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Assessment of Changes in Shear Strength Parameters for Soils below Circular Machine Foundation

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PAPER INFO	ABSTRACT
	This paper focuses on the response of circular machine foundation resting on different soils (sand and clay) through studying the variation of soil shear strength parameters and strain with the number of cycles. The objective of the current study is to explore the results related to the parameters of the dynamic load (number of loading cycles and frequency of load) related to the circular footing of a machine on the dynamic shear strength parameters (for sand soil ($\phi°dyn$) and for clay soil (Cudyn)) in addition to the amplitude strain foundation. A special setup was designed and manufactured to simulate the vertical vibration of a circular machine foundation. A steel circular machine foundation with a diameter of 150 mm was used to represent the footing. A total of 6 cases were examined to take into account the effects of different parameters including different frequencies (0.5, 1, and 2 Hz); state of sand (medium and dense) which corresponded to relative densities of (50 and 80%), while the state of clay (medium and stiff) corresponded to undrained shear strengths (50 and 70 kPa). All tests were carried out under load amplitude of 2.5 kN. It was found that the rate of increase in shear strength parameters for the soil under a circular machine foundation decreases remarkably when increasing the frequency for both types of soil under the footing. While little change in the shear strength parameters, or even no change was observed under the effect of other locations. Moreover, the amplitude strain decreased when increasing the frequency for both types of soil.

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1. INTRODUCTION

The machine foundations should be designed to transmit the dynamic forces of machines to the soil through the foundation thus reducing the harmful effects due to vibration [1]. The response of the soil to dynamic loads differs from that in static loads, and it is a fact of great importance to the stability of structures. Soil strain behavior can be recognized as highly hysteresis and non-linear, and the actual behavior of the soil is usually flexible plastic, which reveals closer estimates of displacement when exposed to a working load. Soil type also influences the responses under dynamic loading conditions. The most influential factors that separate the different soil types are the particle size distribution. Well-graded materials are unlikely to lose energy under dynamic loading, while uniform soils are likely to lose their dynamic load carrying capacity [2].

In the design of the shallow foundation, the bearing capacity of the soil has an essential role in the spectrum. Foundation transmits projected loads to the soil below without failure. The minimum value of the ultimate dynamic bearing capacity of shallow foundations on sands obtained between static to dynamic loading range can be estimated by using a friction angle $\phi°_{dyn}$ (internal friction angle under dynamic load), such that in Equation (1) [3]. While ultimate bearing-capacity of foundations resting on clay soils can be considering the strain-rate influence caused by dynamic loading is taken into account in the undrained cohesion determination. In contrast with sand, the, undrained cohesion of soaked clays rises with the strain rate increasing, Carroll [4] suggested that:

$$\phi°_{dyn} = \phi°_{stat} - 2 \qquad \text{(in sand)} \qquad (1)$$

$$Cu_{dyn} = 1.5\, Cu_{stat} \qquad \text{(in clay)} \qquad (2)$$

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Baidya et al. [5] declared an experimental exploration for the dynamic reaction of foundation on limited stratum underlain by a solid layer. The stratum thickness effect and the dynamic reaction of the foundation system were experimentally investigated, by conducting "the vertical vibration test" using mechanical oscillator on different stratum depths with different static weights and different eccentric angles "ϕ". With an increase in the constant weight, the natural regularity and the amplitude reduce, and with an increase in ϕ, the natural regularity reduces and the sounding amplitude also increases.

Fattah et al. [6] investigated the experimental behavior of dry sandy soil under foundations subjected to vertical cyclic stress load. It was believed that there is a rise in the angle of internal friction after testing under periodic load with different foot models. The rate of increase of sand shear strength (friction angle) depends on the rate of development of permanent stress.

Investing dynamics properties is therefore very sensitive and challenging task. This demads complex mathematical analysis for the incorporation of various aspects of design. Kirar et al. [7] presented a discussion about various dynamic soil properties those are essential in the machine foundation design and the methods to evaluate them. Some of the established correlations between the important dynamic soil properties and general soil properties are also presented. It was observed that the resonant frequency of the soil-foundation system decreased with an increase in the excitation force while resonant amplitude increases with an increase in the excitation force level.

Bender-element (BE) tests were conducted by Cabalar et al. [8] on clay-sand mixtures to investigate the variation of small strain-shear modulus (G_{max}) with the sand content and the physical characteristics (size, shape) of the sand grains in the mixtures. Three different gradations (0.6–0.3 mm, 1.0–0.6 mm and 2.0–1.0 mm) of sands having distinct shapes (rounded, angular) were added to a low-plasticity clay with mixture ratios of 10, 20, 30, 40 and 50% clean clay. The tests indicated that both the G_{max} and unconfined compressive strength (q_u) values of the specimens with angular sand grains were measured to be lower than those with rounded sand grains, for all sizes and percentages. As the percentage of sand in the mixture increases, the G_{max} values increase, while the q_u values decrease.

Venkateswarlu and Hegde [9] carried out numerical analyses to understand the performance of the machine foundations resting on the geocell reinforced beds. The analyses were carried out by using finite element software PLAXIS 2D. The hypothetical case of the circular machine foundation of 1 m diameter resting on the saturated silty sand was analyzed. Mohr-Coulomb failure criteria was used to simulate the behavior of the soil. Initially, the numerical model was validated with the existing results reported in the literature. Three different cases, namely, unreinforced, geogrid reinforced and geocell reinforced were considered. The depth of the placement of the geocell and geogrid was also varied. At the optimum location of geocell, 61% reduction in the displacement amplitude was observed as compared to unreinforced foundation bed. Similarly, as compared to geogrid, more than 50% reduction in the displacement was observed in the presence of geocell. In addition,163% increase in the damping ratio of the soil was observed in the presence of geocell. In this way, the study highlights the possible new applications of geocell in supporting the machine foundations.

A rigid circular foundation with diameter of 150 mm was subjected to two modes of vibration each mode applies with two frequencies by Fattah et al. [10]. The foundation was placed at three depths within dry sand with two relative densities in a test model with dimensions of (800×800×1000) mm. It was concluded that the edge points stresses for circular foundation showed an increase from one side to another (the increase in the direction of the rocking mode) by150-100%, while most test models subjected to vertical vibration mode had a depression under the center of the foundation making peak stress levels just around the center of footing.

The objective of the current study is to explore the results related to the parameters of the dynamic load (number of loading cycles and frequency of load) related to the circular footing of a machine on the dynamic shear strength parameters (for sand soil (ϕ°_{dyn}) and for clay soil (Cu_{dyn})) in addition to the amplitude strain of the foundation.

2. TESTING MATERIAL AND TEST PROGRAM

Two types of soil are used in this research; the first type is sand which was brought out of Karbala city in Iraq. The physical properties of the sand are illustrated in Table 1. Figure 1 shows the sample soil grain size distribution. The second type of soil used in this research is clay which had been brought from a river embankment

TABLE 1. Physical properties of sand soil

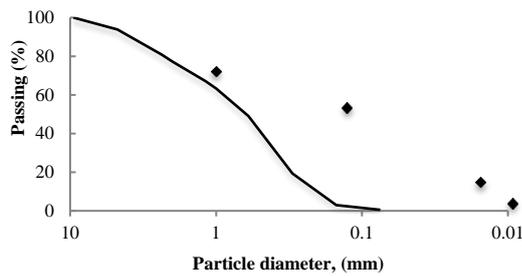| Index properties	Value	Specification Ref.
Specific gravity, Gs	2.66	[11]
Uniformity coefficient, C_u	3.91	[11]
Curvature coefficient, C_c	0.77	[11]
Classification of soil-USCS	SP	[11]
Maximum dry-unit weight (kN/m³)	18.63	[11]
Minimum dry-unit weight (kN/m³)	15.71	[11]
Maximum void-ratio	0.66	-
Minimum void-ratio	0.4	-
Angle of internal-friction ϕ° at R.D =50%	39.5°	[11]

Figure 1. Grain size distribution curve of sandy soil

in the south of Baghdad (Iraq). Its physical properties are listed in Table 2. Consolidation test was carried out on clayey soils prepared at two undrained shear strengths; 50 and 70 kN/m² according to ASTM D2435 specifications [11]. The results are presented in Table 3.

The experimental work was carried out using a steel tank of dimensions (800 x 800 x 1000 mm) made of steel plate with a thickness of 6 mm, double-sided, to hold the soil. These dimensions were chosen to persuade the boundary effects of physical models subject to dynamic loading. To get uniform density along the depth of the model, layers of soil of thickness 100 mm each were laid consequently and manually pressed to the specified levels.

TABLE 2. Physical properties of clay used

Test	Value	Specification
Liquid limit (LL) %	46	
Plastic limit (PL) %	21	[11]
Plasticity index %	25	
Specific gravity (Gs)	2.65	[11]
Gravel%	0	
Sand%	4	
Silt%	35	[11]
Clay%	61	
Activity	0.41	-
Expansion index, Cr	0.05	0.039

TABLE 3. Consolidation test results for medium and stiff clay

Parameter	Medium State	Stiff State
Undrained shear strength, Cu	50 kN/m²	70 kN/m²
Initial void ratio, e_o	0.38	0.23
Dry unit weight, γ_{dry}	19.3	21.2
Saturated unit weight, γ_{sat}	21.6	23.3
Compression index, Cc	0.1	0.059

3. MODEL SETUP

In order to simulate conditions as close as possible to those occurring in the field, a special testing machine has been designed and manufactured with attachments. The loading system is operated hydraulically and fixed to the rigid structure of the machine to adequately withstand the loading capacity as shown in Figure 2. The load application device was constructed from the following parts: 1. the steel loading-frame, 2. the system of electrical hydraulic, 3. loading-spreader plate, 4. settlement-measuring device, 5. the system of data monitoring and acquisition. Steel container (800*800*1000 mm).

3. 1. Angle of Internal Friction Measurement Device   The concept of such tool was borrowed from the laboratory tool known as "Making ring Penetrometer" made by ELE company for laboratory tools manufacturing. A similar tool comprising of 60 mm distance across cone having a length of 40 mm plus a shank of a breadth of 25 mm plus a length of (120 mm) had been fabricated. This device is used to find the internal friction angle of the sand used in the tests at any loading cycle. This device is connected to the hydraulic cylinder system through the work of the grooves that allow to be installed in the structure of the machine as shown in Figure 3. When the cone completely penetrates the soil, the soil reaction (F) required to maintain this penetration is recorded.

Figure 2. Details of the loading system

| (a) | (b) |

Figure 3. Measuring device for soil shear resistance; a. Components, b. Measuring device

It is important to note that when the cyclic load is used, the frequency as well as the form of the desired function must be determined as a relationship between time (in seconds) and the applied force. This is done by using a unit called C-type. The mathematical form is slightly different from that of the function in practice, as shown in Figure 4.

The load amplitude was 2.5 kN applied at differenet frequencies; 0.5, 1 and 2 Hz.

3. 2. Estimating the Angle of Internal Friction After Dynamic Loading

To estimate the angle of internal friction after number of cycles of loading, a procedure had been implemented. The relationship between the reaction of soil (F) and the angle of internal friction $\phi°$ was found by preparing thirteen soil model samples at different relative densities ranging from loose (R.D. = 30%) to very dense (R.D. = 90%). The direct shear test device was used to measure the angle of internal friction of the thirteen samples. For calculating the response of the used sand, a steel loading cone was put on a small example having the dimensions of (300×300×300 mm) as shown in Figure 5. The soil reaction was measured via a loading cell in addition to a digital display device. To this end, the tool velocity had been set at (2 mm/min.) for all measurements with applied pressure of (2.5 kN). The results of the soil reaction, unit weight and the angle of internal friction for the thirteen samples at relative densities are presented in Table 4. The relation of soil resistance to penetration (F) with the soil unit weight and relation between the soil resistance (F) along with the relative density of sand can be seen in Figures 6 and 7.

$$\text{Unit weight} = 0.0033\ F + 15.98 \qquad (3)$$

$$\text{Relative density} = 0.104\ F + 6.531 \qquad (4)$$

A pressure/tension loading cell from "SEWHA", model S-beam type (SS300), was used to calculate the persistent loading applied. The cell was linked to a numerical weight indicating tool in order to display loading amounts.

3. 3. Measuring of the Undrained Cohesion of Clay

The second point was determining the variation of shear

strength after carrying out dynamic tests on model footings on clayey soil. The undrained shear strength was measured using a portable vane shear device.
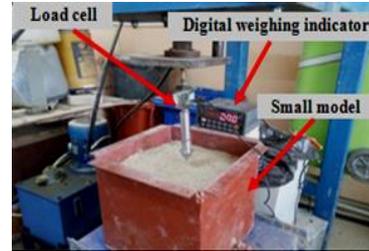

Figure 5. Manufactured apparatus for measuring the angle of friction

TABLE 4. Mobilized soil-reaction, unit weight, and angle of internal friction of sand

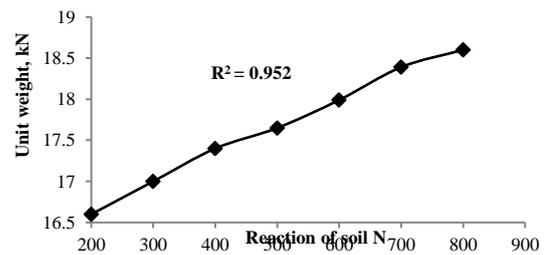| Test No.	Relative density R.D.%	Unit weight γ_d in kN/m³	Angle of internal friction $\phi°$	Reaction of soil F in N
1	30	16.48	35.2	245.77
2	30.2	16.49	37.8	247.41
3	37.3	16.68	38.3	305.58
4	44.2	16.87	39.4	320.78
5	50	17.04	39.5	360.97
6	55	17.19	40.2	404
7	60	17.34	40.4	541.14
8	64	17.46	40.4	590.21
9	70.4	17.66	40.8	620.60
10	76.6	17.85	41.2	654.81
11	80	17.96	42	708.15

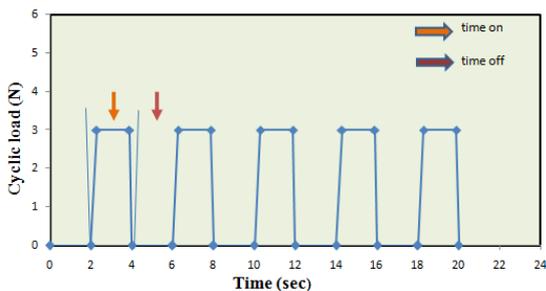**Figure 6.** Soil reaction vs. unit weight

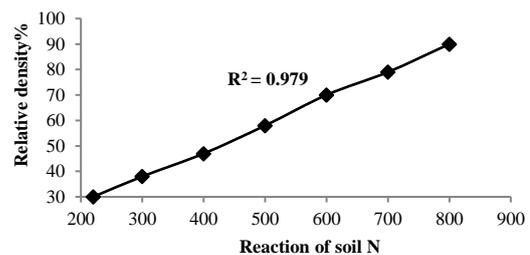**Figure 4.** Realistic load-time relationship

Figure 7. Soil reaction vs. relative density

4. RESULETS AND DISCUSSION

The bearing capacity of shallow foundations under static loads has been extensively studied and data are reported in literature. However, foundations can be subjected to dynamic loads which could be in different modes and directions. Such loading may induce large permanent deformation in soil by affecting its shear strength [12]. Thus the bearing capacity of foundations under dynamic loads has also been extensively studied and reported in literature. Nevertheless, most of the previous studies have been based on theoretical procedures with no supportive experimental data especially when examining the behavior of the bearing capacity of machine foundation under dynamic loading. Therefore, this research comes to study the bearing capacity under machine foundation by experimental work.

4. 1. Effect of Dynamic Load on the Angle of Internal Friction of Sand
The shear strength of soil is of special relevance among geotechnical soil properties for it is one of the essential parameters for analyzing and solving stability problems, besides bulk density. In all tests, the angle of internal friction was measured under the footing at the middle and the end of the test (i.e., after 500 and 1000 loading cycles, respectively). It was also measured at different locations in the model before and after the dynamic load test.

Figure 8 shows the variation in the angle of friction before, during and after the tests of circular model of footing on medium and dense sand. The results are summarized in Table 5. It is noticed in Table 5 that the angle of internal friction of the soil located under the footing is considerably affected, while little change in the angle of internal friction on points located at the footing
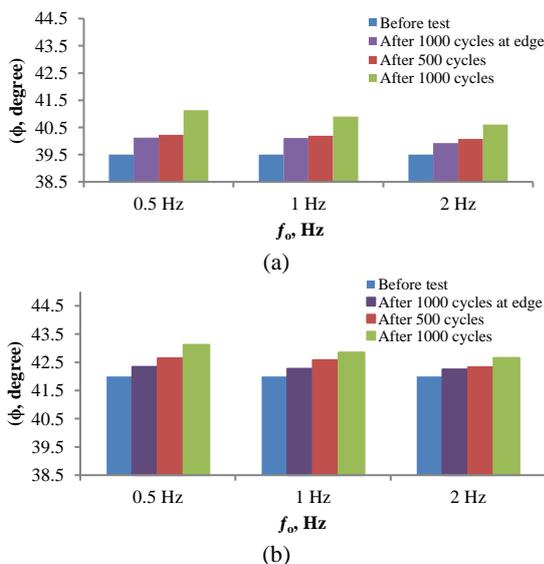
TABLE 5. After test values of internal friction angle of sand

Load = 0.25 ton	After 1000 cycles at edge	After 500 cycles at center	After 1000 cycles at center
a. Medium sand			
f_o= 0.5 Hz	39.72	39.92	40.153
f_o=1 Hz	39.66	40.00	40.08
f_o= 2 Hz	39.61	39.74	39.97
b. Dense sand			
f_o= 0.5 Hz	42.34	42.64	43.12
f_o= 1 Hz	42.27	42.57	42.84
f_o= 2 Hz	42.25	42.32	42.65

edge or other location in model. The reason for this is that the soil particles in the failure zone do not always follow the path of least resistance, resulting in higher shear strength of soil, which leads to higher bearing capacity.

During cyclic loading, the sand undergoes recoverable and irrecoverable strains. Under a given cyclic load, the recoverable strain is reasonable constant and the irrecoverable strain accumulates with number of cycles [13].

4. 2. Undrained Shear Strength under Dynamic Load
Because it is necessary to know the strength and some deformation characteristics of soil under dynamic loading, the undrained shear strength has been measured at different locations below the center and edge of footing, using portable vane shear device, before and after the dynamic loading test was performed. Figure 9. shows the variation of the undrained shear strength under dynamic loading. It can be noticed that the undrained shear strength of clay increased about 9 -25%. This is
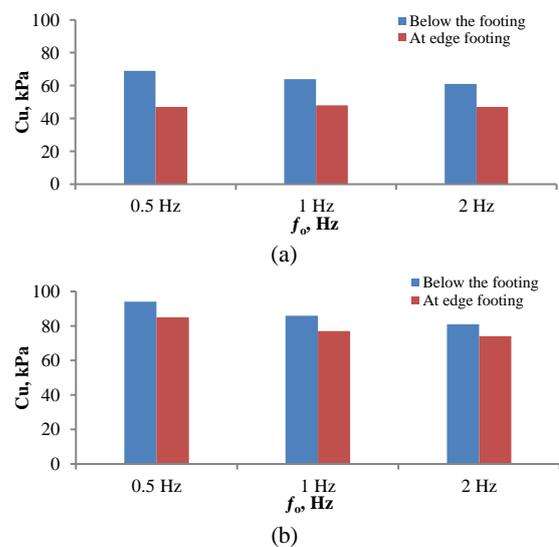

Figure 8. Opreating frequencies vs. angle of internal friction of sand; a. Medium sand, b. Dense sand

Figure 9. Opreating frequency vs. undrained shear strength; a. Medium clay, b. Stiff clay

because of compression of clay caused by dynamic loads. In addition, there is a rapid reorientation of soil particles which overides the repulsive forces between clay particles and brings them close together resulted in strong structure of the clay. Table 6 illustrates the value of undrained shear strength at different frequencies for medium and stiff clayey soil.

4. 3. Cumulative of Strain for Soil   The response of soils subjected to dynamic loading is affected by different factors. The most important factors are soil type, stress or settlement and specific test conditions. In addition, the loading conditions, of a given dynamic test, imposed on soil affect its response. In particular, the dynamic response of such soils depends on the frequency and type of dynamic loading.

Figures 10 and 11 show the relationship between number of load cycles and strain of soil (S_N/H) where (S_N) is the settlement of the surface footing at any number of cycles and (H) is the thickness of the soil layer in the steel box. Table 7 presents the strain values at the

TABLE 6. Undrained shear strength after 1000 cycles in clay

Location	After 1000 cycles at edge	After 1000 cycles below footing
Cu, kPa	**50**	
$f_o = 0.5$ Hz	48	69
$f_o = 1$ Hz	46	65
Cu, kPa	**70**	
$f_o = 0.5$ Hz	85	94
$f_o = 1$ Hz	74	86

Figure 11. Number of cycles vs. rate of strain in clay for load amplitude (0.25 ton); a. Medium clay, b. Stiff clay

end of 1000 cycles at different frequencies for both types soil. It can be seen that the strain decreases with the frequency. This is caused by low load frequency that provides enough time for the soil compression and so this results in increased rate of strain.

The strain has increased with decreased frequency. There was a sharp increase in strain up to the cycle (500) and then there was a gradual increase until it levels out at (800) to (1000) cycles depending on the frequency used. This increase can be attributed to the increase in the period of loading time during each cycle. In addition, the total period taken by the slow frequency test was greater than the period taken by the rapid frequency test within the same number of cycles.

The trend of the strain confirms with the findings reported by [14, 15] who found that the behavior of foundation settlement 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).

TABLE 7. The values of cyclic strain at different frequencies for both soils.

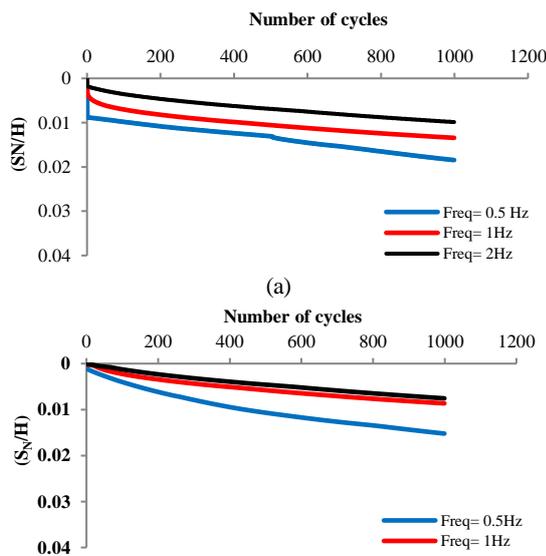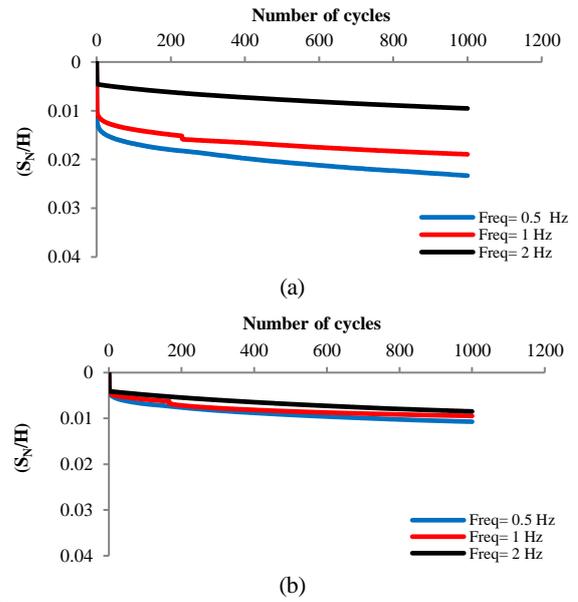| Soil type	Sand		Clay	
f_o, Hz	Medium	Dense	Medium	Stiff
0.5	0.018	0.014	0.022	0.015
1	0.013	0.008	0.018	0.008
2	0.009	0.006	0.010	0.006

Figure 10. Number of cycles vs. rate of strain in sand for load amplitude (0.25 ton); a. Medium sand, b. Dense sand

4. LIMITATIONS OF THE PRESENT WORK

The present work, which deals with the dynamic response of machine foundations to steady state dynamic loading, clarifies the response of soil and foundation to such loading condition. The present work cannot be considered as a complete study of the response of machine foundations to dynamic loading (in addition to the data available inliterature), which are restricted to the number of variables studied especially for the measurements of stresses inside soil media. Other parameters that influence the behavior of such machine foundations have not been taken intoconsideration in this work because of the limited time available and cost. Hence, the limitations within the testing program are the footing size, the soil is sand and clay with specific properties in addition to the type of the manufactured machine with harmonic loading fuction.

5. CONCLUSIONS

1. The shear strength parameters for footings under dynamic load had increased according to the dynamic strain amplitude. The higher the dynamic strain amplitude, the higher was the rate of shear strength parameters increase.
2. The induced shear strength parameters after the application of the dynamic load decrease when the load frequency increases from (0.5) to (2) Hz. This is because more energy is carried away by the waves, which originate not only from the base of the foundation, but also from the vertical faces of the foundation in contact with the soil.
3. The strain has increased with decreased frequency. There was a sharp increase in strain up to the cycle (500) and then there was a gradual increase until it levels out at (800) to (1000) cycles depending on the loading frequency.
4. Higher strains were obtained for model footing on looser sand or softer clay.

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Persian Abstract

چکیده

در این مقاله با بررسی تغییر پارامترهای مقاومت برشی خاک و کرنش با تعداد چرخه‌ها، بر پاسخ فونداسیون دستگاه دایره‌ای که روی خاک‌های مختلف (شن و ماسه) استراحت می‌کند، تمرکز می‌شود. هدف از مطالعه حاضر، کشف نتایج مربوط به پارامترهای بار دینامیکی (تعداد چرخه بارگیری و فرکانس بار) مربوط به پایه دایره‌ای یک دستگاه بر روی پارامترهای مقاومت برشی پویا (برای خاک شنی (ϕ°_{dyn}) و برای خاک رس (Cu_{dyn}) علاوه بر فونداسیون بر کرنش دامنه، است. برای شبیه‌سازی لرزش عمودی یک پایه ماشین دایره‌ای، یک مجموعه ویژه طراحی و ساخته شده است. یک پایه ماشین دایره‌ای با قطر ۱۵۰ میلی‌متر برای نشان دادن پایه استفاده شد. در مجموع ۶ مورد برای در نظر گرفتن اثر پارامترهای مختلف از جمله فرکانس‌های مختلف (۰/۵، ۱ و ۲ هرتز) مورد بررسی قرار گرفت. حالت شن (متوسط و متراکم) که با تراکم نسبی (۵۰ و ۸۰٪) مطابقت داشت، در حالی که حالت رس (متوسط و سفت) مطابق با مقاومت برشی زهکشی‌نشده (۵۰ و ۷۰ کیلو پاسکال) بود. تمام آزمایشات تحت دامنه بار KN ۲/۵ انجام شد. مشخص شد که سرعت افزایش پارامترهای مقاومت برشی برای خاک تحت یک دستگاه دایره‌ای هنگام افزایش قابل ملاحظه‌ای فرکانس برای هر دو نوع خاک زیر کاهش می‌یابد. در حالی که تغییر کمی در پارامترهای مقاومت برشی یا حتی هیچ تغییری تحت تأثیر مکان‌های دیگر مشاهده نشده است. علاوه بر این، کرنش دامنه هنگام افزایش فرکانس برای هر دو نوع خاک کاهش یافته است.