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Experimental Model for the Machine Foundation Response with Skirt Under Earthquake Loading in Sandy Soil

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Abstract

The machine foundation sometimes carries the vibration load developed from the machine run and the seismic load simultaneously. This issue is not covered enough in previous research, especially in the case of laboratory models. Therefore, this paper presents a laboratory model for the response of singly and doubly skirted foundations subjected to seismic loads in sandy soil. The soil was prepared to attain a relative density of 70% in a steel container with a dimension of (50*50*55) cm using the rain technique. Tests were conducted under the dynamic response with a frequency of machine of 30 Hz. A shake table is used; it is exposed to the Halabja earthquake with an intensity of (0.1 g). In addition, three directions of the machine concerning the axis of an applied load (0°,45°,90°) are selected. The ratio of the skirt depth to the machine foundation width (Ds/B) (single and double skirt) was (0,0.25,0.5). The results showed that high displacement can be obtained when the direction of rotation of the machine's operation is parallel to the direction of the earthquake, also reduced when the angle is 90° compared with 0^0. The best case for reducing lateral and vertical displacement is a double skirt at (Ds/B) =0.5 reached (15% and 13%) comparing to single and without skirt respectively.

Keywords: Skirts foundation, Machine foundation, Halabja earthquake, Dynamic response, Sandy soil

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1. Introduction

In general, earthquakes occur all over the world and can lead to significant damage in civil engineering projects [1] and [2]. Earthquakes cannot be predicted or even prevented [3]. To reduce the impact of earthquake problems, there must be a broad understanding of the dynamic loads resulting from the occurrence of earthquakes and to which the soil is exposed [4] and [5]. The seismic design of foundations depends on the amount of settlement of those foundations when earthquakes occur [6]. Seismic intensity is an important factor in determining the extent of settlement of the foundation [7] and [8].

As the distance between the foundation and the source of the seismic load increases, the effect of the seismic load decreases, the settlement of the foundation decreases, and the lateral displacement of the foundation also decreases by Al-Ameri et al. [9]. The direction of the seismic settlement of foundations built on sandy soil is usually estimated using simple analytical methods, but this estimation is not clearly understood [10]. In Iraq, these risks were noted based on the most recent earthquake in November 2017, which was called the Halabja earthquake [11]. To simulate the whole and most representative cases, the foundation sometimes carries the static and vibrational load, one of the well-known sources of the vibration produced by machines [12].

The dynamic load and earthquake impact should be considered in the design of the machine foundation. It is one of the most important elements in manufacturing constructions such as fertilizer,

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steel, petrochemical complexes, and power generation plants, consisting of several centrifugal and reciprocating machines [13] and [14]. The machine foundation usually supports the machine and transfers its loads to the ground and should determine its ability to stabilize and continue operating before and after the earthquake [15] and [16].

To reduce the settlement and the vibrations resulting from operating the machine when it reaches the soil, skirts are added to the machine foundation [17], which is a shallow foundation and consists of a base on the perimeter of this base, which is thin panels (skirts) [18]. These panels (skirts) are installed at different depths in the soil, and skirts are installed vertically within the soil [19]. The skirts used are sometimes of different lengths and different thicknesses and may include inner skirts in addition to outer skirts to enhance the stability of the foundation in the soil when loads are placed on it [20]. Among the factors affecting the effectiveness and efficiency of the work of skirts are [21].

1- The effect of skirt diameter.
2- The relative density of sandy soil.
3- Skirt depth, or how much the skirts are planted in the soil.
4- The Surface roughness of the model.

It is usually used in sandy soil because it is unstable soil and can move easily under the influence of loads, skirts help confine the sandy soil, stabilize it, make it a single mass under the foundations, and prevent it from moving when exposed to different loads [22], and [23].

It has recently been shown that it is possible to use skirted foundation as one of these methods because it has the following advantages: it is cheap, easy to install, and has less impact on the surrounding environment when used. [24].

The skirts are attached to the foundation and fixed well, it resembles an inverted bucket with a depth of D and a width of B. It comes in different shapes, including square, rectangular, and circular. The design of these skirts in all shapes improves the foundation's performance when exposed to loads [25]. As the depth of the skirt increases, that is, the ratio of the depth of the skirt to the width of the foundation D/B, the stability of the foundation increases when it is subjected to loads [26]. The settlement of the foundation is less in the case of a double skirt than in the case of a single skirt [27].

Based on previous studies, the performance of machine foundations in sandy soil is detailed in many studies. While not taking into account the number of variables like the presence of a skirt on the machine's foundation performance. On the other hand, the previous data included the influence of earthquake loading on the performance of traditional foundations. These studies do not include, for example, the influence of machine orientation concerning the earthquake direction, as well as the behavior of the foundation in case of combined vibration and earthquake load, which means the possible case for the project in the earthquake zone.

Based on that, conducting a practical test on laboratory models of skirted foundations in sandy soil when exposed to seismic loads becomes an important issue that needs to be addressed. The foundations connected to the single and double skirts were chosen in a rectangular shape to increase the surface area of the foundations to bear the vertical loads resulting from the vibration of the machine as well as the lateral loads resulting from the seismic load. In addition, it enhances the stability of the sandy soil sandwiched between the skirts and the foundation surface of the machine.

Therefore, this study includes the effect of the seismic load on the machine foundation with different orientations. As well as the effect of the presence of skirts (singly and doubly) with different ratios of the depth of the skirt to the width.

2. Testing program.

The testing program can be divided into the following stages:

2.1 Preparation of sand

Laboratory tests were carried out for it, as illustrated in Fig. 1 and Table 1. It was classified as poorly graded uniform sand (SP) according to the Unified Soil Classification System (ASTM,2006) D 2487 (Unified Soil Classification System).

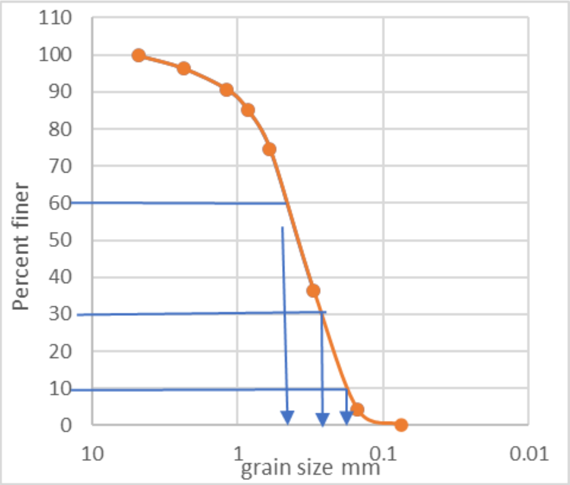

Fig. 1 The sand's grain size distribution curve.

Table1: Characteristics of soil.

Property	**Value**	**Standardization of the test**
Relative density Dr%	70	(ASTM,2006) D 2487
Cohesion, c(N/m2)	0	ASTM D3040-04(2006)
The angle of internal friction φ°	37	ASTM D3040-04(2006)
Specific gravity, Gs	2.68	ASTM D 854 (2006)
Maximum dry unit weight, γd max (kN/m^3)	18.64	ASTM D 4253 - (2006)
Minimum dry unit weight, γd min (kN/m^3)	15.95	ASTM D 4254 - (2006)
Grain size analysis D10(mm)	0.18	ASTM D 422 and ASTM D 2487 (2006)
D30(mm)	0.31	ASTM D 422 and ASTM D 2487 (2006)
D60(mm)	0.47	ASTM D 422 and ASTM D 2487 (2006)
Coefficient of uniformity, Cu	2.6	ASTM D 422 and ASTM D 2487 (2006)
Coefficient of curvature, Cc	1.13	ASTM D 422 and ASTM D 2487 (2006)

2.2 Model Apparatuses

The model consists of the following parts, as shown in Fig. 2.

1. Steel container with dimension (50*50*55) cm.
2. Rotary machine with foundation at dimension (20*25) cm [28-32].
3. Four sensors to measure vertical displacement.
4. Sensors to measure lateral displacement (two LVDT).
5. A sensor to measure the machine's acceleration.
6. Steel frame.
7. Hoper raining sand.
8. Shaking table device.
9. Digital tachometer
10. Machine foundation with skirted.

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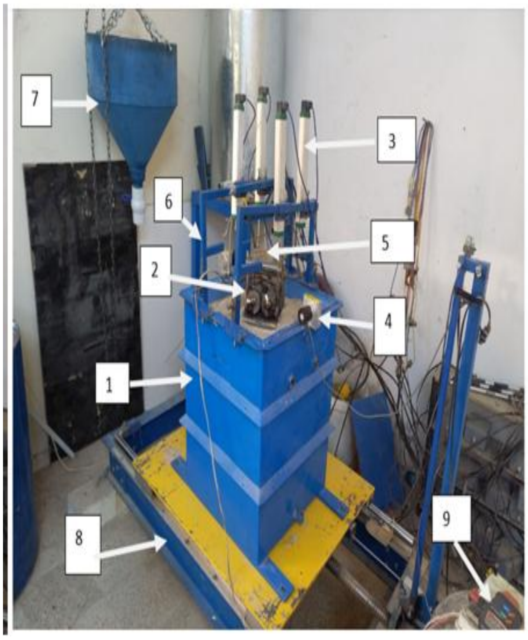


(A) with a skirt (B) without a skirt.

Fig. 2 Experimental details of the machine foundation and shaking table device (a)With a skirt, (b) Without a skirt.

2.3 Test details

This experimental study was conducted on a steel container, and cork with a thickness of 5cm was placed surrounding the walls of the steel container to reduce the reflection of the wave resulting from the impact of earthquake movement. This steel container is placed above the shaking table device and is fixed with screws to prevent deflection during experimental seismic shock. After that, the sand-raining hopper method was used [33-36]. The sand was poured into the steel container from a sand-raining hopper at a fixed height of 115 cm. The sand rain hopper is then raised 10 cm above the final level inside the steel container. This process continues until it reaches the final level. Finally, in the latest stage, the relative density was obtained, as shown in Fig. 3.

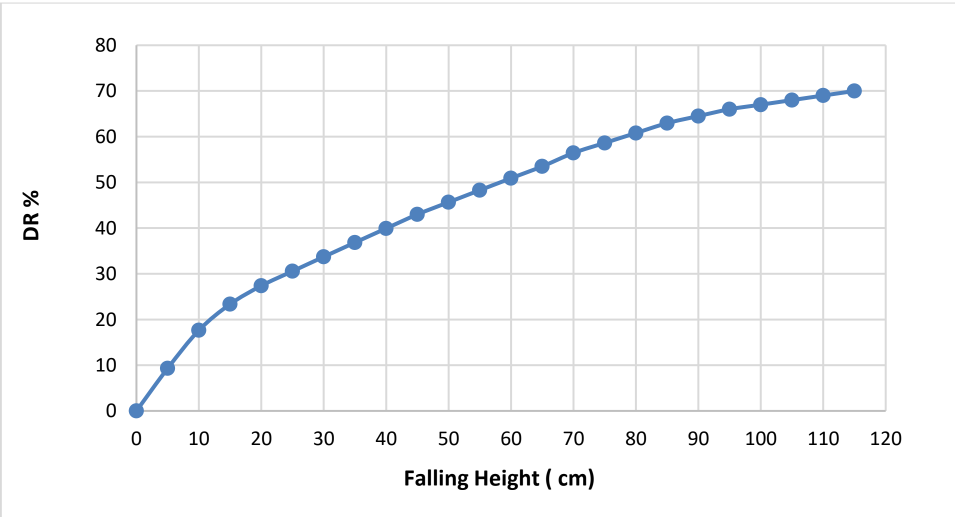


Fig. 3 Curve of relative density.

Single skirts were taken with a depth of (50,100) mm and a thickness of 5 mm, as well as double skirts with a depth of (50,100) mm and a thickness of 5 mm on the outside and 2.5 mm on the inside. These skirts were connected to the machine foundation through the welding process, as shown in Fig. 4.

After that, the skirted under the machine foundation was placed on the sandy soil, and loads were placed on it to enter it into the sandy soil [28], as shown in Fig. 5. In this experiment, the parametric study, such as the angle of the loading machine (0°,45°,90°) shown in Fig. 6. In addition, the frequency of the machine (30) Hz during the operation of the machine is shown in Fig. 7.

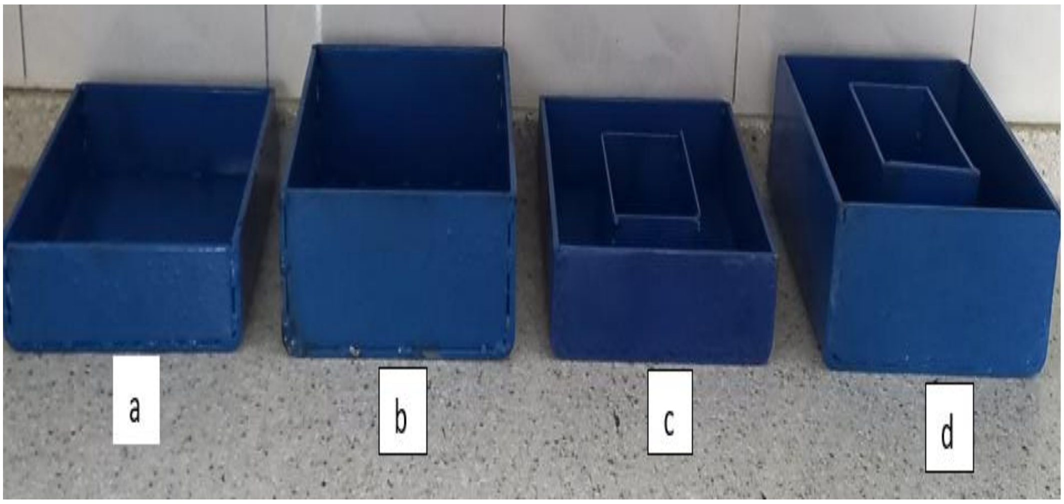
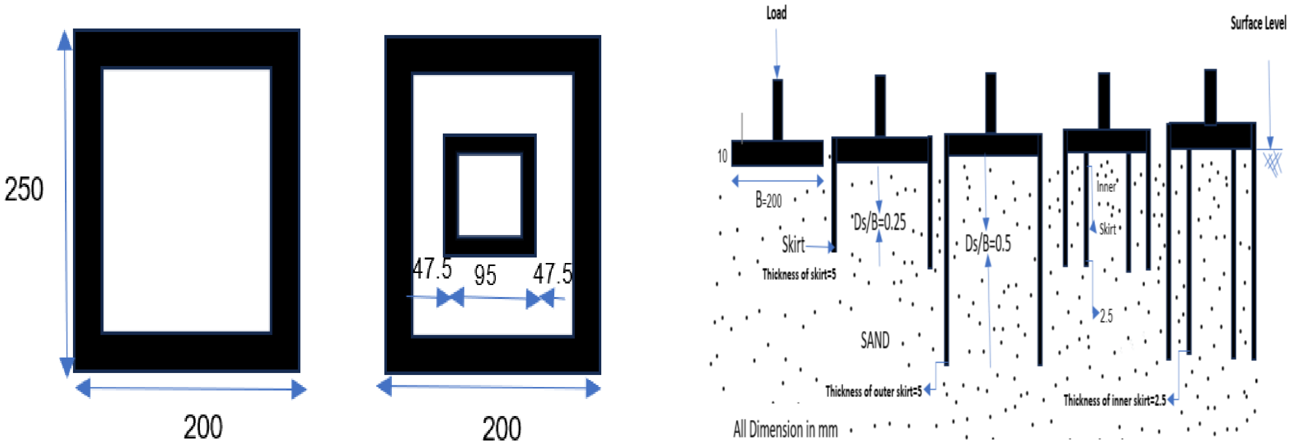


Fig. 4 Laboratory model of machine foundation skirts: a, b Single skirt at a depth (50,100) mm and c, d Doubly skirt at a depth (50,100) mm.



(A) doubly skirted (B) Cross section of singly and doubly skirted

Fig. 5 Diagram view of singly and doubly skirted [37].

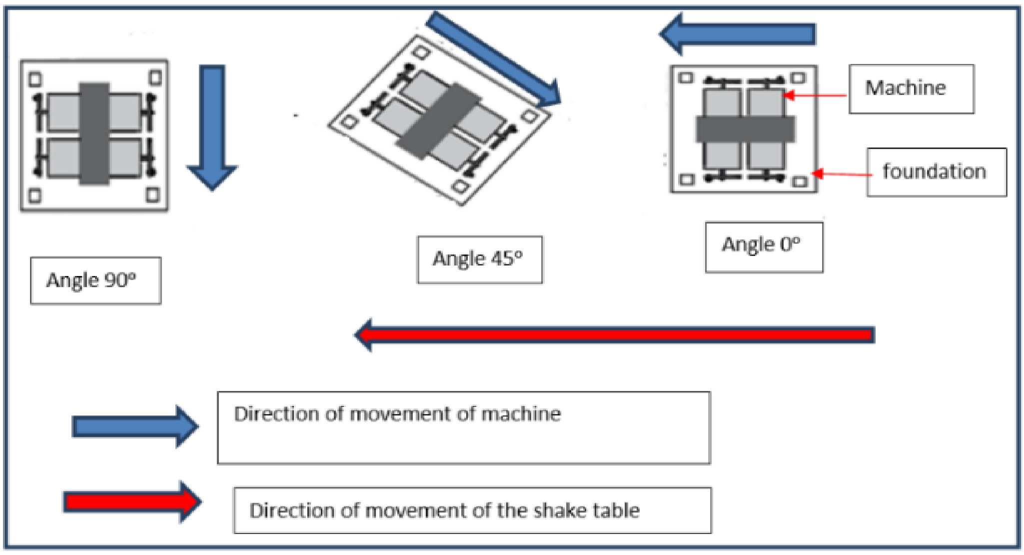


Fig. 6 Direction of positioning the machine according to the direction of movement of the shake table within different angles (0^0,45^0,90^0).

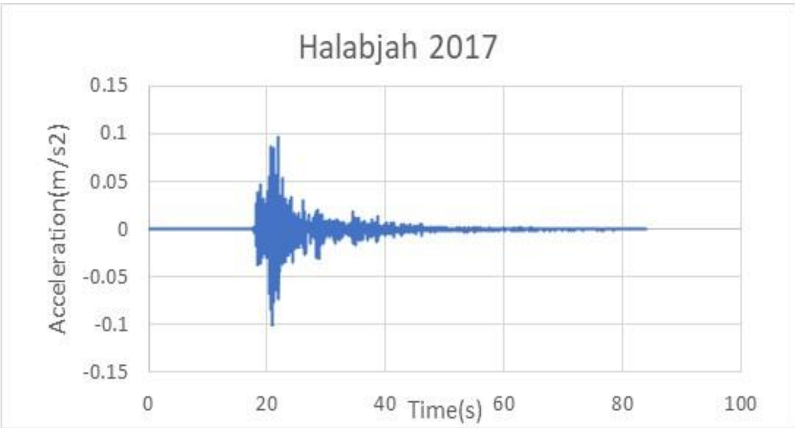


Fig. 7 Halabja input motion.

3. Result and Discussion

This study deals with a laboratory model of the behavior of machine foundation skirts under seismic load in sandy soil. In this case, the lateral and vertical acceleration of the machine, as well as the lateral and vertical displacement of the foundation simultaneously when applied seismic load.

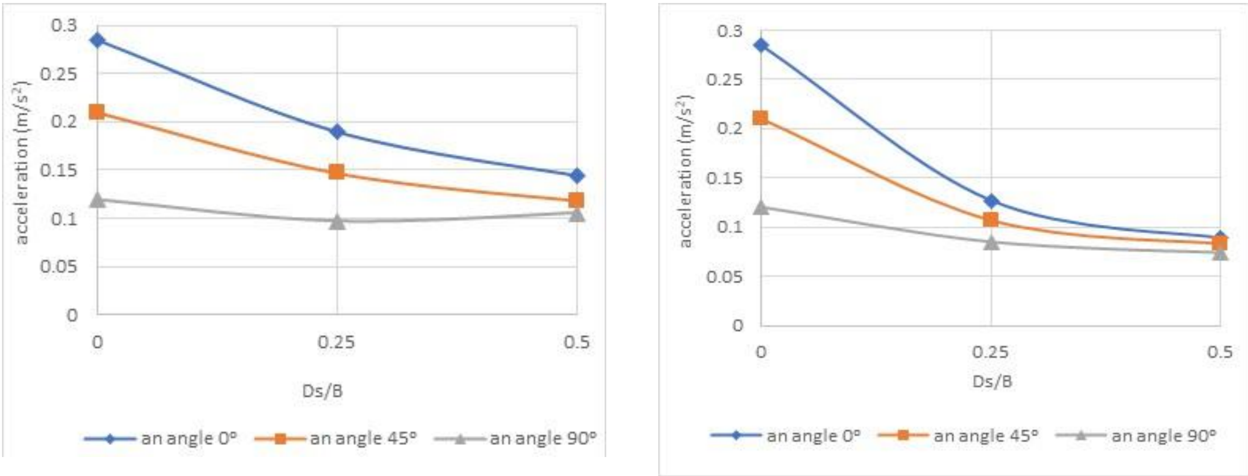
3.1 Acceleration

For the frequency of 30 Hz as illustrated in Fig.7, the difference in lateral acceleration vs. (Ds/B=0) of the machine foundation without a skirt under the influence of the Halabja earthquake in sandy soil, as shown in Fig. 8 (a). There are differences in acceleration between an angle 0° and an angle 45° and with 90°, the increase in the acceleration reached (36%, and 137%) respectively while the decrease when skirted singly and (Ds/B) =0.25 reached (29%, and 96%) respectively. Also, it is lower at (Ds/B) =0.5 reached (22%, and 37%) respectively.

In addition, it decreased even more in the case of double skirts as shown in Figure 8(b), acceleration was (19%, and 49%) respectively at (Ds/B) =0.25, and very less at (Ds/B) =0.5 reached (7%, and 20%) respectively.

As shown in Fig. 9 (a), the difference in vertical acceleration also increases at (Ds/B=0) and reaches (27%, and 165%, respectively. While it decreases when skirted singly at (Ds/B=0.25), the percent recorded at (22% and 62%) and (17% and33%) for (Ds/B=0.5).

On the other hand, in the case of double skirts as shown in Figure 9 (b) acceleration is more decrease and reaches (19%, and 41%) respectively at (Ds/B) =0.25, and becomes very less at (Ds/B) =0.5 reaches (16% and 27%).



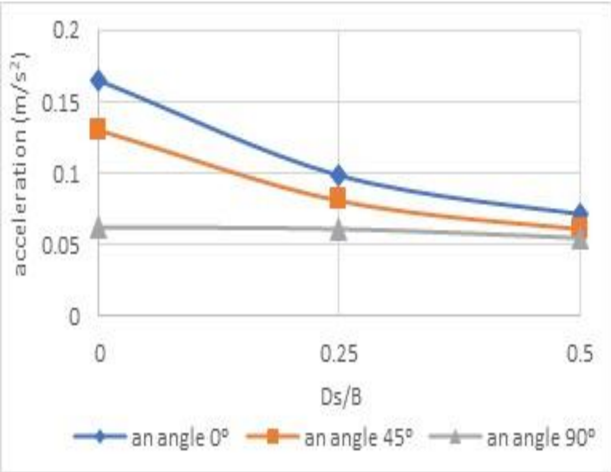
(A) at singly skirted

(B) at doubly skirted.

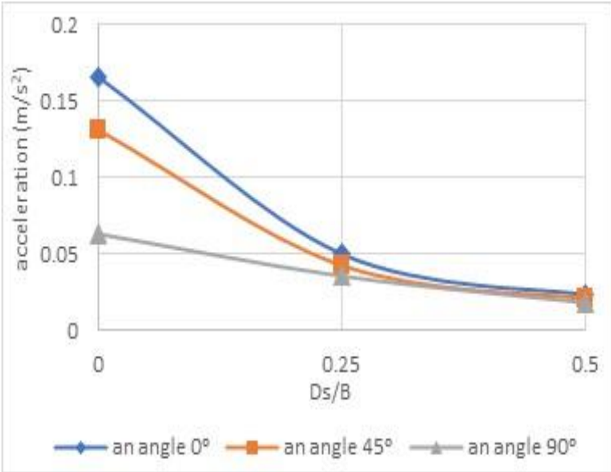
Fig. 8 Maximum lateral acceleration vs Ds/B.

It can be noticed that the acceleration is in the lateral direction and the vertical direction is higher when the machine foundation is placed on the surface of the sandy soil. The acceleration decreases when an addition of the skirt (singly and doubly) is to the machine foundation with a difference ratio of (Ds/B). This is due to the phenomenon of damping vibrations in skirted foundations increasing with the increase in the depth of the skirt, which reduces the acceleration compared to the foundation when placed on the surface of the soil. The sandy soil absorbs some vibration energy as the depth of the foundation planted in the sandy soil increases, which reduces the acceleration of the foundation.

The shear resistance of the foundation increases as its depth increases, which reduces the possibility of its vibration. Likewise, loads are distributed over a larger area as their depth increases, which reduces their effect on the foundation. The area of the foundation increases with its depth, which allows the loads to be distributed over a larger area. The solidity of the foundation also increases with the skirts as their depth increases, which makes it more resistant to vibrations, as the density of the soil increases with its depth, which increases the solidity of the foundation. The deeper the skirt, the less influence external factors such as earthquakes will have on the foundation skirts, the results are also recommended by [38], and [39].



(A) At singly skirted



(B) At doubly skirted.

Fig. 9 Maximum vertical acceleration vs Ds/B.

3.2 Displacement

In the frequency of 30 Hz, and compared between angles from 0° to 45° and 90° (illustrated in Fig. 4) the percentage of difference in the lateral displacement of the machine foundation without a skirt is shown in Fig.10(a), the displacement at the surface reaches (100%, and 178%) respectively.

The lateral displacement decreases in the case of the machine foundation with a single skirt at (Ds/B =0.25) and (Ds/B=0.5) reached (78% and 155%) and (21% and 101%), respectively. In addition, the lateral displacement of the machine foundation becomes very small when double skirts at (Ds/B=0.25) and (Ds/B=0.5) are reached (64% and 146%) and (15% and 72%), respectively. Shown in Fig.10(b).

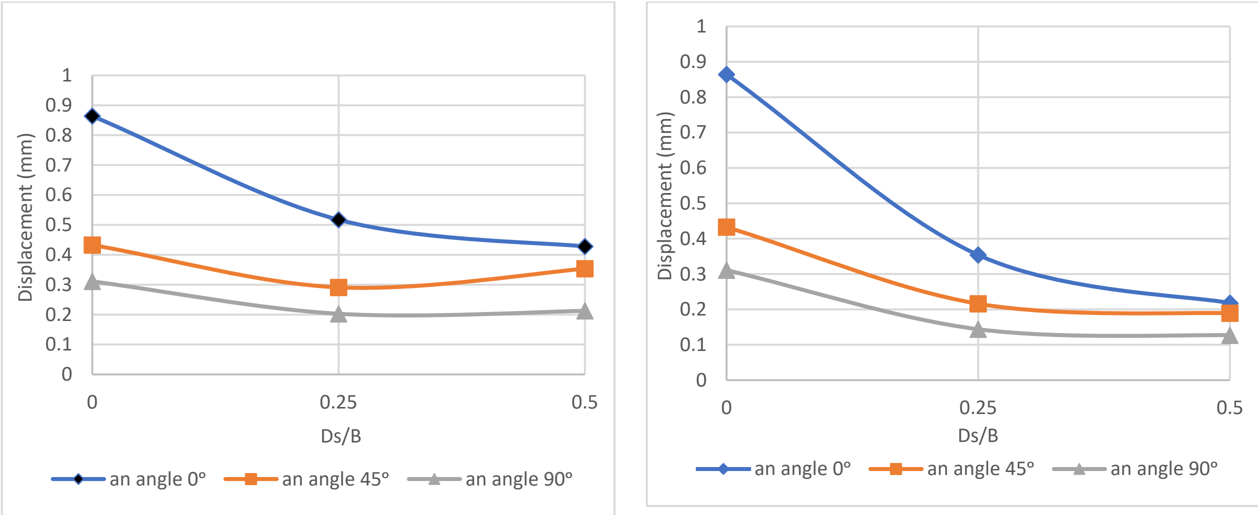
The percentage of difference in the vertical displacement is shown in Fig. 11 (a). In this case, the percentage of increase in vertical displacement when the machine foundation without a skirt was reached (50% and 105%). Comparing the machine foundation with a skirt at (Ds/B =0.25) and (Ds/B=0.5), the vertical displacement is less reach, (26% and 44%) and (17% and 36 %), respectively. Also, the vertical displacement is much less, as shown in Fig. 11(b) in the case of the machine foundation with a double skirt at (Ds/B =0.25) and (Ds/B=0.5) reached (18% and 32%) and (13% and 24%), respectively. It can be noticed that the displacement is in the lateral direction and the vertical direction is higher when the machine foundation is placed on the surface of the sandy soil.

The displacement decreases when an addition of the skirt (singly and doubly) is to the machine foundation with a difference ratio of (Ds/B). This is because friction resistance increases as the depth of the foundation with skirts increases, as the contact surface area between the foundation and the sandy soil increases. This leads to an increase in the friction between the foundation and the soil, which enhances the resistance to lateral and vertical displacement. In addition to confining the soil between the skirts and the bottom of the foundation surface, thus creating one solid and more cohesive mass, when exposed to loads, the result is also recommended [29].

As the length of the skirt increases, that is, the ratio of the depth of the skirt to the width of the foundation (D/B) increases, and the settlement of the foundation decreases when it is exposed to loads, the result is also recommended by Lepcha et al. [30]. The shear resistance of the sandy soil also increases, which works to resist the lateral forces that try to move the sandy soil, thus reducing the possibility of the foundation slipping. The bearing strength of the soil also increases when it is exposed to dynamic loads without sinking, thus reducing the possibility of foundation settlement occurring; the result is also recommended [31].

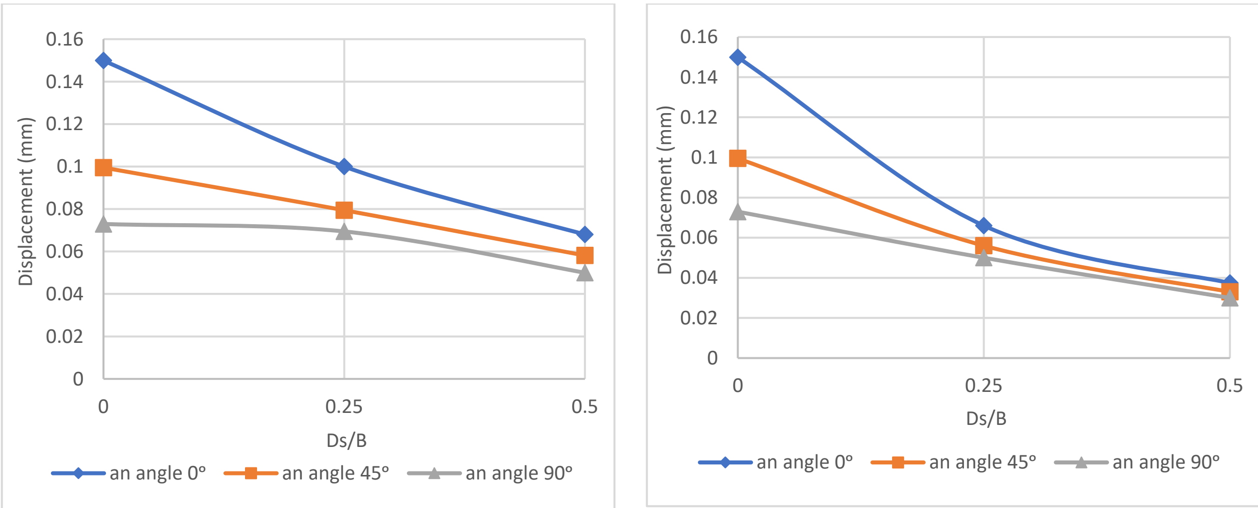
There is a better distribution of the dynamic loads to which the foundation is exposed with skirts, as the dynamic load is distributed over a greater distance from the sandy soil.

This reduces the dynamic load on each unit area of sandy soil, which reduces the possibility of the foundation slipping or settling. The ideal case for reducing lateral and vertical displacement is the double skirt case, as the foundation becomes more stable with the increase in the depth of the skirts, as well as when the skirts are placed double. This makes the foundation more resistant to the dynamic loads it is exposed to and reduces the possibility of vertical and lateral displacement.



(A) at singly skirted (B) at doubly skirted.

Fig. 10 Maximum lateral displacement vs Ds/B.



(A) at singly skirted (B) at doubly skirted

Fig. 11 Maximum vertical displacement vs Ds/B.

4. Conclusions

The results of the response of the machine foundation with skirts (single and double) under seismic load in sandy soil. With the use of different lengths for foundations with skirts (0, 0.25, 0.5), and placing them at different angles (0^o, 45^o, 90^o) to the direction of movement of the Halabja earthquake, the following conclusions can be drawn.

1. The acceleration (vertical and lateral) is higher when the direction of rotation of the machine's operation is parallel to the direction of the earthquake movement and less with the angle of 90^o. The acceleration is higher when the machine foundation is placed on the surface of sandy soil without a skirt, and becomes much less in the case of machine foundation with a skirt (singly and doubly) at (Ds/B=0.25) and (Ds/B=0.5) the percent recorded at (17% and 16%), (22% and 7%) respectively.

2. The displacement value (lateral and vertical) increases when the direction of rotation of the machine's operation is parallel to the direction of the earthquake and less when the angle is 90°. The displacement value (lateral and vertical) increases when the machine foundation is placed on the surface of sandy soil without a skirt. It decreases when the machine foundation with a skirt (singly and doubly) at (Ds/B=0.25) and (Ds/B=0.5), the percent recorded at (21% and 15%), (17% and 13%), respectively. The safest case is doubly a skirted.

Conflict of Interest

The authors declare that there are no conflicts of interest regarding the publication of this manuscript.

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