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RESPONSE OF CIRCULAR MACHINE FOUNDATION RESTING ON SANDY SOIL TO HARMONIC EXCITATION

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Abstract

This paper focuses on the effect of the machine's circular foundation on the variation of surface settlement, vertical displacement and stress with a number of cycles. A special setup was designed and manufactured to simulate the vertical vibration of a machine foundation. Six laboratory model footings were prepared on medium and dense dry sand separately. A circular steel model of (150 mm) diameter was used to represent the footing. The models were tested under dynamic load amplitude of 0.25 ton and different frequencies of 0.5, 1, and 2 Hz. It was found that the rate of increase in settlement decreased remarkably when increasing the frequency for both types of sand. While increasing the soil relative density under the same load and frequency resulted in a decrease of the settlement. Moreover, the amplitude displacement decreased when increasing frequency and relative density. The resulting stress due to the dynamic load below the foundation decreased with depth. Besides, there is a little difference in the induced dynamic stress between the depths B and $2B$. The stress had increased when the frequency and sand relative density were decreased under the same load amplitude.

Keywords: Amplitude displacement, Machine foundation, Settlement, Stress.

1. Introduction

Continuous improvements in power generation technologies lead to gigantic turbo machineries, which generate considerably higher dynamic forces and stresses on the foundation. The machine foundations should be designed so as to transmit the dynamic forces of machines to the soil through the foundation thus negating the harmful effects due to vibration.

The dynamics problems of common soil have the response from both the foundations of the machine for the soil sediments and dynamic loads and earth structures for earthquake loads. There are many types of machines, which produce various dynamic forces. The typically considered machines are listed as follows [1]:

- Impact machines.
- Rotary machines.
- Reciprocating machines.
- Other machine types.

Usually, the dynamic load, generated by these types of equipment, based on rotating imbalances.

Based on their operating frequencies, machines can also be classified into three categories [2] as follows:

- Low to a medium frequency of (0 -8.32 Hz), e.g., reciprocating machines
- Medium to a high frequency of (5 - 16.07 Hz), e.g., diesel and gas engines.
- Very high frequency of more than (16.07 Hz), e.g., electric motors and turbo generators.

Srinivasulu, and Vaidyanathan [3] listed some of the vital requirements of a machine-foundation-soil system, which can be itemized as follows:

1.1. Resonance check

Resonance should be avoided. Therefore, wherever probable, the operating frequency (ω_o) must be lesser than the natural frequency (ω_n) of the system, (the foundation is high tuned) and then:

(ω_o/ω_n) must be less than (0.5).

If the natural frequency happens to be less than the operating frequency, (the foundation is low tuned), then:

(ω_o/ω_n) must be more than (2.0).

As a result, the frequency design criterion is written as:

(ω_o/ω_n) < 0.5 or (ω_o/ ω_n) > 2.0.

1.2. Amplitude check

The amplitudes of acceleration or velocity or displacement related to the system of the machine–foundation–soil must be within recognized limits.

Several methods are available for the analysis of vibration characteristics of machine foundations. The commonly used methods are [4]:

- The linear elastic spring method: This method deals with the problem of foundation vibration as a spring-mass model, neglecting soil damping.
- The elastic half-space analogues theory: This theory is used to determine the values of equivalent soil springs and damping then makes use of the theory of vibration to determine the response of foundation.
- The impedance function method: This method also provides for soil spring and damping while being applicable for surface and embedded foundations.

Many researchers used theoretical approach to explain the behaviour of soil under vibrating load such as Sung [5] who presented the first acceptable solution for this vertical vibration of a rigid disk with a mass on an elastic half-space but this solution is not understood by most engineers.

Lysmer and Richart [6] produced a convenient and accurate single degree of freedom analogy for vertical vibration of a rigid disk wherein it, the displacement motion**.**

A theoretical method for analysing the dynamic response of the foundation soil system is based on a number of simplifying an assumption regarding soil properties and system geometry. In particular, real non-linear hysteric soil properties are generally not included or are approximate. As a result, the application of theoretical results is questionable in many cases [7].

Therefore, there has existed a great need for experimental studies to clarify the ambiguities produced by using simplified mathematical models.

The response of soil under the circumstances of dynamic is an essential constituent of numerous researches. The soil behaviour beneath the loading of dynamic is based on a lot of significant features [8].

Boumekik et al. [9] presented laboratory tests for estimating the dynamic stress of the soil persuaded by a "vibrating foundation prototype for three specific points of the foundation-soil interface zone". In fact, the testing prototype provides satisfying findings to simulate the behaviour of a superficial foundation below a dynamic and cyclic loading. A significant increase in the relative density of the medium dense sand was observed because of the particles' retightening in the level of the central zone, which creates an increase in their compactness. As a result, the axial over stresses will contain the trend for being transferred to the bends due to the primary confinement.

The tentative examines of the behaviour of dry medium and a loose sandy soil beneath the act of a particular impetuous load was carried out by Ali et al. [10]. Various declining masses from various heights were accomplished by using the declining weight deflect meter for providing the energy of a single pulse. The soils responses were assessed at various positions (i.e., a vertical direction under the plate, which is impact and at a horizontal spacing from the centreline of the plate). These responses usually contain velocities, displacements and accelerations, which are developed because of the impact acting at the top as well as various depth ratios inside the soil by using the declining weight deflect meter. It was found that increasing the depth of footing embedment causes: the amplitude of the history of force-time boosts by about approximately 10-30%. Because of the improvement occurred in the confinement as the embedment depth increased, the soil displacement response would reduce by approximately 25-35% for the slack sand, 35-40% for the medium sand because of the rising of the overloaded pressure as the depth of embedment increased.

The objective set for the present research is to investigate the outcomes associated with the parameters of the dynamic load (number of cycles and load frequency) related to the foundation of a machine on the amplitude displacement, settlement and stress in the soil at different depths. The investigation also includes explaining the influence of sand relative density on the dynamic response. This study investigates the influence of machine foundations rested on homogenous sand soil. Further research work in future can be conducted to capture the behaviour of different types of machine foundations rested on, for example, non-homogenous soils under different soil conditions.

2. Material Used and Testing Program

The type of soil utilized in the current work is sand, which was brought out of the province of Karbala in Iraq. Its properties were obtained by standard tests performed on two different relative densities; dense and medium. The physical characteristics for sand appear to be categorized as Poorly Graded (SP) as it is declared by the Unified Soil Classification System (USCS). Table 1 summarizes the properties of the sand and Fig. 1 shows the grain size distribution of this soil.

Table 1. Sand properties [11].

Index properties	Value	Specification
Specific gravity (SG)	2.66	ASTM D 854
Coefficient of uniformity, C_u	3.91	ASTM D 422
Coefficient of curvature, C_c	0.77	ASTM D 2487
Soil classification (USCS)	SP	
Maximum dry unit weight (kN/m^3)	18.63	ASTM D 4253
Minimum dry unit weight (kN/m^3)	15.71	ASTM D 4254
Maximum void ratio	0.66	
Minimum void ratio	0.4	
Angle of internal friction ϕ at RD = 50%	39.5°	ASTM 3080
Angle of internal friction ϕ at RD = 80%	42°	ASTM 3080

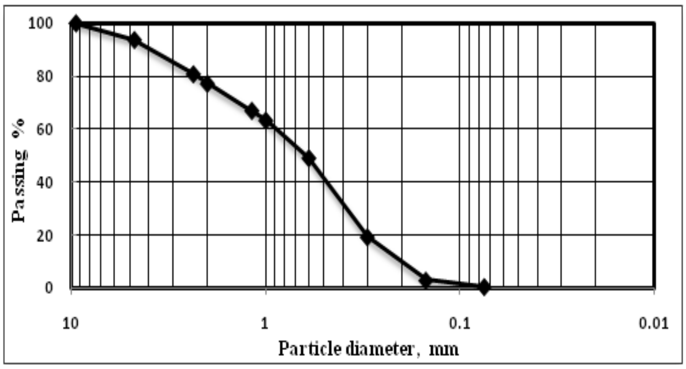


Fig. 1. Grain size distribution curve of sand soil.

The experimental work was conducted using a steel cubical tank of dimensions (800×800×1000 mm) having 6 mm of thickness, slicked both faces, to hold the soil. These dimensions were selected to convince the boundary influences of physical models exposed to dynamic loading. To ensure a uniform density throughout the model depth, 100 mm thick layers of soil were placed layer by layer and compacted manually to the marked levels.

3. Model Setup

In order to simulate the circumstances as similar as possible to those, which are taking place in the field, a particular investigative device with accessories were manufactured and designed. The loading system is hydraulically mounted enhancing of the solid structure of the apparatus to bear sufficiently new loading amplitude as presented in Fig. 2.

The device of load application was created from the following parts:

- The frame of loading.
- The system of electrical hydraulic.
- Loading spreader plate.
- Settlements measuring device.
- The system of data logging and acquisition.
- Steel container (800*800*1000 mm).

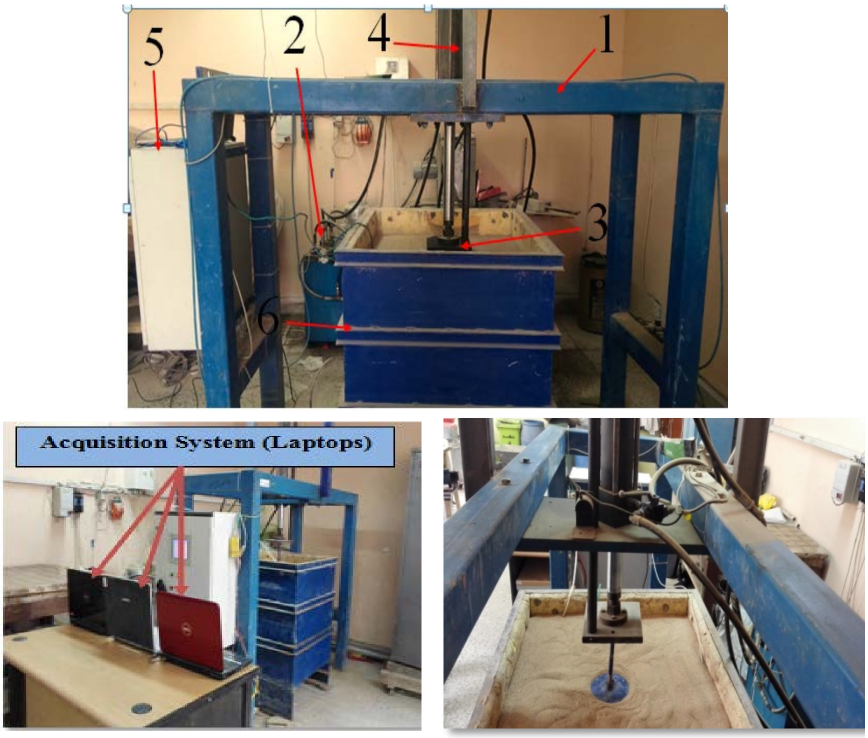


Fig. 2. Details of the loading system.

4. Instrumentation

4.1. Vibration meter

This device had been employed to measure the amplitude of vertical displacement of points below footing depth of (*B*) as shown in Fig. 3. The vibration meter was locally manufactured to measure large movements within three directions (*x*, *y*, and *z*). Aforementioned produced vibration device includes ADXL345 type accelerometer that is a little, tinny and small power 3-axis accelerometer having sign condition electrical energy output.

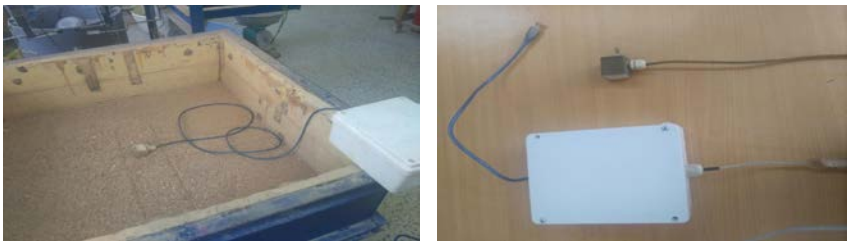


Fig. 3. Vibration meter.

4.2. Tactile pressure sensors

Ultra-thin flexible tactile flexi force pressure sensors of (1500 kPa) capacity model are used to determine the stress under the footing at depths (*B*) and (2*B*) in the soil layers as shown in Fig. 4. Two load pressure senores have been used because the distribution of stresses in the soil is often deep and to investigate the change in stress at different depths under dynamic load. The dimensions of those tactile stress senores allowed installing enough of them in the soil. These dimensions are (14 mm) width, (0.203 mm) thickness and (9.53 mm) diameter of the sensing area.

Fig. 4. Tactile pressure sensors.

5. Results and Discussion

5.1. Effect of dynamic loading on settlement

Figures 5 and 6 and Table 2 present the relationship found between the number of cycles of loading and footing settlements on medium and dense sand under the same load amplitude using different frequencies (0.5, 1 and 2 Hz). Generally, the curves pursue the identical trend, there is a sharp increase in the settlement approaching the cycle 500, then, there is a regular increase to level out between 800 to 1000 cycles basing on the frequency used.

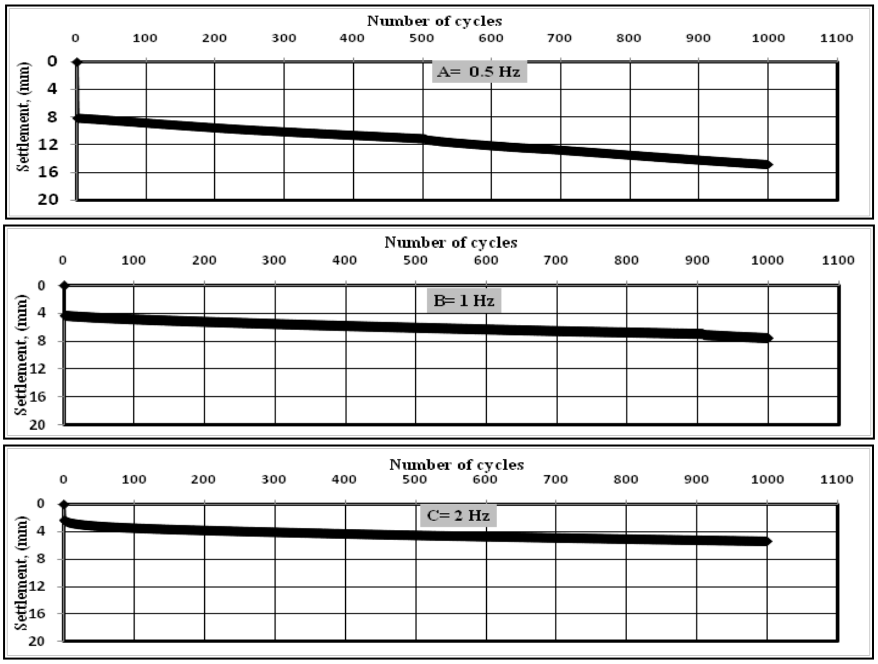


Fig. 5. Relation between number of cycles and settlement for footing on medium sand with RD = 50%.

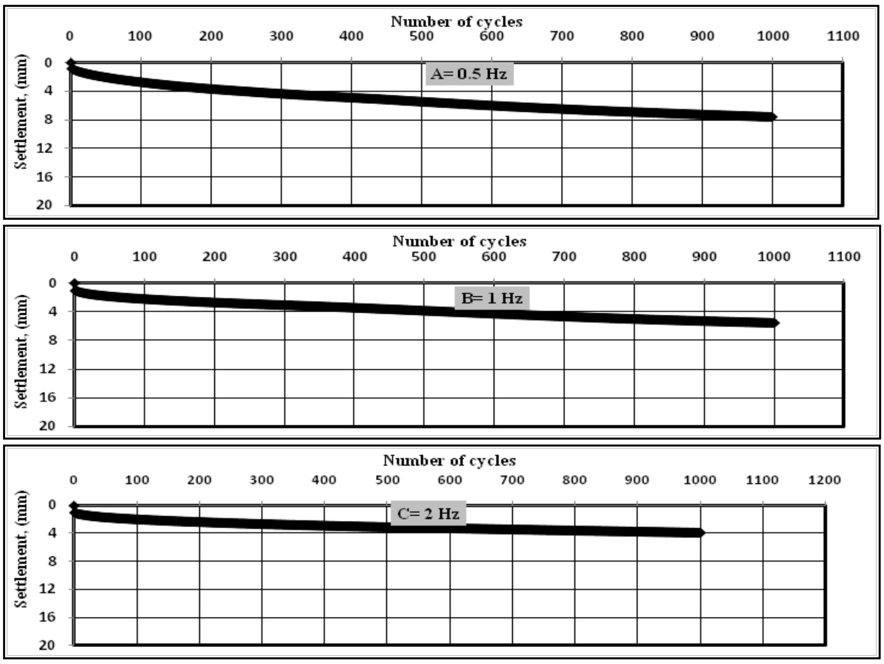


Fig. 6. Relation between number of cycles and settlement for footing on dense sand with RD = 80%.

Table. 2. The surface settlement (mm) after 1000 cycles at different frequencies.

Frequency (Hz)	**0.5 Hz**		**1 Hz**		**2 Hz**	
RD%	**50%**	**80%**	**50%**	**80%**	**50%**	**80%**
0.25 ton	12.6	7.12	9.13	5.61	5.95	4.27

This may be attributed to an increase in particle stresses. The trend of the settlement confirms with the findings by Tutunchian et al. [12] who found that the behaviour of foundation settlement during under the load frequency has three main modes; the first mode during the dynamic excitation, the second mode during the free vibration of the system, and the third mode during the time that the soil-foundation system reached to its physical equivalence (i.e., reach the strain to the stability stage).

On the other hand, it is evident that the settlement had increased when the loading frequency was decreased, for both relative densities of sand. It can be noticed that the settlement had increased by (41%) and (68%) when the frequency was decreased from (2 to 1 Hz) and (1 to 0.5 Hz) respectively. This is because the low frequency of loading provides enough time for soil densification and so it leads to increased settlement.

The results reveal that the increase in the settlement in the medium sand is larger than that of the dense sand under identical frequency and load condition. These findings are consistent with the results of Al-Ameri [13] who revealed that by increasing the relative density, the footing surface settlement on sand decreases.

5.2. Effect of dynamic loading on the amplitude of displacement

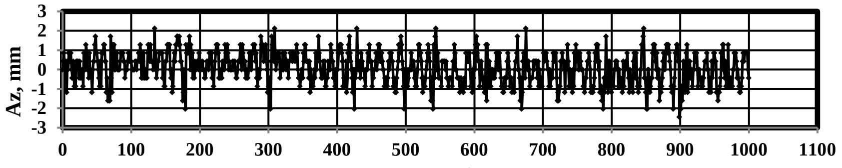
The displacement resulting amplitude (*Az*) for the vibrating foundation on medium and dense sand soil is given in Figs. 7 and 8. From these figures, it can be seen that the relation of the (*Az-N*) was created as the assessed amplitude of displacement with the cycle's number.

From the findings of the test, it is noticed that the tendency of all investigation findings is unique. Accordingly, this can be recognized because of the conditions of the test and the soil dynamic response.

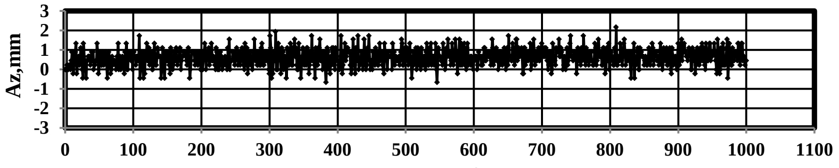
Usually, in many engineering applications, it is preferred to reach the utmost dislocation amplitude related to the motion. Therefore, the utmost values are gathered from Figs. 7 and 8 and summarized in Table 3.

On other hands, the *Az* decreases with increasing frequency, the increase in the (*Az*) value occurs under low frequency i.e., (0.5 Hz), the rate of decrease in the amplitude of displacement values were (33) % and (26) % when the frequency values were ranging from (0.5 to 1 Hz) and (1 to 2 Hz), respectively.

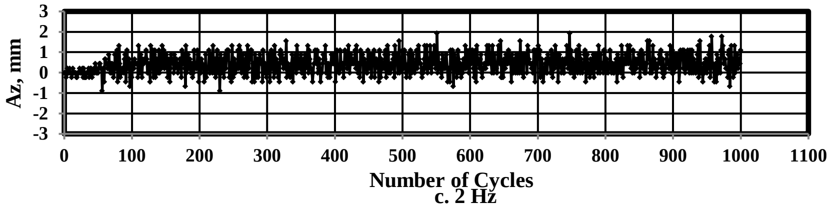
This behaviour is due to that the soil particles become unstable and do not find enough time for displacement. The decrease in (*Az*) when the soil change from medium to the dense condition was about (32) % under the same dynamic load frequency.



a. 0.5 Hz

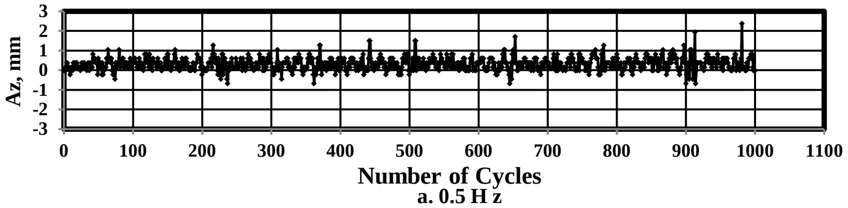


b. 1 Hz

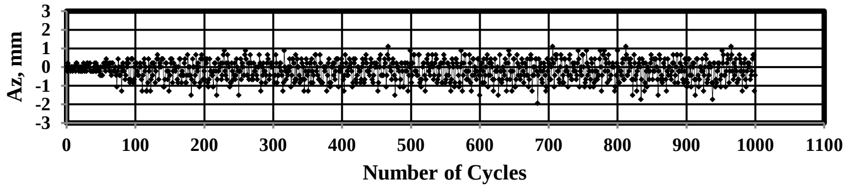


c. 2 Hz

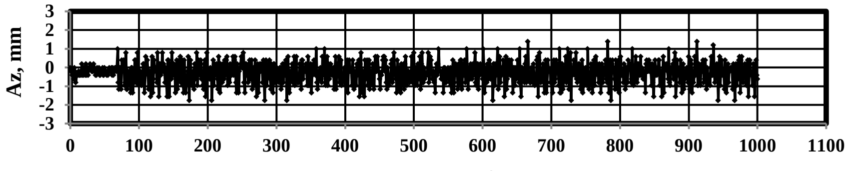
Fig. 7. Relation between number of cycles and amplitude displacement for footing on medium sand with RD = 50%, under different load frequencies.



a. 0.5 H z



b. 1 Hz



c. 2 Hz

Fig. 8. Relation between number of cycles and amplitude displacement for footing on dense sand with RD = 80% under different load frequencies.

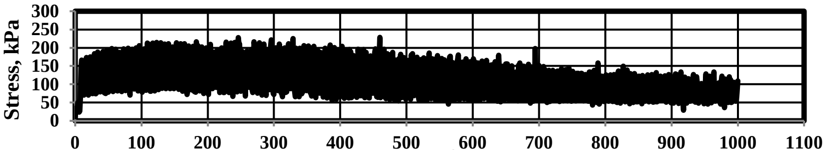
Table. 3. The maximum amplitude displacement (mm) after application 1000 cycles at different frequencies.

Frequency (Hz)	0.5		1		2	
RD%	**50**	**80**	**50**	**80**	**50**	**80**
0.25 ton	2.66	1.72	2.16	1.53	1.98	1.34

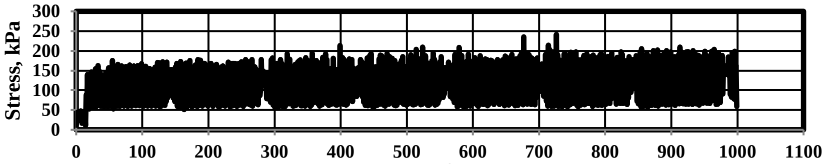
Comparison of results was made with those obtained by Fattah et al. [14] who determined from a restricted component investigation on machine foundations, in which, the perpendicular displacements reduced when increasing the relative, density. This examination is approximately in agreement with the results of Fattah et al. [14]. The results were validated when a comparison is made with the findings of Fattah et al. [15] who concluded that an increase in stress levels by approximately 20% was found when decreasing the vibration frequency from 2 Hz to 1 Hz when applying vertical vibration mode. Decreasing vibration frequency from 2 Hz to 1 Hz in pitching and vertical vibration mode causes a general increase to the total settlement by (20% -77%) for the majority of the test models that have been tested.

5.3. Effect of dynamic loading on the stress in the soil

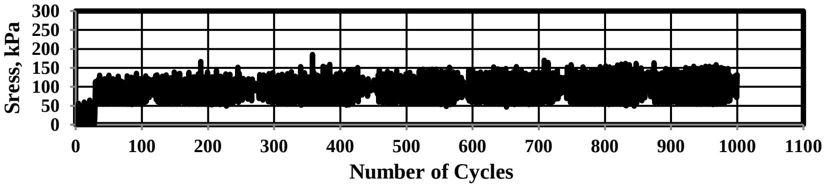
Figures 9 to 12 show the relation between transmitted stresses versus a number of cycles measured by the two sensors below the footing. As it is noticed in the figures, the stress at nearly for all tests start at a particular level and remain at this phase for a period, and then the stress increased quickly for the next period in order to get the maximum magnitude and after that decreased for the other period and then increased. The figures show that there is a remarkable decrease in the stress value by increasing the frequency from 0.5 to 1 Hz and 1 Hz to 2 Hz.



a. 0.5 Hz

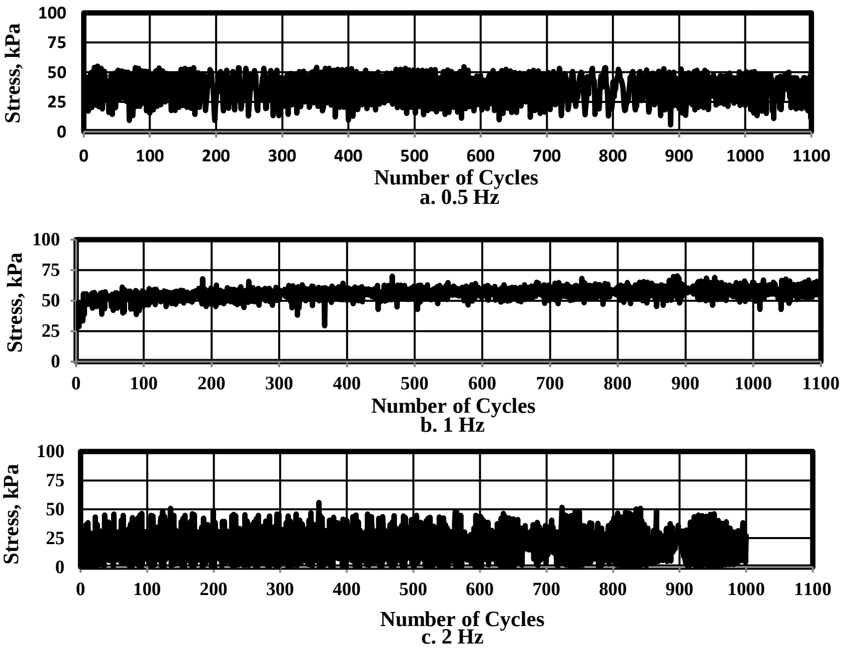


b. 1 Hz



c. 2 Hz

Fig. 9. Relation between number of cycles and stress at depth *B* below the footing on medium sand with RD = 50% under different load frequencies.

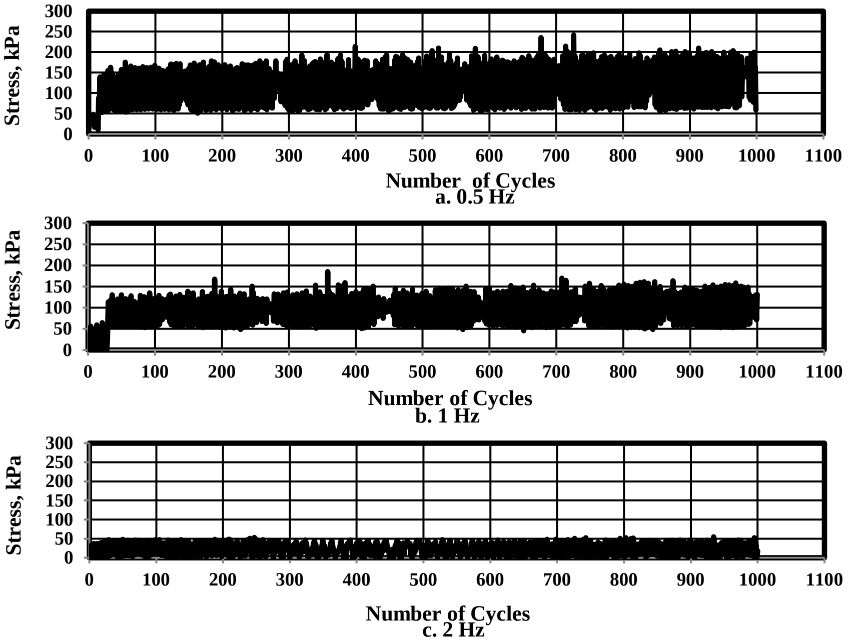


a. 0.5 Hz

b. 1 Hz

c. 2 Hz

Fig. 10. Relation between number of cycles and stress at depth 2B below the footing on medium sand with RD = 50% under different load frequencies.

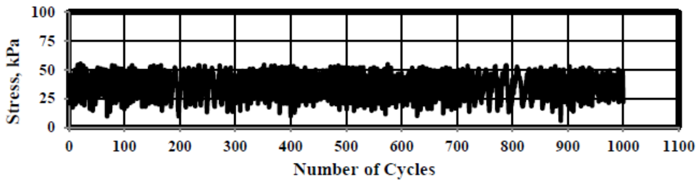


a. 0.5 Hz

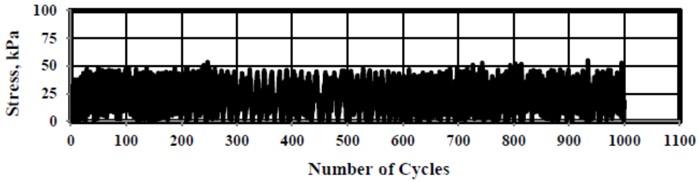
b. 1 Hz

c. 2 Hz

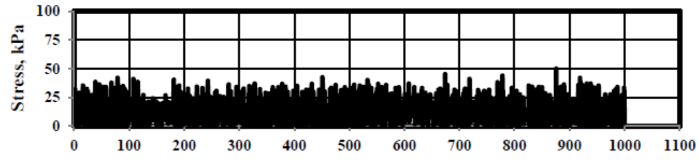
Fig. 11. Relation between number of cycles and stress at depth *B* below the footing on dense sand with RD = 80% under different load frequencies.



a. 0.5 Hz



b. 1 Hz



c. 2 Hz

Fig. 12. Relation between number of cycles and stress at depth 2*B* below the footing on dense sand with RD = 50% under different load frequencies.

Theist results agree with the findings by Fattah et al. [16] who concluded that the dynamic stress increments resulting from the dynamic load on the foundation but reduce with depth, as the operating frequencies increase the stresses requires greater depth to be stabilized with depth. In other words, when the operating circular frequency increases, the dynamic stresses spread to a greater depth. This behaviour is valid for a loose and dense state with a difference in percentages of increasing. On the other hand, it is observed that, the increase in the relative density from medium to dense led to a significant decrease in stress generated in the sand under the same load amplitude and frequency, since the effect of soil densification leads to less amount of stresses to be transmitted to the specified depths (i.e., *B* or 2*B*) as shown in Figs 13 and 14.

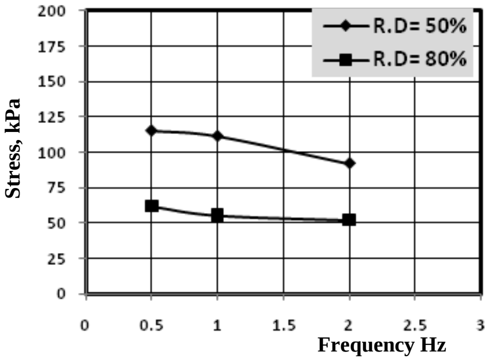


Fig. 13. Relation between frequency and maximum average stress below the footing at a depth = *B*.

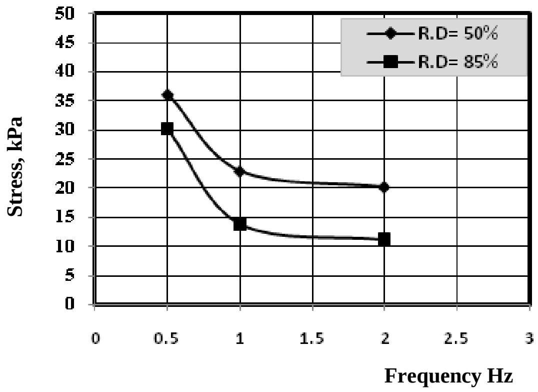


Fig. 14. Relation between frequency and maximum average stress below the footing at a depth = 2*B*.

6. Conclusions

Based on the findings of this research, the following conclusions have been drawn:

- In general, as the frequency increases, the surface settlement decreases under the identical load amplitude and the relative density. The rate of increase in settlement approximately reaches 40% as the frequency changes from 2 Hz to 1 Hz while this rate is approximately 60% when the frequency changes from 1 Hz to 0.5 Hz. This means that the rate of surface settlement increases as the frequency decreases.
- As the relative density decreases, the surface settlement increases under identical load amplitude and frequency conditions. The rate of change increases by about 8%, 12% and 20% for frequencies 0.5, 1 and 2 Hz, respectively.
- In general, as the frequency decreases, the amplitude displacement increases under identical load amplitude and sand relative density. The rate of changes in amplitude displacements are approximately 52% and 20% for the frequencies decreased from (2 Hz to 1 Hz) and (1 Hz to 0.5 Hz) respectively.
- The transmitted stress due to dynamic load increased with decreasing the frequency for footings on both medium and dense sand.
- By increasing the relative density of sand, the maximum average stress reduces at depths (*B* and 2*B*). Increasing sand's relative density from (50%) to (80%) caused a significant decrease in the maximum average stress at depths (*B* and 2*B*) by about 39 %, 57% and 64% at frequencies of 0.5, 1 and 2 Hz respectively under the same load amplitude.

Nomenclatures

Az	Amplitude of displacement, mm
B	Width of footing, mm
C_c	Coefficient of curvature
C_u	Coefficient of uniformity
N	Number of cycles

Greek Symbols

ϕ	Angle of fraction, degree
ω_n	Natural frequency, Hz
ω_o	Operating frequency, Hz

Abbreviations

ASTM	American Society for Testing and Materials
SG	Specific Gravity
RD	Relative Density
SP	Poorly Graded Sand
USCS	Unified Soil Classification System

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