Effect of Embedment Depth for Circular Footing on the Amplitude of Displacement under Dynamic Load

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Abstract The effect of the embedment depth of a circular footing resting on dry sand and subjected to dynamic load on the amplitude of soil displacement (Az) was investigated in the present study. In order to simulate the conditions occurring in the field, a special testing apparatus with accessories was designed and manufactured to study the effect of dynamic load on soil. A total of 18 cases were examined to take into account the effects of different parameters, including different frequencies (0.5, 1, and 2 Hz); relative densities (medium sand, R.D= 50% and dense sand, R.D= 80%); and corresponding unit weights (17.52 kN and 18.33 kN). All tests were carried out under load amplitude of 0.5 tons. The behaviour of the soil underneath the footing was examined by measuring the amplitude of displacement Az using a vibration meter placed at a set depth (B) under the footing. It was found that when the embedment depth is changed from zero (at surface) to 0.5 B and then to B the value of amplitude of the displacement Az is reduced. The percentage of reduction in Az was about 4 to 39 % at depth 0.5 B, and about 37-77 % at depth B.

Keywords: Machine foundation, Sand, Strain, Amplitude of displacement.

1. Introduction

The response of soil under dynamic loads usually differs from that under constant static loads, a fact of great significance for the constancy of structures. The behaviour of soil strain can be described as hysteretic and highly non-linear, and the actual behaviour of soils is normally elasto-plastic, which provides better estimations of displacement when...
subjected to a working load. The soil type also affects responses under conditions of dynamic loading. The most important factors separating various soils a type is the distribution of the grain size. Well-sorted materials are less likely to lose power under dynamic loading, while uniform soils are more likely to lose power under dynamic loading [Richart et al., (1970)].

The amplitudes of displacement or velocity or acceleration of machine foundations should be within permissible limits, but these permissible limits depend upon the operating frequency of the machine as well as the soil type and other characteristics. In no case, however, should the permissible amplitude exceed the limiting amplitude prescribed for the machine by the manufacturer [Srinivasulu and Vaidyanathan, (1976)].

Barkan., (1962) proposed values of permissible amplitude for different types of machine, based on his observations of machine performance, as given in Table (1):

| Machine Type                                      | Permissible amplitude (cm) |
|---------------------------------------------------|----------------------------|
| 1 Low-speed machinery (500 rpm)                   | 0.02 to 0.025              |
| 2 Hammer foundations                              | 0.1 to 0.12                |
| 3- High-speed machinery (1500 rpm):               |                            |
| a- Vertical Vibrations                            | 0.004 to 0.006             |
| b- Horizontal Vibrations                          | 0.007 to 0.009             |
| 4- High-speed machinery (3000 rpm):               |                            |
| a- Vertical Vibrations                            | 0.002 to 0.003             |
| b- Horizontal Vibrations                          | 0.004 to 0.005             |

Ali et al., (2018) performed an experimental study on the behaviour of dry dense sand under the action of a single impulsive load. The research included studying the effect of footing embedment and footing area on soil behaviour and dynamic response. Different masses falling from different heights were used to provide the single pulse energy and examined using the falling weight deflectometer (FWD). The responses of different soils were then evaluated at different locations (vertically below the impact plate and horizontally away from it). These responses included; displacements, velocity and
accelerations. The study concluded that increasing the footing embedment depth increases the amplitude of the force-time history by about 10 to 30% due to increases in the degree of confinement. This is accompanied by a decrease in the displacement response of the soil of about 40 to 50% due to increases in the overburden pressure when the embedment depth increases, which leads to increases in the stiffness of sandy soil. There is also increase in the natural frequency of the soil-foundation system by about 20 to 45%. For surface foundations, the foundation is free to oscillate in vertical, horizontal, and rocking modes; however, embedding the footing causes the surrounding soil to restrict oscillation due to confinement which leads to an increase in the natural frequency. Moreover, Ali et al., (2018) found that the soil density increased with depth because of compaction, which makes the soil behave as if it were a solid medium. Increasing the footing embedment depth thus increases the damping ratio by 50 to 150% due to the increase in soil density as D/B increases, which causes the soil to tend to behave as a solid medium, activating both viscous and strain damping Das., (1983).

2. Research Methodology

The present work aimed to study the behavior of machine foundations resting on sandy soil subjected to vibration dynamic loadings. This research was carried out by considering a circular footing with diameter 150 mm placed on dry sandy soil. The boundary of the problem was achieved experimentally by using non-reflecting boundary materials (styropor cork). The variables taken into considerations were:

1. The depth of embedment of footing studied by placing the footing at the surface, then 0.5B and B below the soil surface.
2. The operating frequency studied at 0.5, 1 and 2 Hz.
3. The effect of relative density of the sand, studied by resting the foundations on sand in a medium state (Dr = 50 %) and a very dense state (Dr = 80%).

For all parameters, the response of the soil-foundation system was evaluated by means of the following measurements:
1. The strain \((S_{N}/H)\) of the footing was measured at the footing: \(S_{N}\) = settlement of the surface footing at any number of cycles, and \(H\) = thickness of the soil layer in the steel box.

2. The amplitude of displacement \(A_{z}\) at depth \(B\) below the footing.

3. Experimental Work and Material Used

Several methods are available to determine the displacement amplitude of machine foundations. Most of these methods consider the underlying soil as being in a medium state, however Al Mosawe et al., (2015). Small-scale experiments were thus performed to simulate a physical model of machine foundation on two types of soil so that the total numbers of tests was 18.

The physical characteristics for sand categorised as poorly graded (SP) with the Unified Soil Classification System (USCS). Table 1 summarises the properties of the sand used, and Fig. 1 shows the curve of the grain size distribution.

Testing was conducted in a steel cubical tank of dimensions 800×800×1000 mm with walls of 6 mm thickness, slicked on both faces, used to hold the soil. These measurements were selected to replicate the boundary influences of physical models exposed to dynamic loading. To ensure the uniformity through the model depth, 100 mm thick layers of soil were placed layer by layer and compacted manually to the marked level.

In order to simulate conditions in the field as closely as possible a specific investigating device with accessories was designed and manufactured to study the effect of machine vibration on soil. The loading system was a hydraulically mounted enhancement of the solid structure of the apparatus that was able to bear sufficient new loading amplitude as presented in Figure 2.

The device was created from the following parts:

1- Loading frame.
2- Electrical hydraulic system.
3- Load spreader plate.
4- Settlement measuring device.
5- Data logging and acquisition systems.
6- A steel container (800*800*1000 mm).

Table 2: 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 (C_u)   | 3.91   | ASTM D 422 and ASTM D 2487     |
| Coefficient of curvature (C_c)     | 0.77   |                                 |
| Soil classification (USCS)         | SP     |                                 |
| Maximum dry unit weight (kN/m³)   | 18.63  | ASTM D 4253                    |
| Minimum dry unit weight (kN/m³)   | 15.71  | ASTM D 4254                    |
| Maximum void ratio                | 0.66   | ......                          |
| Minimum void ratio                | 0.4    | ......                          |
| Angle of internal friction (φ) at | 39.5°  | ASTM 3080                      |
| R.D =50%                          |        |                                 |
| Angle of internal friction(φ) at  | 42°    | ASTM 3080                      |
| R.D=80%                           |        |                                 |

Fig. 1: Grain size distribution curve of the sand.

Fig. 2: Individual testing equipment parts.
A vibration meter was used to measure large movements in three directions (x, y, and z). The vibration device included an ADXL345 type accelerometer that is a little small power 3-axis accelerometer with sign condition electrical energy output as shown in Figure 3.

![Vibration meter](image1)

![Vibration meter](image2)

Fig. 3: Vibration meter.

4. Results and Discussion
4.1 Effect of embedment depth on strain

The depth of footing is an important parameter governing the ultimate bearing capacity of the soil. The ratio of the depth of footing to its width is called the embedment depth ratio and varies from 0 to 1 Kazi et al., (2014). The laboratory tests suggest that as the depth of footing ($D_f$) increases, the strain decreases, as presented in Figures 4 and 5 for both soil states and as shown in Table 3 under the same conditions. In general, when other factors are held constant, the bearing capacity of the soil goes on increasing as the depth or width of the foundation increases as depicted by Dixit and Patil., (2010). However, the embedment of footing in dense sand reduces the $S_N/H$ more than similar burial in medium sand as the dense soil is stiffer.
Fig. 4: Relationship between number of cycles and strain for footing on sandy soil at different depths with load amplitude 0.5 ton in R.D= 50%.
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Fig. 5: Relationship between number of cycles and strain for footing on sandy soil at different depths with load amplitude 0.5 ton in R.D = 80%.

Table 3: The S/H after application of 1000 cycles at different depths of footing.

| Depth   | 0.5 Hz R.D=50% | 0.5 Hz R.D=80% | 1 Hz R.D=50% | 1 Hz R.D=80% | 2 Hz R.D=50% | 2 Hz R.D=80% |
|---------|----------------|----------------|--------------|--------------|--------------|--------------|
| Surface | 0.0531         | 0.0267         | 0.041        | 0.0258       | 0.03         | 0.0211       |
| D_τ = 0.5 B | 0.0365       | 0.0151         | 0.0327       | 0.0120       | 0.0254       | 0.0103       |
| D_τ = B   | 0.0263         | 0.0138         | 0.0245       | 0.0114       | 0.0224       | 0.0096       |

4.2 Effect of embedment depth on amplitude of displacement

The resulting amplitudes of displacement (A_z) for the vibrating foundation in medium and dense sand is given in Figures 6 to 11 and Table 4. From these figures, it can be seen that a relationship of the A_z-N was established as the measured amplitude of displacement to the number of cycles. However, the trend of all test results is unique. This may be attributed to the test conditions and the dynamic response of soils. In engineering practice, it is always desirable to get the maximum displacement amplitude of motion; hence, the maximum values from the Figures are summarised in Table 4. For footings placed at the surface, the ratio between measured A_z for medium sand and dense sand are 1.13 to 1.56. For embedded footings, this ratio becomes 1.01 to 1.43 and 1.06 to 1.67 for medium and dense sand, respectively. This means that the embedment of footing causes a remarkable reduction in amplitude between surface and embedment cases due to the increase in damping caused by the soil-foundation system as well as the mobilization of the soil-structure interaction (SSI) due to the embedment of footing.

This observation is in close agreement with the findings of Fattah et al., (2015), who concluded from finite element analysis of machine foundations that the vertical
displacements for loose, medium, and dense sand decreased when the embedment of foundations increased.

![Graphs showing the relationship between number of cycles and amplitude of displacement for footing at surface under load amplitude 0.5 ton in R.D= 50%.

Fig. 6: Relationship between number of cycles and amplitude of displacement for footing at surface under load amplitude 0.5 ton in R.D= 50%.](image-url)
Fig. 7: Relationship between number of cycles and amplitude displacement, mm for footing at depth 0.5 B under load 0.5 ton in RD= 50%.
Fig. 8: Relationship between number of cycles and amplitude displacement mm for footing at depth B under load 0.5 ton in RD= 50%.

Fig. 9: Relationship between number of cycles and amplitude of displacement for footing at surface under load amplitude 0.5 ton in R.D= 80%.
Fig. 10: Relationship between number of cycles and amplitude displacement, mm for footing at depth 0.5 B under load 0.5 ton in RD= 80%.
Fig. 11: Relationship between number of cycles and amplitude displacement mm for footing at depth B under load 0.5 ton in RD= 80%.

Table 4: The absolute maximum amplitude (A$_{z_{max}}$) after application of 1000 cycles at different depths of footing.

| 0.5 ton | 0.5 Hz | 1 Hz | 2 Hz |
|---------|--------|------|------|
|         | R.D=50% | R.D=80% | R.D=50% | R.D=80% | R.D=50% | R.D=80% |
| surface | 3.931 | 2.784 | 2.982 | 2.400 | 2.390 | 2.144 |
| D$_f$ = 0.5 B | 2.145 | 2.150 | 1.984 | 1.872 | 1.864 | 1.673 |
| D$_f$ = B | 2.007 | 1.74 | 1.836 | 1.654 | 1.758 | 1.556 |

5. Conclusions

1- In general, as the frequency increases, the strain decreases under identical load amplitudes and relatives sand density. The increment in strain reaches approximately 40% as 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- As the relative density of sand decreases, the strain increases under identical loads amplitudes and frequencies. The amplitude of displacement also increases under the same load amplitude and frequency, with the rate change increasing about 8% for frequencies of 0.5 Hz, and about 12.5% for 1 Hz and 20% for 2 Hz.
3- In general, as the frequency decreases, the amplitude of displacement increases under identical load amplitude and relative thickness. The rate of change in vertical displacement is approximately 52% as the frequency decreases from 2 Hz to 1 Hz and 20% where the frequency changes from 1 Hz to 0.5 Hz.

4- As the depth of footing ($D_f$) increases, the strain and amplitude of displacement decrease where other parameters remain constant.

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