Effect of Embedment Depth on Raft Foundation Settlement Under Seismic Load

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Abstract. Dynamic loads highly influence soil properties and may cause real damage to structures and buildings. This article reports the experimental results from 24 tests to study the settlement of flexible and rigid raft foundation with different embedment depth rested on dense sandy soil. A small scale building model of dimension 200*200 mm and 320 mm in height was performed with reinforced concrete raft foundation of 10 mm thickness for flexible raft and 23 mm for rigid raft. The shaking table technique was used to simulate the seismic effect, the shaker was sat to give three different excitation frequencies 1.2, and 3 Hz and displacement amplitude equal to 13 mm, the foundation was placed at four different embedment depths (0, 0.25B=50mm, 0.5B=100mm, and B=200mm), where B is the raft side length. The results of the tests indicate that the foundation embedment have a positive effect for its ability to minimize the settlement for both flexible and rigid raft foundation and for all the excitation frequencies.

1. Introduction
Studying the effect of earthquake excitation on shallow foundations is an essential field for several decades, especially, for geotechnical engineers [1]. Generally, foundation can be classified into two major groups, shallow foundation and deep foundation. The first group contains: wall- footing, combined-footing, spread-footing and raft-foundation. The second group is: piles, piers, caissons and drilled-shaft-foundations [2]. Shallow foundations are regarded as higher safety comparing with pile foundations when subjected to heavy earthquake since design requirements involve that shallow foundations located on hard soil stratum of high bearing capacity [3]. Raft foundation is usually utilized where soil and load conditions might lead to high differential settlement for individual spread footings and for buildings with substantial overturning moments in regions of high seismicity or in high irregularity superstructure. Several factors effected the dynamic response of foundations such as the shape, dimensions, flexibility and foundation mass, depth of soil layer over bedrock, the effect of inhomogeneity, nonlinearity of soil behaviour, the embedment depth of the foundation, and anisotropy of soil properties, as stated by [4].

2. Model preparation and experimental work
Physical models are performed at much smaller scale than the actual size of proto type because the aim of physical models are to get the indicated patterns of response more rapidly and with more control over the details of the model [5]. 4 tests were performed inside a rigid steel cylindrical container of 700 mm in
diameter and 600 mm in height, the inside of the container is covered by styropor sheets to prevent the wave reflection which cause additional stresses and eliminate the friction between the container faces and soil. To perform a physical model, a concrete model footings of size 200 × 200 × 10 mm for flexible raft and 200×200×23 mm for rigid raft, was used, the thickness that separates the flexible raft and rigid raft was calculated by relative stiffness factor (K) method using equation (1), it was equal to 16 mm [6], see Figure 1. The foundation model was placed centrally in the soil. A steel frame of 320 mm in height was fixed on the raft foundation to represent the building height and to hold the additional mass of 40 kg weight, this weight was calculated according to the allowable total settlement of raft foundation, building height and soil depth under raft foundation were considered to be constant 320 mm and 450 mm respectively. The used soil is dry dense sand of 70% relative density passing through sieve No.10 (2.0 mm) and retained on sieve No.200, properties of the used sand are summarized in Table 1 with the standard of the test, hygroscopic water content (≈0.5-3.0%) was mixed with the sandy soil before compaction to make sure a small cementation of soil. The soil was located inside the container in layers and then compacted to the required density which equal to (16.86) kN/m² by a steel hammer of (4.5) kg, the falling height was between (150-200) mm and the No. of blows were (4) for each layer which was founded by making a relation between the No. of drops and the developed dry density, sand-cone method was used according to [7]. to insure the required density. A vibration of (1, 2 and3) Hz in x- direction was applied to the foundation using the shaking table technique which manufactured by [8], see Figure 2.

\[
k = \frac{E}{12Es} \left( \frac{d}{b} \right)^3
\]

Where:

\(E, Es = \) Modulus of compressibility of the foundation (26000 MPa), soil (17 MPa) respectively
\(b = \) Length of the section in the bending axis (200 mm)
\(d = \) Thickness of the raft foundation (was calculated by Eq.1 for K=0.5)
\(K=\)the relative stiffness factor (for K<5 the raft foundation is flexible)

3. Instrumentation and measurement of dynamic response

3.1. Linear Variable Differential Transformer (LVDT)
The maximum total settlement of raft foundation was recorded using two LVDTs placed at the edge and middle of the upper surface of raft foundation. The LVDTs transducers were calibrated by comparing the output voltage with a known deflection (using digital vernia).

3.2. Data Logger
The LVDTs were calibrated and connected to the data logger unit which provides a connection with the computer lap top. The data logger was calibrated to give direct readings for raft foundation settlement for both flexible and rigid raft. The data logger is of 2 channels for LVD readings, to attain the required accuracy, 10 reading were recorded every 1 second for each channel. The whole illustration of test components and measuring devices can be seen in Figure 3.
Table 1. Physical and mechanical properties of the used sand

| Property                                                                 | Value   | Standard of the test |
|--------------------------------------------------------------------------|---------|-----------------------|
| Specific Gravity, $G_s$                                                  | 2.68    | [9]                   |
| Gravel (> 4.75 mm), %                                                    | 0       |                       |
| Sand (4.75-0.075 mm), %                                                  | 99.5    | [10]                  |
| Silt and clay (< 0.075 mm), %                                           | 0.5     |                       |
| Unified soil classification system (USCS), Soil Type                     | SP      | [11]                  |
| Relative Density, DR%                                                    | 70      | —                     |
| Maximum dry unit weight $\gamma_d$ min, kN / m$^3$                       | 17.385  | [12]                  |
| Minimum dry unit weight $\gamma_d$ min, kN / m$^3$                       | 14.365  | [13]                  |
| Dry unit weight (used) $\gamma_d$, kN / m$^3$                           | 16.85   | —                     |

Figure 2. Shaking table photo.

(a) Testing model  
(b) Testing instruments

Figure 3. General view of testing model and instruments.
4. Results and discussion
The total settlement of raft foundation with time was recorded at the edge and the middle of the raft model using LVDTs.

4.1. Effect of embedment on the settlement of raft foundation
To study the effect of increasing the embedment depth on total settlement under dynamic load, the embedment depth of flexible and rigid raft foundation was increased from zero to (0.25B, 0.5B and B), Figures 4, 5 and 6 show the results of this variation. It can be seen that maximum total settlement decrease with increasing the embedment depth for all the excitation frequencies and for both flexible and rigid rafts, this results agrees well with [4] who stated that embedment gives noticeable decrement in dynamic response (displacement and excess pore water pressure) for all soil types but with different degrees. The summary of changing the maximum total settlement with the embedment depth for different earthquake excitation was recorded and presented in Table 2. Table 3 summaries the percentages of maximum settlement reduction comparing with surface embedded foundation. This behavior of raft foundation can be illustrated by the following points:

- More embedment depth means more contact surface area provided by basement walls gives larger side frictional forces which reverse the foundation settlement.
- Increasing embedment depth provides more confining pressure at the edges of the foundation leads to increase its stiffness and reduce the settlement.

![Figure 4. Variation of maximum total settlement with embedment depth under 1Hz.](image)

![Figure 5. Variation of maximum total settlement with embedment depth under 2Hz.](image)
Figure 6. Variation of maximum total settlement with embedment depth under 3Hz.

Table 2. Summary of variation of the maximum total settlement with embedment depth.

| Embedment Depth | Raft Type | Maximum Total Settlement (mm) | 1Hz | 2Hz | 3Hz |
|-----------------|-----------|-------------------------------|-----|-----|-----|
| 0               | Flexible  | 0.5                           | 1.7 | 6.3 |
|                 | Rigid     | 0.46                          | 1.57| 4.45|
| 0.25 B          | Flexible  | 0.26                          | 1.38| 1.85|
|                 | Rigid     | 0.23                          | 1.06| 1.41|
| 0.5 B           | Flexible  | 0.21                          | 1.26| 1.79|
|                 | Rigid     | 0.18                          | 0.82| 1.04|
| B               | Flexible  | 0.18                          | 0.62| 0.65|
|                 | Rigid     | 0.09                          | 0.56| 0.63|

Table 3. Summary of reduction percentages due to increasing embedment depth.

| Embedment depth (mm) | Raft foundation type | Reduction percentage | 1Hz | 2Hz | 3Hz |
|----------------------|----------------------|----------------------|-----|-----|-----|
| 0.25 B               | Flexible raft        | 48%                  | 19% | 71% |
|                      | Rigid raft           | 50%                  | 32% | 68% |
| 0.5 B                | Flexible raft        | 58%                  | 26% | 72% |
|                      | Rigid raft           | 61%                  | 48% | 77% |
| B                    | Flexible raft        | 62%                  | 64% | 90% |
|                      | Rigid raft           | 80%                  | 64% | 86% |

- As the vertical side area of basement increased as a result of increasing embedment depth, the applied forces transmitted to the surrounding soil by shear stresses, this dissipation of applied forces leads to reduce the settlement (the settlement is a function of the force).
Increasing the embedment depth increase in the system damping and result in reducing the footing vibration and settlement.

Figure 7 shows the effect of 3Hz excitation frequency on the soil at the case of zero embedment depth, the soil seems to be failed.

(a) flexible raft foundation.  
(b) rigid raft foundation.

**Figure 7.** The foundation failure under 3Hz excitation frequencies and zero embedment depth

### 4.2. Effect of raft thickness (flexible and rigid) on settlement

To investigate the dynamic behavior of flexible and rigid raft foundation, two different thicknesses are used flexible of 10 mm thickness and rigid of 23 mm thickness. The settlement – time readings had been recorded for all the tests, Figures 8, 9 and 10, represent the tests of 0.5B.

![Figure 8](image)

**Figure 8.** Settlement-time history at 0.5 B embedment depth, under 1Hz

![Figure 9](image)

**Figure 9.** Settlement - time history at 0.5 B embedment depth under 2Hz.
embedment depth for (1,2 and 3) Hz excitation frequency which had been chosen as a typical case to represent the effect of raft thickness on settlement with time. From figures, it can be seen that the total settlement of raft with time gave higher reading for flexible foundation than the rigid one. This response is attributed to the higher stiffness of raft foundation resulting from its higher thickness, moreover, increasing the thickness means larger side contact area and higher frictional force which resist the footing settlement. Figures 11, 12 and 13, show the effect of raft thickness for all embedment depths under 1Hz, 2Hz, and 3Hz respectively, from figures, it's clear that maximum settlement results for flexible raft were higher than those for rigid raft foundation, this conclusion agrees well with [14] who stated that the settlement of raft foundation under dynamic loading decreases with decreasing the ratio of raft diameter to raft thickness. Moreover, raft thickness of 10 mm (flexible) is more economical than raft thickness 23 mm.

Table 4 summarizes the percentages of reduction in maximum total settlement for rigid raft comparing with flexible raft foundation.

![Figure 10. Settlement - time history at 0.5 B embedment depth under 3Hz.](image)

![Figure 11. Variation of maximum settlement of flexible and rigid raft foundation under 1Hz.](image)
Figure 12. Variation of maximum settlement of flexible and rigged raft foundation under 2Hz.

Figure 13. Variation of maximum settlement of flexible and rigged raft foundation under 3Hz.

Table 4. Summary of redaction percentages of rigid raft maximum settlement comparing with flexible raft maximum settlement.

| Embedment depth | Reduction Percentage |
|-----------------|----------------------|
|                 | 1Hz  | 2Hz  | 3Hz  |
| 0               | 8%   | 8%   | 29%  |
| 0.25B           | 12%  | 23%  | 24%  |
| 0.5B            | 14%  | 35%  | 42%  |
| B               | 50%  | 10%  | 3%   |

5. Conclusions

- Generally, the experimental results indicated that the foundation embedment have a positive effect on raft dynamic response because it minimizes the settlement of foundation.
As the embedment depth increased from zero to B, the maximum settlement decreased by (62.64%, and 90%) for flexible raft under (1,2, and 3) Hz respectively, for rigid raft the maximum settlement decreased by (80%,64%, and 86%) under (1,2, and 3) Hz, respectively.

Generally, the larger reduction in the induced maximum settlement was when the embedment depth increased from zero to 0.25 B as the maximum settlement decreased by (48%,19%, and 71%) for flexible raft under (1,2, and 3) Hz respectively, for rigid raft the maximum settlement decreased by (50%, 32%, and 68%) under (1,2, and 3) Hz respectively. This reduction became smaller when the embedment depth increased to 0.5B comparing with raft embedded at 0.25B as the maximum settlement decreased by (19%,9%, and 3%) for flexible raft under (1,2, and 3) Hz respectively, and (22%, 23%, and 26%) for rigid raft under (1,2, and 3) Hz respectively. When the embedment depth increased to B, the percentages of reduction of maximum settlement comparing with that of raft embedded at 0.5B, were increased to be (14%, 51%, and 64%) for flexible raft under (1,2, and 3) Hz respectively, and (50%, 32%, and 39%) for rigid raft under (1,2, and 3) Hz, respectively.

The maximum settlement of rigid raft foundation was less than that for flexible raft foundation, the percentages of reduction of rigid raft maximum settlement comparing with flexible raft maximum settlement were ranged between (8% to 50%) as the embedment depth increased from zero to B under 1Hz excitation frequency. For 2Hz excitation frequency, the range was between (8% to 35%). When the excitation frequency became 3Hz, the range was between (3% to 42%).

For 3Hz excitation frequency, in case of zero embedment depth, the soil seems to be failed for flexible and rigid raft foundations.

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