The Effect of Machine Vibration on the Settlement and Excess Pore Water Pressure in Saturated Sand

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ABSTRACT

This paper focuses on the effect of machine vibration on the variation of excess pore water pressure and settlement of saturated sand. A special setup is designed and manufactures to simulate the vertical vibration of the machine. A total number of 36 model tests are conducted on sand using three relative densities (35, 60 and 85%) representing loose, medium and dense sand respectively. These tests were performed on saturated sand, and tested under dynamic load. Different load amplitudes (0.4, 0.6 and 0.8 kN) and different frequencies (0.16, 0.5, 1 and 2 Hz) were used.

The results show that, the settlement in saturated sand under vibrating load increases with increasing load amplitude while it decreases with increasing frequency and relative density, but the rate of settlement decreases as the load increment increases. The maximum increase in settlement ratio reaches about 36% when the load amplitude changes from 0.4 to 0.6 kN while it is only 21% when the load amplitude changes from 0.6 to 0.8 kN.

The excess pore water pressure increases with increasing the load amplitude, frequency and relative density. The rate of change in excess pore water pressure increases about 30% as the load amplitude increases from 0.4 kN to 0.6 kN while it increases only 21 % when the load amplitude increases from 0.6 kN to 0.8 kN under the same frequency and relative density.

Keywords: Machine vibration. Saturated sand. Settlement. Excess pore water pressure.

تاثيراهتزاز الماكنة على الهطول وضغط ماء المسام الفائض للتربة الرملية المشبعة

الخلاصة

هذا البحث تركز على تاثير اهتزاز الماكنة على تغير ضغط الماء المسام الفائض والهطول في الرمل المشبع, تم تصميم وتصنيع منضومة خاصة لتمثيل الاهتزاز العمودي للماكنة. بلغ مجموع الفحوصات التي انجزت في هذا البحث ٣٦فحصا استخدمت فيها ثلاث كثافات نسبية (٣٥,٦٠و٨٥%) والتي تمثل التربة الضعيفة, المتوسطة والقوية

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على التوالي. هذة الفحوصات انجزت على تربة رملية مشبعة وتحت تاثير الحمل الديناميكي .استخدم في الفحوصات احمال ديناميكية وهي (٠,٦، ٠,٤، و٠,٨) كيلو نيوتن وبترددات مختلفة (١٦،,١,٥،٠,٠و٢) هيرتز.

اظهرت النتائج ان الهطول في الترب المشبعة وتحت تأثير الحمل الديناميكي يزداد مع زيادة الحمل المسلط بينما يقل مع زيادة التردد و الكثافةالنسبية. ولكن معدل الهطول يقل مع زيادة الحمل . ان اعلى زيادة في معدل الهطول بلغ حوالي ٣٦% عندما يتغير الحمل من ٠,٤ الى ٠,٦ كيلونيوتن ولكن هذه الزيادة تصل ٢١% عندما يتغير الحمل من ٠,٦ الى ٨,٠كيلونيوتن ان ضغط ماء المسام الفائض يزداد بزيادة مقدار كل من الحمل الديناميكي والتردد والكثافة النسبية. ان معدل التغير في ضغط الماء الفائض يزداد بحدود ٣٠% عندما يتغير الحمل من ٠,٤ الى ٠,٦ كيلونيوتن بينما تصل الزيادة الى ٢١% عندما يتغير الحمل من ٠,٦ الى ٨,٠ كيليونيوتن تحت نفس التردد والكثافة النسبية .

INTRODUCTION

The design of the vibratory machine foundation is more complex than that of a foundation which supports only static load. In machine foundation, the designer must consider in addition to the static load, the dynamic load caused by the working of the machine. Therefore, the designer should be well conversant with the problem concerning dynamic behavior of the foundation and the soil underneath. In general most of the settlement in saturated sandy soil under static load completed by the time construction is occurs. When the soil is subjected to dynamic load, it will suffer excessive settlement and great losses of strength due to the tendency of soil to densify and buildup of excess pore water pressure, consequently the effective stress will decrease and a great damage can occur.

Most of the settlement in saturated sandy soil under static load occurs when the time of construction is completed. Due to dynamic load (The loading may be characterized as dynamic when it varies with time, value and / or direction, Aguiar, 2008), additional settlement will occur due to soil densification and the development of excess pore water pressure. The displacement due to vibratory loading can be classified under two major divisions (Das, 1983):

A. Cyclic displacement due to the elastic response of the soil-foundation system to the vibratory loading, and

B. Permanent displacement due to compaction of soil below the foundation.

There are many types of machines that generate different periodic forces. The most important are (ACI Code, 351)**:**

1-Reciprocating machines

2- Impact machines

3- Rotary machines

4- Other machine types

The dynamic load may be due to earthquake, wave induced oscillation offshore structure and pile driving, traffic and rail induced vibration and machine vibration. Most of the researches focused on the dynamic load due to earthquake and offshore wave, but very little information were available about the effect of machine vibration on the performance of machine foundation and the soil underneath. This paper address itself to the effect of machine vibration on saturated sand by conducting experimental work using small scale models.

Preivous Studies

Many researchers used theoretical approach to explain the behavior of soil under vibrating load such as Sung (1953) who presented the first acceptable solution for this vertical vibration of a rigid disk with mass on an elastic half space but this solution is not understand by most engineers.

Theoretical method for analysis of the dynamic response of foundation-soil system is based on a number of simplifying assumptions regarding soil properties and system geometry (Hushmand, 1983).

Mandal and Baidya (2003), studied the experimental dynamic response of a foundation subjected to vertical mode of vibration on dry sand. The tests carried out in the filed using two different pits; one with rigid base and the other with a large depth simulating the half space.

Wang et al (2005), carried out a test to investigate the response of the developments of settlement and excess pore pressure of foundation on sandy soil. It was shown that the sand surrounding the bucket softens or even liquefies at the first stage as loading amplitude increased over a critical value, at later stage, the bucket settles and the sand layer consolidates gradually. With the solidification of the liquefied sand layer and the settlement of the bucket, the movement of the sand layer and the bucket reach a stable state.

Jafarzadeh and Asadinik. (2008), developed a model to investigate the influence of shape, mass, and embedment of foundation on the dynamic response of foundation resting on a sand layer. It was found that reflection of waves cause resonance in system in addition to inertia effect. Radiation damping of tests around resonance was little because of the presence of boundaries. Equivalent circular footing yield reasonably good estimate of the response for rectangular foundation with values of L/B(L=length of foundation, B=width of foundation) at least less than 2. Also, it has been seen that embedment decreases sharpness of impedance function and also its value depends on particular frequency. On the other hand, embedment overly increases damping of the system but it does not strongly affect stiffness coefficient.

Experimental Work

Material Used and Testing Program

Karbala sand was used in the present study. Standard tests were performed to determine the physical properties of the sand. The details of these properties are given in Table (1).Grain size distribution of soil used is shown in Figure 1. A total number of 36 model tests were performed using three relative densities (35%, 60% and 85%) corresponding to loose, medium and dense sand respectively.

All models, which are tested dynamically were conducted on saturated sand, under three load amplitudes corresponding to 0.4, 0.6 and 0.8 kN using four frequencies 0.16, 0.5, 1 and 2 Hz for each load amplitude.

Table (1): Physical properties of sand

No.	Index Properties	Value
1	Specific gravity	2.65
2	D 10 (mm)	0.148
3	D 30 (mm)	0.35
4	D 60 (mm)	0.58
5	Coefficient of Uniformity (Cu)	3.91
6	Coefficient of Curvature (Cc)	1.42
7	Maximum Void ratio	0.7
8	Minimum Void ratio	0.4
9	Maximum dry unit weight (kN/m^3)	18.9
10	Minimum dry unit weight (kN/m^3)	15.56
11	Water content (%)	19
12	Angle of internal friction (R.D =35%)	34°
13	Angle of internal friction (R.D =60%)	38°
14	Angle of internal friction (R.D=85 %)	41°
15	Coefficient of Permeability at (R.D= 35%)	3.2×10^{-2}cm/sec
16	Coefficient of Permeability at (R.D= 60%)	3.4×10^{-3}cm/sec
17	Coefficient of Permeability at (R.D= 85%)	3.6×10^{-4}cm/sec
18	Soil classification(USCS)	SP

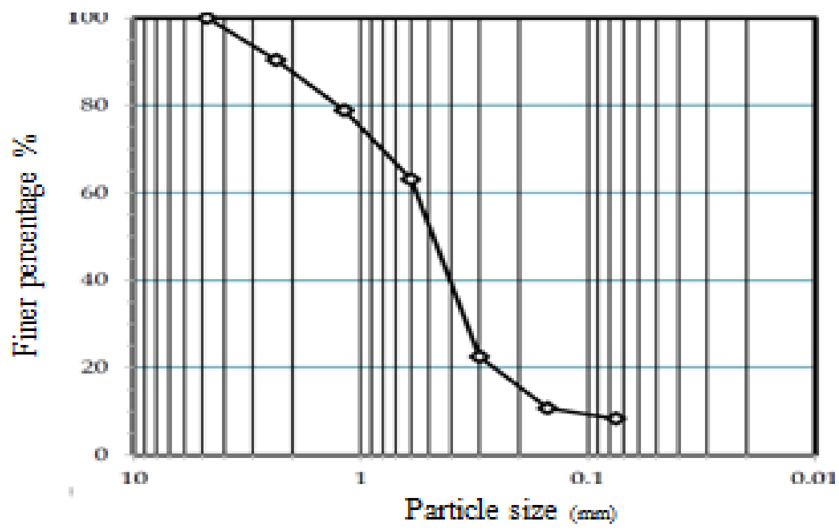


Figure (1): Grain size distribution

Setup Design and Manufacture

To study the behavior of the machine vibration on saturated sand, it is necessary to simulate the conditions as close as possible to those occurring in the field. To achieve this aim, a special testing apparatus and other accessories were designed and manufactured as shown in Figure (2). The apparatus has the capability of applying different dynamic loads with different frequencies.

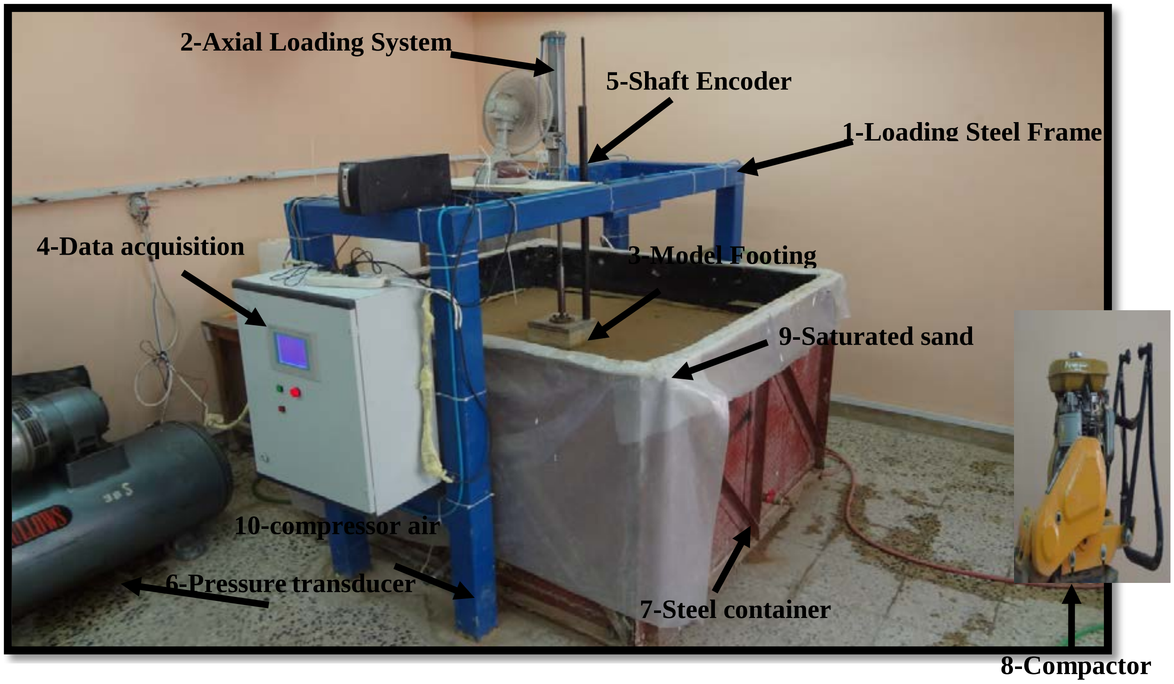


Figure (2): Individual Testing Equipment Parts.

Loading steel frame

To support the verticality of piston system used in applying the central concentrated load, a steel frame was designed and constructed .The steel frame consists mainly of four columns and four beams. The cross sectional area of each column and beam are made of steel with square cross section area of (100 mm×100 mm) and 4 mm thick. The dimensions of the steel frame (length× width× height) are (1700 mm× 700 mm×1700 mm).

A 20 mm thick steel plate with dimensions of (700 mm×500 mm) was welded on the center of the frame in order to carry the air jack system and the settlement measurement device (Encoder).

Axial loading system

The axial dynamic load is applied through the air jack. The compressed air is passing from the compressor toward the force release valve (R.V) through air filter and pressure control valve. The air filter is used to purify the air. The pressure control valve is used to control the load applied on footing.
The compressed air is moving through flexible tube toward the pneumatic directional valve (R.v) which is fixed on steel plate**.**

Model footing

A square footing (200 mm×200 mm) stainless steel with 20 mm thick is manufactured to simulate the machine foundation.

Data acquisition

To study and investigate the real behavior of the tested models during the application of the dynamic load, it is necessary to find a new procedure to measure and sense the occurring displacement and excess pore water pressure during the test, which enable the tests to obtain the total accurate information that consist of a huge data of readings in a very short time. For this reason the data acquisition was used.

Shaft encoders

A shaft encoder type (Rotary) can be defined as an electro-mechanical device that converts the angular positions or motion of the shaft to an analog or digital code. The output of incremental encoder provides information about the motion of the shaft which is typically further processed elsewhere into information such as speed, displacement, revolution per minute (rpm) and position.

Pressure transducers

To measure the pore water pressure at any position on saturated sand, a pressure transducer type "KELLER, Germany", model (PR-23R) was used. The pressure transducer capacity ranges from 0-1bar and 0.001bar sensitivity.

Steel containers

The steel container was constructed to host the bed of soil. The container can be dissembled and assembled because it is made of five separate parts, one for the base and the others for the four sides of the container. The internal dimensions are 1500 mm length, 1500 mm width and 1000 mm depth. The size of the container is adopted so to minimize the boundary reflections.

5. Sand Deposit Preparations

The sand deposit was prepared using a small vibratory plate compactor.
A predetermined weight of sand was used. For each layer which was sufficient to create a layer of thickness of 1/3h (where h is the total height of the sand deposit). Each layer of sand is compacted gently by small vibratory plate compactor (500 mm x800 mm) according to the required relative density.

The cell pressure was planted at a specific point (at the middle of the sand deposit under the center of the footing). For tests on saturated sand, the water valve was connected to a water inlet, through which water is allowed to flow upward direction, maintaining uniform and laminar flow condition. Saturation is achieved by flooding the sand over night. Excess water at the surface was removed using sponge and the water level in the tank was kept in flush with top surface of sand.. Figure (3) represents the stage of the sand deposit preparation. Table (2) summarizes the different states of the sand used.

Table (2): Different states of sand used.

State of Sand	Dry unit Weight(γdry) kN/m^3	Void Ratio (e)	Angle of Friction(φ)	Relative density (R.D %)
Loose	16.67	0.59	34°	35%
Medium	17.76	0.49	38°	60%
Dense	18.44	0.44	41°	85%

Figure (3): Stages of the preparation of the test model

Model Setup

After the completion of the preparation of saturated sand deposit, the top surface was leveled to get as near as possible a flat surface. The footing was then brought in contact with top surface of the bed of the model.

After the preparation of footing on the surface layer of sand, dynamic load was applied throughout a predetermined sequence. The application of dynamic load continues up to 10^4 cycles.

Results and Discussions

Model Test Results under Dynamic Load

To study the effect of load amplitude, three relative densities were used loose, medium and dense. For each relative density, three load amplitudes are used (0.4, 0.6 and 0.8 kN). For each load amplitude four frequencies were used corresponding to (0.16, 0.5, 1 and 2 Hz).

Effect of dynamic load on settlement:

1) Load amplitude: Figure (4) shows the variation of settlement ratio(S/B) (S, the settlements divided by the footing width(B)) and logarithm of number of cycles. For loose. It can be noted that the settlement ratio increases with increasing load amplitude under the same frequency and relative density. This increment is attributed to increases in to particle stresses. Similar results were obtained for medium and dense sand and as listed in table (3) summarizes the results of settlement ratio after 10^4 cycles.

2) Frequency: Figure (5) to (7) each shows the variation of settlement ratio with frequency at different relative densities. In general, for all relative densities, the settlement ratio increases with decreasing the value of frequency because the increase of the loading frequency, the effected area increase and the settlement decreases. Table (4) summarizes the results of settlement ratio after 10^4 cycles at different frequencies.

Effect of dynamic load on excess pore water pressure:

1) Load amplitude: Figure (8) shows the variation of load amplitude and excess pore water pressure through 10^4 cycles. It can be seen that, the maximum excess pore water pressure occurs at load amplitude 0.8 kN under the same frequency and relative density. Table (5) summarizes the results of excess pore water pressure at 10^4 cycles at different load amplitudes.

2) Frequency: The variation of excess pore water pressure at 10^4 cycles with frequency is shown in Figure (9) to (11), it can be seen that as the frequency increases , the excess pore water pressure increasing under the same load amplitude and relative density. This is due to the fact that, increasing the frequency mean the applied load became so fast that does not give enough time for excess pore water pressure to dissipate Table (6) summarizes the results of excess pore water pressure at different frequencies at 10^4 cycles.

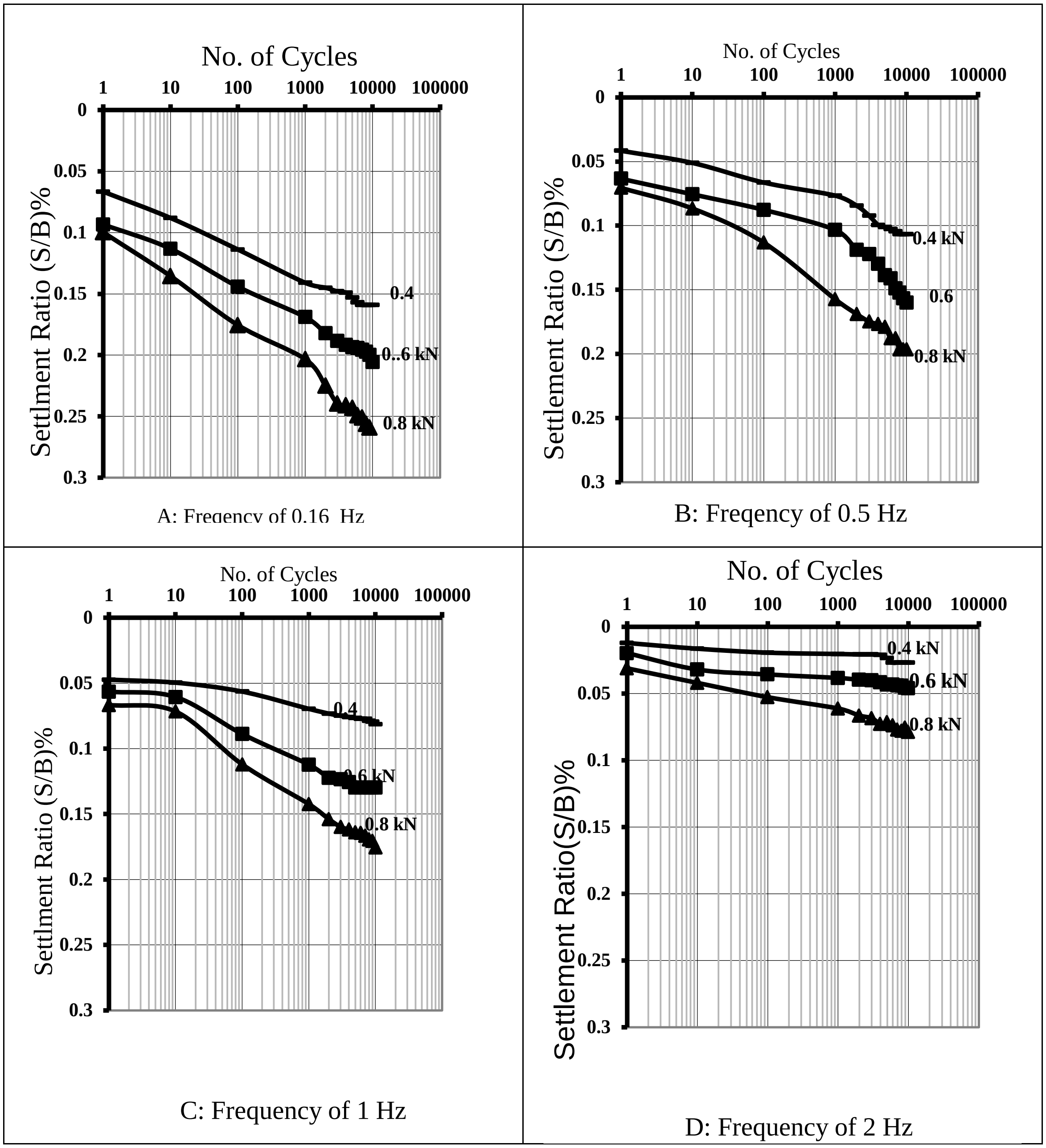


Figure (4): Relationship between logarithm number of cycles and settlement for loose sand.

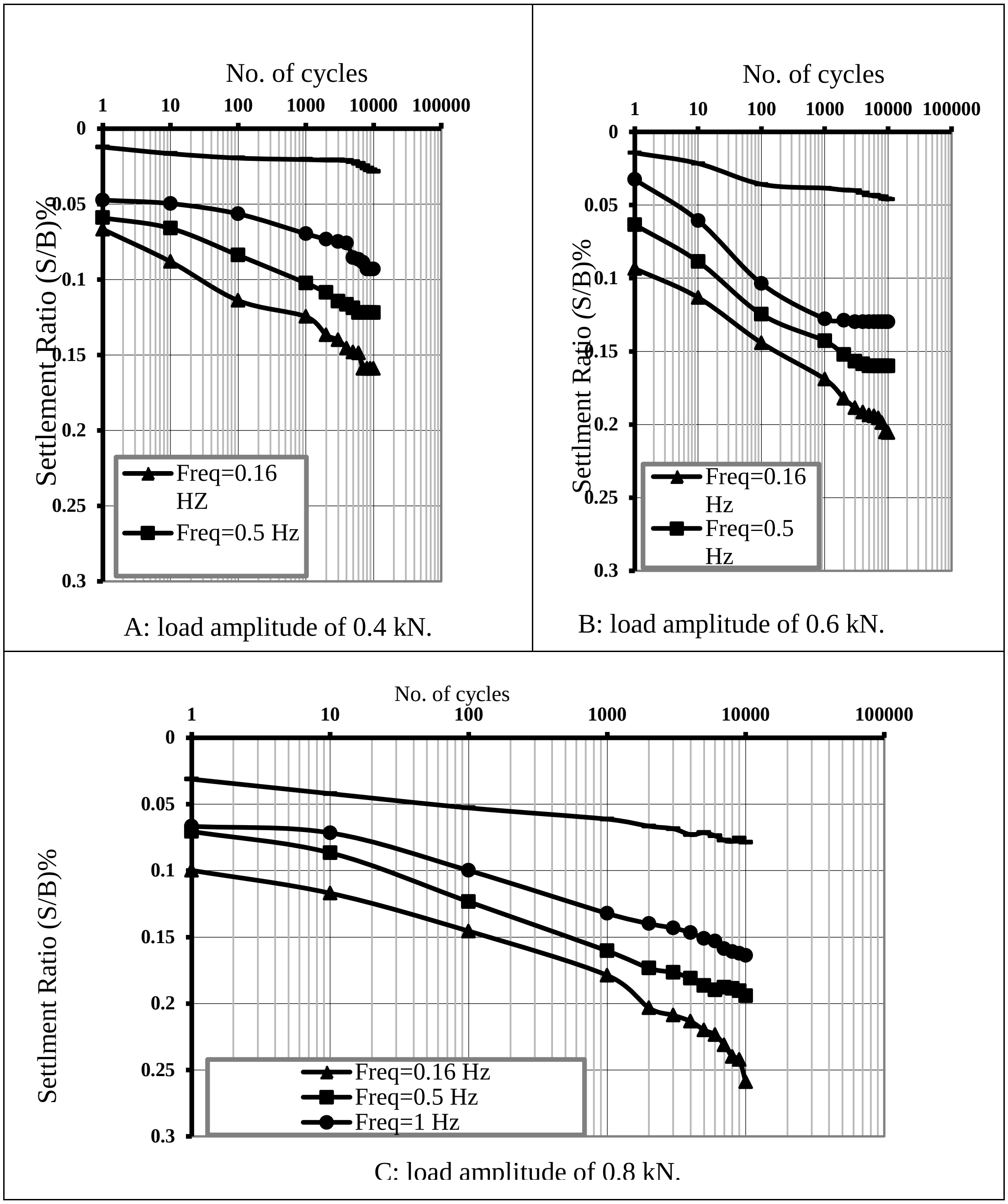
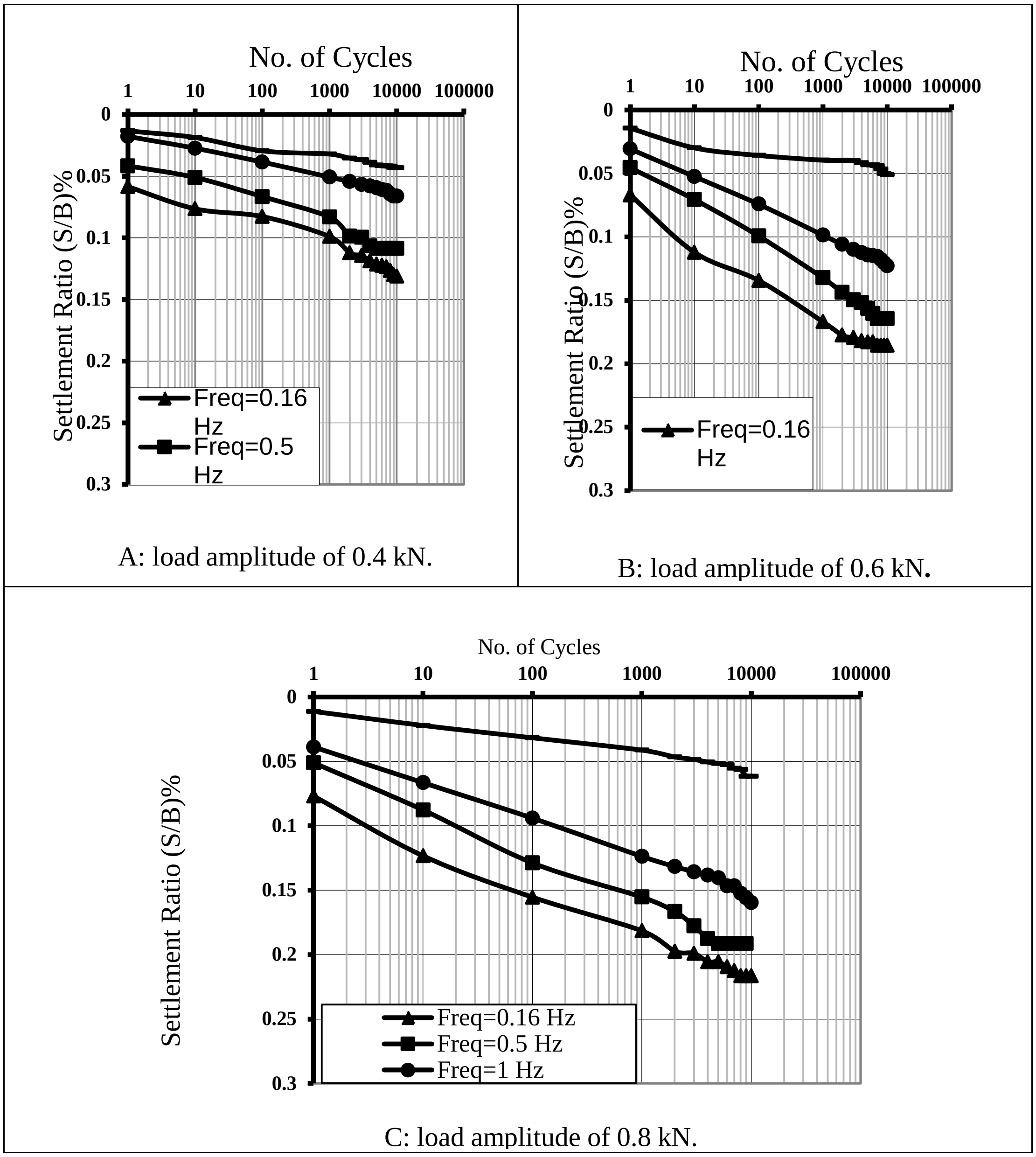


Figure (5): Relationship between logarithm numbers of cycles and settlement for loose sand.

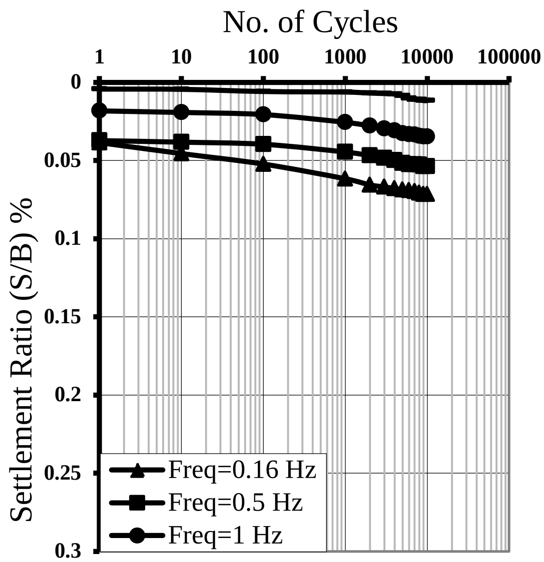


A: load amplitude of 0.4 kN.

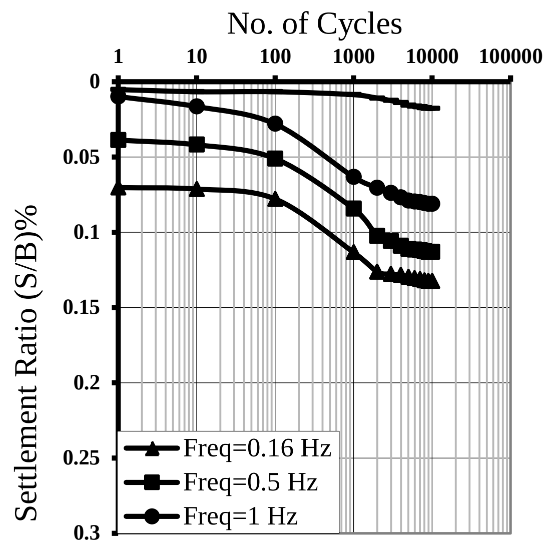
B: load amplitude of 0.6 kN.

C: load amplitude of 0.8 kN.

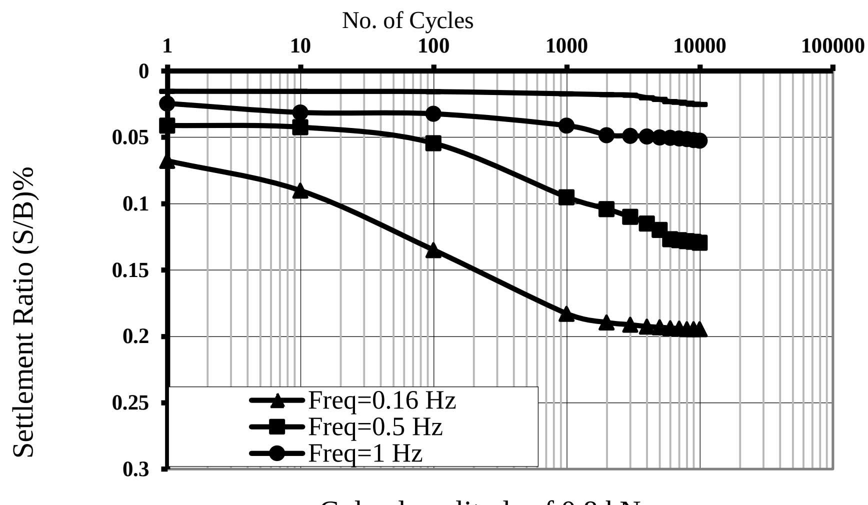
Figure (6): Relationship between logarithm numbers of cycles and settlement ratio for medium sand.



A: load amplitude of 0.4 kN.



B: load amplitude of 0.6 kN.



C: loadamplitude of 0.8 kN .

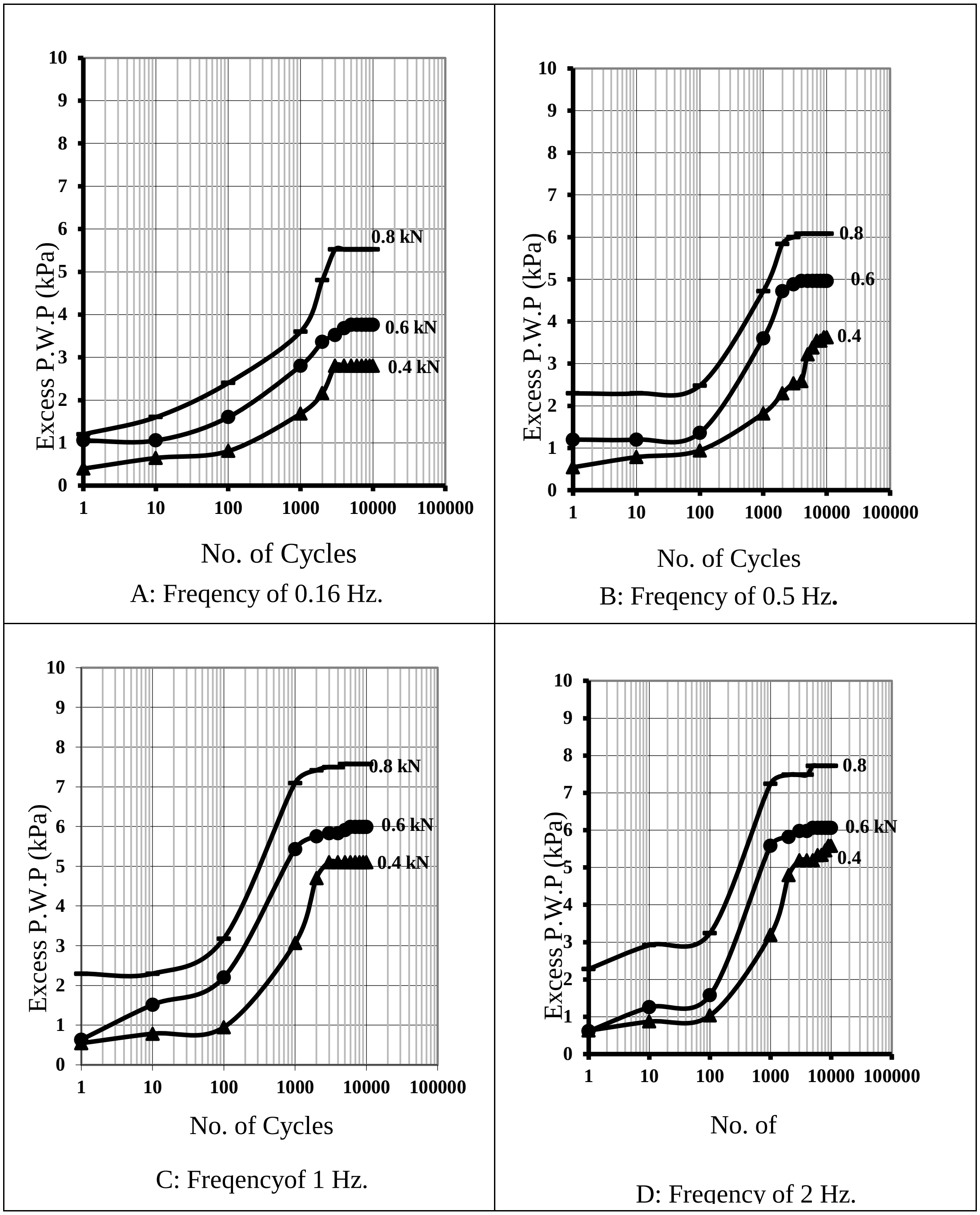
Figure (7): Relationship between logarithm numbers of cycles and settlement ratio for dense sand.

Table (3): Settlement ratio after 10^4 cycles at different load amplitudes.

State of soil	Frequency Hz	Settlement ratio at different load amplitude		
		0.4 kN	**0.6 kN**	**0.8 kN**
Loose	0.16	0.159	0.205	0.259
Medium		0.122	0.182	0.211
Dense		0.071	0.132	0.194
Loose	0.5	0.121	0.162	0.196
Medium		0.109	0.142	0.181
Dense		0.053	0.112	0.119
Loose	1	0.092	0.129	0.175
Medium		0.066	0.12	0.159
Dense		0.034	0.046	0.061
Loose	2	0.026	0.045	0.078
Medium		0.021	0.043	0.047
Dense		0.011	0.022	0.038

Table (4): Settlement ratio after10^4 cycles at different frequencies.

State of soil	Load (kN)	Settlement ratio at different frequencies			
		0.16 Hz	**0.5 Hz**	**1 Hz**	**2 Hz**
Loose	0.4	0.159	0.121	0.092	0.026
Medium		0.122	0.109	0.066	0.021
Dense		0.071	0.053	0.034	0.011
Loose	0.6	0.205	0.162	0.129	0.045
Medium		0.182	0.142	0.12	0.043
Dense		0.132	0.112	0.046	0.022
Loose	0.8	0.259	0.196	0.175	0.078
Medium		0.211	0.181	0.159	0.047
Dense		0.194	0.119	0.061	0.038



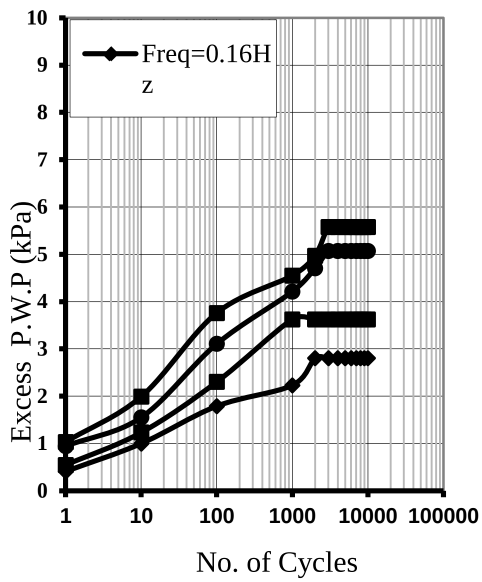
A: Freqency of 0.16 Hz.

B: Freqency of 0.5 Hz.

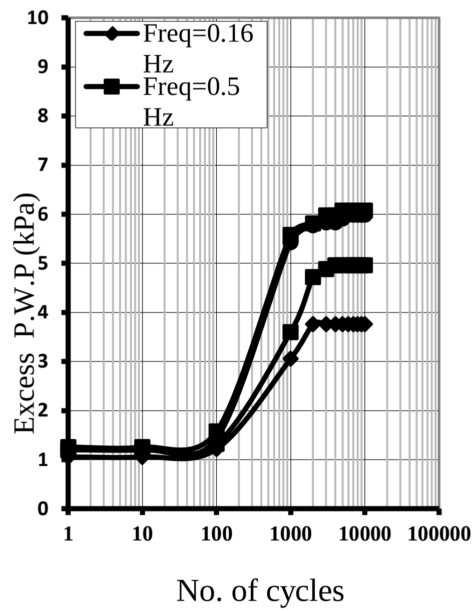
C: Freqencyof 1 Hz.

D: Freqency of 2 Hz.

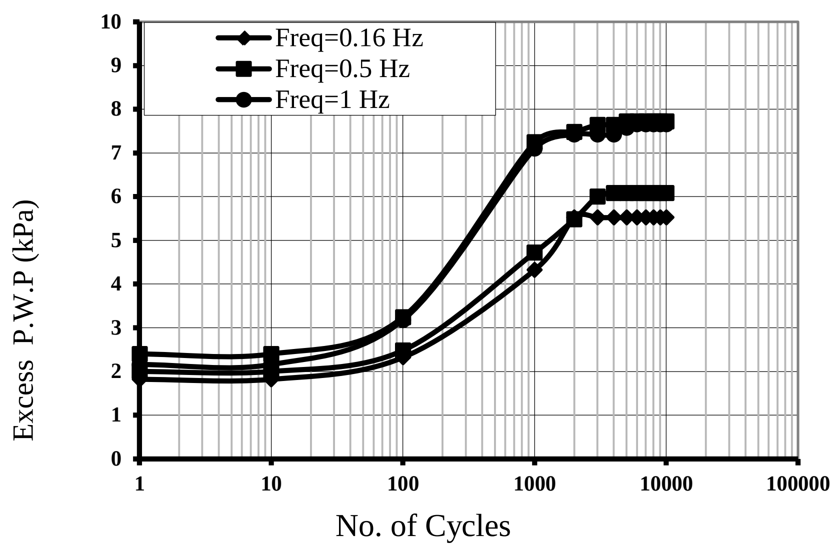
Figure (8): Relationship between logarithm number of cycles and excess pore water pressure (kPa) for dense sand.



A: load amplitude of 0.4 kN.



B: load amplitude of 0.6 kN.



C: load amplitude of 0.8 kN.

Figure (9): Relationship between logarithm number of cycles and excess pore water pressure (kPa) for loose sand.

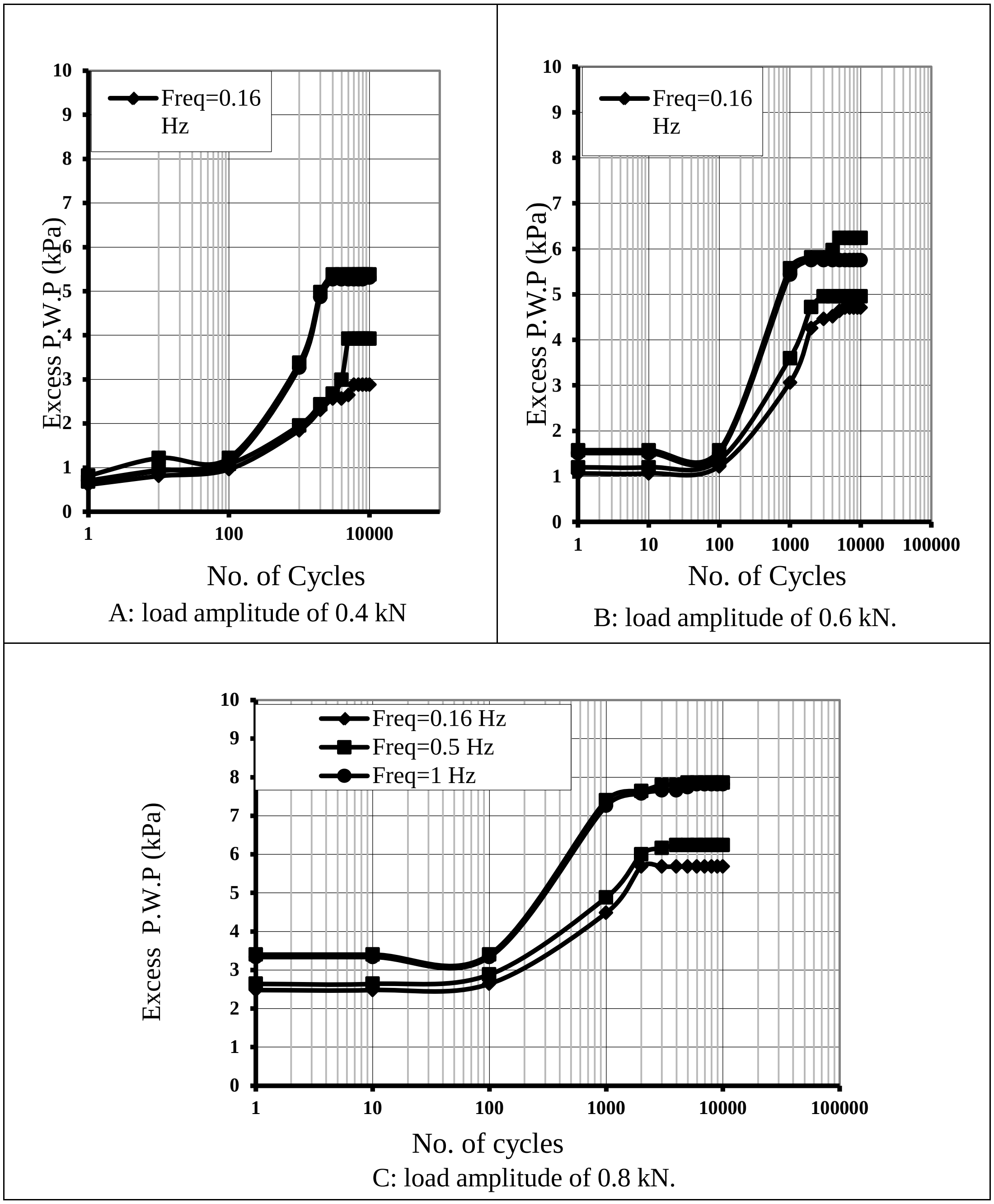
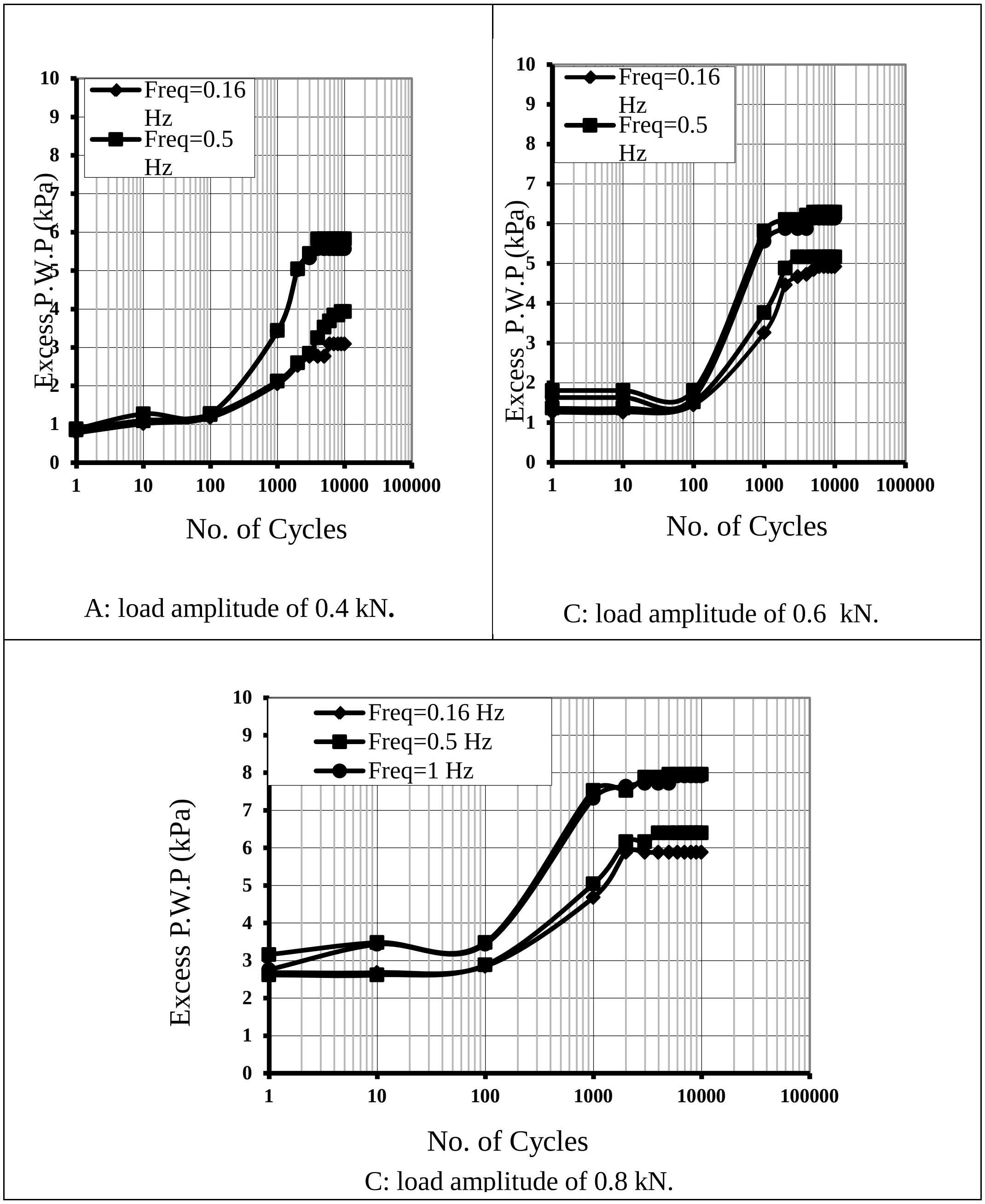


Figure (10): Relationship between logarithm number of cycles and excess pore water pressure (kPa) for medium sand.



A: load amplitude of 0.4 kN.

C: load amplitude of 0.6 kN.

C: load amplitude of 0.8 kN.

Figure (11): Relationship between logarithm number of cycles and excess pore water pressure (kPa) for dense sand.

Table (5): Excess pore water pressure after 10^4 cycles at different load amplitudes.

State of soil	Frequency Hz	Excess pore water pressure (kPa) at different load amplitudes		
		0.4 kN	0.6 kN	0.8 kN
Loose	0.16	2.8	3.76	5.52
Medium		2.88	4.71	5.58
Dense		3.08	4.91	5.88
Loose	0.5	3.62	4.96	6.08
Medium		3.89	5.52	6.4
Dense		3.99	5.6	6.5
Loose	1	5.14	5.75	7.6
Medium		5.22	5.99	7.81
Dense		5.3	6.12	7.91
Loose	2	5.37	6.05	7.72
Medium		5.57	6.24	7.88
Dense		5.82	6.28	7.96

Table (6): Excess pore water pressure at different frequencies after 10^4 cycles

State of soil	Load (kN)	Excess pore water pressure at different frequencies			
		0.16 Hz	0.5 Hz	1 Hz	2 Hz
Loose	0.4	2.8	3.62	5.14	5.37
Medium		2.88	3.89	5.07	5.57
Dense		3.08	3.99	5.3	5.82
Loose	0.6	3.76	4.96	5.75	6.05
Medium		4.71	5.52	5.99	6.24
Dense		4.91	5.6	6.12	6.28
Loose	0.8	5.52	6.08	7.6	7.72
Medium		5.58	6.4	7.81	7.88
Dense		5.88	6.5	7.91	7.96

CONCLUSION

1-In general, as the load amplitude increases, the settlement ratio increases under the same frequency and the relative density. The increment in settlement ratio approximately reaches 36% when the load amplitude changes from 0.4 kN to 0.6 kN while the increment is approximately21% when the load amplitude changes from 0.6 kN to o.8 kN. This means that the rate of settlement increases as the load amplitude increases.

2-The settlement ratio increases as the frequency decreases under the same load amplitude and relative density.

3-As the relative density increases, the settlement ratio decreases under the same load amplitude and frequency.

4-In general, as the load amplitude increases, the excess pore water increases under the same frequency and relative density. The rate of change in excess pore water pressure is approximately 30% as the load amplitude increases from 0.4 kN to 0.6 kN and 21% when the load amplitude change from 0.6 kN to o.8kN

5-The excess pore water pressure increases with increasing the value of frequency under the same load amplitude and relative density.

6-As the relative density increases, the excess pore water pressure increases under the same load amplitude and frequency.

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