Effect of mode of vibration on the response of machine foundation on sand

Khalid W. Abd Al-kaream¹, Mohammed Y. Fattah² and Zeyad S. M. Khaled³

¹ Assist. Lecture, Civil Eng. Dept., University of Technology, Iraq.
² Professor, Civil Eng. Dept., University of Technology, Iraq.
³ Assistant Professor, Civil Eng. Dept., University of Al-Nahrain University, Iraq.

E-mail: Khalid_phar@yahoo.com

Abstract In this paper, the influence of the following parameters on different modes of vibration response of model footings on sand is studied: (vertical, rocking and pitching load amplitude and frequency). To achieve the objective of this study, the model footing was selected to be rectangular footing with an aspect ratio (L/B= 1.33) i.e (L= length and B= width). A physical model was manufactured to simulate a steady-state harmonic dynamic load applied at different operating frequencies with the same load amplitude (0.5 ton). A total of (9) cases was performed taking into account different parameters. The loading frequency ranged from (0.5) to (2) Hz and the footing was rectangular with an aspect ratio (L/B = 1.33). The soil type used was dry sand having a relative density of (50%). The behavior of the soil underneath the footing was examined by measuring the strain using a shaft encoder and the amplitude of displacement using a vibration meter. It was found that the change in vibration mode made little effect of the final strain values under the same frequency and the amplitude of displacement in (Z) direction, while the amplitude of displacement in (Y) is higher, occurring under rocking vibration and higher value amplitude of displacement in (X) direction under pitching vibration under the same frequency.

Keywords
Machine foundation, Mode of vibration, Strain, Amplitude displacement.

1. Introduction
Usually dynamic loading is produced by the earthquakes natural forces, wave of wind, road traffic, blasting as well as neighboring machines may be transferred to the basis throughout an organizational system or may be throughout the soil (Augir, 2008).

The difficulties related to the design of foundation to resist the dynamical load either from enhancing machinery or from the external origins still need distinct solutions by considering the conditions of local soil as well as the environment. Firstly, the foundation should be in accordance with the criteria for loadings that are static, after that, it should be mostly satisfactory for the resistance of the dynamical loadings. In order to understand the behavior of structure subjected to dynamic lucidly, one of the most study mechanics of types modes vibration caused by the dynamic load. A typical inflexible foundation is usually subjected to dissimilar vibration modes. Under the influence of superimposed loads, the foundation of a structure can vibrate in six different modes; three translational vertical, horizontal and longitudinal and three rotational rocking, pitching and yawing (Richart, 1962).
The most important variable affecting the problem of machine foundations is the shear modulus of the soil. Considering the shear modulus as state variable, it was found that by the empirical method, the maximum displacement decreases when the shear modulus increases as the type of soil is sand; and the maximum displacement is smaller than the case when the type of soil is clay (Fattah et al., 2007).

The aim of this paper is to investigate the effect of mode of vibration on the dynamic response of machine foundation resting on sandy soil.

2. Experimental Work

2.1 Material Used and Testing Program

The type of soil utilized in the current work is sand. Its properties were obtained by standard tests performed on medium sand. Table 1 summarizes the physical characteristics for sand, which appears to be classified as poorly graded sand (SP) according to the Unified Soil Classification System (USCS) as shown in figure 1.

The experiments’ testing was conducted using a steel cubical tank of (800×800×1000 mm) sizes having 6 mm of thickness, slicked both faces, to hold the soil. Such dimensions are being chosen to satisfy the physical models border effects, which are subjected to the dynamical loading. To certify the uniformity through the model depth, 100 mm thick layers of soil were placed layer by layer and compacted manually to the marked levels as shown in figure 2.

Table 1. Physical properties of the tested sand.

| Index properties                      | Value | Specification                  |
|---------------------------------------|-------|--------------------------------|
| Specific gravity (Gs)                 | 2.66  | ASTM D 854                    |
| Gravel (> 4.75 mm) %                  | 7     |                                |
| Sand (0.075-4.75 mm) %                | 91    |                                |
| Silt and clay (< 0.075 mm)%           | 2     |                                |
| Coefficient of uniformity (Cu)        | 3.91  |                                |
| Coefficient of curvature (Cc)         | 0.77  | ASTM D 422 and ASTM D 2487    |
| Soil classification (USCS)            | SP    |                                |
| Maximum dry unit weight (kN/m²)       | 18.64 | ASTM D 4253                   |
| Minimum dry unit weight (kN/m²)       | 15.72 | ASTM D 4254                   |
| Maximum void ratio                    | 0.66  |                                |
| Minimum void ratio                    | 0.4   |                                |
| The angle of internal friction (ϕ) at R.D =50% | 39.5° | ASTM 3080                     |

Figure 1. Grain size distribution of the sand.
2.2 Characterization of the Testing Model System
The loading system is hydraulically mounted strengthening of the steel structure of the device to adequately bear new loading amplitude as shown in figure 3. The load application device was made up from; a loading steel frame, an electrical hydraulic system, data acquisition, and logging system, a shaft encoder for settlement measurement, a steel box container.

2.3 Model Footing
Foundation was used in the research, a (150*200 mm) foundation of rectangular steel. Foundation was supplied with points of threaded contact to apply the load of vibration on, usually three points for the rectangular basis, the first point of connection is placed at the middle of the basis to convey a perpendicular force for achieving a vertical vibration mode, while the second and third are located at one third the distance from the edge of the long and short side consecutively as demonstrated in figure 4.
2.4 Vibration meter
A vibration meter was used for calculating the displacement amplitude of points below the footing of depth (B) as shown in figure 5. The vibration meter was made to calculate the high displacement in a way of three directions (x, y, and z). This artificial meter of vibration composed of ADXL335, which is thin, small, low power and complete meter of 3-axis vibration with sign conditioned power productivities.

3. Results and Discussion
To study the effect of different modes vibration on the rectangular footing, the relative density was used 50%, load amplitude used is 0.5 ton and the frequencies were 0.5, 1 and 2 Hz.

3.1 Effect of mode of vibration on the rate of strain
To investigate the effect of vibration modes, rectangular footing with an aspect ratio i.e length/width (L/B= 1.33) was tested. Figures 6 to 8 demonstrate the $S_N/H$ presents the strain, the strain is equal to settlement divided by thickness of layer soil below the base of footings after application of the dynamic load, each figure shows the strain below the footing for dissimilar modes of vibration under a load of amplitude 0.5 ton to get better perception of mode of vibration effect, exclusively. Comparing the vibration modes effect (vertical V.M., rocking R.M. and pitching P.M.) on the strain as shown in figures, it can be observed that for vertical mode of vibration, the maximum of strain occurs under rectangular footings, the decrease of percentage is extremely associated with the decrease in the frequency and foundation depth. When the mode of vibration is changed from vertical to rocking, the $S_N/H$ decreases about (36%) and the decrease reaches (65 %) when the rocking is replaced with pitching mode under the same conditions. Because of the increment of the rotation magnitude, the contact area of foundation with soil turns to be smaller as well as moving in the direction of the
foundation edge because of the elevating at the other side and the bearing resistance along the entire area of contact might be equivalent to the resistance of the ultimate bearing. Figure (9) show the variation of the effect modes vibration on the $S_{\text{SN}}/H$ after $10^3$ cycles underneath the same amplitude of load and dissimilar frequencies.

![Figure 6. Relation between number of cycles and strain under vertical mode vibration.](image)

![Figure 7. Relation between number of cycles and strain for rocking mode vibration.](image)
3.2 Effect of the mode of vibration on the amplitude of displacement

Comparing result of amplitude of displacement for different modes vibration (vertical, rocking and pitching) above rectangular footing with aspect ratio (L/B= 1.33) as shown in figures 10 to 12 and table 2. It can be observed that the maximum value of amplitude displacement occurs in (Z) direction under vertical mode of vibration, while in rocking mode vibration the maximum value of amplitude displacement occurs in (Y) direction and in pitching mode vibration greater than amplitude displacement in (X), because the contact applied load above rectangular foundation with aspect ratios tends to have an increase in the last quarter point compared to the first quarter point this leads to a reduction the value amplitude displacement, the decrease percentage is highly related to the increase in frequency.
Figure 10. Relation between number of cycles and amplitude of displacement under the vertical mode of vibration.
Table 2. Maximum amplitudes of displacement for different modes of vibration.

| Load | 0.5 Hz R.D=50% | 1 Hz R.D=50% | 2 Hz R.D=50% |
|------|----------------|--------------|--------------|
|      | V.M (A_Z)     | R.M (A_Y)    | P.M (A_H)    | V.M (A_Z)     | R.M (A_Y)    | P.M (A_H)    | V.M (A_Z)     | R.M (A_Y)    | P.M (A_H)    |
| 0.5 ton | -2.24      | -2.06        | -2.2         | -1.92         | 1.67         | -1.77        | -1.76         | -1.35        | -1.58        |

Figure 11. Relation between number of cycles and amplitude of displacement under rocking mode of vibration

Figure 12. Relation between number of cycles and amplitude of displacement under the pitching mode of vibration.
This agrees with the finding of Fattah et al. (2018) who found that the amplitude of displacement decreases with the increase in frequency under the same condition (load amplitude, relative density and modes of vibration). Al-Mosawi et al. (2015) found that for dry and saturated conditions, the maximum amplitude of displacement decreases with an increase in the relative density of sand and contact area of footing and increases with an increase in the amplitude of loading.

4. Conclusions:
Based on the experimental work results from preparing to finalize the results, the main points to be concluded are as follows:
1. In general, as the frequency of vibration increases, the $S_n/H$ decreases under the same load amplitude, mode of vibration and relative density. The increment in strain approximately reaches 40% when the frequency changes from 2 Hz to 1 Hz, while the increment is approximately 60% when the frequency changes from 1 Hz to 0.5 Hz. This means that the strain increases as the frequency decreases.
2. When the vertical vibration mode is used, in contrast to rocking and pitching vibration mode, there is generally a reduction in the total $S_n/H$ recorded under the same condition.
3. In case of foundation on sandy soil subjected to vertical dynamic loading, the increase in the amplitude of displacement ($A_{y_{max}}$) in ($Z$) direction, the amplitude of displacement ($A_{x_{max}}$) is greater when the footing is under rocking vibration and the maximum amplitude of displacement ($A_{x_{max}}$) occurs under pitching mode vibration.

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