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Dynamic Behavior of Machine Foundation on Two-Layer Soil System

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Abstract:

In this paper, a dynamic analysis of strip machine foundation is placed at the middle of the top surface of two-layer saturated sand with different states (i.e. loose, medium and dense), and vertical harmonic excitation is carried out with assessment of liquefaction potential and building up of the excess pore water pressure. The dynamic analysis is performed numerically by using finite element software, PLAXIS 2D. The soil is assumed as elastic perfectly plastic material obeys Mohr-Coulomb yield criterion. A harmonic load is applied at the foundation with amplitude of 25 kPa at a frequency of 5 Hz.

A parametric study is carried out to evaluate the dependency of machine foundation on the modular ratio of soil layers. It was concluded that the displacement decreases remarkably when E1 (elastic modulus of the top soil layer) is duplicated 2-4 times E2 (elastic modulus of the underlying soil layer), then the effect decreases. The pore water pressure increases remarkably when E1 is increased to about 5 times E2, then the effect decreases. Liquefaction potential zone (when the effective stress approximately equals to zero) forms first near the end of the loading adjacency to the surface at shallow depth of the soil and extended to few meters for all frequencies.

Keywords: Dynamic, soil, machine foundation, two layers, Liquefaction.

التصرف الديناميكي لأساس ماكنة على تربة ذات نظام ثنائي الطبقة

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الخلاصة:

في هذا البحث، أجري تحليل ديناميكي لأساس شريطي لماكنة مشيد على سطح طبقتين من الرمل المشبع بالماء بحالات مختلفة (مفكك و متوسط و كثيف)، وتم تسليط حمل شاقولي انسجامي لدراسة احتمال حدوث حالة تسييل للتربة و تنامي ضغط ماء مسامي. و قد أجري تحليل ديناميكي عددي باستعمال برنامج العناصر المحددة PLAXIS 2D . و قد افترض أن التربة تسلك سلوكا مرنا- لدنا تاما تتبع معادلة الفشل لمور- كولومب. و قد سلط حمل انسجامي على الأساس و بقيمة عليا مقدارها 25 كيلوباسكال بتردد مقداره 5 هرتز.

و قد أجريت دراسة معاملات لتقييم اعتماد أساس الماكنة على نسبة المعاملات لطبقات التربة.

وقد وجد أن الازاحات تتناقص بشكل ملحوظ عندما يضاعف E1 (معامل المرونة للطبقة العليا) بمقدار (2-4) مرات بقدر E2 (معامل المرونة لطبقة التربة السفلى) ثم يتلاشى التأثير عند زيادة قيمة E1 أكثر من ذلك، و يتزايد مقدار ضغط ماء المسام بشكل ملحوظ عند زيادة قيمة E1 بمقدار حوالي 5 مرات بقدر E2 ثم يتلاشى التأثير بعد ذلك. ان منطقة احتمال حدوث التسييل (عندما يكون الاجهاد المؤثر صفرا) تتكون أولا عند نهاية منطقة تسليط الحمل و بالقرب من السطح عند أعماق ضحلة للتربة ثم تمتد داخل التربة لعد أمتار و لجميع قيم التردد.

Introduction:

Machine foundations require a special consideration because they transmit dynamic loads to soil in addition to static loads due to weight of foundation, machine and accessories. The dynamic load due to operation of the machine is generally small compared to the static weight of machine and the supporting foundation (Prakash and Puri, 2006)[10]. All foundations in practice are placed at a certain depth below the ground surface. As a result of this, embedment plays a significant role on the overall response of the foundation and needs to be carefully evaluated too (Chowdhury and Dasgupta, 2009)[5]. Increasing the depth of embedment of fondation may be a very effective way of reducing the vibration amplitudes. The beneficial effects of embedment, however, depend on the quality of contact between the embedded sides of the foundation and the soil. The quality of contact between the sides of the foundation and the soil depends upon the nature of the soil, the method of soil placement and its compaction and the temperature (Prakash and Puri, 2006)[10]. A number of theoretical formulations have been derived and field experiments have been conducted to study the embedment effect of soil on the overall response of the foundations.

Satisfactory design of a machine foundation needs information on soil profile, depth of different layers, physical properties of soil and ground water level. These information can be obtained by usual sub-surface exploration techniques (Prakash and Puri, 2006)[10]. For the dynamic analysis of machine foundations, soil properties, such as Poisson's ratio, dynamic shear modulus, and damping of soil, are generally required. The values are usually obtained either from field and laboratory tests or from theoretical correlation with other engineering soil parameters (Chowdhury and Dasgupta, 2009)[5]. For machine foundations, the amplitudes of dynamic motion, and consequently the strains in the soil, are usually low (strains less than 10−3 %) (American Concrete Institute, 2004)[2]. It should be remembered that even under low strain, soil behavior is essentially non-linear though at low strain it does show some kind of linearity. Poisson's ratio ν, which is the ratio of the strain in the direction perpendicular to loading to the strain in the direction of loading, is used to calculate both the soil stiffness and damping. Poisson's ratio can be computed

from the measured values of wave velocities traveling through the soil. Generally, Poisson's ratio varies from 0.25 to 0.35 for cohesionless soils and from 0.35 to 0.45 for cohesive soils. (American Concrete Institute, 2004)[2].

Dynamic shear modulus

Dynamic shear modulus *G* is the most important soil parameter influencing the dynamic behavior of the soil-foundation system. Together with Poisson's ratio, it is used to calculate soil impedance. The dynamic shear modulus represents the slope of the shear stress versus shear strain curve. Most soils do not respond elastically to shear strains; they respond with a combination of elastic and plastic strain. For this reason, plotting shear stress versus shear strain results in a curve not a straight line. The value of *G* varies based on the strain considered. The lower value of the strain, the higher the dynamic shear modulus (American Concrete Institute, 2004)[2].

Spyrakos and Xu (2004)[13] conducted parametric studies to investigate the effects of foundation-soil flexibility and mass as well as foundation embedment on the response. It was concluded that foundation flexibility plays an important role on the dynamic response of foundations, especially for foundations subjected to vertical loads.

First, the effect of foundation flexibility on surface foundations was evaluated. Four relative stiffnesses, Kr and a relative mass density Mr were considered for the vertical loads. The effect of foundation flexibility on both massless and massive foundations can be evaluated. For both the vertical case, the foundation with the largest and the smallest stiffness correspond to rigid and very soft foundations, respectively, whereas the other two stiffness values correspond to flexible foundations.

Rayhani and El Naggar (2008)[11] developed a numerical model using a fully coupled nonlinear finite-difference program (FLAC) to predict the seismic response of a rigid foundation in soft soil. The numerical model was verified or calibrated by comparing its predictions with the measured responses of two centrifuge model tests on uniform and layered clay. The numerical simulations were conducted for representative set of weak to strong shaking events. The validated model was then used to study the effects of thickness of soil profile and layering on earthquake amplification and soil–structure interaction. In addition, the embedment effects of foundation were investigated. It was found that most amplification occurred within the first 30 m of the soil profile, which is in agreement with most modern seismic codes that evaluate local site effects based on the properties of the top 30 m of the soil profile. However, the peak spectral acceleration moved toward longer periods as the soil depth increased. The presence of a top soft layer within the profile can significantly increase the ground motion amplification relative to the case of a uniform soil profile with the same average shear wave velocity of the top 30 m of the soil profile. The peak accelerations of soil beneath the structure increased due to strong interaction between the soil and the foundation. The embedment of the structure decreased the amplitude of the response spectra significantly.

Vivek and Ghosh (2012)[14] studied dynamic interaction of two closely spaced embedded strip foundations under the action of machine vibration. One of the footings was excited with a known vibration source placed on the top of the footing, called the active footing. The objective was to study the effect of dynamic excitation of active footing on the nearby passive footing through a homogeneous c-ϕ soil medium. The analysis was performed numerically by using finite element software, PLAXIS 2D. The soil profile was assumed to obey the Mohr-Coulomb yield criteria. The analysis was performed under two different loading conditions; sinusoidal dynamic loading with constant amplitude and varying amplitude. Under the dynamic excitation, the settlement behavior of interacting footings is studied by varying the spacing between the footings. In addition, the variation of normal and shear stress developed below the passive footing was also explored. The response of the adjoining passive structure was found to be significant up to a spacing of 2B (B is foundation width) from the actual excited structure.

The purpose of this work is to investigate the response of a shallow foundation subjected to harmonic load simulating the form of load function of machine. The paper investigates the effect of modular ratio of underlying soil layers on the dynamic response (displacement and pore water pressure) of the foundation.

Definition of the Basic Problem:

Dynamic finite element analysis of strip foundation under vertical harmonic excitation is carried out in this research. A 3 m wide strip foundation with multiple thicknesses is placed at the middle of the top surface of two layers: the top layer is sand of different densities underlying by medium sand. The analysis is performed numerically using the finite element software, PLAXIS 2D version 8.2. 15-noded triangular isoperimetric elements are used to discretize the soil medium under the plane strain condition. The boundaries of the soil are taken as (30 m) wide and (20 m) deep far away from the foundation to minimize the boundary effect. To investigate the excess pore water pressure build up under machine foundation due to harmonic excitation, the soil is assumed to be saturated with water table coincides with the ground surface. The boundary conditions and other modeling details considered for strip foundation are shown in **Figure (1).** Total fixities (ux = uy = 0) are applied at the base of the model and horizontal fixities (ux = 0) are applied at the extreme vertical boundaries restraining the motion along the horizontal direction. Absorbent boundaries are applied along vertical and horizontal boundaries to avoid the reflection of stress waves back to the failure domain. It should be noted that in this analysis, a vertical vibration is applied and the vertical displacements and excess pore water pressure are measured at the top central point of the foundation (node A in **Figure (1)).** It is important to mention here that all cases are analyzed for duration of (60 sec) with time step taken as ($\Delta t = 0.0256$ sec).

Material Properties

The properties are classified into three groups:

Soil properties: The uppermost soil used in this parametric study is rested on medium sand. The soil deposit is assumed to obey the advanced Mohr-Coulomb yield criterion, with parameters adopted from (Bowels, 1996)[3] and (Murthy, 2006)[8] except the dilatancy parameter. The effect of dilatancy is taken into account in the present study. The dilatancy of sand depends on both the density and the friction angle. It is suitable in PLAXIS to use the value of cohesion c > 0.2 kPa for cohesionless sands and dilatancy angle $\psi = Ø - 30$ for the soils with $Ø > 30$, and $\psi = 0$ for the soils with $Ø < 30$ (Brinkgreve et al., 2002 a). Due to this, the value of cohesion is assumed equal to 1 kPa to avoid complications and the value of the angle of dilatancy is assumed as ($\psi = Ø - 30$). The properties of all soil types are listed in **Table (1).**

Foundation properties: The concrete foundation is assumed as a linear elastic material with parameters shown in **Table (1).** The weight of the machine depends upon its type as suggested by Leonards in (1962)[7] as shown in **Table (2).** Based on this table, the ratio between weight of foundation and weight of machine is approximately taken as 2.16 (i.e. weight of machine = 10 kN).

Sinusoidal excitation

The most common problem involving dynamic loading is that of foundation for machinery. Reciprocating machines and poorly balanced rotating equipment cause periodic dynamic forces q (Lambe and Whitman, 1979)[6]:

$$q = a \sin \omega t \qquad \text{(1)}$$

where:

a = maximum amplitude of dynamic force = 25 kPa,
$\omega = 2\pi f$ with f = operating frequency = 5 Hz, and
t = time.

Typical operating frequencies range from (3 Hz) for large reciprocating air compressors to about (200 Hz) for turbines and high-speed rotary compressors (Al-Sherefi, 2000)[1]. The values of amplitudes range between 25 and 100 kPa while the frequency range between 5 and 50 Hz.

Table .(1) Material properties.

Material	Material properties	Unit	Sand
Soil	Unit weight, γ	(kN/m^3)	18.5 **
	Young's modulus, E	(kN/m^2)	35000 **
	Poisson's ratio, ν	-	0.32 **
	Friction angle, ϕ	(°)	35 **
	Cohesion, c	(kN/m^2)	1
	Dilatancy angle, ψ	(°)	5
	Horizontal permeability, k_x	(m /sec)	10^{-4} **
	Vertical permeability, k_y	(m /sec)	10^{-4} **
Foundation	Young's modulus of concrete, $E_{concrete}$	(kN/m^2)	2×10^7 *
	Unit weight of concrete, $\gamma_{concrete}$	(kN/m^3)	24 *
	Poisson's ratio of concrete, $\nu_{concrete}$	-	0.15 **
Machine	Weight of machine, $W_{mach.}$	(kN/m^2)	10 *

* From Bowles, (1996).
** From Murthy, (2006)[8].

Table (2) - Guidelines for choosing weight of foundation block (Leonards, 1962)[7].

Type of engine	Weight of foundation/weight of engine
Gas engines one cylinder	3.00
Gas engines two cylinders	3.00
Gas engines four cylinders	2.75
Gas engines six cylinders	2.25
Gas engines eight cylinders	2.00
Diesel engines two cylinders	2.75
Diesel engines four cylinders	2.10
Diesel engines six cylinders	2.10
Diesel engines eight cylinders	1.90
Rotary converter	0.50-0.75
Vertical compound steam engine coupled to generator	3.80
Vertical triple-expansion steam engine coupled to generator	3.50
Horizontal cross-compound engine coupled to generator	3.25
Horizontal steam turbine coupled to generator	3.00-4.00
Horizontal steam turbine coupled to generator	3.50
Vertical diesel engine coupled to generator	2.60
Vertical gas engine coupled to generator	3.50

Results of Analysis

Loading and consequently the amount of displacement has a significant effect on the accuracy of analyses (effect of strain range) and determining the range of displacement in which accurate results can be obtained from each model is an important issue.

Figures (2) to (4) show the dynamic response of displacement and pore water pressure when the top soil layer has the same properties of the sandy soil (E1 = E2).

Figures (5) to (7) show the dynamic response of displacement and pore water pressure when the top soil layer has stronger properties than the underlying the sandy soil (E1 = 2E2) while **Figures (8) to (10)** show the dynamic response of displacement and pore water pressure when the top soil layer has (E1 = 5E2) and **Figures (11) to (13)** show the dynamic response of displacement and pore water pressure when the top soil layer has (E1 = 10E2).

Figure (14) presents the relationship between the maximum displacements induced through the foundation in different conditions of top soil stiffness. It can be noticed that the displacement decreases remarkably when E1 is duplicated 2-4 times E2, then the effect decreases.

Figure (15) presents the relationship between the maximum excess pore water pressure generated in the saturated sandy soil in different conditions of top soil stiffness. It can be noticed that the pore water pressure increases remarkably when E1 is increased to about 5 times E2, then the effect decreases.

For very dense soils, the presence of non-zero initial static driving shear stresses can lead to reduction in the rate of generation of pore pressures during cyclic loading. As each cycle of loading produces an incremental increase in pore pressure, and some resultant reduction in strength and stiffness, the driving shear stresses then act to produce shear deformations that cause dilation of the soil, in turn reducing pore pressures as stated by Seed et al., (2003)[12].

The sand modeled in the present study is medium; therefore no dilation was indicated through the loading stage.

The rate of the liquefaction increases with the increase of the initial void ratio (or decrease of density) or amplitude and frequency of loading, and increases with decrease of the modulus. The pore pressure increases slowly at the beginning and then increases fast up to the maximum which is equal to the sum of the initial pore pressure and the initial effective stress (after liquefaction, the fluctuating pore pressure caused by the loading is not considered). The the pore pressure oscillates uniformly with time.

The effective vertical stress is an important property for computing the excess pore-pressure as well as for evaluating the liquefaction potential of the soil (Chang et al., 2007)[4]. Whether a soil will liquefy or not is determined by the load on the soil causing liquefaction as well as the resistance of the soil against liquefaction.

It can be noticed that the liquefaction potential zone (when the effective stress approximately equals to zero) forms first near the end of the loading adjacency to the surface at shallow depth of the soil and extended to few meters for all frequencies. This observation qualitatively agrees with previous finding of Osinov, (2000)[9]who stated that the vertical distribution give rise to a signal liquefaction zone few meter thick, with is located in the upper part of the layer.

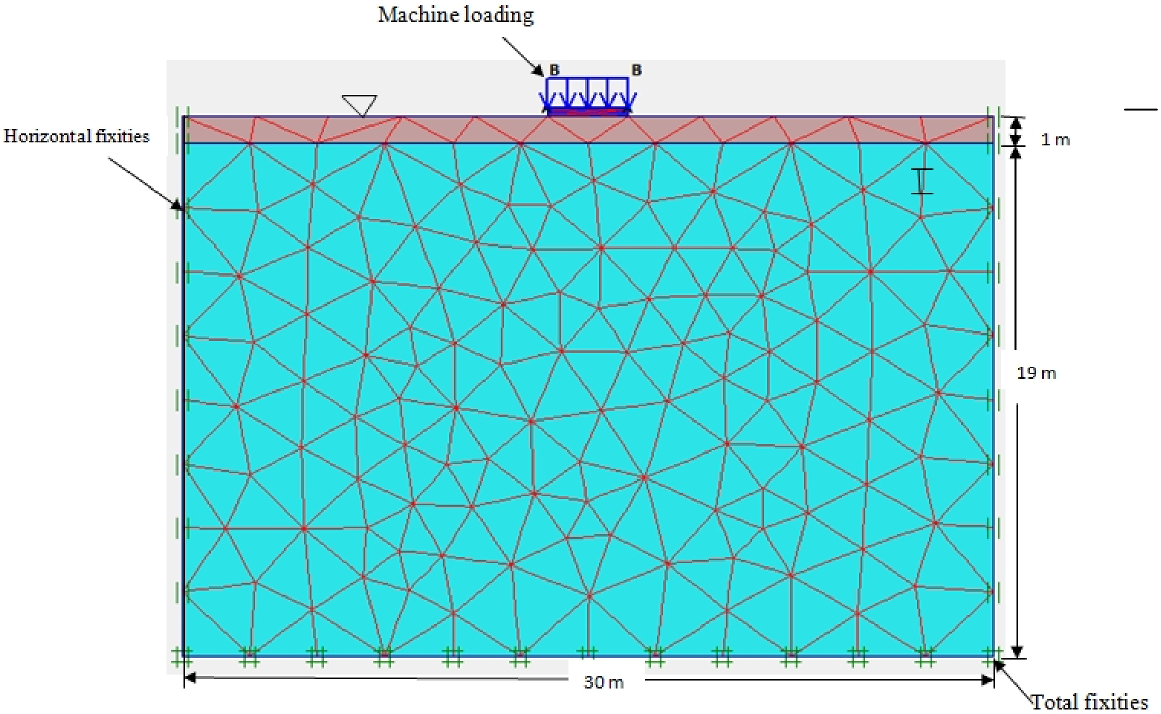

Fig .(1) Finite element mesh and boundary condition of the machine foundation problem.

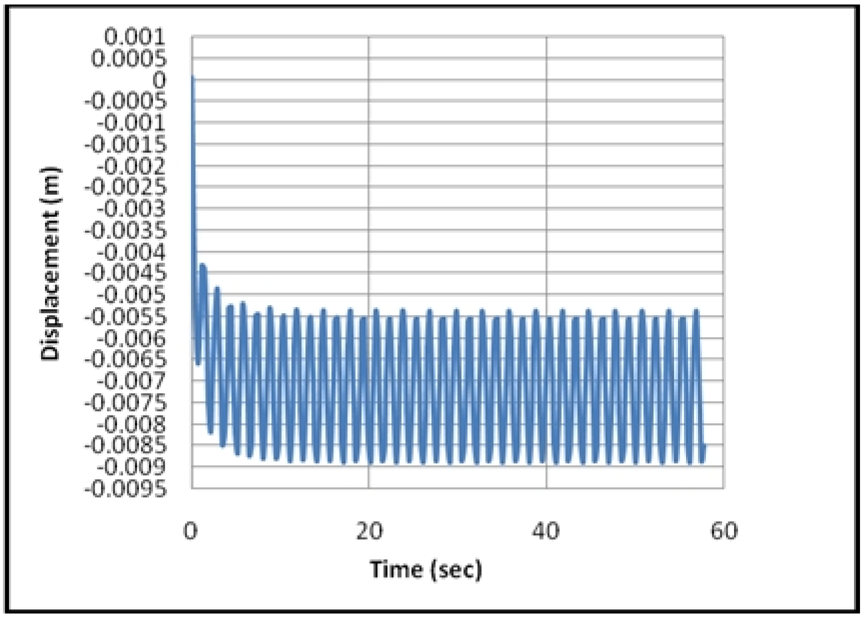

Fig .(2) displacement-time response for elastic-plastic analysis for foundation at surface with thickness 0.3 rested on medium sand (E_1=E_2) with a = 25 kPa and *f* = 5 Hz (max. displacement = -8.878e-3 m).

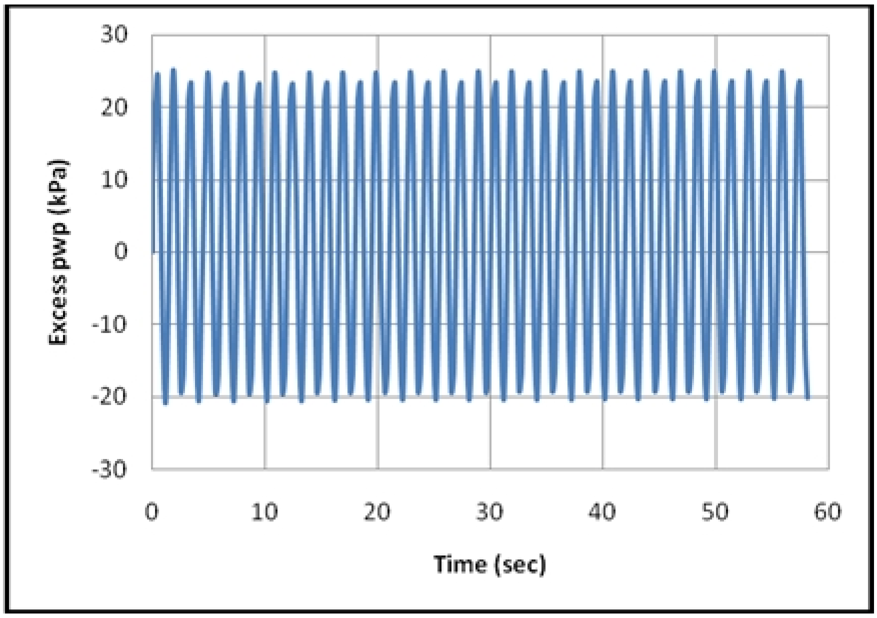

Fig .(3) Excess pore water pressure-time response for elastic-plastic analysis for foundation at surface with thickness 0.3 rested on medium sand (E_1=E_2) subjected to harmonic load with a = 25 kPa and *f* = 5 Hz (max excess pwp. = 24.921 kPa).

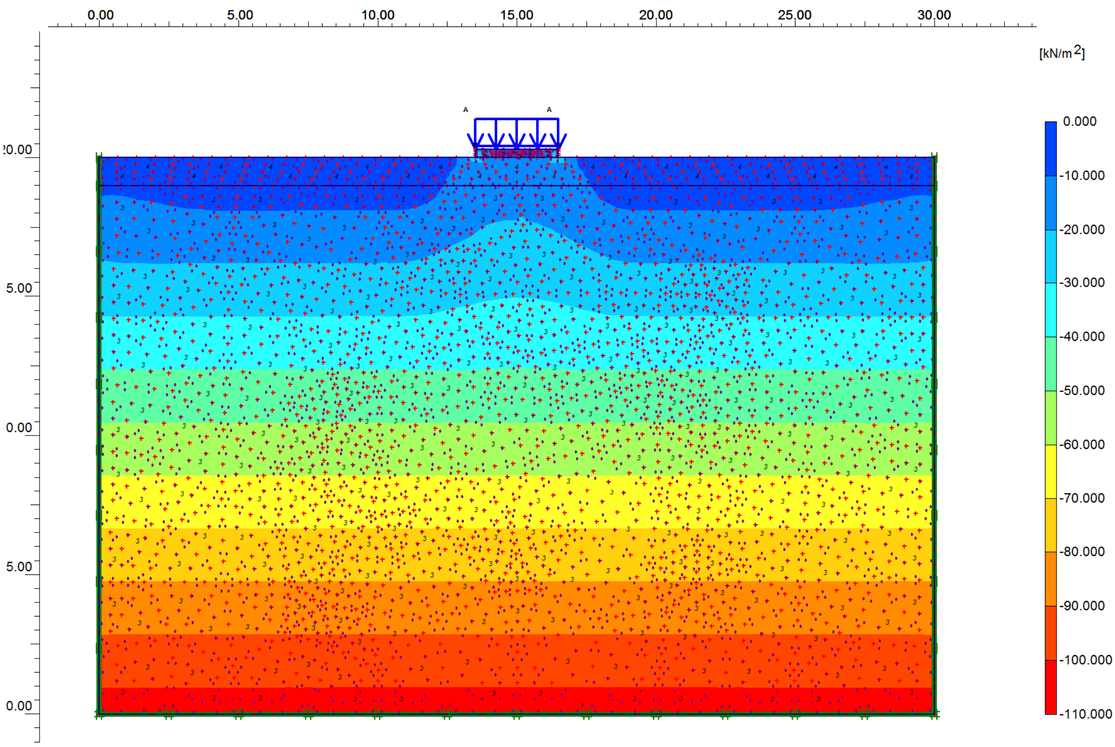

Fig .(4) Distribution of vertical effective stresses in medium sand (E1 = E2) at time 60 from harmonic excitation with amplitude = 25 kPa and *f*= 5 Hz under a strip foundation.

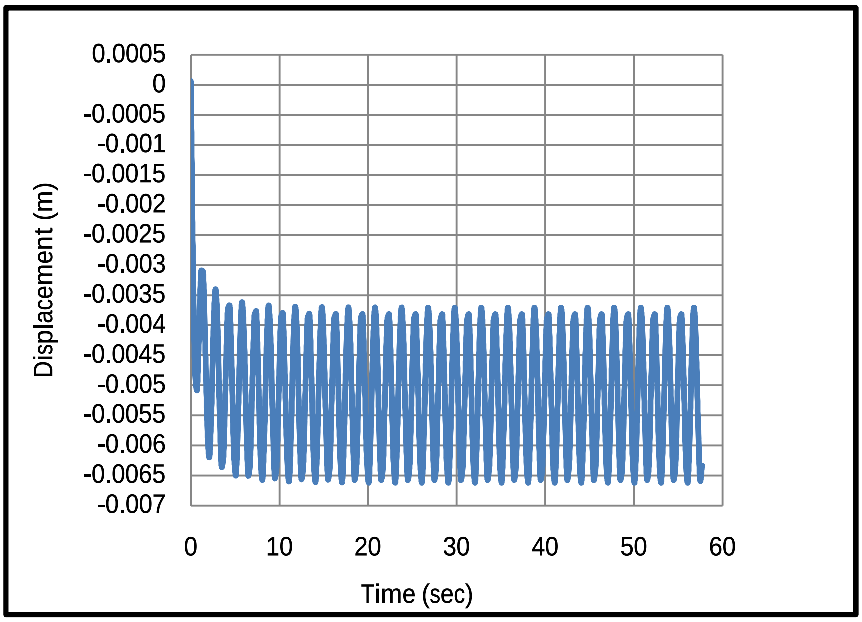

Fig .(5) displacement-time response for elastic-plastic analysis for foundation at surface with thickness 0.3 rested on medium sand (E_1=2E_2) with a = 25 kPa and *f* = 5 Hz (max displacement = -6.615e-3 m).

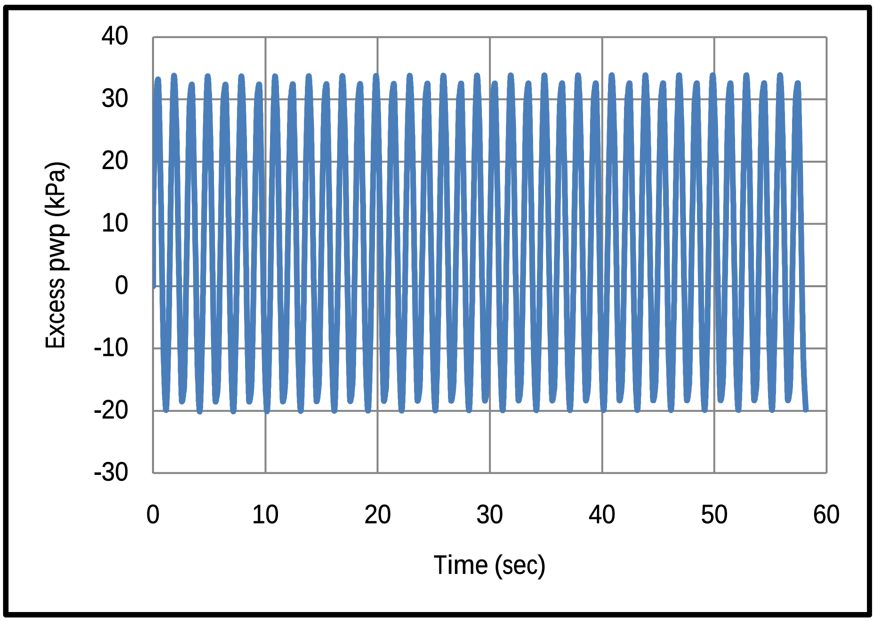

Fig .(6) Excess pore water pressure-time response for elastic-plastic analysis for foundation at surface with thickness 0.3 rested on medium sand (E_1=2E_2) subjected to harmonic load with a = 25 kPa and *f* = 5 Hz (max excess pwp. = 33.817 kPa).

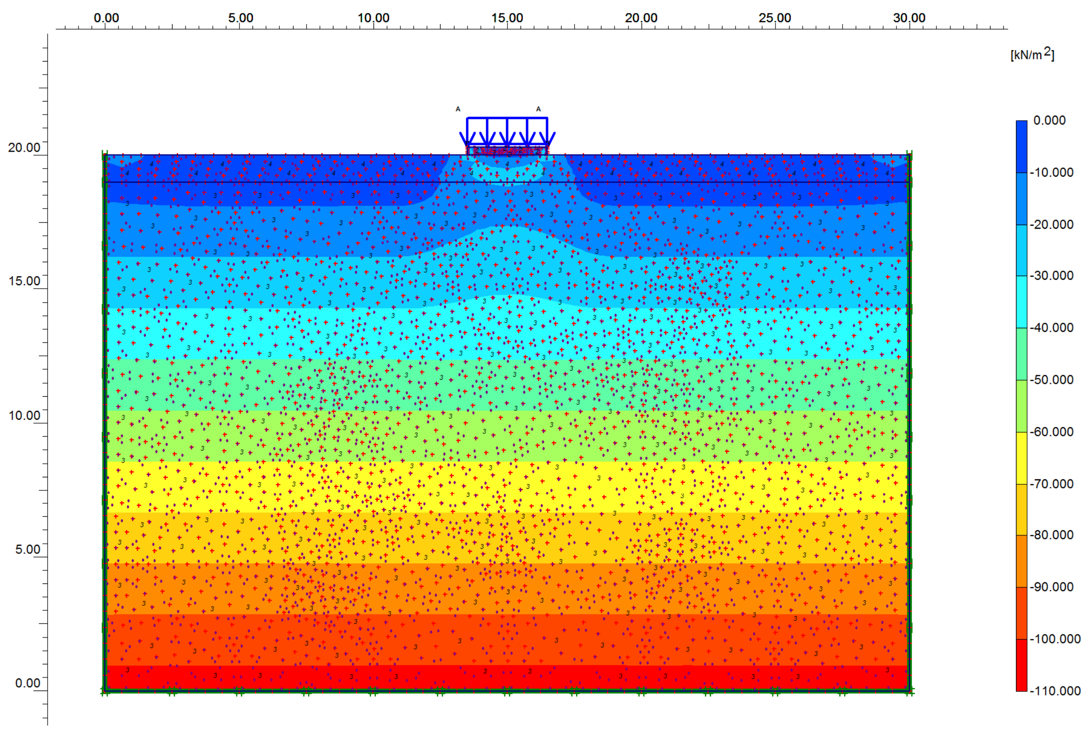

Fig .(7) Distribution of vertical effective stresses in medium sand (E_1=$2E_2$) at time 60 from harmonic excitation with amplitude = 25 kPa and *f* = 5 Hz under a strip \ foundation.

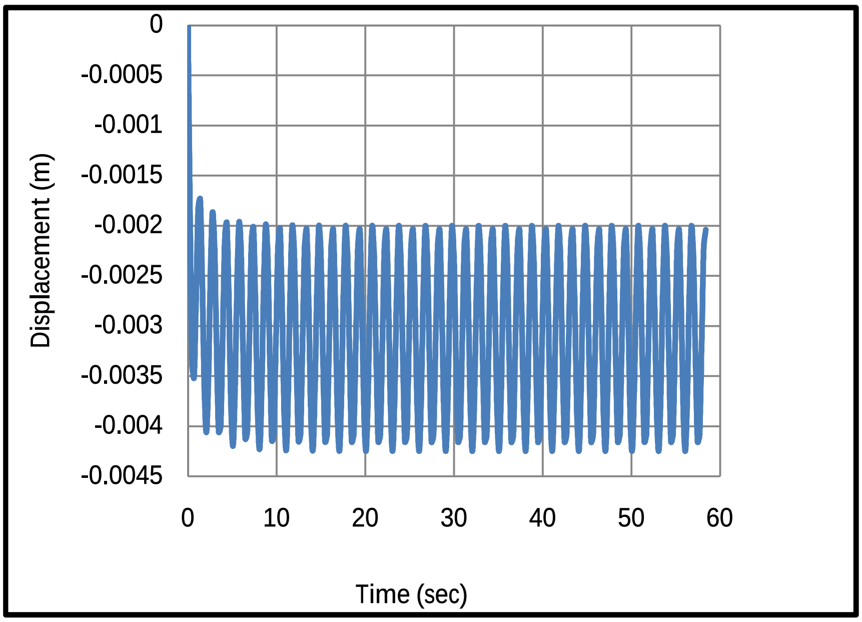

Fig .(8) displacement-time response for elastic-plastic analysis for foundation at surface with thickness 0.3 rested on medium sand (E_1=$5E_2$) with a = 25 kPa and *f* = 5 Hz (max displacement = -4.247e-3 m).

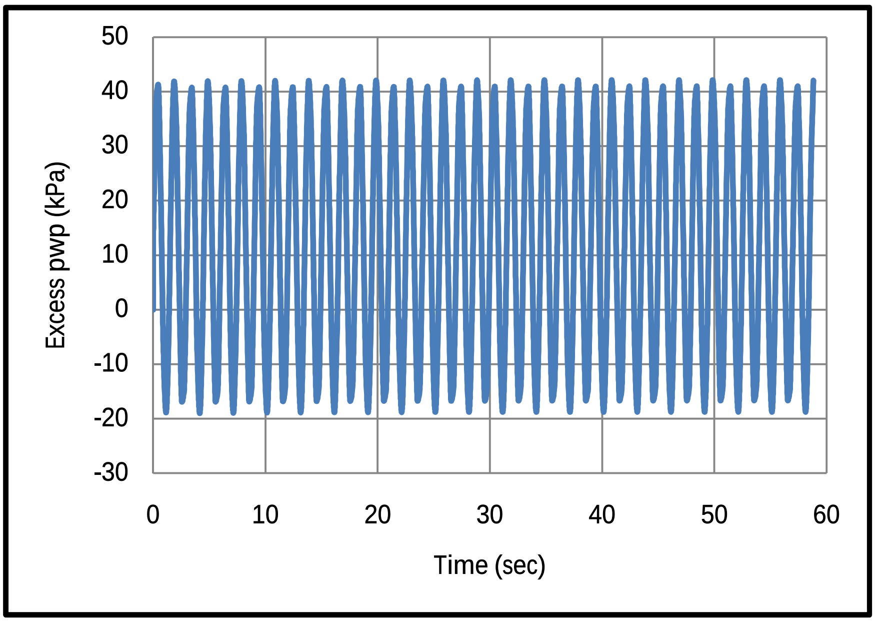

Fig .(9) Excess pore water pressure-time response for elastic-plastic analysis for foundation at surface with thickness 0.3 rested on medium sand (E_1=5E_2) subjected to harmonic load with a = 25 kPa and *f* = 5 Hz (max excess pwp. = 42.042 kPa).

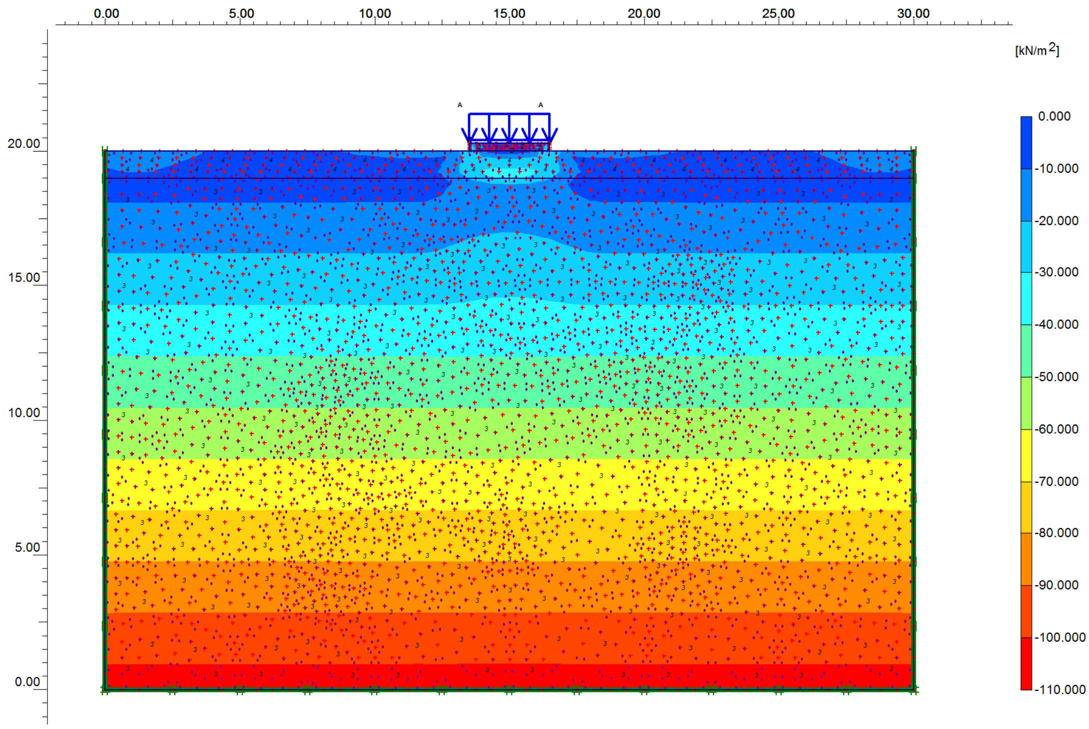

Fig .(10) Distribution of vertical effective stresses in medium sand (E_1=5E_2) at time 60from harmonic excitation with amplitude = 25 kPa and *f*= 5 Hz under a strip foundation.

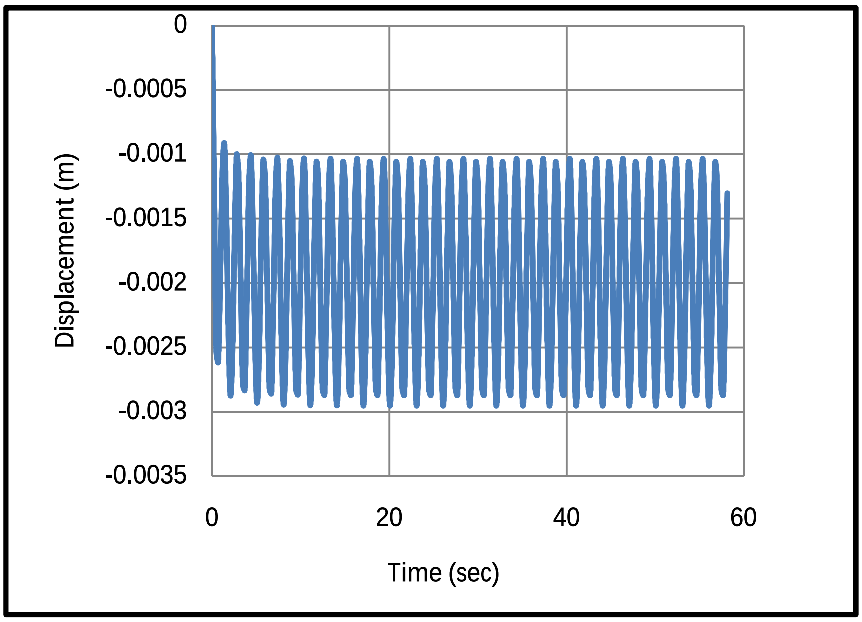

Fig .(11) Displacement-time response for elastic-plastic analysis for foundation at surface with thickness 0.3 rested on medium sand (E_1=10E_2) with a = 25 kPa and *f* = 5 Hz (Max displacement = -2.952 e-3 m).

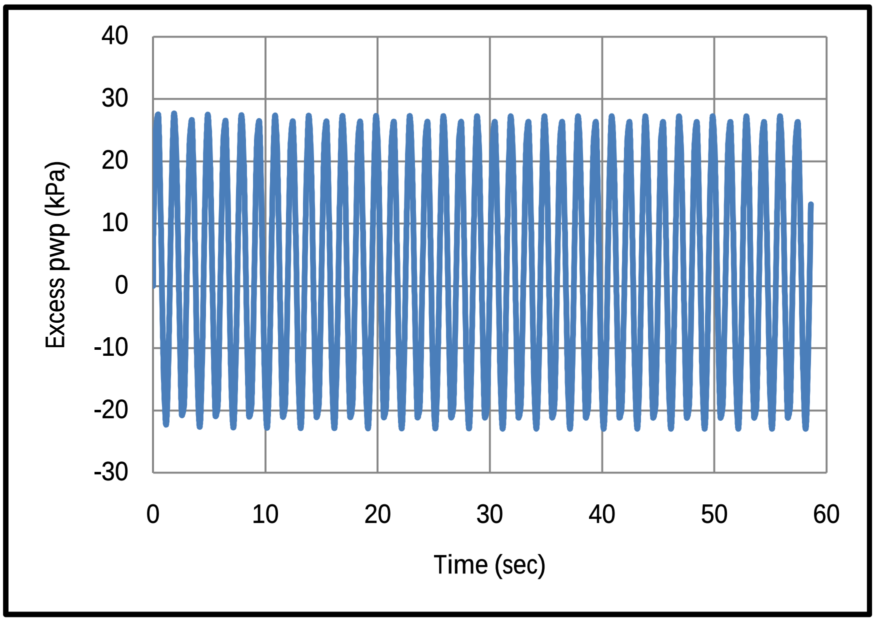

Fig .(12) Excess pore water pressure-time response for elastic-plastic analysis for foundation at surface with thickness 0.3 rested on medium sand (E_1=10E_2) subjected to harmonic load with a = 25 kPa and *f* = 5 Hz (max excess pwp. = 27.128 kPa).

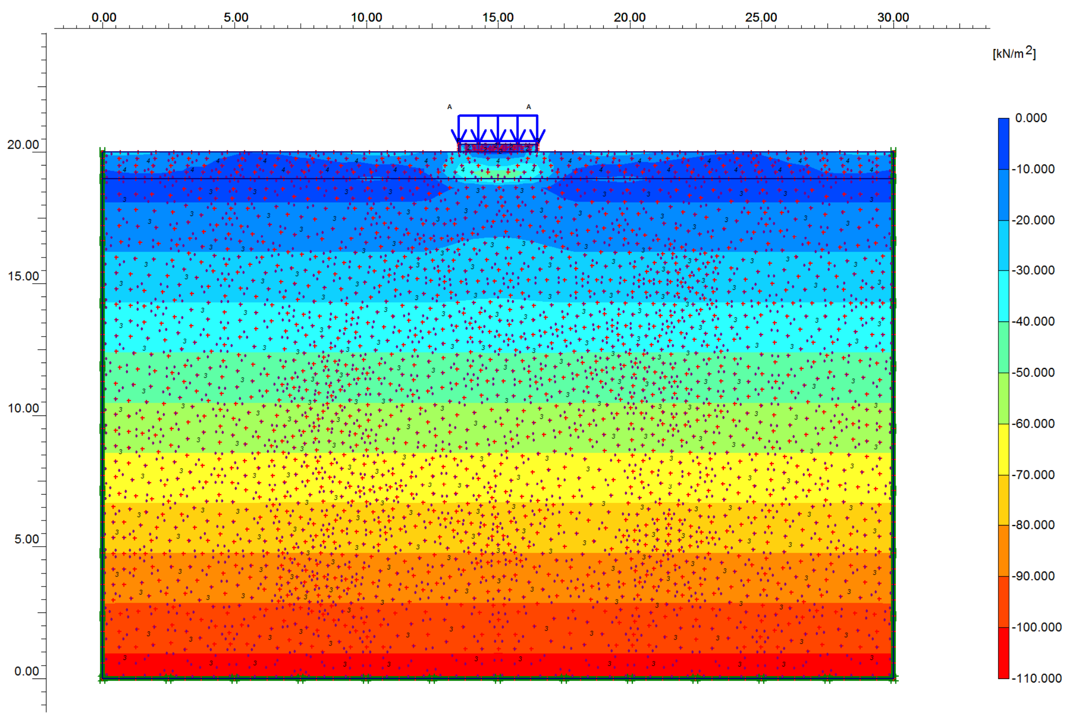

Fig .(13) - Distribution of vertical effective stresses in medium sand (E_1=10E_2) at time 60 from harmonic excitation with amplitude = 25 kPa and *f*= 5 Hz under a strip foundation.

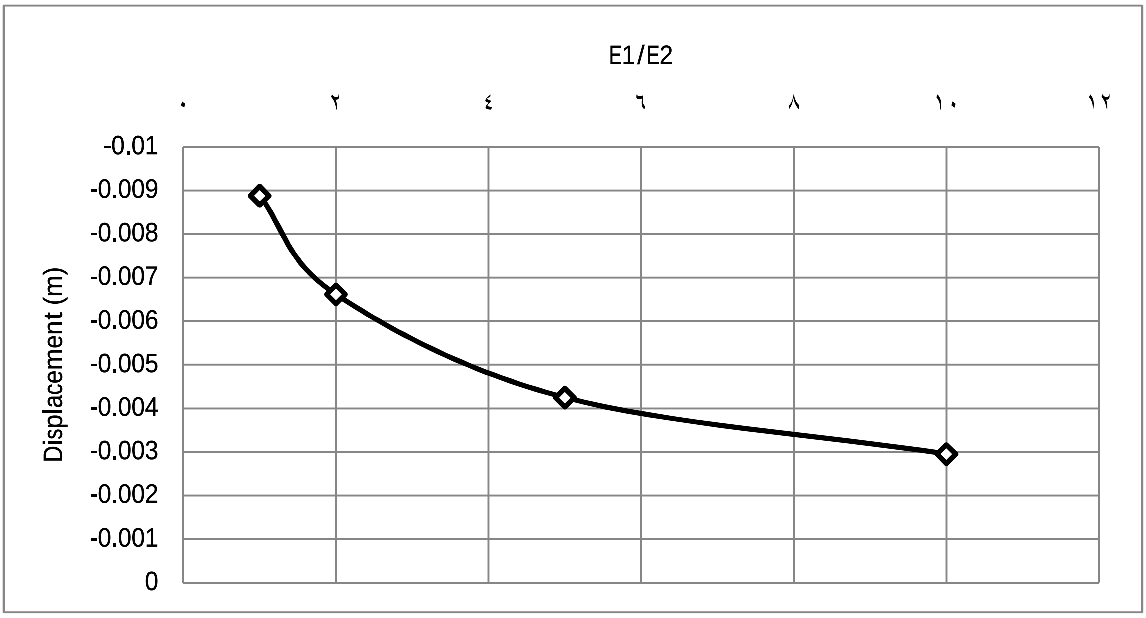

Fig .(14) Variation of the maximum displacement with E1/E2 for foundation at surface with thickness (h = 0.3 m) and without damping (ξ = 0) for loose, medium sandy soil.

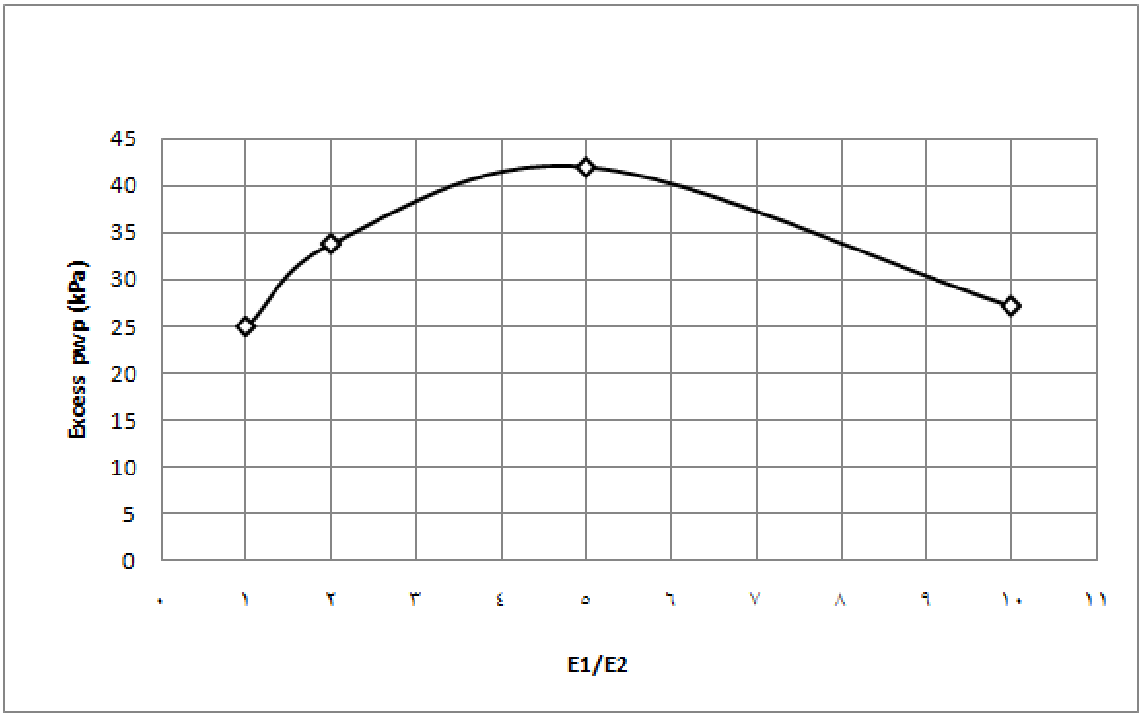

Fig .(15) Variation of the maximum excess pore water pressure with E1/E2 for foundation at surface with thickness (h = 0.3 m) and without damping (ξ = 0) for, medium sandy soil.

Conclusions

1. The displacement decreases remarkably when E1 is duplicated 2-4 times E2, then the effect decreases.
2. The pore water pressure increases remarkably when E1 is increased to about 5 times E2, then the effect decreases.
3. The sand modeled in the present study is medium; therefore no dilation was indicated through the loading stage.
4. Liquefaction potential zone (when the effective stress approximately equals to zero) forms first near the end of the loading adjacency to the surface at shallow depth of the soil and extended to few meters for all frequencies.

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