RESONANCE FREQUENCY OF MACHINE FOUNDATIONS RESTING ON SATURATED SANDS

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Abstract. *Liquefaction is the rapid loss of shear strength in cohesionless soils subjected to dynamic loading, that it is a state of saturated cohesionless soil when its entire shear strength is reduced to zero due to pore water pressure caused by vibration. Liquefaction depends on the nature, magnitude and type of dynamic loading. An entire stratum may be liquefied at the same time under shock loading, or liquefaction may start at the top and proceed downward with steady-state vibrations.The present research is concerned with predicting liquefaction potential and the pore water pressure under the dynamic loading in the dynamic analysis of foundations based on the fully saturated sandy soil using the finite element method by QUAKE/W computer program. As a case study, machine foundations on fully saturated sandy soil in different cases of soil densification (loose, medium and dense sand) are analyzed. A harmonic dynamic load is considered. A parametric study is carried out to investigate the effect of several parameters including: the amplitude of the dynamic load and the frequency of the dynamic load. The equivalent linear elastic model is adopted to model the soil behaviour. The results showed that liquefaction and deformation develop fast with the increase of loading frequency. The soil overburden pressure affects the soil liquefaction resistance at large depths. When the foundation is constructed over loose saturated sand, liquefaction may take place at a frequency ratio equals 1.0. This finding highlights the importance of studying the liquefaction potential when analyzing machine foundations on such soils. When the soil beneath the machine foundation is medium or dense, the frequency ratio at which liquefaction may occur is greater than 1.0. It can be noticed that the time of initial liquefaction decrease as the frequency of dynamic load increases.*

1 INTRODUCTION

Soil liquefaction is a major cause of damage during earthquakes. "Modern" engineering treatment of liquefaction related issues evolved initially in the wake of the two devastating earthquakes of the 1964 and 2011 Japan. Over the nearly four decades that have followed, a significant progress has occurred. Initially, this progress was largely confined to improve the ability to assess the likelihood of initiation of liquefaction in clean, sandy soils. Additional potential problems associated with both silty and gravelly soils, and the important additional issues of post-liquefaction strength and stress deformation behaviour also began to attract increased attention (Seed et al., 2003).

Amini and Duan (2002) described a numerical model which is used to study the soil liquefaction resistance at high confining pressures. A two-dimensional numerical model was set up. Base accelerations with different magnitudes and frequencies were applied to the model. The pore water pressure and effective stress at different depths in the model were monitored during shaking. It was found that, soil liquefaction resistance increases with the increasing of confining pressure at large depths. At a large acceleration magnitude, the liquefaction can occur at virtually any depth. It was concluded that at a lower frequency, the liquefaction occurred faster at large depths.

Ashford et al. (2004) described a pilot test program that was carried out to determine the appropriate charge weight, delay, and pattern required to induce liquefaction for full-scale testing of deep foundations. The results of this investigation confirmed that controlled blasting techniques could successfully be used to induce liquefaction in a well-defined, limited area for field-testing purposes. The tests also confirmed that liquefaction could be induced at least two times at the same site with nearly identical results. Excess pore pressure ratios greater than 0.8 were typically maintained for at least 4 minutes after blasting. Settlement was typically about 2.5% of the liquefied thickness, and about 85% of the settlement occurred within 30 min after the blast.

Sitharam et al. (2004) studied methods of determining the dynamic properties as well as potential for liquefaction of soils. Parameters affecting the dynamic properties and liquefaction have been brought out. A simple procedure of obtaining the dynamic properties of layered ground has been highlighted. Results of a series of cyclic triaxial tests on liquefiable sands collected from the sites close to the Sabarmati river belt have been presented. Simple method was used to obtain the equivalent modulus of layered system. Cyclic strain-controlled triaxial tests to evaluate the dynamic properties and liquefaction potential of sands have been carried out. It has been brought out that the material immediately beneath the foundation plays a dominant role in controlling the dynamic response. Material at a depth greater than twice the width of the foundation plays an insignificant role. A major reduction in the shear modulus and a corresponding increase in the damping of sand occur in the large shear strain range. As the initial densities of sand increase, the shear modulus shows clearly an increasing trend. However, more or less the same values of shear modulus occur beyond 0.5% shear strain level irrespective of their initial density. As a result of application of cyclic loads on the soils, pore water pressure builds up steadily and reaches initially applied confining pressure depending on the magnitude of cyclic shear strain as well as the density of the soil. At higher cyclic shear strain amplitudes, the pore water pressure builds up fast and there is triggering of liquefaction at lower cycles.

Jin et al. (2008) tested samples of saturated loose sand under bi-directional cyclic loading to characterize liquefaction and cyclic failure, by using an advanced soil static and dynamic universal triaxial and torsional shear apparatus. Tests were performed with two cyclic components involving the horizontal shear stress (torsional shear stress) and the vertical shear stress (stress difference between vertical normal stress and horizontal normal stress) to provide an approximate presentation of wave or seismic loading conditions. Samples were consolidated under various initial static horizontal shear stresses and subsequently subjected to a specified level of dynamic loading. Three stress levels of dynamic load were concerned. Results showed that the developed pore water pressure decreases linearly as initial static horizontal shear stress increases and decreases exponentially as consolidation stress ratio increases.

Lu et al. (2010) investigated the responses of saturated sand under horizontal vibration loading induced by a bucket foundation. The saturated sand liquefies gradually since the vibration loading is applied on. The maximum displacement on the surface of sand layer occurs near the loading end and in this zone; the sand is compressed and moves upwards. The liquefaction zone was developed from the upper part near the loading side and stopped gradually under the vibrating loading on one side of the saturated sand; liquefaction occurs first near the loading end and then develops faraway. The deformation becomes up-heave near the loading end and degrades faraway gradually. It was found that:

- The liquefaction and the deformation develop fast with the increase of the loading amplitude and the frequency and the decrease of the modulus.
- The liquefaction may occur under vibration loading on the side from the foundation side to a finite distance. It needs to be considered in the design of platform.

It can be concluded from previous studies on liquefaction show that most of them considered on earthquake induced liquefaction and that little studies talked liquefaction caused by mechanical factors. Some equipments or heavy machines used during construction particularly on saturated sandy soil might cause some vibration and consequently, a loose soil will be ready for liquefaction.

2. DESCRIPTION OF THE PROBLEM

A saturated porous foundation soil 30 m wide and 20 m deep is modelled by a finite element analysis. A 2 m wide footing is placed at the middle of the top surface. The foundation will be subjected to dynamic load of harmonic excitation described by the following equation:

$$\mathbf{F\ (t) = a_{o.}\ \sin\ (\omega.\ t)} \qquad \ldots\ldots\ldots\ldots\ldots (1)$$

The duration of this dynamic load is 60 sec. with a time step $\Delta t = 0.1$ sec. In order to study the pore water pressure changes under such loading condition, the soil is assumed to be saturated; i.e. the water table coincides on the ground surface. The properties of the sand are summarized in Table 1. The plane strain problem is analyzed using the QUAKE / W (2004) program which is a geotechnical finite element software product used for the dynamic analysis of earth structures subjected to earthquake shaking and other sudden impact loading. QUAKE/W is part of GeoStudio and is, consequently, the integration of QUAKE/W and other products within GeoStudio greatly expands the type and range of problems that can be analyzed beyond what can be done with other geotechnical dynamic analysis software. It is formulated for two-dimensional plane strain problems. QUAKE/W program can be used as a stand alone product, but one of its main attractions is the integration with the other GeoStudio products.

The finite element mesh used for the analysis is shown in Figure 1. The mesh consists of 8 noded quadrilateral isoparametric elements. Equivalent linear elastic model is used in the analysis. The time of the analysis is taken as 100 sec with $\Delta t = 0.1$ sec. The analysis is repeated for three types of soils; loose, medium and dense sand. The results are presented at selected points A, B, C, D and E at different depths below the foundation in order to study the depth of soil affected by the dynamic load.

The relationships used for the equivalent linear elastic model include the shear modulus reduction function of Figure 2, the relationship between the cyclic number ratio and pore pressure ratio of Figure 3 and the cyclic deviator stress with number of cycles as given in Figure 4.

3. DETERMINATION OF NATURAL FREQUENCY, ω_n

The natural frequency of the system is given by:-

$$\omega_n = \sqrt{\frac{k}{m}} \quad \text{…. (2)}$$

where : ω_n is the natural frequency in radians per second .

$$f_n = \frac{1}{2\pi} \cdot \sqrt{\frac{k}{m}} \quad \text{…. (3)}$$

where f_n is natural frequency in cycles per second .

Thus $$f_n = \frac{1}{2\pi} \times \sqrt{\frac{k}{m_f + m_s}} \quad \text{…. (4)}$$

where : m_f = mass of machine foundation, and

m_s = mass of the participating soil mass.

Barkan (1962) gave the following relation for the natural frequency.

$$\omega_n = \sqrt{C_u \frac{A}{m}} \quad \text{…. (5)}$$

where : C_u = coefficient of elastic uniform compression**,**

A = contact area of foundation with soil.

The coefficient of elastic uniform compression C_u depends upon the soil type. It can be obtained from the following relation:

$$C_u = 1.13 \frac{\mathbf{E}}{(\mathbf{1} - \boldsymbol{\upsilon}^{\mathbf{2}})} \times \frac{\mathbf{1}}{\sqrt{\mathbf{A}}} \quad \text{…. (6)}$$

To simplify comparison between the results for three states of sandy soil (loose, medium and dense), it is noticed that when the frequency changes from 5 to 10 rad/sec. (approximately from static to dynamic), the response in displacement and pore water pressure is very pronounced. This can be attributed to inertia effects. Further increase of frequency leads to smaller effect on displacement and pore water pressure (Fattah et al., 2013).

4. COMPARISON OF LIQUEFACTION WITH RESONANCE

Some of the important requirements for a machine–foundation–soil system can be listed as follows (Rao, 2011):

1. Settlements should be within permissible limits.
2. Foundation block should be structurally adequate to carry the loads.
3. The combined center of gravity (CG) of machine and foundation and the center of contact area (with the soil) should lie on the same vertical line as far as possible, and
4. Resonance should not occur.

In case of machine foundations, the mass of soil, m_s, participating in vibration needs to be determined in calculating the natural frequency.

The value of mass of machine and foundation is equal to the mass of the participating soil mass, the values of mass of machine and foundation m_f , is calculated using Newton's law:-

$$m_f = \frac{\mathbf{a_o}}{\mathbf{g}} \quad \text{….(7)}$$

where: a_o = amplitude force = 10, 20, 40 and 60 kN. = weight of foundation.

g = acceleration due to gravity = 9.806 m/sec^2.

The spring stiffness can be determined from the Barkan’s method:

Hence, the value of spring stiffness is equal to 34957.6 kN/m.

where: E_c = Modulus of elasticity for concrete ≈ 21 MN/m^2.

υ_c = Poisson's ratio for concrete = 0.2,

A = area of the machine (foundation) = 2 m^2.

The natural frequencies are determined using Equation (2); $\omega_n = \sqrt{\frac{k}{m}}$

A summary of the results is listed in Table 2.

Figure 5 shows the relationship between the frequency ratio (ω/ω_n) and the maximum displacement caused by the vibration for machine foundations constructed over loose, medium and dense sand.

Considering that the liquefaction condition is the controlling factor, Figure 6 is drawn between the frequency ratio and the maximum pore water pressure at which liquefaction takes place.

From Figure 5, it can be noticed that, the relationship takes the shape of the conventional relation between the frequency ratio and the dynamic magnification factor. The peak of displacement increases as the amplitude of the dynamic force increases. It can be concluded that the maximum displacement takes place at a frequency ratio greater than 1.0 as it is expected where the resonance can occur when ($\omega/\omega_n = 1$). The critical frequency ratio (ω/ω_n) moves away from 1.0 as the amplitude of dynamic force increases.

From Figure 6, it can be noticed that at some instances, when the foundation is constructed over loose saturated sand, liquefaction may take place at a frequency ratio equal to 1.0. This finding highlights the importance of studying the liquefaction potential, when analyzing machine foundations on such soils. When the soil beneath the machine foundation is medium or dense, the frequency ratio at which liquefaction may occur is greater than 1.0.

Figure 7 shows the effect of frequency of the dynamic load on the time of initial liquefaction at amplitude load (a_o = 10 kN), while when the amplitude load equals to (20, 40 and 60 kN), the time of initial liquefaction equals 10 sec. It can be noticed that the time of initial liquefaction decrease as the frequency of dynamic load increases.

The following notes could be obtained from results of analysis:

- During loading, the pore pressure increases at the first stage and then decreases gradually. The reason is that, at the first stage the sand layer intents to contract, but the water is difficult to drain, the strength of the sand decreases, so the sand begins to compress and the pore pressure decreases gradually.
- The soil overburden pressure affects the soil liquefaction resistance at large depths. The liquefaction resistance and time for initial liquefaction increase with increasing depths.
- Liquefaction occurs faster at shallow depths for all ranges of frequency and amplitude. This finding does not comply with that of (Amini and Duan, 2002) who, during his numerical study on the liquefaction resistance of soil at high confining pressure, found that at a lower frequency, liquefaction occurs faster at large depths.
- The maximum displacement on the surface of sandy layer occurs near loading end, after this point the soil is compressed and surface displacement is begin to decrease till reaching zero with increasing distance away from the end of vibration loading. For this reason it is important to take the effect of vibration on a finite distance from the side of reason of disturbance in foundation design.
- Maximum displacement increases with decrease the modulus of elasticity (the soil changes from dense to loose sand) this conclusion is compatible with the finding of Lu et al. (2010), who found that the sand surface near the loading side becomes up-heave first and then develops to faraway, the deformation degrades from the loading side to far away and the deformation became larger when the modulus of elasticity of sandy layer is smaller The smaller the modulus is, the faster the development of the liquefaction zone is.

5. CONCLUSIONS

As a result of the finite elements analysis carried out in this study and discussion presented, the following conclusions could be made:-

1. Liquefaction occurs faster at shallow depths for all cases of frequency. Liquefaction mostly occurs within the top 10 m below the ground surface, although, it can occur up to about 20 m deep.
2. Liquefaction and deformation occur faster with the increase of loading amplitude and frequency, when the foundation is constructed over loose saturated sand. The time of initial liquefaction decreases as the frequency of dynamic load increases.
3. The soil overburden pressure affects the soil liquefaction resistance at large depths. Liquefaction resistance and time for initial liquefaction increase with increasing depth. Liquefaction may propagate to a point at depth of about five times the foundation width.
4. The relationship between the frequency ratio (ω/ω_n) and the maximum displacement takes the shape of the conventional relation between the frequency ratio and the dynamic magnification factor. The peak of displacement increases as the amplitude of the dynamic force increases. It can be concluded that the maximum displacement takes place at a frequency ratio greater than 1.0 as it is expected where the resonance can occur

when (ω/ω_n=1). The critical frequency ratio (ω/ω_n) moves away from 1.0 as the amplitude of dynamic force increases.

5. At some instances, when the foundation is constructed over loose saturated sand, liquefaction may take place at a frequency ratio equal to 1.0. This finding highlights the importance of studying the liquefaction potential, when analyzing machine foundations on such soils. When the soil beneath the machine foundation is medium or dense, the frequency ratio at which liquefaction may occur is greater than 1.0.

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Material Properties	Loose sand	Medium sand	Dense sand
Modulus of elasticity, E (kN/m^2)	20000	40000	60000
Poisson's ratio, υ	0.2	0.3	0.4
Unit weight γ_t, (kN/m^3)	14.0	17.0	22.0

Table 1: Properties of the sandy soil used in the parametric study.

a_o (kN)	m_f (kg)	ω_n (rad/sec)	ω (rad/sec)	ω/ω_n
10	1019.783	4.14	5	1.207
			10	2.415
			25	6.038
			50	12.077
20	2039.567	2.927	5	1.708
			10	3.416
			25	8.541
			50	17.082
40	4079.135	2.07	5	2.415

			10	4.83
			25	12.077
			50	24.154
60	6118.702	1.69	5	2.958
			10	5.917
			25	14.792
			50	29.585

Table 2: Values of frequency at which the maximum response of foundation is obtained.

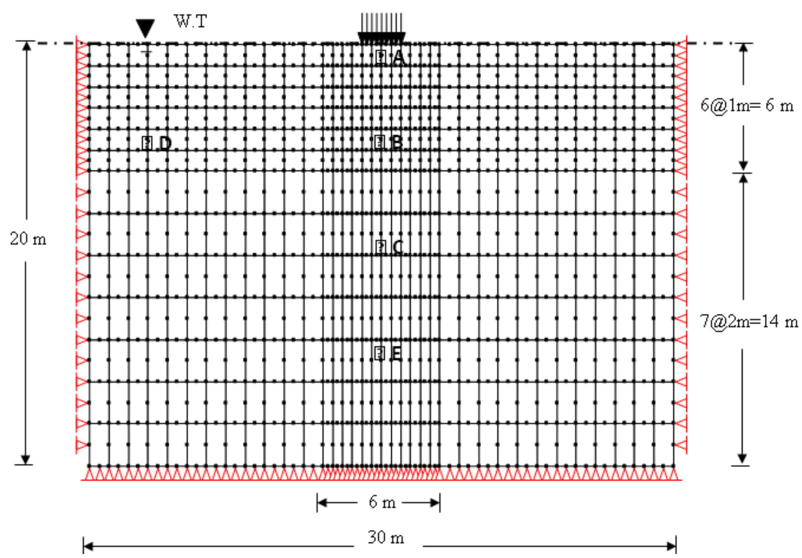


Fig. 1 - Typical finite element mesh.

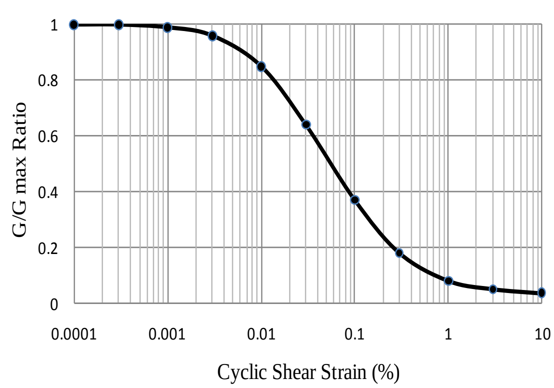


Fig. 2 - Shear modulus reduction function (Seed and Idriss, 1970).

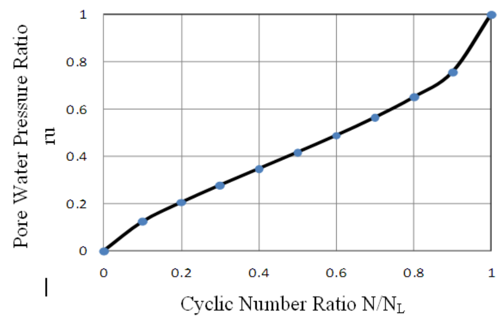


Fig. 3 - Cyclic number ratio N/N_L versus pore pressure ratio r_u (Seed and Booker, 1977).

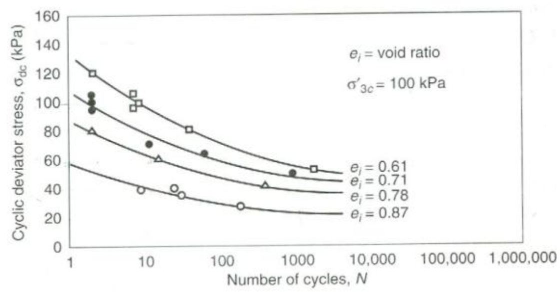
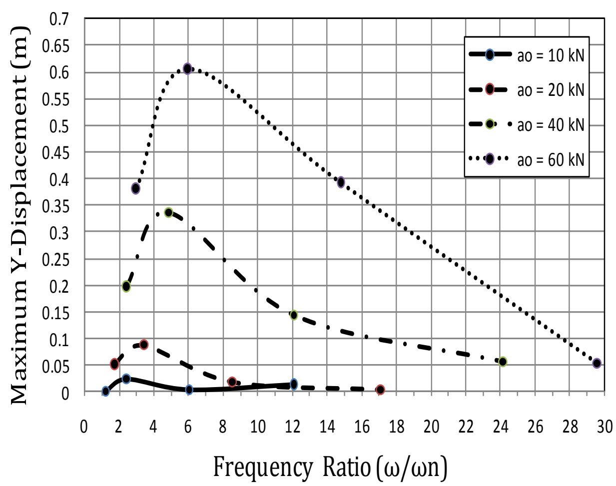
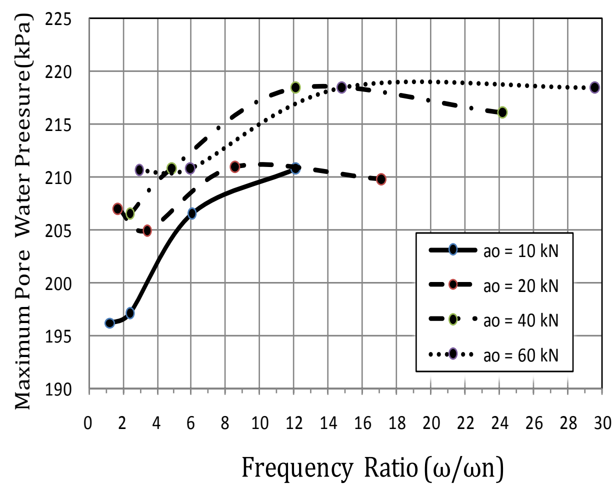


Fig. 4 - Cyclic test results on Sacramento River Sand (Kramer, 1996).



Loose sand



Loose sand

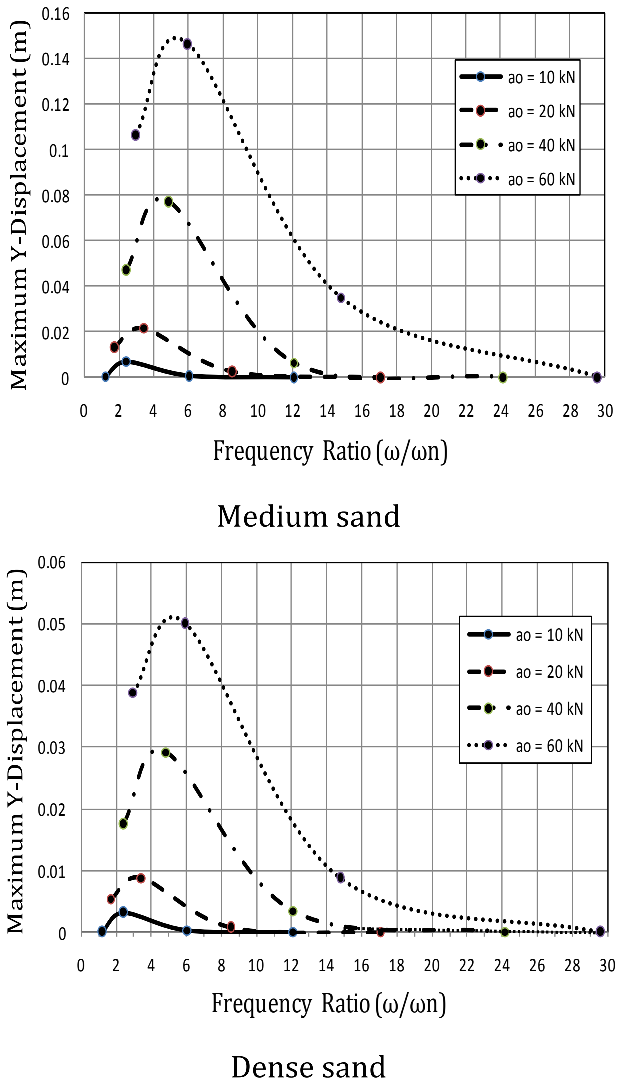


Fig. 5 - Variation of the maximum displacement with the frequency ratio at time (60 sec.), in sandy soil at different densities.

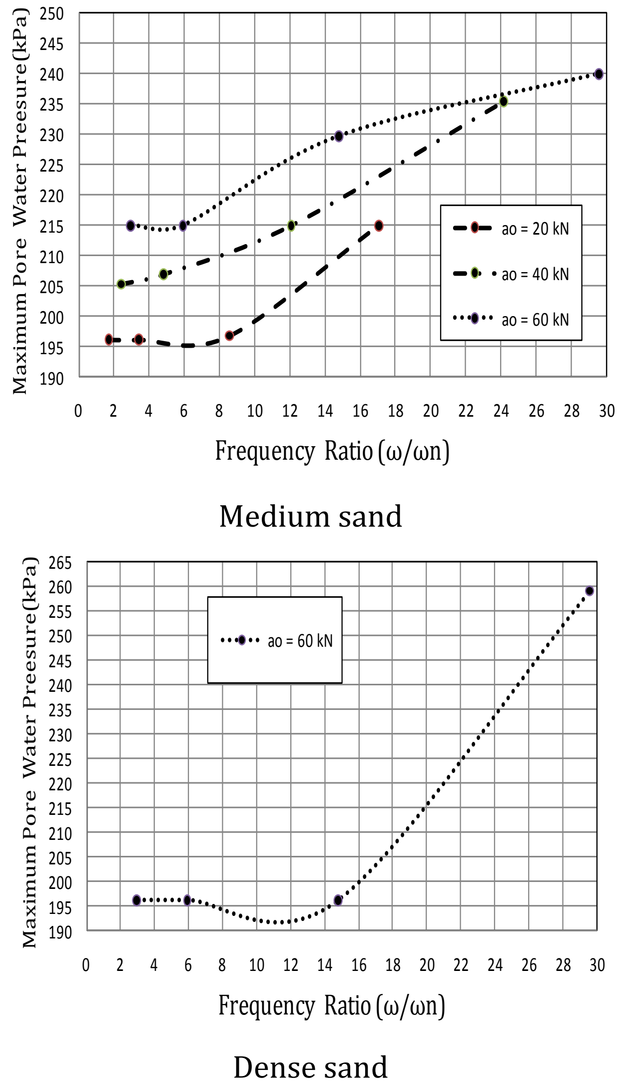


Fig. 6 - Variation of the maximum pore water pressure with the frequency ratio at time (60 sec.), in sandy soil at different densities.

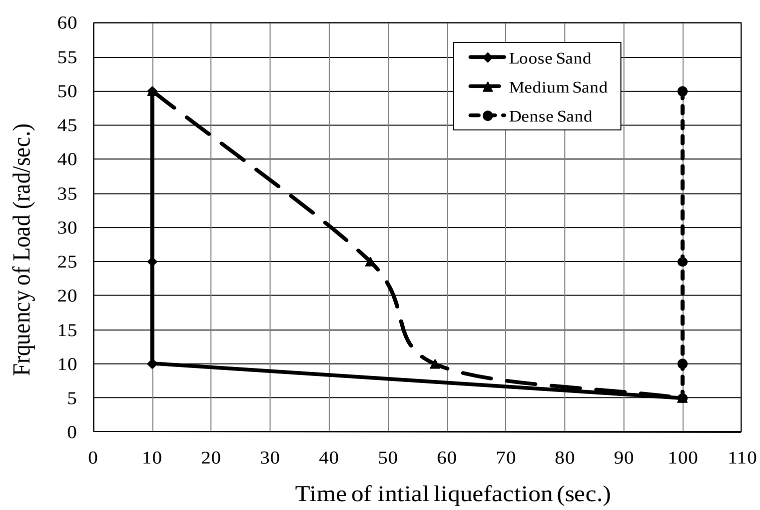


Fig. 7 - Effect of frequency of the dynamic load on the time of initial liquefaction (a_o = 10 kN) at point B in sandy soil at different densities.