Effect of Saturation of Sandy Soil on the Displacement Amplitude of Soil Foundation System under Vibration

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ABSTRACT

In this study, the response and behavior of machine foundations resting on dry and saturated sand was investigated experimentally. A physical model was manufactured to simulate steady state harmonic load at different operating frequencies. The effect of relative density, depth of embedment, foundation area as well as the imposed harmonic load was investigated. It was found that the amplitude of displacement of the foundation increases with increasing the amplitude of dynamic force and operating frequency meanwhile it decreases with increasing the relative density of sand, degree of saturation, depth of embedment and contact area of footing. The maximum displacement was noticed at 33.34 to 41.67 Hz. The maximum displacement amplitude response of the foundation resting on dry sand models is more than that on the saturated sand by about 5.0 to 10 %.

Keywords: displacement amplitude, settlement, steady state dynamic, absorbed boundary.

تأثير اشباع التربة الرملية بالماء على الاستجابة الديناميكية للازاحة تحت تأثير احمال الاهتزاز

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الخلاصة

في هذا البحث، تم عمل دراسة عملية لاستجابة أسس المكائن المعرضة للاهتزازات والمستندة على تربة رملية جافة ومشبعة تماماً بالماء. حيث تم تصنيع أنموذج مختبري لغرض إجراء الدراسة العملية لتسليط الأحمال الحركية ذات النمطِ العمودي المتناسقِ الإهتزاز، وبعدد دورات مختلفة والمسلطة على تربة رملية. وتم دراسة تأثير تغير الكثافة النسبية، عمق الطمر، مساحة الاساس. وُجد ان الازاحات العمودية الحركية تزداد بزيادة ذروة الحمل الحركي وعدد دورات المحرك ووجد أن تلك الإزاحات تقل بزيادة الكثافة النسبية للتربة الرملية، وزيادة عمق طمر الأسس، وزيادة مساحة التلامس بين الاساس والتربة فضلاً عن زيادة درجة التشبع. ووُجد ان اقصى قيمة للإزاحة الشاقولية تكون عند اهتزاز المحرك بتردد يتراوح بين 33.34 الى 41.67 هيرتز. ووُجد أن مقدار الإزاحة الشاقولية للتربة الجافة اكبر من الإزاحة الشاقولية للتربة المشبعة بنسبة 5.0 الى 10.0 %.

الكلمات الرئيسية: سعة الازاحة، الهبوط، الحالة الديناميكية المنتظمة، الحدود الماصة.

1. INTRODUCTION

Machine foundations is regarded as the most important elements of industrial structures like power plants, steel plants, petrochemical complexes, fertilizer plants etc., which consist of a number of reciprocating and centrifugal machines, these play an important part to ensure efficient operation of the process, and that the output of the product is of the required quality, **Chowdhury** and **Dasgupta, 2010**.

The response of soil subjected to dynamic loading depends on many factors such as permeability, relative density, the nature of the dynamic loading, the magnitude and rate of strain, **Daghigh, 1993**.

Kassir et al., 1989, studied the dynamic response of a circular footing experiencing oscillatory vertical motion on the surface of a liquid-filled, porous, elastic half-space. From their theoretical study, it was found that the presence of ground water in the elastic medium affects the magnitude and character of the influence functions over the frequency range of practical interest and should be included in determining the response of surface structures to dynamic loadings.

Al-Homoud and **Al-Maaitah, 1996,** found that there is an increase in natural frequency and a reduction in amplitude with the increase in degree of saturation of sandy soil subjected to vertical forced vibration loading. On the other hand, for free vibration test, the results showed that for different footing models resting on sandy soil, there is an increase in damping ratio with increasing in the degree of saturation. As well as the damping ratio of footing on saturated sand is higher than that on dry sand.

Kim et al., 2001, performed an intensive study for the dynamic analysis for foundations of vibrating equipment. The analysis took into consideration the soil structure interaction. As shown in **Fig. 1**, it was concluded that the dynamic response of foundation with ground water (dash line) is higher than this without the groundwater (solid line) in the lower frequency domain. The amplitude of horizontal vibration is 13.3 μm calculated with groundwater and 4.5 μm calculated without the groundwater at the operating speed of 8.45 Hz.

Livaoglu and Dogangun, 2007, investigated the effect of saturation ratio on shear modulus and damping parameters of sand. It was concluded that the dynamic stiffness and damping characteristic were substantially independent of saturation ratio in the range of 25 to 75%. However, by approaching the full saturation state, the values of modulus fall sharply and damping of loose samples increases dramatically from corresponding values of unsaturated levels.

Al-Shammary, 2013, performed numerical study to investigate the dynamic response of strip footing resting on saturated sandy soil. The numerical study was executed by finite element software, PLAXIS 2D. A parametric study was carried out to evaluate the dependency of machine foundation on various parameters including the amplitude of the dynamic load, the frequency of the dynamic load, the damping of soil mass, the thickness of the foundation, and the embedment of foundation. It was found that the embedment generally leads to a beneficial reduction in dynamic displacement response for all soil types but with different degrees depending on the other parameters such as soil density and damping ratio.

2. RESEARCH OBJECTIVES

The main objectives of this research are to study the effect of steady state harmonic loading on the response of foundation-soil system resting on sandy soil with different saturation conditions. The influence of footing size and depth of embedment would be elaborated in the present research.

3. RESEARCH METHODOLOGY

The present work is aimed to study the behavior of machine foundation resting on dry and saturated sandy soil subjected to vibration dynamic loadings. This research is carried by considering two sizes of rectangular footings. The sizes was (100×200×12.5 mm) and (200×400×5.0 mm) for intermediate to rigid rectangular footings. The footings were placed on sandy soil. The boundary of the problems was achieved experimentally by using nonreflecting boundary materials (styropor cork). The setups of the experimental components are illustrated in **Fig. 2**. The variables that were taken into considerations are:

a) Size of footing,
b) The depth of embedment was studied by placing the footing at the surface and at a depth of 50 mm below the soil surface.
c) The operating frequency was studied at different values starting from 500 to 3500 rpm. The unbalanced weight was not changed throughout the study.
d) The soil was studied for two conditions of saturation, dry and saturated sand.
e) The effect of relative density of the sand was studied. Foundations are rested on sand at loose state (Dr=30 %) and very dense state (Dr=80%).

For all the above-mentioned parameters, the response of the soil-foundation system was evaluated by conducting the following measurements:

- The force-time history of the force applied by the machine on the center of foundation surface.
- The vertical displacement-time history of the footing at one point.
- The vertical total settlement of the footing at the end of machine oscillation was measured at one point.

4. MATERIALS USED IN THE EXPERIMENTS

The physical properties of sand used include specific gravity, grain size distribution and the maximum and minimum dry unit weights of the sand. A summary of the test results with standard specification followed for each test is presented in **Table 1**.

According to the Unified Soil Classification System (USCS), the sand is classified as (SP) and described as poorly graded sand. The material of footing was steel. The initial Young's modulus of the steel used is 140. GPa and the secant modulus is 37.26 GPa. In addition, the unit weight of the steel used is about 77.6 kN/m^3.

5. TESTING PROGRAM AND EXPERIMENTAL WORKS

In general, the testing program consists of two major parts. The first part is devoted to dry sand models with total number of tests of 56. The tests were performed in loose and dense soil state. Two footing sizes and the models were tested at the surface of the footing and at a depth of 5.0 cm. The second part is concerned with saturated sand models with total number of 28 models. The same parameters were taken into consideration except that the models were prepared from dense sand only. The details of abbreviation for the tested samples as well as example of models naming are explained below.

DL1020S: **D**ry **L**oose state sand, footing **10×20** cm, footing placed at the **S**urface.

SD2040E: **S**aturated **D**ense state sand, footing **20×40** cm, footing **E**mbedded

5.1 Testing Program and Experimental Works

A series of model loading tests were conducted inside a rigid steel box of dimensions (1200×1000×600 mm), made of steel plate of 5.0 mm thickness. These dimensions were chosen to satisfy the boundary effects of physical models subjected to dynamic loading. The overall

description of test components and measuring devices is shown in **Fig. 2**. To create a physical model, a small container was manufactured from steel plate. The container, which has the dimensions of (length 1200 mm, width 1000 mm and height 600 mm), was used to prepare the bed of soil. The tested soil is clean sand passing through ASTM standard sieve No. 10 (2.0 mm) and retained on the ASTM standard sieve No. 100 (0.150 mm) to obtain uniform sand.
Two alloy steel model footings of size (200 × 100 × 12.5) mm and (400 × 200 × 5.0) mm were placed centrally over the prepared soil layer, and then a mechanical oscillator was fixed to the footing to act as a single unit. The size of the footing was chosen to obtain intermediate to rigid footing.

In the present model, special boundary conditions were adopted by using cork (styropor) sheets of 30.0 mm thickness. The styropor cork sheets can reduce the slight friction that might be developed between the box faces and soil as well as it works as absorbing boundaries to prevent reflected waves.
Preliminary tests were performed to check the efficiency of such materials as boundary absorbing purposes. This approach was achieved by measuring the dynamic response at the boundaries with and without absorbing layers.

5.2 Sample Preparation

Tamping and pouring procedures were used to prepare the sandy soil inside the steel box. This method was followed to ensure the desired relative density as well as to ensure the same method of sample preparation in loose and dense state. In addition to that, hygroscopic water content (≈ 0.5-3.0%) was added to the sand prior to compaction and pouring to ensure small cementation of soil before testing. This water content is regarded as uncontrolled water content that is always present within the sample without oven drying.
For the loose state sand models, the sample was prepared by pouring the soil inside the box from a certain height. The hygroscopic water content for loose state was about 0.5-1.0%. The suitable height was decided by making a relation between the height of falling and the resulting dry density. It was found that a 30 cm falling height gave the desired value of dry density. For the sake of accuracy and reducing the sources of sample disturbance, the box was divided into sub layers of 50.0 mm. Filling operation throughout the test was performed using galvanized metal hopper with height of 30 cm having a valve to control sand raining by hand. On the other hand, for dense state soil models, hygroscopic water content of (2.0-3.0 %) was added to the sample to ensure compactness and cementation of soil within the model. The box was divided into sub layers of about 50 mm thickness; each layer was compacted using standard hammer.
After sample preparation commenced, the density was checked using sand balloon for field density test according to (ASTM D2167 08) specification. The variation of the resulting density was ±5 %. This variation is considered acceptable.
For preparation of saturated models, the soil was saturated by pouring a known minimum quantity of water that is required for saturation. This quantity of water was calculated from the basic relations in soil mechanics. For achieving permanent saturation of sand, additional water was added to the sample prior to test. Care was taken to ensure that no water could be draining out from the steel box.

5.3 Description of the Vibratory Machine

The model machine of the mechanical oscillator used in this study is shown in **Fig. 3.a**. The mechanical oscillator consists of a rotating disc manufactured from steel with diameter (54.0) mm and thickness (5.1) mm. A single mass (m_e) is placed on the rotating disc at an eccentricity

of (22.0) mm from the axis of rotation. This arrangement rotates in one direction when it is driven through a shaft by an AC motor having a maximum rated speed of up to 3500 rpm. Such an arrangement induces a vibratory force at the base of the oscillator. This vibratory force can be estimated from Eq. (1).
The basic principle of this device can be found in different textbooks such as **Bhatia, 2009**. Depending on the orientation of the counter-rotating shaft, a vertical dynamic force can be applied. The amplitude of vertical force produced (F_o) is:

$$F_o = m_e\, e\, \omega_r^2 \quad \textbf{(1)}$$

where:
ω_r is the circular operating frequency of the machine,
e is the eccentric distance from the shaft to the unbalanced mass m_e, and
m_e is the unbalanced mass.
For this type of oscillator, the function of the harmonic vertical mode of vibration is sinusoidal. Therefore, the applied dynamic force F (t), at any time (t) is given by:

$$F(t) = F_o \sin \omega_r t = m_e\, e\, \omega_r^2 \sin \omega_r t \quad \textbf{(2)}$$

In this research, a special AC Drive was used to control the speed of rotation. Calibration of this device with Tachometer was done to check the accuracy of the AC Drive. By varying the voltage supplied to the motor with the aid of the speed AC Drive, the speed of the motor and hence the oscillator can be varied which, in turn, causes a change in frequency of vibration induced by the oscillator.

5.4 Dynamic Load Measurement (F-t History)

For measuring the vibration force, a dynamic load cell was used specially for this purpose. The dynamic load cell was MLC215C-3T supported with MEP105A weighing indicator shown in **Fig. 3.b**, **Manyyear Technology Company Limited, 2011**. For obtaining high sensitivity of readings, the output lead wires of the dynamic load cell were connected to the Vishay Digital Strain Indicator that was provided with an analog output. The output signal from the strain indicator was captured by using a digital storage oscilloscope **TWINTEX (TSO 1202, 200MHz)** and then connected to data acquisition system by laptop computer device as shown in **Fig. 2**. The operation of storage type oscilloscope was enhanced with computer interface system that makes it more familiar to the computer uses, **Oscilloscope User Manual, 2011**.

5.5 Measurement of the Amplitude of Footing Displacement

The vertical amplitude of footing (Az) was measured at the surface of the footing. Vibration meter (**HG 6360**) of one channel was used in the test. This vibration meter has a working capacity of 0.001 to 4.0 mm, it is capable of measuring the displacement, velocity, and acceleration of motion depending on the function set prior to the test, **Operation Manual, 2011**. In addition, all the collected data can be transferred to the computer easily through built in software. During the tests, one vibration meter was used on the surface of the footing. The components of the HG 6360 vibration meter are shown in **Fig. 4**. The vibration meter within the testing models is shown in **Fig. 2**.

6. EXPERIMENTAL TEST RESULTS AND DISCUSSION

The displacement amplitude of footing (Az) was measured for all the tested models. The displacement was measured by using vibration meter. This device is used with computer interface software. The data can be directly taken from the software or it can be taken as displacement amplitude-time history (Az-t).

The test results of the displacement amplitude with time are obtained during tests, it was found that the trend of the test results is not unique for all the tests. This may be attributed to the test conditions and the dynamic response of soil. In addition, this trend is clear for the loose state models, while for dense state, the trend seems to be unique for all the tested models.

In most engineering practice, it is always desirable to get the maximum displacement amplitude of motion. Hence, the maximum values are picked up and presented in **Fig. 5 and Fig. 6**, and summarized in **Table 2.**

It can be seen that the displacement amplitude (Az) for dry dense sand models is less than that of dry loose sand models. For footing placed at the surface, the ratio of dense sand models amplitude to loose sand models is ranging from (0.27 to 1.00) and (0.03 to 0.94) for footing size (100×200 mm) and (200×400 mm), respectively. Meanwhile, for embedded footings this ratio becomes (0.24 to 0.99) and (0.10 to 0.97) for footing size (100×200 mm) and (200×400 mm), respectively. These results are attributed to the increase in the stiffness and the modulus of elasticity of dense sandy soil that makes the soil stiffer and resist vibrations as well as to it could be attributed to the trench and sidewall effects.

The displacement amplitude (Az) of the footing size (200×400 mm) is less than that of footing of size (100×200 mm). This is true for all dry models except model for dry loose sand and some of the saturated sand models. As can be seen, for dry loose sand models, the ratio between footing size (100×200 mm) to footing size (200×400 mm) is ranging from (1.29 to 1.75) and (1.12 to 4.79) for footing placed at the surface and embedded, respectively. On the other hand, for dry dense sand the ratio becomes (1.00 to 10.83) and (1.50 to 10.91) for footing placed on the surface and embedded, respectively. Meanwhile, for saturated dense sand, the rate of reduction reduces and goes from (1.10 to 3.61) for footing placed on the surface, while the behavior of embedded footing in saturated dense sand seems to have opposite behavior to the aforementioned trend. The reduction in response for large contact area is attributed to the reduction in the stresses due to large contact area.

On the other hand, the displacement amplitude (Az) of saturated soil samples exhibits the same resonance frequency, except for sample of footing size (200×400 mm) and embedded at 5.0 cm. This is due to the presence of water within the soil particles that may require high frequency to produce resonance phenomenon.

7. SUMMARY AND CONCLUSIONS

From the discussions carried out in the previous sections and other observations made during the experimental approach, the following conclusions are made.

- For dry and saturated conditions, the maximum amplitude of displacement decreases with increasing the relative density of sand and contact area of footing and increase with increasing the amplitude of loading. The maximum displacement amplitude response of the foundation resting on dry sand models is more than that on the saturated sand by about 5.0 to 10 %. The maximum displacement amplitude of footing is reduced to half when the size of footing increases to double for dry and saturated sand. The percentage of reduction in dry sand is more than that of saturated sand.

- The general response of the force-time history relationship possesses erratic distribution (fluctuated) at low operating speed, meanwhile for high operating speed (> 3000 rpm), the relationship exhibits sine wave trend.
- The embedment of footing in sandy soils leads to beneficial reduction in dynamic displacement response for all soil types in different percentages accompanied by an increase in soil strength.
- The maximum displacement amplitude exhibits its maximum value at the resonance frequency, which is found to be about 33.34 to 41.67 Hz.
- The maximum amplitude of displacement of saturated medium dense sand is less than that of loose sand. This means that the maximum displacement increases with decrease in the modulus of elasticity as well as the smaller the modulus is, the quicker the development of liquefaction zone.
- The displacement amplitude of saturated loose sand is greater than that of the dry sand especially when the frequency is greater than the resonance frequency.
- The amplitude of displacement of saturated sand models is slightly greater than that of the dry models. This is mainly attributed to the effect of water that may restrict the movement of soil particles during vibrations.

REFERENCES

- Al-Homoud, A. S. and Al-Maaitah, O. N., 1996, *An Experimental Investigation of Vertical Vibration of Model Footings on Sand*, Soil Dynamics and Earthquake Engineering, 15, No. 7, pp. 431-445.

- Al-Shammary, W. T. S., 2013, *Numerical Analysis of Machine Foundation on Saturated Sandy Soil*, M.Sc. Thesis, Building and Construction Engineering Department, University of Technology, Iraq.

- American Society of Testing and Materials (ASTM), 2006, *Standard test method for specific gravity of soil solids by water pycnometer*, ASTM D854, West Conshohocken, Pennsylvania, USA

- American Society of Testing and Materials (ASTM), 2006, *Standard Test Method for Particle Size-Analysis of Soils,* ASTM D422-63 (2002), West Conshohocken, Pennsylvania, USA

- American Society of Testing and Materials (ASTM), 2006, *Standard Test Method for Maximum Index Density and Unit Weight of Soils Using a Vibratory Table*, ASTM D4253-00 (2006), West Conshohocken, Pennsylvania, USA

- American Society of Testing and Materials (ASTM), 2006, *Standard Test Method for Minimum Index Density and Unit Weight of Soils and Calculation of Relative Density,* ASTM D4254-00 (2006), West Conshohocken, Pennsylvania, USA

- American Society of Testing and Materials (ASTM), 2006, *Standard Test Method for Direct Shear Test of Soils Under Consolidated Drained Conditions*, ASTM D3040-04, West Conshohocken, Pennsylvania, USA

- American Society of Testing and Materials (ASTM), 2006, *Standard Test Method for Density and Unit Weight of Soil in Place by the Rubber Balloon Method*, ASTM D2167-01 (2004), West Conshohocken, Pennsylvania, USA

- American Society of Testing and Materials (ASTM), 2006, *Standard Test Method for Unconsolidated-Undrained Triaxial Compression Test on Cohesive Soils*, ASTM D2850-03a, West Conshohocken, Pennsylvania, USA

- American Society of Testing and Materials (ASTM), 2006, *Standard Test Method for Permeability of Granular Soils (Constant Head)*, ASTM D2434-68, West Conshohocken, Pennsylvania, USA

- American Society of Testing and Materials (ASTM), 2006, *Standard Test Method for Classification of Soils for Engineering Purposes (Unified Soil Classification System)*, ASTM D2487-06, West Conshohocken, Pennsylvania, USA

- Bhatia, K., 2009, *Foundations for Industrial Machines: Handbook for Practicing Engineers*, CRC.

- Chowdhury, I. and Dasgupta, S. P., 2010, *Dynamics of Structure and Foundations-A Unified Approach: 2. Applications*, CRC Press.

- Daghigh, Y., 1993, *Numerical Simulation of Dynamic Behavior of an Earth Dam during Seismic Loading*, Ph.D. Thesis, Delft University of Technology, Netherlands.

- Kassir, M., Bandyopadhyay, K. and Xu, J., 1989, *Vertical Vibration of A Circular Footing on A Saturated Half-Space*, International Journal of Engineering Science, 27, No. (4), pp. 353-361.

- Kim, Y.-S., Miura, K., Miura, S. and Nishimura, M., 2001, *Vibration Characteristics of Rigid Body Placed on Sand Ground*, Soil Dynamics and Earthquake Engineering, 21, No. (1), pp. 19-37.

- Livaoglu, R. and Dogangun, A., 2007, *Effect of Foundation Embedment on Seismic Behavior of Elevated Tanks Considering Fluid–Structure-Soil*

Interaction, Soil Dynamics and Earthquake Engineering, 27, No. (9), pp. 855-863.

- Manyyear Technology Company Ltd., 2010, *www.manyyear.com*.

- Operation Manual, 2011, *Digital Vibration Meter Model HG 6360*, HUATEC Co., Ltd , www.huatecgroup.com

- User Manual, 2011, *Digital Storage Oscilloscope TSO-1202 Series Version No.: V1.6*, Twintex Electronics Co., Ltd , www.twintex.com.tw

NOMENCLATURE

Symbol	Meaning
ADS	data acquisition system
ASTM	american Society for Testing and Materials
Az	vertical displacement amplitude (mm)
Az-t	displacement Amplitude-Time History
Cc	coefficient of curvature
cps	cycle per second (Hz)
Cu	uniformity coefficient
D_{10}	diameter corresponding to percent passing of 10 % (mm)
D_{30}	diameter corresponding to percent passing of 30 % (mm)
D_{60}	diameter corresponding to percent passing of 60 % (mm)
DD1020E	dry dense soil supporting rectangular footing of 10×20 cm and embedded 5 cm in soil
DD1020S	dry dense soil supporting rectangular footing of 10×20 cm placed at the surface
DD2040E	dry dense soil supporting rectangular footing of 20×40 cm and embedded 5 cm in soil
DD2040S	dry dense soil supporting rectangular footing of 20×40 cm placed at the surface
DL1020E	dry loose soil supporting rectangular footing of 10×20 cm and embedded 5 cm in soil
DL1020S	dry dense soil supporting rectangular footing of 20×40 cm placed at the surface
DL2040E	dry loose soil supporting rectangular footing of 20×40 cm and embedded 5 cm in soil
DL2040S	dry loose soil supporting rectangular footing of 10×20 cm placed at the surface
Dr	relative density
e	eccentric distance from the shaft to the unbalanced mass m_e
e_{max}	maximum void ratio
e_{min}	minimum void ratio
F_o	amplitude of dynamic force (N)
F_t	transition surface (N)
F-t	force-time history
Gs	specific gravity

Symbol	Meaning
k	coefficient of Permeability (m/min)
LVDT	linear Variable Differential Transformer
m_e	eccentric mass in the manufactured machine (kg)
rpm	radian per minute
SD1020E	saturated dense soil supporting rectangular footing of 10×20 cm and embedded 5 cm within soil
SD1020S	saturated dense soil supporting rectangular footing of 10×20 cm placed at the surface
SD2040E	saturated dense soil supporting rectangular footing of 20×40 cm and embedded 5 cm within soil
SD2040S	saturated dense soil supporting rectangular footing of 20×40 cm placed at the surface
S_t	total settlement (mm)
STO	storage Types Oscilloscope
USCS	unified Soil Classification System
ϕ	angle of internal friction
γ_{dmax}	maximum dry unit weight (kN/m^3)
γ_{dmin}	minimum dry unit weight (kN/m^3)
ω_r	circular frequency of the system (rpm)

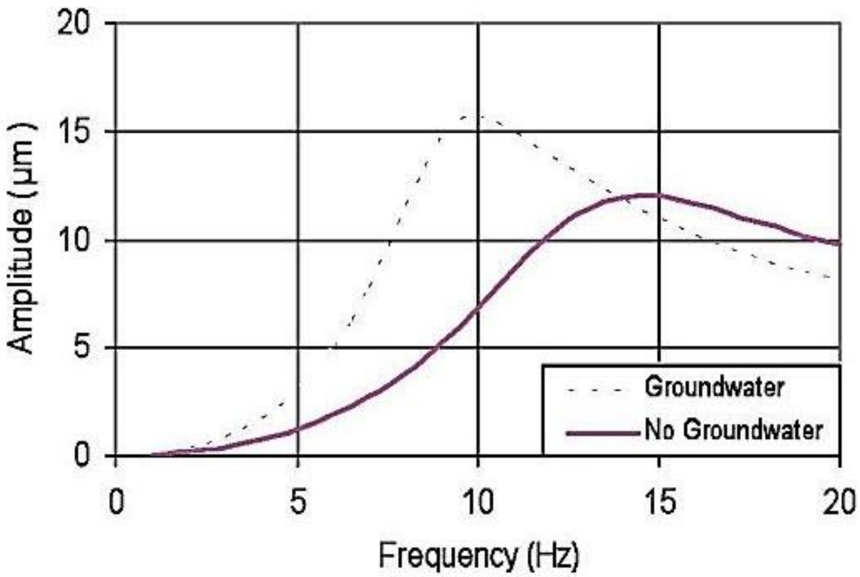


Figure 1. Effect of groundwater on dynamic response of pump foundation ,**after Kim et al., 2001**.

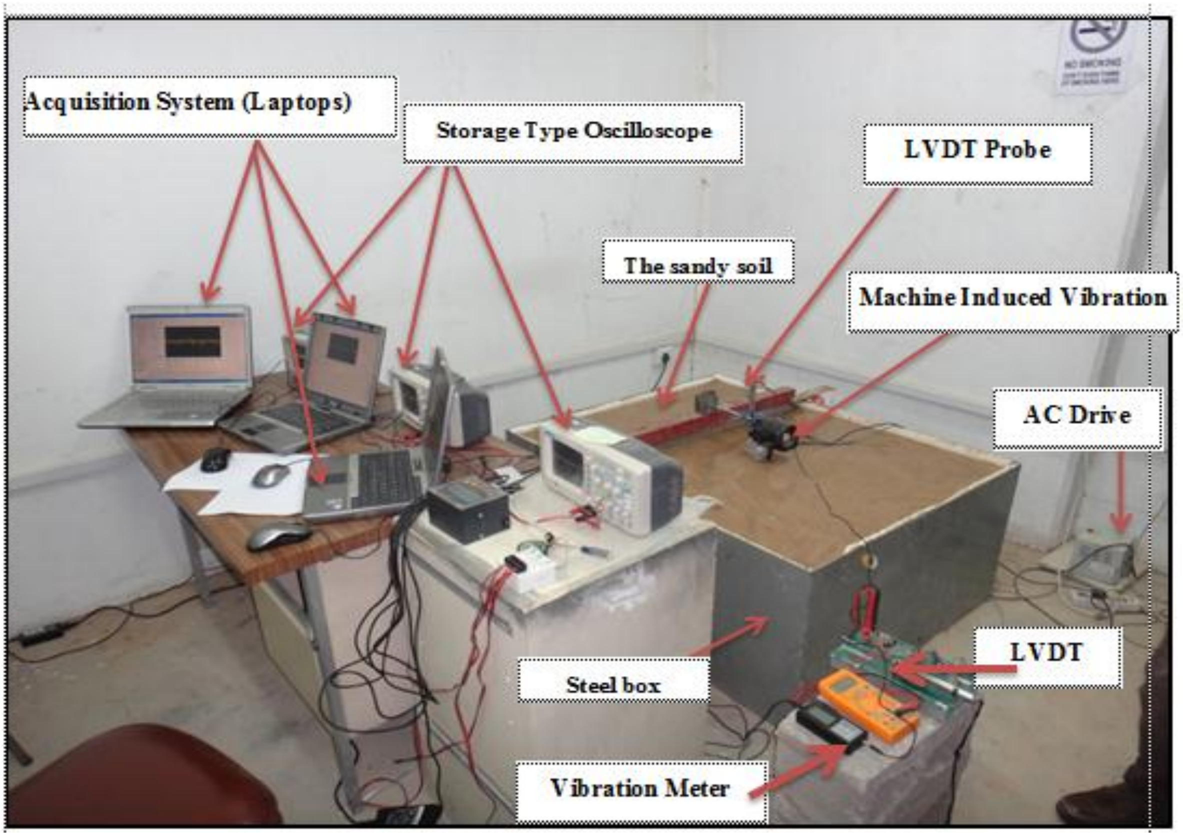
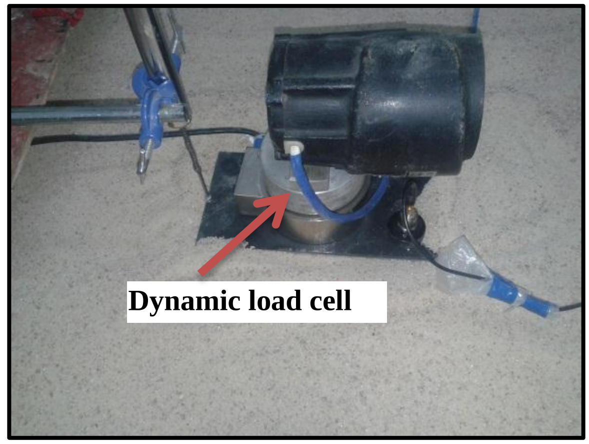


Figure 2. General view of the testing models and instruments.

Table 1. Physical and mechanical properties of the used sand.

Property			Value	Standard of the test
Specific gravity, Gs			2.65	ASTM D 854
Gravel (> 4.75 mm) %			0	ASTM D 422 and ASTM D 2487
Sand (0.075-4.75 mm)%			96	
Silt and clay (< 0.075 mm)%			4	
Coefficient of curvature, Cc			1.55	
Coefficient of uniformity, Cu			1.73	
D_{10}, D_{30}, D_{60} (mm)			0.11, 0.18, 0.19	
USCS-soil type			SP	
Dense state relative density, Dr, %			80.0	
Loose state relative density, Dr, %			30.0	
Maximum dry unit weight, γ_{dmax}, kN/m^3			18.2	ASTM D 4253-00
Minimum dry unit weight, γ_{dmin}, kN/m^3			14.3	ASTM D 4254-00
Dry unit weight in loose state (Used), kN/m^3			15.4	------
Dry unit weight in dense state (Used), kN/m^3			17.3	------
Angle of internal friction , ϕ	Loose state (30%)	Dry	28.0	ASTM D 3080
		Soaked	26.0	
	Dense state (80%)	Dry	40.0	
		Soaked	36.0	
Coefficient of permeability, k, m/sec		Loose state (30%)	0.0360	ASTM D2434-68
		Dense state (80%)	0.0065	

a) Machine for inducing vibration



b) Location of the dynamic load cell

Figure 3. Equipment for inducing vibratory dynamic load.

Figure 4. HG 6360 vibration meter and its components.

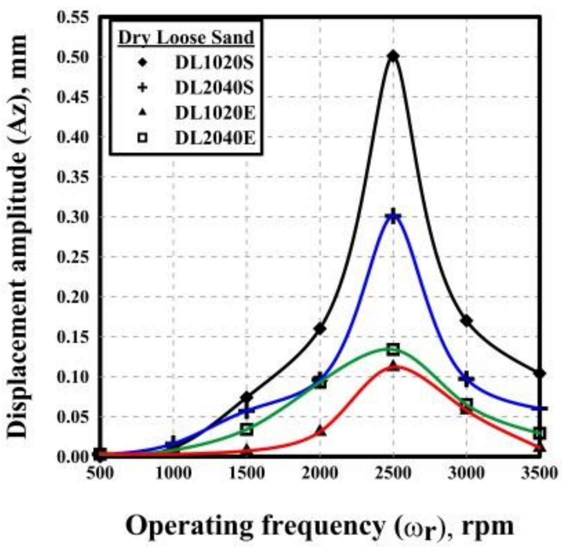


Figure 5. The maximum displacement amplitude versus operating frequency for dry loose sand models.

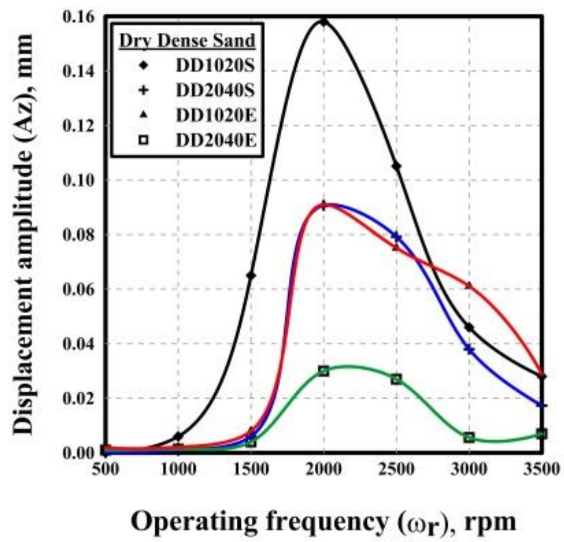


Figure 6. The maximum displacement amplitude versus operating frequency for dry dense sand models.

Table 2. Displacement amplitude for different test conditions from experimental tests.

Test No.	Test Condition	Operating Frequency, ω_r rpm	Az, mm	S_t, mm
1	**DL1020S**	500	0.0001	0.01
2		1000	0.0111	3.00
3		1500	0.0740	7.00
4		2000	0.1600	8.35
5		2500	0.5010	13.00
6		3000	0.1700	21.00
7		3500	0.1040	25.00
8	**DL2040S**	500	0.0030	0.00
9		1000	0.0162	0.30
10		1500	0.0572	0.80
11		2000	0.0961	1.55
12		2500	0.3010	2.15
13		3000	0.0970	3.60
14		3500	0.0601	7.00
15	**DL1020E**	500	0.0030	0.00

Test No.	Test Condition	Operating Frequency, ω_r rpm	Az, mm	S_t, mm
16		1000	0.0081	0.20
17		1500	0.0340	0.75
18		2000	0.0930	4.20
19		2500	0.1340	5.95
20		3000	0.0651	8.50
21		3500	0.0292	12.00
22	**DL2040E**	500	0.0040	0.05
23		1000	0.0030	0.10
24		1500	0.0071	0.10
25		2000	0.0310	1.10
26		2500	0.1120	1.70
27		3000	0.0580	2.55
28		3500	0.0110	5.45
29	**DD1020S**	500	0.0001	0.00
30		1000	0.0060	0.06
31		1500	0.0650	0.70
32		2000	0.1580	0.90
33		2500	0.1510	1.00
34		3000	0.0460	2.00
35		3500	0.0280	4.00
36	**DD2040S**	500	0.0001	0.00
37		1000	0.0010	0.05
38		1500	0.0060	0.10
39		2000	0.0907	0.60
40		2500	0.0792	0.70
41		3000	0.0380	0.75
42		3500	0.0173	0.90
43	**DD1020E**	500	0.0020	0.00
44		1000	0.0021	0.05
45		1500	0.0080	0.08
46		2000	0.0910	0.50
47		2500	0.0751	0.30
48		3000	0.0611	0.40

Test No.	Test Condition	Operating Frequency, ω_r rpm	Az, mm	S_t, mm
49		3500	0.0288	1.10
50	DD2040E	500	0.0010	0.00
51		1000	0.0014	0.00
52		1500	0.0040	0.00
53		2000	0.0300	0.05
54		2500	0.0270	0.10
55		3000	0.0056	0.15
56		3500	0.0070	0.25
57	SD1020S	500	0.0011	0.05
58		1000	0.0020	0.60
59		1500	0.0650	3.25
60		2000	0.3820	5.50
61		2500	0.1482	10.10
62		3000	0.0910	13.00
63		3500	0.0783	20.95
64	SD2040S	500	0.0010	0.05
65		1000	0.0033	-0.05
66		1500	0.0180	0.45
67		2000	0.2120	1.35
68		2500	0.0980	2.35
69		3000	0.0800	3.15
70		3500	0.0230	4.95
71	SD1020E	500	0.0250	0.10
72		1000	0.0411	0.50
73		1500	0.0940	0.85
74		2000	0.2780	0.90
75		2500	0.1802	2.25
76		3000	0.0480	4.75
77		3500	0.0250	7.00
78	SD2040E	500	0.0082	0.05
79		1000	0.0090	0.00
80		1500	0.0044	0.05
81		2000	0.2008	0.10

Test No.	Test Condition	Operating Frequency, ω_r rpm	Az, mm	S_t, mm
82		2500	0.2880	0.50
83		3000	0.0890	0.55
84		3500	0.0640	0.85