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Effect of Frequency of Harmonic Dynamic Load on the Response of Sandy Soil

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Abstract

This study explores how different values of frequencies of harmonic dynamic load affect the vertical displacement of soils located directly underneath the foundation. A wide range of frequencies (1 – 50 Hz was selected in this study, in addition to four types of sandy soil underneath the foundation: loose, medium, dense and very dense with modulus of elasticity, E of 7000, 19000, 36000 and 70000 kN/m^2 respectively. Each type of soil was subjected to three levels of distributed dynamic stresses named 100, 200 and 300 kN/m^2. The simulation was carried out theoretically using a two-dimensional software finite element model (FEM) in PLAXIS 2-D package. Two models were used to simulate the soil: elastic and Mohr–Coulomb (M-C) models. The results showed that the vertical displacement underneath the foundation decreases with increasing the load frequency for all types of sandy soil investigated in this study and for all values of dynamic load. There is a sharp drop in vertical displacement when the load frequency increased from 1to 10 Hz. The vertical displacement remains constant regardless the value of dynamic load when the load frequency exceeds 30 Hz. Finally, the drop in vertical displacement at first parts of curves (frequency from 1 to 10 Hz.) is sharper in loose sand compared with other types of sandy soil i.e. medium, dense and very dense.

Keywords: Sandy soil, Harmonic dynamic load, Load frequency, Numerical modeling, Modulus of elasticity, Vertical displacement.

1. Introduction

The behavior of soil under dynamic load is completely different from its behavior under static load. Early studies by Seed and Idriss [1] and Kramer [2] helped to understand how soil medium behaved under dynamic loading. However, it remains less clear how the frequency of dynamic load alters soil behavior. The goal of the study is to provide a tool for engineers that not only predicts how soils respond to frequency of harmonic dynamic load but also explains these responses as much as possible. Notably, the soil does not dissipate energy as efficiently as expected in other words, its extraction rate is very low meaning that the soil retains dynamic energy longer, and this explains the way of the variation of displacement with time. This phenomenon must be taken into account in design of machine; foundation subjected to seismic and other structures exposed to different types of dynamic loads [1], [2], [4], [8], [9].

The studies established key parameters of soil like shear modulus and damping. Later, Vucetic and Dobry [3] introduced more advanced models that approach the complex and nonlinear behavior of soil under cyclic loading taking the plasticity of the soil into account. More numerical studies, such as the study performed by Nguyen et al. [4], have validated the numerical model against experimental one. Studies conducted by Sivapriya et al. [5] and Allawi et al. [6] refined these models further, highlighting the effect of different of dynamic loads and frequencies on the behavior of sandy soil. Additional works by Sun et al. [7], Ates et al. [8] and Cui et al. [9] have investigated load–settlement behavior for a sandy soil subjected to different types of dynamic loads like random and pulse and seismic, highlighting that sandy soils often have a low rate of dissipation of energy. Generally, the soils tend to hang on to energy rather than dissipate it quickly and the rate of dissipation depends on the type and nature of the soil itself.

Further studies by Wichtmann et al. [10] and Liu et al. [11] have experimentally and numerically explored dynamic soil-structure interaction and the impact of seismic and cyclic loads on sandy soil. Research conducted by Ungureanu et al. [12] and Hataf et al. [13] has advanced the modeling of sandy soil behavior under various of dynamic loading conditions, illustrating the importance of soil heterogeneity in real-world applications. These two studies combined numerical analysis with experimental simulation. Additionally, recent findings by Samanta et al. [14] and Nong et al. [15] have contributed new insights into the behavior of sandy soils under harmonic and pulse loading conditions. The studies focused on investigating deformation and the stress-strain relationship.

The current study investigated how different values of frequencies of harmonic dynamic load effect the vertical displacement of soil and foundation. In addition, the load frequency, the soil modulus of elasticity and the value of dynamic load were also investigated in this study. The simulation was carried out using a two-dimensional finite element model (FEM) in 2-D PLAXIS package. Two models were used to simulate the soil: elastic and Mohr–Coulomb (M-C) models.

2. Methodology

In this study, the vertical displacement at the point located directly beneath the center of foundation resting on the sandy soil was studied. The effect of load frequency (f) on the vertical displacement was investigated for all types of sandy soil and for all levels of dynamic load. Four types of sandy soil were selected in this study named loose, medium, dense, and very dense. Table1 shows the properties of the soils used. In addition to, three levels of dynamic stress were subjected to foundation: 100, 200 and 300 kN/m^2, assigned as load 1, load 2 and load 3 respectively.

Table 1: Properties of the soil used (after Burt Look, [16])

Soil type	Elastic modulus, E (kN/m^2)	Soil friction, φ (^{O})	Unit weight, γ (kN/m^3)	Poisson's Ratio, υ
Loose	7000	30	15	0.3
Medium	19000	35	17	0.3
Dense	36000	40	19	0.3
V. dense	70000	45	21	0.3

A two-dimensional FEM model, PLAXIS package used in this study. The soil is modeled using elastic and Mohr–Coulomb models.

Regarding the boundary condition of the problem in this study, standard fixities were used. This boundary condition gives total and horizontal fixities at bottom and vertical boundaries respectively. On the other hand, to avoid dynamic wave reflection at the ended lines of the geometry a special boundary available in PLAXIS 2D was used called Absorbent Boundary. The normal and shear stresses at these boundaries are [17]:

$$\sigma_n = -C_1 \cdot \rho \cdot V_p \cdot \dot{u_x} \quad (1)$$

$$\tau = -C_2 \cdot \rho \cdot V_s \cdot \dot{u_y} \quad (2)$$

where:

V_p: Longitudinal or compressive velocity of the wave

$V_p : \sqrt{(E_{oed}/\rho)}$ (3)

E_{oed}: $(1-\upsilon).E / (1+\upsilon)(1-2\upsilon)$ (4)

G: $E / 2(1+\upsilon)$ (5)

E_{oed}: oedometer modulus of elasticity

$\dot{u_x}$: Velocity wave towards x

$\dot{u_y}$: Velocity wave towards y

E: Modulus of elasticity (kN/m^2)

G: Shear modulus (kN/m^2)

ρ: Soil density (kg/m^3)

υ: Poisson's ratio of the soil

C1, C2 = Relaxation coefficient

The relaxation coefficients (C1, C2) were added to the formulas of normal and shear stresses, Eqs. (1) and (2) respectively, in order to express the wave absorption at the boundaries. The values of C1 and C2 are taken as 1.0 and 0.25 respectively in the case of shear and compressive waves [18]. The dimensions of the foundation used in this study 1 m thick and 4 m width. A plane strain model was used in analysis to simulate the long side of foundation, i.e. zero strain at his side.

3. Results and discussion

Figure 1 shows the variation of vertical displacement (mm) with dynamic load frequency (Hz) at a point located directly beneath the center of the foundation using elastic model of soil. Generally, it can be seen that the vertical displacement decreases with increasing the load frequency. The sharp drop in vertical displacement occurs when the load frequency increases from 1 Hz to about 10 Hz. Then the vertical displacement reaches a steady state when the load frequency exceeds 30 Hz for all values of load. This means that at this stage of dynamic load frequency (more than 30 Hz), the vertical displacement remains constant regardless of the value of the load. This conclusion gives an advantage to high frequency machine compared to the low frequency one in reducing vertical displacement. This behavior is due to that as the load frequency increases, the effective period of the load decreases therefore the vertical displacement decreases. This behavior is valid for all types of soils used in current study i.e. soft, medium, dense and v. dense.

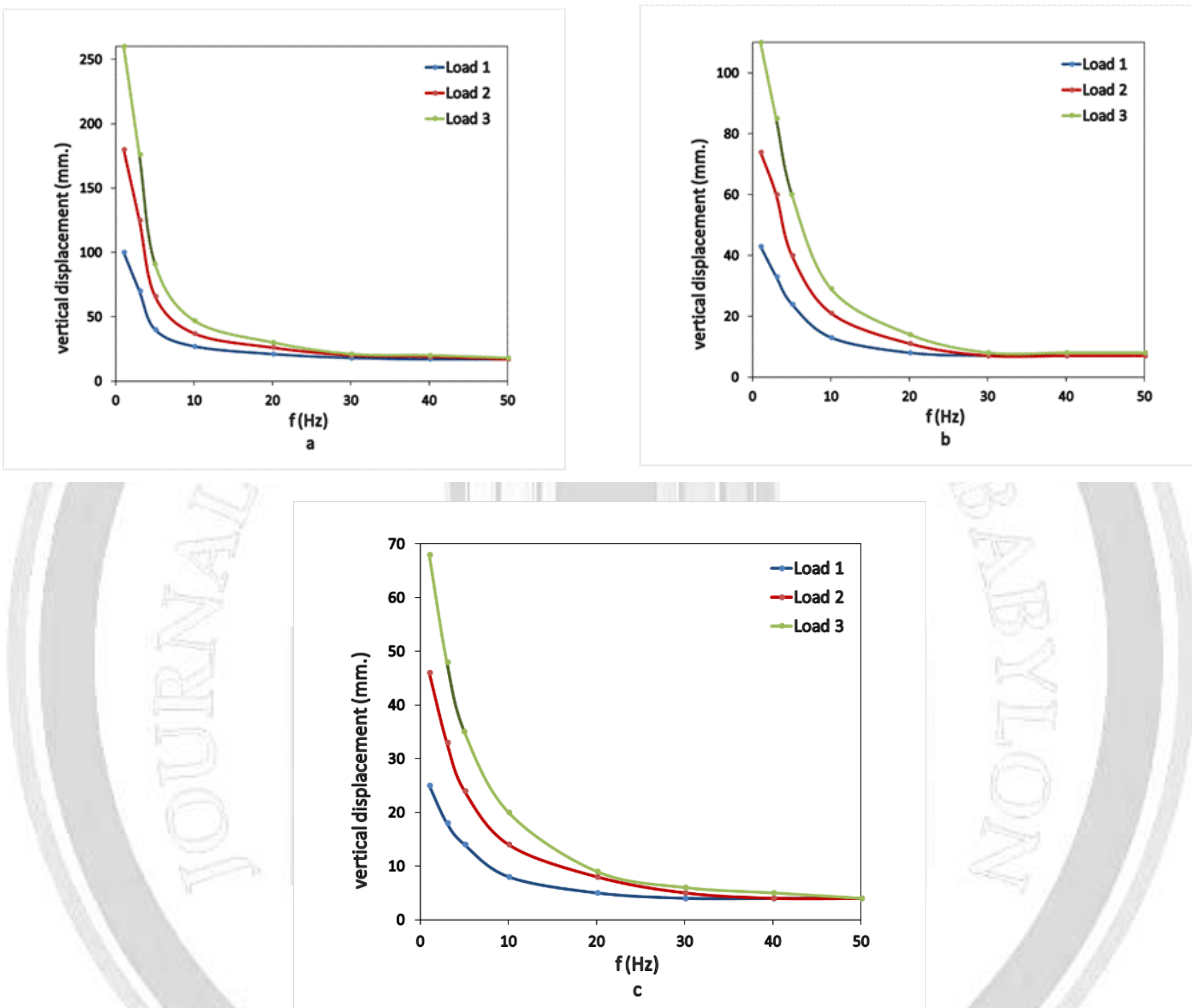

Figure 1. Load frequency (f) versus vertical displacement for a) loose b) medium c) dense d) v. dense soils using elastic model of soil

Figure 2 also shows the variation of vertical displacement with load frequency but by using Mohr–Coulomb (M-C) model for the soil. It can be noted that the curves are similar to counterparts of those of elastic model (Fig.1) regarding the sharp decline in vertical displacement for load frequency between 1 and 10 and the steady state of vertical displacement when load frequency exceeds 30 Hz. Howeverthe M-C model gives higher values of vertical displacement.

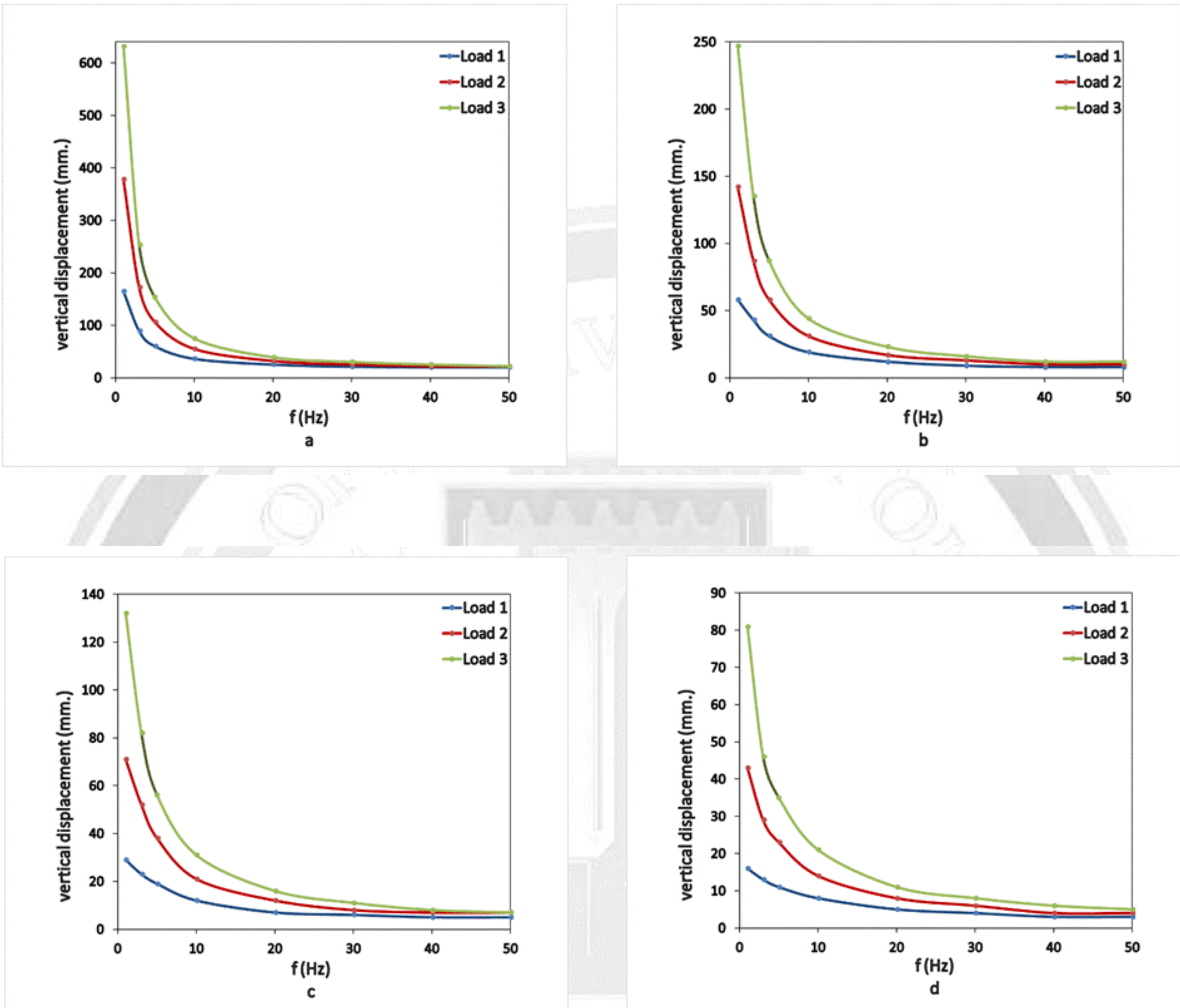

Figure 2. Load frequency (f) versus vertical displacement for a) loose b) medium c) dense d) v. dense soils using M.C model of soil

Figure 3 shows the comparison in vertical displacement between two soil models used in current study, i.e. linear elastic model and Mohr–Coulomb (M-C) model. It can be noted that the M-C model gives high value of vertical displacement compared with linear elastic model. This difference between the two models is due to the nature of each model, whereas the M-C model depends on the elastic – perfect plastic properties of the soil.

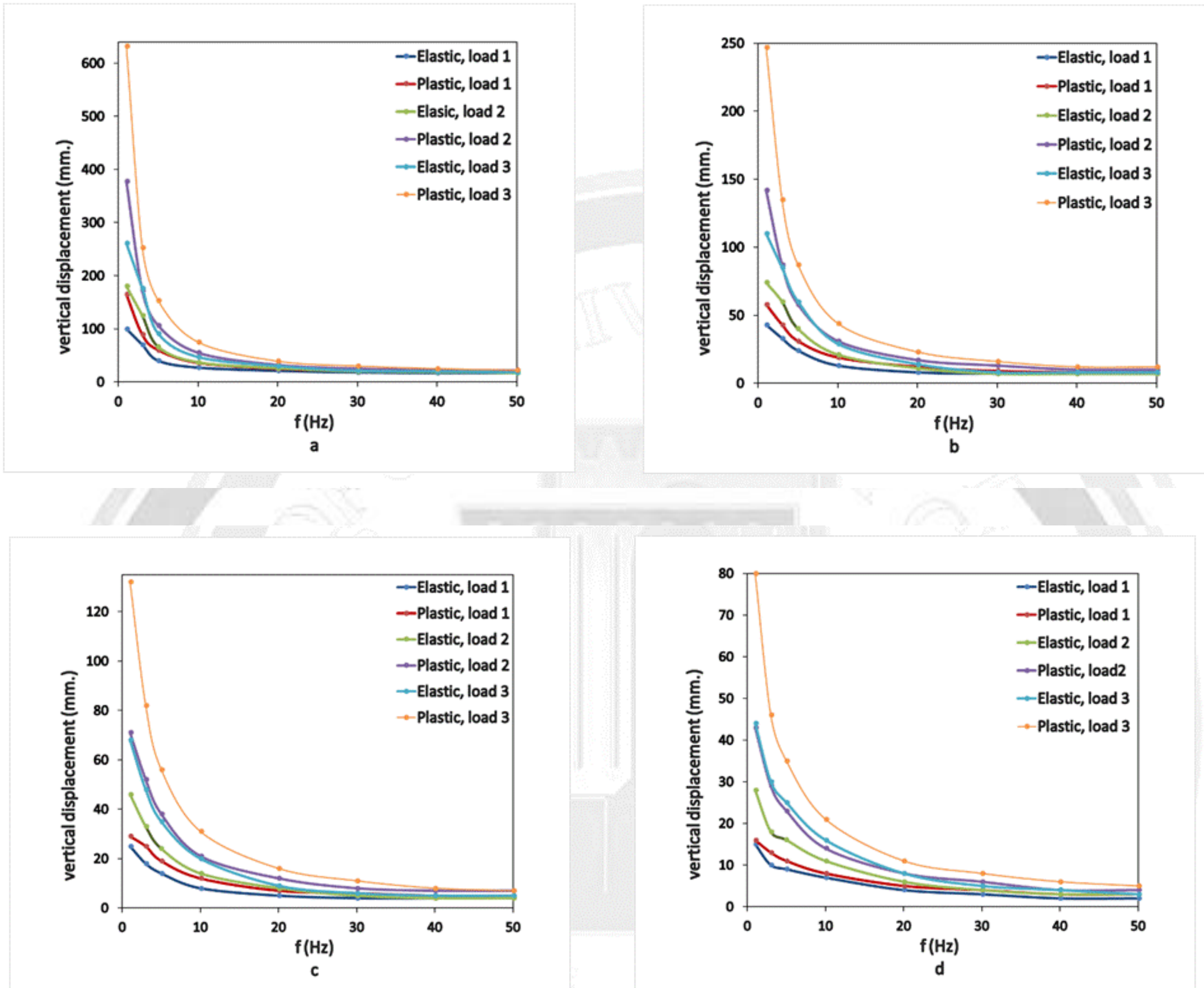

Figure 3. Load frequency (f) versus vertical displacement for a) loose b) medium c) dense d) v. dense soils using elastic and M.C model of soil

Figs. 4 and 5 studied the effect of type of sandy soil on the variation of vertical displacement with load frequency for elastic and M-C models respectively and for all levels of dynamic load. It can be noted that there is a gap in vertical displacement between loose sand from one side and other types of sandy soil from other side. In addition, the drop in vertical displacement at first part of the curves (frequency between 1 and 10) is sharper in loose sand.

It can be noted from all above figures that there are some high and unreasonable values of vertical displacement, especially in loose sand, high value of dynamic load and low value of load frequency. The current study deals with a wide range of parameters to provide a broad database of variation of vertical displacement with studied parameters.

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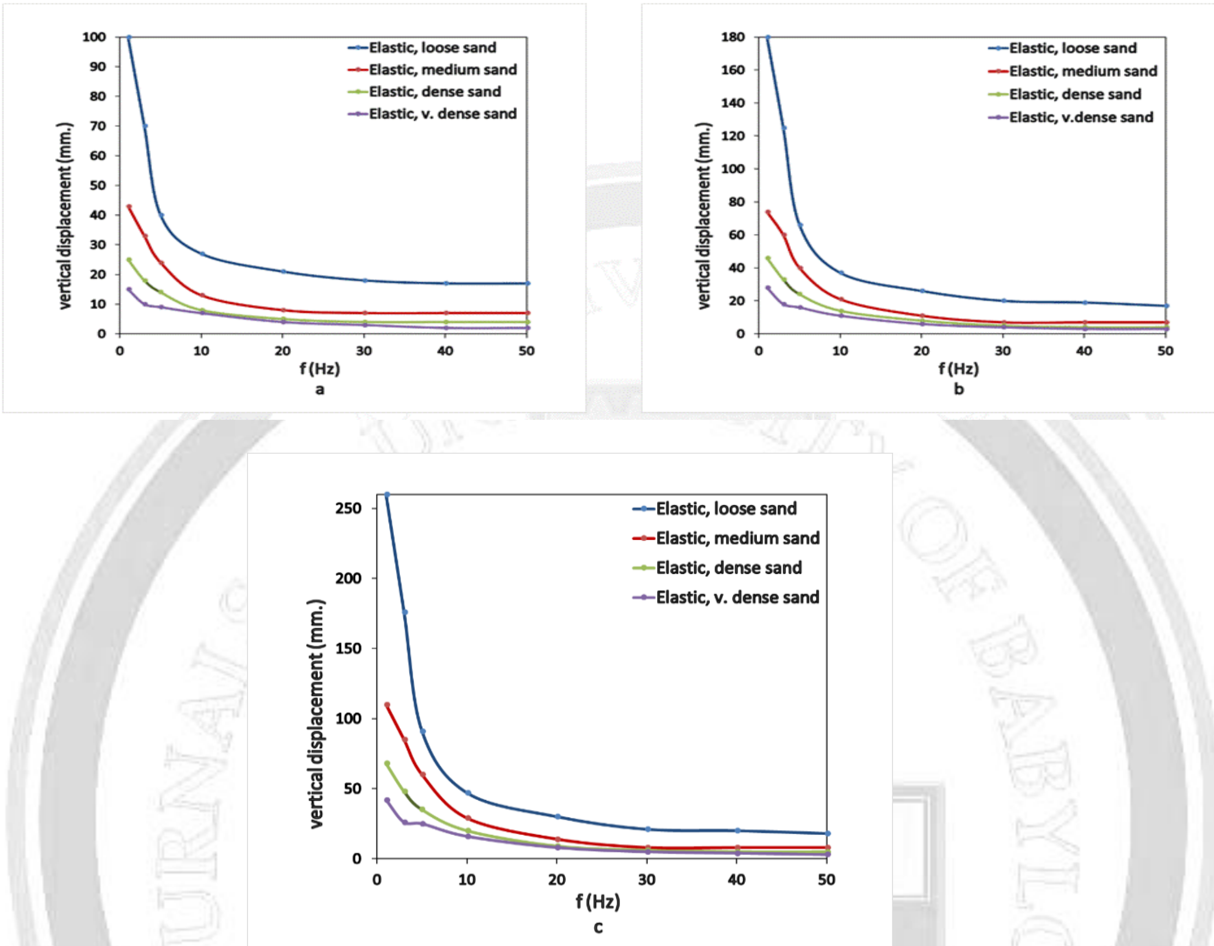
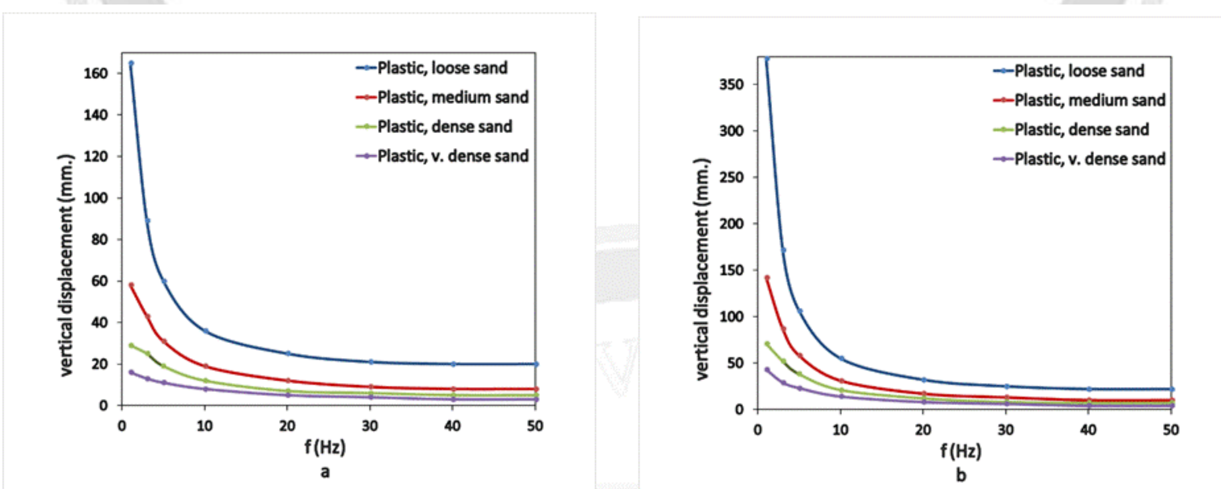


Figure 4. Load frequency (f) versus vertical displacement for a) load = 100 kN/m^2, b) load = 200 kN/m^2 c) load = 300 kN/m^2 using elastic model of soil



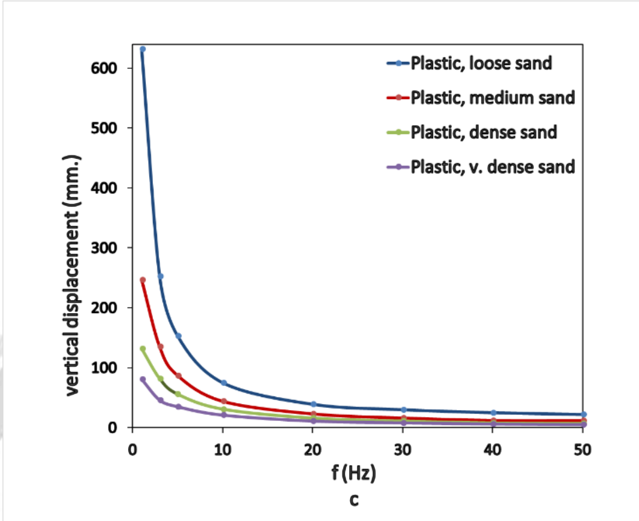


Figure 5. Load frequency (f) versus vertical displacement for a) load = 100 kN/m^2, b) load = 200 kN/m^2 c) load = 300 kN/m^2 using M.C model of soil

4. Conclusions

1- The vertical displacement decreases with increasing the load frequency for all types of sandy soil investigated in this study and for all values of dynamic load.

2- The reduction in vertical displacement with load frequency is valid for two soil models adopted in this study, i.e. elastic and Mohr–Coulomb (M-C) models.

3- There is a sharp drop in vertical displacement when the load frequency increased from 1 to 10 Hz.

4- The vertical displacement remains constant regardless the value of dynamic load when the load frequency exceeds 30 Hz.

5- The Mohr–Coulomb model gives higher values of vertical displacement than the elastic model for all investigated parameters.

6- The drop in vertical displacement at first parts of curves (frequency from 1 to 10 Hz) is sharper in loose sand compared with other types of sandy soil, i.e. medium, dense and very dense.

7- From practical point of view, for example, the loose sand can not be used as a machine base unless some improvements are made.

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تأثير تردد الحمل الديناميكي المتوافق على استجابة التربة الرملية

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الخلاصة

تتناول هذه الدراسة تأثير القيم المختلفة لترددات الحمل الديناميكي التوافقي على الإزاحة العمودية للتربة الواقعة مباشرة تحت الأساس. تم اختيار مدى واسع من الترددات (1 – 50 هرتز) في هذه الدراسة، بالإضافة إلى أربعة أنواع من التربة الرملية أسفل الأساس وهي : مفككة، متوسطة، كثيفة وكثيفة جدا مع معاملات المرونة، 7000، 19000، 36000 و 70000 كيلو نيوتن / م 2 على التوالي. تم إخضاع كل نوع من انواع التربة لثلاث مستويات من التحميل الديناميكي الموزع وهي 100, 200 و 300 كيلو نيوتن / م ^{2}. تم اجراء المحاكاة باستخدام نموذج العناصر المحددة ثنائي الابعاد في حزمة برنامج بلاكسز ثنائي الابعاد. واستُخدم نموذجان لمحاكاة التربة: النموذج المرن ونموذج موهر– كولومب. أظهرت النتائج أن الإزاحة العمودية أسفل الأساس تتناقص مع زيادة تردد الحمل ولجميع أنواع التربة الرملية المدروسة في هذه الدراسة ولجميع قيم الحمل الديناميكي. ويُلاحظ انخفاض حاد في الإزاحة العمودية عند زيادة تردد الحمل من 1 إلى 10 هرتز. وتبقى الإزاحة العمودية ثابتة بغض النظر عن قيمة الحمل الديناميكي عندما يتجاوز تردد الحمل 30 هرتز. وأخيرًا، يكون انخفاض الإزاحة العمودية عند الأجزاء الأولى من المنحنيات (التردد من 1 إلى 10 هرتز) أكثر حدة في التربة الرملية المفككة مقارنةً بأنواع أخرى من التربة الرملية، أي المتوسطة والكثيفة والكثيفة جدًا.

الكلمات الدالة:– التربة الرملية، الحمل الديناميكي التوافقي، تردد الحمل، النمذجة العددية، معامل المرونة، الازاحة العمودية.