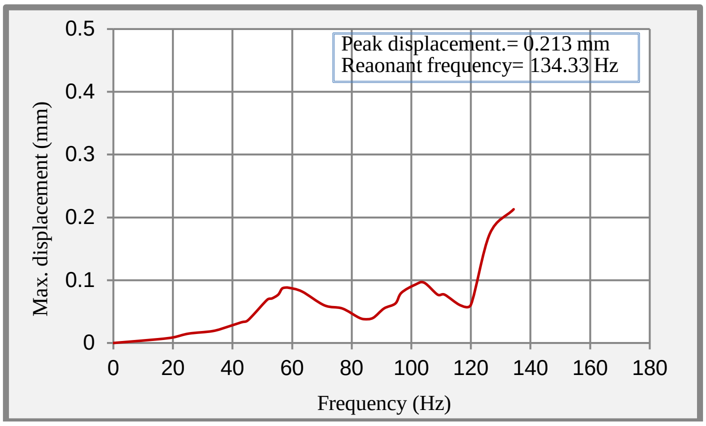


Figure (14): Vertical Displacement versus Frequency at Corner of Four Piles for Non-interacted cap with L/d ratio of (20).

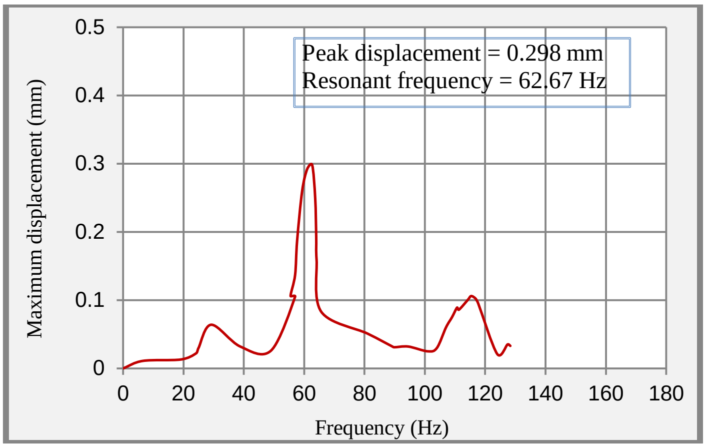


Figure (15): Vertical Displacement versus Frequency at Corner, Three Piles, on Surface with L/d Ratio (13.33).

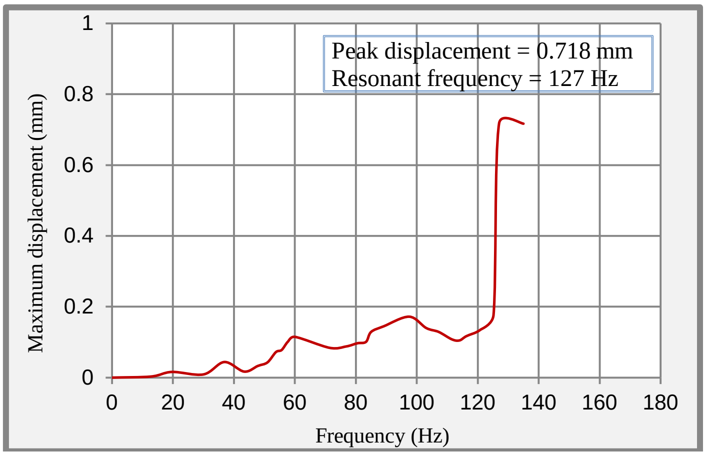


Figure (16): Vertical Displacement versus Frequency at Center, Four piles, on Surface with L/d Ratio of (20).

Figures (17) and (18) show relation between numbers of piles as functions of displacement at the center and the corner of interacted and non-interacted caps for L/d of 13.33.

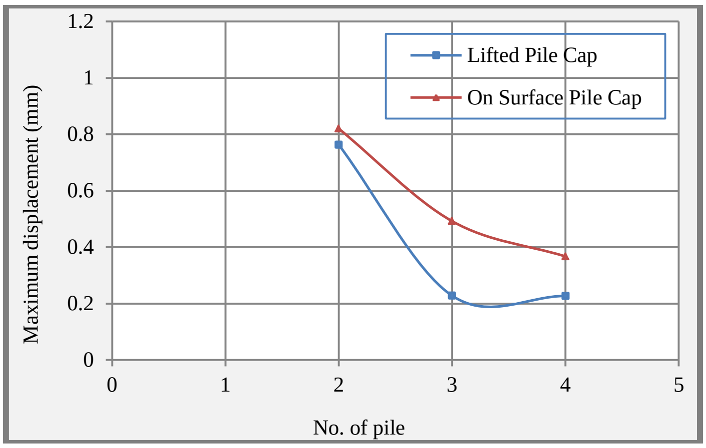


Figure (17): Number of Piles versus Vertical Displacement at the Center.

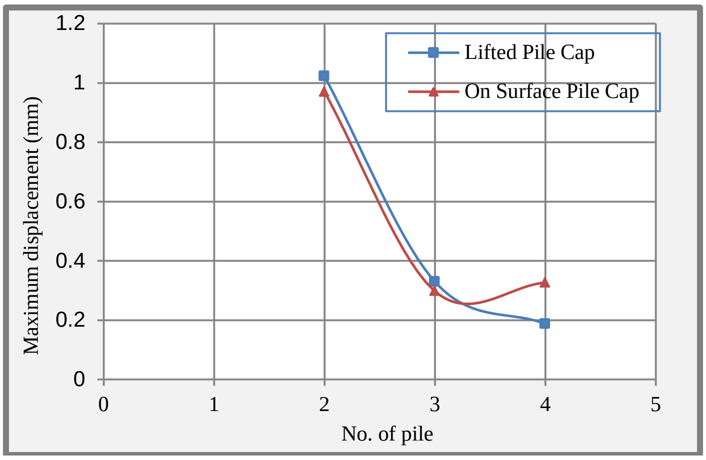


Figure (18): Number of Piles versus Vertical Displacement at the Corner.

As shown in Fig. (17), the vertical displacements at the center for interacted (on surface) pile cap comprising of 2, 3 and 4 piles increase by about (8 %, 116 % and 62 %) respectively, comparing with non-interacted (lifted) cap. While in figure (18), it is found that the vertical displacements measured at the corner decrease by about (5 % and 10 %) for interacted cap comprising of 2 and 3 piles respectively, comparing with the results for non-interacted cap. While for cap comprising of 4 piles the vertical displacements increase by about (74 %).

From the values mentioned above, it can be concluded that pile cap interaction significantly increases the vertical amplitudes in different proportions, depending on number of piles used in the foundation. This increase of the vertical displacements for the interacted cap attributed to more energy induced by the waves created by both the piles and the base of the pile cap.

Figures (19) and (20) show relation between numbers of piles as functions of resonant frequencies at the center and corner of interacted and non-interacted caps for L/d of 13.33.

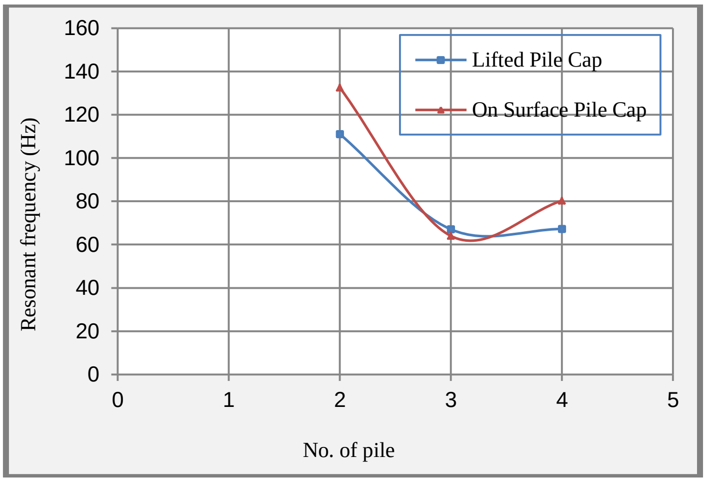


Figure (19): Number of Piles versus Resonant Frequency at the Center.

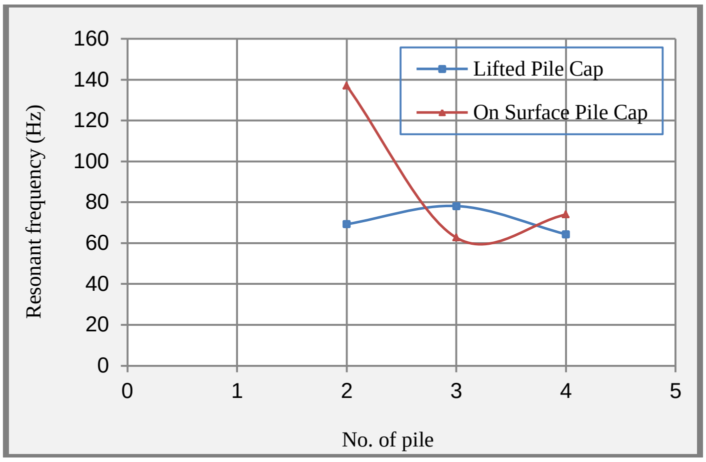


Figure (20): Number of Piles versus Resonant Frequency at the Corner.

From the results shown in figures (19) and (20), the resonant frequencies at the center of interacted caps were found to increase by about (19 % and 20 %) for footings comprising 2 and 4 piles respectively and decrease by about (5 %) for footing comprising 3 piles comparing with non-interacted caps . The resonant frequencies measured at the corner of interacted caps increase by about (98 % and 15 %) for footings comprising 2 and 4 piles respectively and decrease by about (20 %) for footing comprising 3 piles comparing with non-interacted caps.

It has been observed that pile cap interaction increases slightly the resonant frequencies in different proportions depending on number of piles. Novak and Sheta [7] concluded that the dynamic stiffness and damping of pile groups vary with frequency and these variations are more dramatic than with single piles and group stiffness and damping can be either reduced or increased by pile-soil-pile interaction.

Figures (21) through (24) show relation between numbers of piles as function of displacements and resonant frequencies at the center and the corner of interacted and non-interacted caps for L/d of 20.

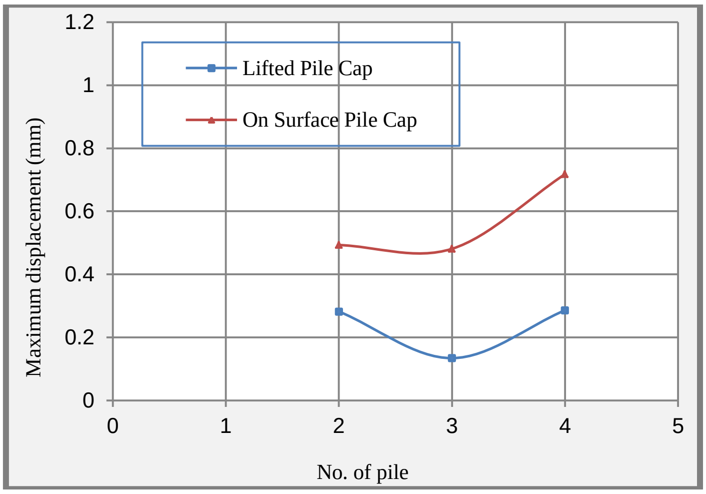


Figure (21): Number of Piles versus Vertical Displacement at the Center.

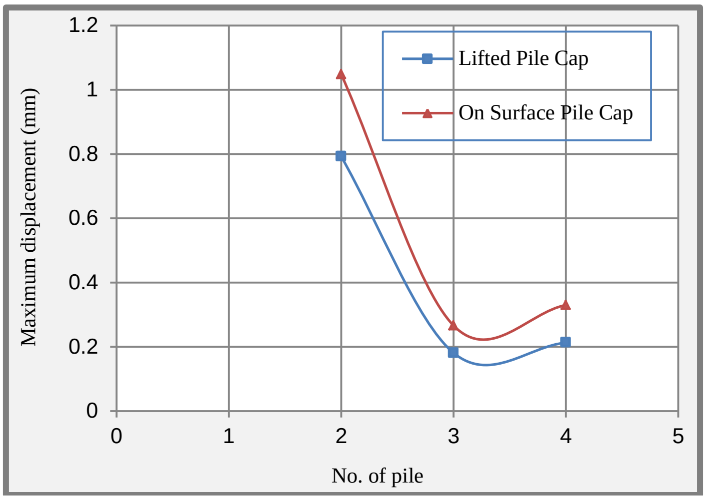


Figure (22): Number of Piles versus Vertical Displacement at the Corner.

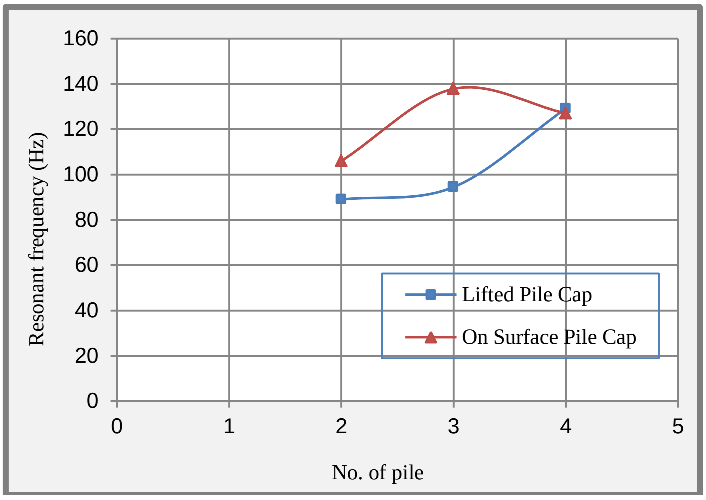


Figure (23): Number of Piles versus Resonant Frequency at the Center

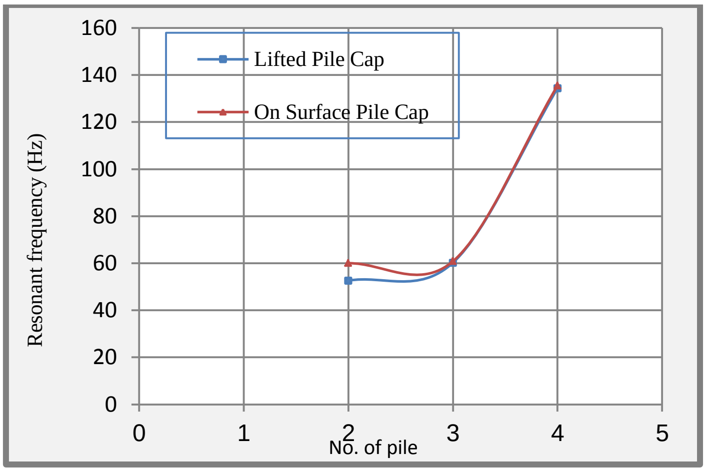


Figure (24): Number of Piles versus Resonant Frequency at the Corner.

By the comparison between interacted and non-interacted piles caps as presented in figures (21) and (22), the vertical displacements at the center of interacted caps were found to

increase by about (75 %, 259% and 151%) for footings comprising 2, 3 and 4 piles respectively comparing with non-interacted caps. The vertical displacements measured at the corner of interacted caps, were found to increase by about (32 %, 47 % and 55 %) for footings comprising of 2, 3 and 4 piles respectively, comparing with non-interacted caps for the same position of measurements.

For L/d ratio is 20, it was observed that the pile cap interaction significantly increases the vertical amplitudes with proportions more than that obtained for L/d ratio is 13.3. This increase is due to the caps which were in contact with the soil and increasing length of the piles causes increasing in the interaction between the piles and soil, so more energy is carried away by the transported waves through the piles and caps.

From Figures (23) and (24), the resonant frequencies at the center of interacted caps were found to increase by about (19 % and 46 %) for footings comprising of 2 and 3 piles respectively, and decrease by about (2 %) for footing comprising 4 piles comparing with non-interacted cap. At the corner of interacted cap, the resonant frequencies were found to increase by about (14%, 1% and 1 %) for footings comprising of 2, 3, and 4 piles respectively.

For L/d ratio is 20, it has been observed that the pile cap interaction increases slightly the resonant frequencies in proportions close to that obtained for L/d ratio is 13.3. So the interaction increases the natural frequencies for both series of pile group.

In case of non-interacted caps the vertical amplitudes decreased significantly with increasing piles lengths (especially for cap comprising of 2 and 3 piles). For interacted caps with increasing piles lengths, the vertical amplitudes damped significantly in footing comprising of 2 piles and slightly decreased in footings comprising of 3 piles. This fact had been emphasized by Ladhane and Sawant [16].

Conclusions

The effect of interaction between soil and pile cap on the dynamic behavior of the pile and soil system due to the vibration was studied.

It may be concluded from the obtained results that the oscillation is decreased or vanished with increasing the frequency. In low frequency, the values of displacement are variants, while in high frequency the displacements are stable and approximately have constant values.

There are two peaks of resonance frequency were observed, the first peak is due to the low inducing frequency while the second peak is due to high inducing frequency.

It was found that the cap interaction evidently increases the vertical amplitudes for both series of pile models (no-interacted and interacted caps) in different proportions. These proportions increase significantly with increasing length of the piles.

The caps interaction increases the resonant frequencies for both series of pile models (interacted and non-interacted) with different proportions and the increasing in the length of piles change slightly these proportions. For non-interacted caps the vertical amplitudes decrease significantly with increasing piles lengths (especially in two and three piles). For interacted caps with increasing piles lengths, the vertical amplitudes damped significantly in footing comprising 2 piles and slightly decreased in footings comprising 3 piles.

Remark

This work is part of a Ph.D. research being conducted by the third researcher and supervised by the first and second senior researchers.

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