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Research Article

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Assessing the vibration response of foundation embedment in gypseous soil

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Abstract: One of the most critical engineering problems that occur in the foundations of machines resting on soil is the problem of the transmission of vibration from the machine to the foundation and then to the soil. This leads to increased stresses on the soil layers and increased settlement as well. In this article, an experimental model of the foundation of a rotary machine foundation located on gypseous sandy soil (36% gypsum content) has been studied. The weight of the machine model with the foundation was 26 kPa subjected to 10 Hz frequency. The study comprises investigating the effect of embedment depth on the behavior of the rotary machine foundation. The results indicated that resting the foundation on the surface of the soil leads to an increase in the amplitude displacement and the pressure in the region under the foundation. The increased embedment of the foundation to half the thickness of the foundation (0.5H) leads to a reduction in the displacement of the foundation. The amplitude displacement values remained within the permissible limits, while the settlement decreased about 37%. The increased embedment of the foundation to 1.0H gives more stability to the foundation, and increases the pressure in the soil layers, while the settlement decreases about 50%.

Keywords: embedment depth, machine foundation, vibration, gypseous soil

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1 Introduction

Machine foundation is one of the critical elements, which can be found in industrial structures like power plants, steel plants, petrochemical complexes, and fertilizer plants. It consists of several reciprocating and centrifugal machines which play an important role in ensuring efficient performance of the process. The vibration of a machine is associated with a large settlement of its foundation that may lead to a risk in the performance of the machines [1].

AL-Busoda and Alahmar [2] studied the behavior of dry and soaked gypseous soil under vertical vibration loading. The results showed that the displacement amplitude in the dry state is greater than that in the soaked state. In contrast, the resonant frequency in the soaked state is more significant than in the dry state. Similar, Al-Jeznawi *et al.* [3] stated that the deformation of the pile base is affected by moisture. Al-Helo [4] analyzed a dynamic response of a machine strip foundation resting on two layers of saturated sand in loose, medium, and dense states under a vertical harmonic excitation. It was found that the modulus of elasticity of the soil layers has a significant effect on the displacement. In the case of the modulus of elasticity of the upper layer (E1) greater than 2–4 times that of the elastic modulus of the lower layer (E2), a decrease in displacement occurs. The effect of soil heterogeneity under static and dynamic loading were studied by others [5–7]. Fattah *et al.* [8] investigated numerically the effect of vertical harmonic excitation on a strip machine foundation's behavior with multiple thicknesses resting on a saturated sand. The dynamic response decreases as the foundation embeds to a specific depth of about 1.0 m. Increasing the embedment of the foundation from 0.5 to 1 m causes a decrease in the vertical displacement obviously by 40, 37, and 46% for dense, medium, and loose sand, respectively. Beyond 1.0 m embedment, there are slight changes in the displacement obtained. The embedment increases damping, stiffness, and natural frequency, while the displacement and resonant amplitude reduces [9–11]. Abd-Almuniem [12] studied experimentally the dynamic response of machine foundation resting on sand-granulated rubber mixtures. He concluded that both settlement and amplitude displacements can be reduced by using granular rubber that increases the system's damping. Abdul Kaream *et al.* [13] stated that the bearing capacity of the underlying soil is affected by the shape of the machine foundation. The strain, amplitude displacement, and stress of dry sand under a circular foundation were 41, 17, and 12% higher than that exhibited by square and rectangular foundations. Karim *et al.* [14] studied the effect of machine vibration on the behavior of shallow footing supported by a saturated sandy layer. The risk of liquefaction increased under high amplitude load and frequency. The higher settlement was recorded at the top soil layer.

Previous studies indicated that the embedment depth of the machine foundation plays a major role in the dynamic response of the foundation and soil. Few studies considered the effect of machine vibration on the problematic gypseous soils [3,15–17]. Accordingly, the present study focused on the effect of the embedment depth of the machine foundation on the acceleration, amplitude displacement, settlement, and distribution of the contact pressure of gypseous soil.

2 Experimental work

2.1 Soil properties and sampling

The gypseous soil was taken from the vicinity of the Tikrit city (Al- Qadisiyah district) in the middle of Iraq. The laboratory tests were carried out to obtain the properties of the used soil. The results are listed in Table 1. The soil is classified as poorly graded sand (SP) according to the Unified Soil Classification System.

Table 1: Engineering properties of the soil

Properties	Gypseous Soil
Liquid limit (L.L) (%)	Non-liquid
Plastic limit (P.L) (%)	Non-plastic
Plasticity index (P.I) (%)	—
Gravel (%)	8.25
Sand (%)	83.17
Silt & Clay (%)	8.58
Specific gravity, (Gs)	2.522
USCS-Classification	SP

2.2 Experimental set-up

The testing model consists of four main parts: the test box, loading frame, foundation model, and loading system. The apparatus was manufactured locally and developed with the aid of design charts for machine foundations proposed by Fattah *et al.* [18].

2.2.1 The model of foundation and machine

A model with a rectangular foundation shape was used in this study, with dimensions of 100 mm × 200 mm and 500 mm in thickness. The foundation was made of steel material. It has a smooth bottom face and carries a vibration motor at its center over the motors as shown in Figure 1. Three embedments of foundation (depth of foundation) were adopted in the present study at the surface, no embedment, 0.5H, and 1.0H where H is the thickness of the foundation.

The vertical vibration of the machine foundation was generated by using a mechanical oscillator with a 10 Hz frequency. The machine's weight with foundation is 55 kg equivalent to 26 kPa. The rotation speed is controlled by an AC regulator. It was calibrated by a Tachometer to ensure its accuracy.

2.2.2 The test box

The box model under the study was prepared from a steel material with dimensions 900 mm × 900 mm and a

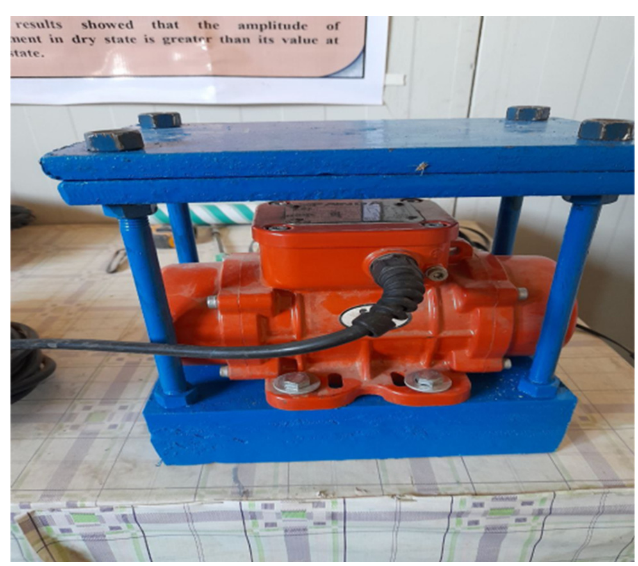

Figure 1: Model of machine and foundation.

Figure 2: The model of steel test box.

height of 800 mm. The box is made from a thick plate of 8 mm thickness to satisfy its rigidity against pressure. The configuration of the steel box model is shown in Figure 2. The soil was compacted inside the test box by dividing the box into layers each of 50 mm in thickness and preparing the soil with field moisture (5.14%) and compacted inside the box to achieve the field density of 15.17 kN/m^3 by using a dynamic compaction method as illustrated in Figure 2.

2.2.3 Instruments used in the study

The vertical displacement amplitude of the foundation in x, y, and z directions was measured at the surface of the foundation and at 1.0B under the foundation. Vibration meter (ADXL345 Digital Accelerometer) of three channels was used in the test.

Five cells of the load pressure and three pore water pressure sensors were inserted in the soil to record the

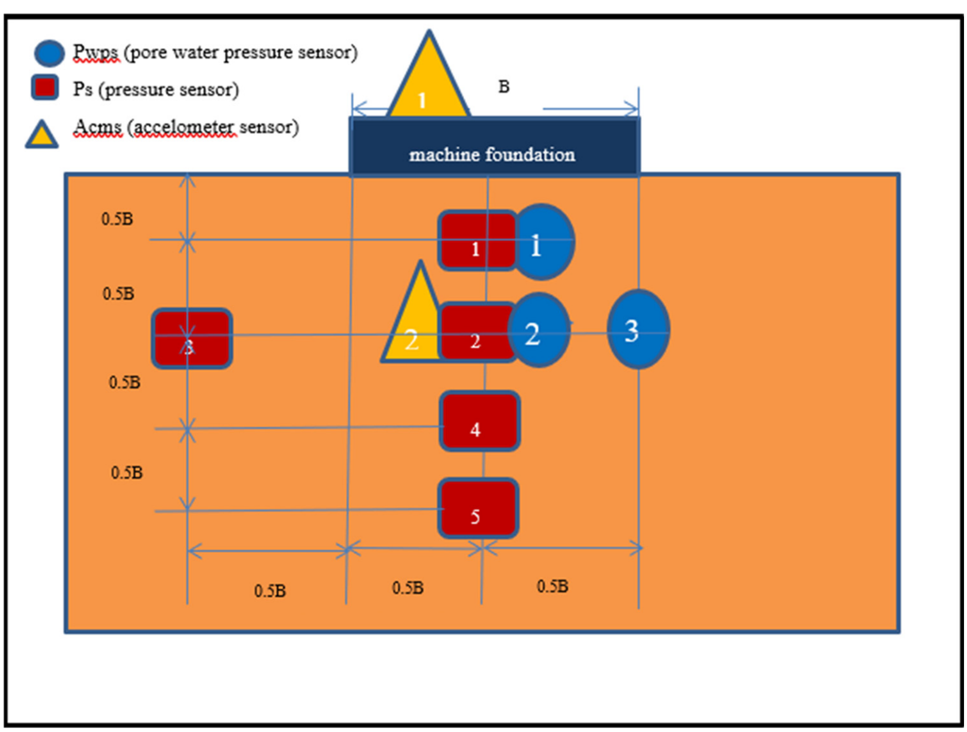

Figure 3: Distribution of sensors inside the soil.

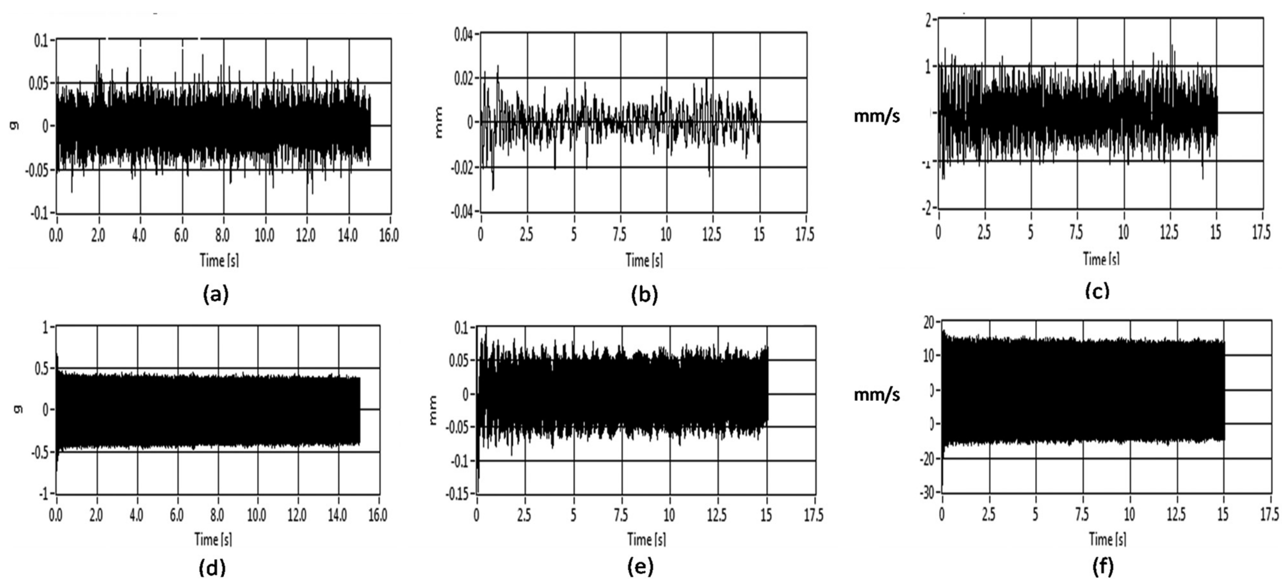

Figure 4: Variation in the amplitude of acceleration, displacement, and velocity with time measured at the surface of foundation embedment (0.5H). (a) Vertical acceleration, a_z; (b) vertical displacement, Az; (c) vertical velocity, Vz; (d) horizontal acceleration, a_v; (e) horizontal displacement, Ay; and (f) horizontal velocity, Vy.

variation in stresses under the foundation at depths 0.5B, 1.0B, 1.5B, and 2B. Figure 3 shows the distribution and locations of pressure cells.

The settlement of the foundation was measured through the LVDT equipment. A data acquisition device of 18 channels type M series was used to read the response of the pressure and displacement sensors.

3 Results and discussion

3.1 Effect of embedment depth on acceleration, displacement, and velocity

The relationship between the three variables acceleration, displacement, and velocity with the excitation period were recorded at the surface and depth 1.0B from the base of the foundation. The results are presented in Figure 4 for surface recording, while Table 2 shows the results for both at the surface and at depth 1.0B below the ground surface. It can be seen that the recorded amplitude displacements above and under the foundation 1.0B are 0.025 mm. The maximum amplitude displacements are within the permissible limit of 0.04–0.20 mm [19]. The horizontal amplitude displacements above and under the foundation 1.0B are 0.085 and 0.03 mm, respectively. The wave velocity in *Y*-direction, *i.e.*, the horizontal direction is higher than that recorded in the vertical *Z*-direction. This can be attributed to the fact that the foundation is moving horizontally freely because there is no side support for the foundation. The foundation without embedment exhibits low acceleration but the speed is high at the surface. However, the recorded speed at a depth of 1.0B is lower than that recorded at the surface due to the restriction of the movement of soil particles.

Table 2: Maximum amplitude under the vertical vibration (10 Hz)

Embedment condition	Measured location	Max. acceleration az (*g*)	Max. displacement Az (mm)	Max. acceleration ay (*g*)	Max. displacement Ay (mm)	Max. velocity Vz (mm/s)	Max. velocity Vy (mm/s)	Max. settlement (LVDT) (mm)
No embedment	At surface	0.075	0.025	0.45	0.085	1.0	15	4
	1.0B	0.07	0.025	0.06	0.03	1.0	1.0	
0.5H	At surface	0.05	0.04	0.05	0.03	1.0	2.0	2.5
	1.0B	0.04	0.025	0.05	0.03	1.0	1.0	
1.0H	At surface	0.15	0.06	0.15	0.05	3.0	3.5	2.0
	1.0B	0.15	0.05	0.12	0.06	3.0	2.5	

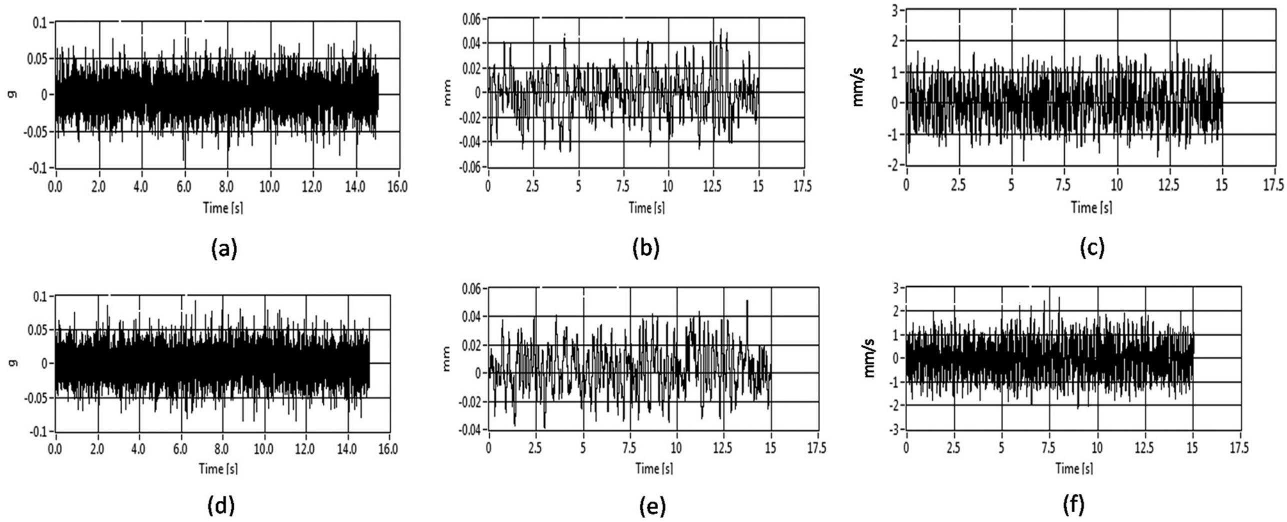

Figure 5: Variation in the amplitude of acceleration, displacement, and velocity with time measured at the surface of foundation embedment (0.5H). (a) Vertical acceleration, az; (b) vertical displacement, Az; (c) vertical velocity, Vz; (d) horizontal acceleration, a_v; (e) horizontal displacement, Ay; and (f) horizontal velocity, Vy.

From the results presented in Figure 5, it can be seen that the maximum amplitude displacement at the surface and at depth 1.0B varied between 0.025 and 0.04 mm of the foundation embedment at a depth of 0.5H which are given in Table 2; they are exhibited within the permissible limits of 0.04–0.20 mm [19]. The horizontal amplitude displacements of the embedment foundation are lower than that recorded when the foundation is located on the soil's surface without embedment. This is due to the stability and restriction of the movement of the foundation due to the embedment which reduced the freedom of movement of the side foundation towards the *Y*-axis; similarly, in the direction of vertical axis *Z* where friction between the soil and the side of the foundation restrict the vertical movement. The wave's speed in the case of an embedment foundation is lower than when the foundation is on the surface without embedment because of the fading of the vibration wave due to collision with soil particles as listed in Table 2.

Figure 6 along with Table 2 shows the acceleration, amplitude displacement, and velocity in the case of foundation embedment by 1.0H. Both the vertical amplitude displacement and horizontal amplitude displacement varied between 0.05 and 0.06 mm which are more significant than those recorded when the foundation was located on the surface of the soil without embedment. It is close to the

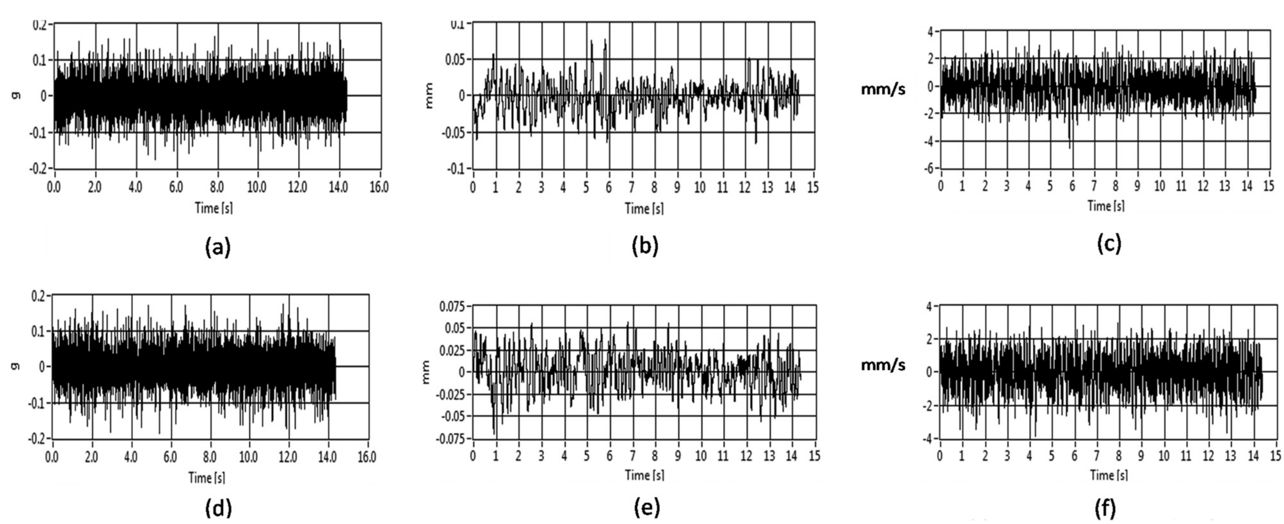

Figure 6: Variation in the amplitude of acceleration, displacement, and velocity with time measured at the surface of foundation embedment (1.0H). (a) Vertical acceleration, az; (b) vertical displacement, Az; (c) vertical velocity, Vz; (d) horizontal acceleration, a_v; (e) horizontal displacement, Ay; and (f) horizontal velocity, Vy.

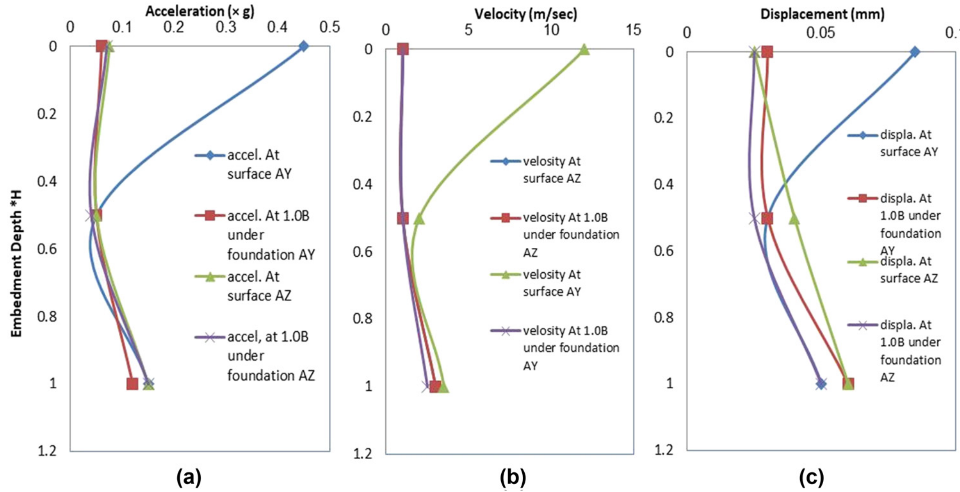

Figure 7: Relationship between embedment depth *vs* (a) acceleration, (b) velocity, and (c) displacement.

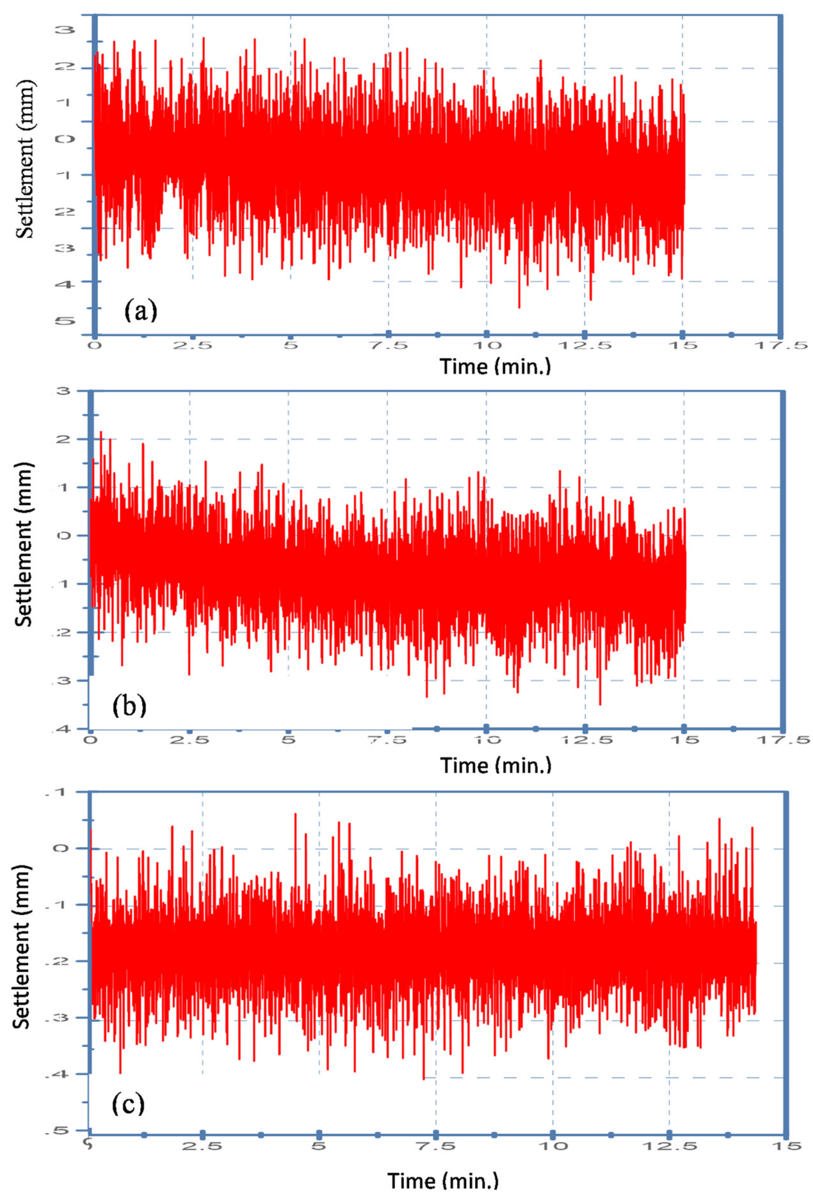

Figure 8: Variation in settlement with time under vertical vibration (10 Hz). (a) No embedment, (b) embedment = 0.5H, and (c) embedment = 1.0H.

results that are recorded when the embedment is 0.5H. This is also because of the stability and the movement restriction of the foundation. This restriction created as a result of the embedment surrounding the foundation has reduced the freedom of movement of the side foundation towards the *Y*-axis and the vertical direction of the *Z*-axis.

The summary of the results of the relation for maximum amplitude, acceleration, displacement, and velocity at horizontal and vertical directions with embedment depth are presented in Figure 7. Karim *et al.* [14] also stated that the displacement decreases with increase in the depth from surface.

3.2 Effect of embedment depth on settlement of foundation

The relationship between the settlement of the foundation and the excitation period is presented in Figure 8. It is known that the amount of the settlement recorded under the machine foundation depends on the frequency level as the low frequency limits the spread waves which affects the near field [20].

The results in Figure 8 show that the settlement of the non-embedment foundation is 4 mm. The settlement of the foundation embedment (0.5H) is 2.5 mm, which is less than the settlement observed when the foundation is located on the surface of the soil (without embedment) by 38%. This is because the foundation becomes confined within the soil, which reduces the force of impact between the foundation and soil and hence reduces the strength of the vibration waves transmitted to the soil particles. This led to a reduction in the rearrangement of soil particles and thereby reduced the total settlement of the foundation. Further foundation embedment, *i.e.*, at 1.0H from the surface, exhibited a settlement of 2.5 mm. The settlement of 1.0H embedment is less than that recorded in the case of non-embedment foundation by 50%, while it is approximately equal to 0.5H embedment. This is, as mentioned previously, because the foundation became confined inside the soil, which led to reduction in the force of collision between the foundation and the soil. Therefore, both the strength of the seismic waves transmitted to soil particles and the rearrangement of the soil particles reduced and, in turn, restricted the foundation's settlement.

The summary of the variation in the effect of embedment on the foundation's settlement is presented in Figure 9. The same results were achieved by others [8,21].

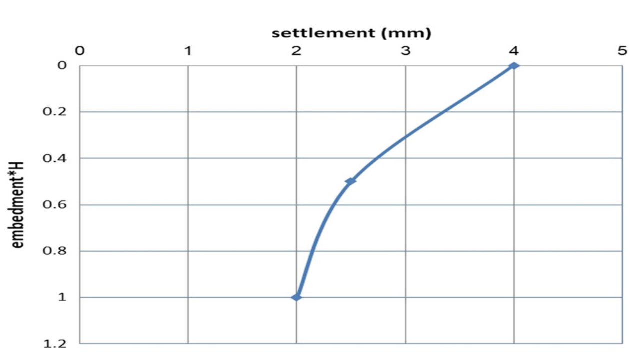

Figure 9: Relation between embedment depth and settlement under the vertical vibration (10 Hz).

3.3 Effect of embedment depth on distribution of pressure under foundation

Through Figure 10 and Table 3, it can be noted that under the frequency of 10 Hz, a significant increase in stress under the non-embedment foundation is recorded, especially the stresses at depths close to the foundation up to the depth 1.0B. The increase in stress was twice the applied pressure. The applied pressure is 26 kPa, while the recorded stresses are 55 and 45 kPa at depths of 0.5B and 1.0B, respectively. These stresses decrease with increased depth but remain higher than the applied pressure. The reason is that the low frequency generates impact force between the foundation of the machine and the soil as impact load causes high-pressure generation on the soil layers. Moreover, the intensity of the pressure on the soil at a 10 Hz frequency has been constant and small since the beginning of the oscillation. Then, it decreases with increased depth during the period of

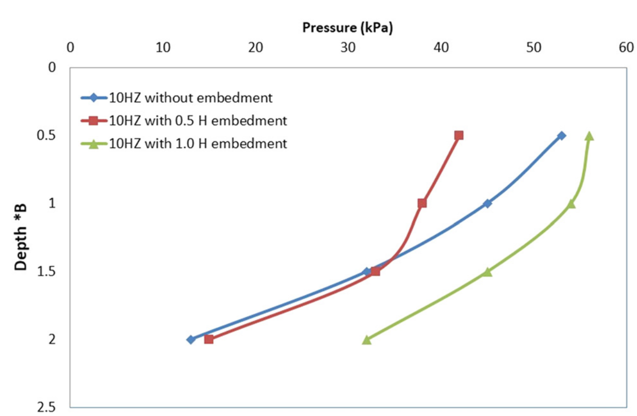

Figure 10: Variation in stresses in soil under vertical vibration.

Table 3: Distribution of pressure under the vertical vibration (10 Hz)

Embedment condition	Max. pressure p1 (kPa)	Max. pressure p2 (kPa)	Max. pressure p3 (kPa)	Max. pressure p4 (kPa)	Max. pressure p5 (kPa)
	Measured location				
	0.5B	1.0B	(1.0B, 1.0B)	1.5B	2.0B
No embedment	55	45	5	32	13
0.5H	42	34	6	33	14
1.0H	56	54	9	45	32

oscillation. The stress on the side of the foundation and at the distance and depth B from the center of the foundation is low and stable over the period of oscillation as shown in Figure 10 and Table 3.

On the other hand, the embedment foundation exhibits a decrease in stress, up to 1.0B depth. It is clear that the embedment causes a reduction in the stress concentration under the foundation. When the foundation embedment is 0.5H, the stresses are decreased to 42 and 34 kPa at depths of 0.5B and 1.0B, respectively. These reduce the stresses due to foundation embedment 0.5H by about 23.6 and 24.4%. Again, the pressure on the soil at 10 Hz frequency has been constant since the beginning of the oscillation and with low intensity. It decreases with the depth of the soil and during the period of oscillation. The pressure on the side of the foundation and at the distance and depth B is low and constant as illustrated in Table 3 and Figure 10.

For the case of 1.0H foundation embedment, it is observed from Figure 10 and Table 3 that under the 10 Hz frequency, there is an increase in the stresses near the foundation as in the case of 0.5H embedment. An expected increase in stresses occurs in the soil under the 1.0H embedment foundation compared to that observed in the case of 0.5H embedment. The stresses increased to 56 and 54 kPa at depth 0.5B and 1.0B, which refer to an increase in stresses by 25 and 37%, respectively. In addition, the value of the stress recorded is higher than that recorded when the foundation is located on the soil surface. It is also noted that the pressure on the soil at 10 Hz frequency remains constant with medium intensity during the period of oscillation. Thereafter, it decreases with increased depth of the soil. Similarly, in other cases, the pressure on the foundation side and at a distance and depth is low and stable along the period of oscillation. Same findings were reported by Abdul Kaream *et al.* [13] that the stresses induced at depth B is higher than that recorded at 2B by 58%. Fattah *et al.* [8] also reported that the stress decreases with depth.

4 Conclusion

The following conclusions can be drawn from the results obtained in the present study:

1. For the increasing embedment of footing from 0H to 0.5H, the vertical acceleration is decreased by about 33% and it is increased by about 100% when the embedment is 1.0H. The vertical displacement increases by about 60 and 140%, respectively when the embedment increased from 0H to 0.5H and 1.0H. The increase in embedment from 0H to 0.5 H is not affected by the vertical velocity, but it increases by 200% when the embedment is 1.0H
2. The horizontal acceleration is decreased by about 88 and 66%, and the horizontal displacement is reduced by about 65 and 29%. Also, the horizontal velocity decreases by about 87 and 77%, when the embedment increases from 0H to 0.5H and 1.0H, respectively.
3. The pressure under the footing is decreased by about 23% when the embedment of the footing increases from 0H to 0.5H, and it increases to the same value when the embedment increases from 0.5H to 1.0H.
4. On increasing the embedment from 0H to 0.5H and 1.0H, the footing's settlement is decreased by 37 and 50%, respectively.

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