Numerical Analysis for The Response of Skirt Circular Shallow Footing Resting on Sandy Soil under Pure Vertical Dynamic Loads

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Abstract: In this paper, the dynamic response of a circular skirt foundation resting on sandy soil subjected to pure vertical dynamic load was analyzed numerically using finite element software, PLAXIS 3D 2020. The linear elastic model was adopted to describe the behavior of the shallow concrete circular foundation with (1m) diameter and (0.2 m) thick and the soil underneath, with and without skirt. Different skirt's length to diameter ratios (L/D) (0.25, 0.5, 0.75, and 1.0), in addition to different skirt thicknesses (0.1, 0.15, and 0.2 m) were anticipated. A harmonic pure vertical load was applied on the foundation with an intensity of (10 kPa) at different frequencies of (10, 30, and 100) Hz. The results show that, in dry sand, skirts improve the foundation performance effectively by increasing its load carrying capacity and reducing the dynamic amplitude, particularly when the skirt (L/D) ratio becomes higher. Furthermore, increasing the applied load frequency decreases the dynamic amplitude due to increasing the inertia forces for both footing and underneath soil. However, the increase in the skirt's thickness does not influence dynamic amplitude, and it can be neglected for design purposes.

Keywords: Skirt footing; circular; sandy soil; numerical analysis; dynamic loading.

1. Introduction

The coupling between soil and structures must be taken into account when analyzing and designing structures constructed on and within the soil. Several methods, Analytical and Numerical, were implemented to achieve this goal. Among the numerical methods, finite element (FE) is a prominent procedure that has been used successfully to solve a wide range of soil-structure interaction problems [1]. The primary goal in designing a machine foundation is to limit movement to capacities that would jeopardize the satisfactory operation of the machine. Thus, a key component of a successful machine foundation design is the accurate analysis of the foundation response to the dynamic loads from the expected operation of the machine [2]. The vibration induced by operating machines was stimulated by elastic waves transmitted through foundations into the soil because they should generate small displacements. The standards for the foundations of the design machine require that the amplitude of displacement of vibration does not exceed a certain value [3]. Therefore, Machine foundations require special consideration because they transmit dynamic loads to soil and static loads due to the weight of the foundation, machine, and accessories. The dynamic load due to the operation of the machine is generally small compared to the static weight of the machine and the supporting foundation [4,5].

All foundations in practice are placed at a certain depth below the ground surface. As a result of this, embedment plays a significant role in the overall response of the foundation and needs to be carefully evaluated [6]. Increasing the depth of embedment of the foundation may be a very effective way of reducing the vibration amplitudes. However, the beneficial effects of embedment depend on the quality
of contact between the embedded sides of the foundation and the soil. Skirted foundation has been demonstrated as an alternative to conventional shallow foundation, where skirt leads to enhancement in bearing capacity and reduction in a settlement. Furthermore, their use is more beneficial in the case of foundations placed in loose sand. The performance of surface likely skirted footing will be slightly better than a shallow footing embedded at a depth equal to the skirt depth. This behavior could be possibly attributed to the additional shear stresses generated at the skirt-soil interface [7]. The study herein presents a practice to examine the performance of skirted foundations using a three-dimensional finite element analysis using PLAXIS 3D 2020. Assessments were accompanied to study the behavior of concrete circular skirted foundations rested on dry dense sandy soil subjected to pure dynamic vertical loads.

2. Numerical study
A typical numerical model was considered, which contained a circular concrete footing (1m) in diameter and (0.2m) in thickness and skirts, attached to the base slab of the footing along its boundary, with different heights and thicknesses rested in dry dense sand. The skirt has different (L/D) ratios (0.0, 0.25, 0.5, 0.75 and 1.0), (where, D: footing diameter, and L: skirt length), and thicknesses (0.1, 0.15 and 0.2) m. Dimensions of the hole model are chosen to be sufficiently remote to reach the acceptable accuracy of the results [8]. The footing with and without being subjected to pure vertical dynamic load with constant intensity (10 kPa) and different frequencies (10, 30, and 100) Hz.

2.1. Finite Element Modeling and Boundary Conditions
As mentioned earlier, dynamic finite element analysis of shallow foundation with and without skirt under vertical harmonic excitation is carried out herein using the finite element software PLAXIS 3D 2020. The boundaries of the soil are taken as (30×30×10 m), which are far away from the foundation to minimize the boundary effect around the machine foundation due to harmonic excitation. Absorbent boundaries are applied along vertical and horizontal boundaries to avoid the reflection of stress waves back to the failure domain. A (1 m) diameter footing exposed to a dynamic load with fixed intensity and different frequencies is placed at the middle of the top surface of a dense sand layer. In this analysis, a vertical vibration is applied, and the vertical amplitude of displacements was measured at the top center point of the foundation. Figure 1 illustrates a schematic diagram of the finite element model.

![Figure 1. Three-dimensional view of the model skirted Circular footing.](image-url)
2.2. Mesh generation - mesh mode
When the boundaries of the model are fully defined, the geometry has to be divided into finite elements in order to perform finite element calculations. A composition of finite elements is called a mesh. The mesh is created in the Mesh mode. The mesh should be sufficiently fine to obtain accurate numerical results. On the other hand, very fine meshes should be avoided since this will lead to excessive calculation times. The PLAXIS 3D program uses a fully automatic generation of finite element meshes. The mesh generation process considers the soil stratigraphy and all structural objects, loads, and boundary conditions. Figure 2 shows the finite element mesh of the numerical model.

![Finite element mesh of the numerical model](image)

**Figure 2.** Finite element mesh of the numerical model (PLAXIS 3D 2020).

3. Foundational models and parameters
The linear elastic model has been utilized to model the response of the soil, as well as the concrete foundation and the skirt. The linear elastic soil model is considered to be appropriate to model the soil response because the operation of machines should spread on very small dynamic stresses to the soil beneath compared with the static stresses (due to machines and foundation weights) in order not to generate large dynamic displacements which lead to unacceptable permanent settlement in the machine foundation [5].

The vibration of the machine has been applied in this stage utilizing a time-history finite element analysis. A total analysis time of (1 second) is considered in the analysis of this stage; this time is enough to capture the maximum amplitude of the dynamic displacement.

3.1 Foundation models
A circular foundation was used with diameters (D=1 m) with a thickness of (0.2 m), it was made of concrete, to simulate the prototype, with unit weight (ϒ = 24 kPa) and Young’s modulus (E=25×10^6 kPa). The diameter of the circular footing and thickness is kept constant throughout the analysis.

3.2. Skirts
Hollow concrete cylinders with several thicknesses (0.10, 0.15, and 0.20) m are assumed to be skirts attached to the outer perimeter of the foundation with different lengths to diameter ratios (0.25D, 0.5D, 0.75D, and 1.0D). These skirts were used to confine the soil laterally under the circular foundation model. Figure 3 illustrates the shape of both foundation and skirt, and Table 1 shows their properties.
Table 1. Finite element parameters of structure elements.

| Properties                        | Skirt | Footing |
|-----------------------------------|-------|---------|
| Material type                     | Concrete | Concrete |
| Unit weight, \( \Upsilon \) (kN/m³) | 24     | 24      |
| Material model                    | Linear elastic | Linear elastic |
| Young's Modulus, E (kN/m²)        | \( 25 \times 10^6 \) | \( 25 \times 10^6 \) |
| Poisson’s ratio (\( \nu \))       | 0.15   | 0.15    |
| Interface strength factor (Rinter)| 1      | -       |

Figure 3. Schematic view of the circular, skirted foundation  
(D: foundation diameter, L: skirt depth, t: skirt thickness).

3.3. Soil properties

Generally, for shallow foundations, the soil underneath should be compacted very well to increase its shearing strength and reduce settlement. Therefore, the soil used in this parametric study was considered to be dry dense sand. In general, specifications and criteria for operating machines required that the allowable permissible displacement amplitude be a very small value and extended between (0.2 mm) for low speed machine (less than 500 RPM) to (0.05 mm) for high-speed machines (more than 3000 RPM) [8]. As mentioned previously, the linear elastic model has been utilized to model the dynamic response of the soil, concrete foundation, and skirts to reduce the large permanent settlement. Table 2 illustrates the properties of soil; these values were selected from [9,10].

Table 2. Material properties.

| Material     | Material properties | Dense sand |
|--------------|---------------------|------------|
|              | Drainage type       | drained    |
| Soil         | Unit weight, \( \Upsilon \) (kN/m³) | 20         |
|              | Young’s modulus, E (kN/m²) | 50000     |
|              | Poisson’s ratio (\( \nu \)) | 0.34      |
| Machine      | Weight of machine, Wmach (kN/m²) | 8         |
4. Sinusoidal excitation

For machinery foundation, the most mutual problem relating to dynamic loading is that, Reciprocating machines and poorly balanced rotating equipment cause periodic dynamic forces ($\bar{q}$) [11].

$$\bar{q} = a \sin \omega t$$

where:

- $a$: maximum amplitude of dynamic force,
- $\omega = 2\pi f$, $f$: operating frequency, and
- $t$: time.

In this study, the amplitude of vertical dynamic load was kept constant and equals (10 kPa), while three frequencies of load application were taken (10, 30, and 100) Hz, and the time was measured (Sec.1) for all calculations.

5. Results and discussion

A response of shallow foundation with and without skirt subjected to pure vertical dynamic load resting on dry dense sand was evaluated numerically. A circular concrete foundation with (1 m) diameter and (0.2 m) thickness with skirt has different (L/D) ratios (0.25, 0.5, 0.75, and 1.0) and thicknesses (0.1, 0.15, and 0.2) m attached to its periphery supports a machine its unit weight (8 kN/m$^2$) and produces dynamic load its intensity is (10 kN/m$^2$) rotated in three different operating frequencies (10, 30, and 100) Hz was examined using PLAXIS 3D 2020. Figures 4 to 6 show the response of foundation without and with skirt for different (L/D) ratios, and thicknesses skirts are subjected to constant dynamic load intensity and different frequencies.

![Figure 4](image-url)

**Figure 4.** Dynamic response of circular, skirted foundation under load frequency of (10 Hz).
5.1 The effect of skirt thickness
From Figures 4 and 5, the alteration of skirt thickness has approximately no effect on the amplitude of displacement particularly when the skirt (L/D) ratio is small, and the operating frequency is low; meanwhile, when (L/D) increased and the frequency is increased, the thickness has a little effect on the amplitude of displaced (decrease the amplitude), for example for a skirt with (L/D = 0.75) and operating frequency equals to (100) Hz, the amplitude decreases from (0.013) mm for skirt thickness equals to (0.1) m to (0.01) mm for skirt thickness equals to (0.2) m. This is related to the fact that for all skirt (L/D) ratios and low to moderate operating frequency (10, 30) Hz, the change in the stiffness of the system (machine, foundation, skirt, and soil) is small due to the small difference between the unit weights for the soil and concrete. However, with increasing operating frequency (100) Hz and skirt (L/D) ratio, the inertia force increased due to increasing frequency and the vibrated mass as well. This finding agrees well with [12], who stated that the foundation thickness has a smaller effect on the dynamic response.

5.2. Effect of loading frequency
Figures 4 and 5 reveal the vertical amplitude of displacement of foundation affected by the frequency of the applied dynamic load, either it was without or with a skirt. The range of this displacement is altered between (0.14 – 0.06) mm for the foundation without skirt for the loading frequencies (10) Hz and (100) Hz, respectively. While for skirt foundation, the attach of the skirt to foundation boundary leads to a decrease the amplitude of displacement, especially for higher (L/D) ratio and frequency, as for example,
for \((L/D = 1.0)\). The amplitude of displacement varies between \((0.1 - 0.01)\) mm when the load frequency ranges between \((10 - 100)\) Hz, as shown in Figure 7. As mentioned earlier, this effect is due to the fact that the machine's speed increases. The amount of inertia forces of the foundation and the soil beneath increases due to increasing operating frequency and vibrated mass.

![Figure 6](image-url)

Figure 6. Dynamic response of circular, skirted foundation under load frequency of \((100\) Hz).

### 5.3. Effect of skirt \((L/D)\) ratio

The effect of altering skirt \((L/D)\) ratio on the response of the foundation for different frequencies can be summarized as: from the directly above figures; it can be clearly noticed that increasing \((L/D)\) ratio decreases the dynamic amplitude of displacement that generated as a result of applying dynamic load, where, the increasing of skirt length in the soil beneath leads to increasing soil confinement under the footing and as a result increasing the soil stiffness for all load frequencies and skirt thicknesses. However, for a small skirt ratio, for example \((L/D = 0.25)\), the skirt has no effect on the displacement amplitude, particularly for low loading frequencies.

It is worthy to state that the decrease in the amplitude of displacement as the length of the skirts increases related to the fact that the skirts help in distributing the load to a greater depth, which enables the skirted foundation system to behave in a manner similar to piers as noted by [13]. This means that the confined soil below the foundation becomes part of the foundation, and hence the load applied by the foundation will be distributed at a greater depth [14,15].
Figure 7. Dynamic circular skirted foundation response with different (L/D) ratios under different load frequencies of (10, 30, and 100) Hz.

6. Conclusions
A three-dimensional finite element model has been developed validated to study the efficiency of using structural skirts to reduce settlement of foundation subjected to machine vibration. The main conclusions are outlined below.

- In the skirt foundation, when subjected to pure vertical load, the displacement amplitude decreases with an increase in (L/D) ratio.
- Skirt Foundation has a significant effect on reducing the amplitude of displacement, especially with increasing the frequency of vibration (increasing the speed of the operating machine).
- The alteration of skirt thickness has approximately no effect on the displacement amplitude, particularly when the skirt (L/D) ratio is small and the operating frequency is low.

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