Finite Element Simulation of Machine Foundation Resting on Soil

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ABSTRACT:

The paper deals with behavior of machine foundation on elastic foundation. The finite elements approach through ANSYS (version 11) computer software is used for simulation of the dynamic response of the foundation under harmonic loading. As a case study previous analytical analysis problem for machine foundation was reanalyzed. In this problem, the element (solid65) was used for modeling the reinforced concrete foundation whereas the element (solid45) was used for modeling the soil beneath the foundation. The interface is modeled by using three-dimensional surface-to-surface (Target170 and Contact174) contact elements connected with concrete and soil.

It can be noted that the finite element analysis agrees with the analytical results, and the difference in the ultimate displacement is about (7.14, 4.6, 27.6, and 12.5)% when the dynamic force is subjected (along X direction (in-phase), along X direction (out of phase), along Y direction (in phase) and along Y direction (out of phase)) respectively.

Keywords: Machine foundation, dynamic loads, finite elements, Harmonic Load.

النمذجة بالعناصر المحددة لأساس ماكنة مستند على التربة

الخلاصة:

ان هذه الدراسة تهتم بدراسة سلوك اساس ماكنة على اساس مرن وتم استعمال طريقة العناصر المحددة من خلال برنامج ال NSYS في نمذجة الاستجابة الديناميكية لاساس معرض لحمل توافقي. في هذه الدراسة تم تحليل اساس ماكنة لدراسة سابقة وقد تم تمثيل الاساس الخرساني المسلح بعنصر (solid65)، وتم تمثيل التربة تحت الاساس بعنصر (solid45)، وقد تم استخدام العنصران (Target170) و (Contact174) لتمثيل التداخل بين الاساس والتربة. وقد بينت النتائج توافق التحليل بالعناصر المحددة مع نتائج الدراسة السابقة وان مقدار الفارق في الازاحة القصوى بحدود (27,6،4,6،7,14، 12,5)% عندما تكون القوة الديناميكية (باتجاه المحور السيني مع زاوية الطور،باتجاه المحور السيني خارج زاوية الطور،باتجاه المحور الصادي مع زاوية الطور،باتجاه المحور الصادي خارج زاوية الطور) على التوالي.

INTRODUCTION:

The finite element method is a numerical technique that can be used to approximate the model parameters (natural frequencies and mode shapes) of complex structural mechanical systems. A finite element model is typical much more detailed than an experimental model (operating deflection shape or experimental model analysis).

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. In a machine foundation the dynamic load is applied repetitively over a very long period of time but its magnitude is small and therefore the soil behavior is essentially elastic, or else deformation will increase with each cycle of loading and may become unacceptable. The amplitude of vibration of a machine at its operating frequency is the most important parameter to be determined in designing a machine foundation, in addition to the natural frequency of a machine foundation soil system.

Previous Studies Related to Dynamic Response of Foundation:

The use of finite element techniques and digital computers in the analysis of space structures during the 1960's and in modeling structures for nuclear and power generation plants has led to a significant progress in the area of structural dynamics. Many modeling techniques have been proposed to model structures subjected to dynamic loading. Many researchers have followed the concept of mathematical models to represent the dynamic response of a physical problem of machine foundations under the effect of dynamic loading.

Lysmer (1965) studied the response of vertical oscillation for circular and rectangular foundation using integral mapping. He changed the interfaces and made a better boundary conditions and came to conclusion that the behavior of a foundation under vertical dynamic load, can be modeled by an oscillator with one degree of freedom (mass-spring-damper system), if the stiffness of spring and the coefficient of damper depend to the frequency of load. He also developed independent coefficient for dynamic response of foundation in low and medium frequency.

Cheung and Zienkiewicz (1965) stated the first solution which employed the finite element method for the analysis of foundation structures on an elastic half-space. The soil was modeled by elastic continuum model, in which the separation between the raft and the soil was not allowed when negative reactions existed.

Dasgupta and Rao (1978), studied the dynamic response of rectangular footings subjected to vertical mode of vibration by finite elements. In their study, the solutions are obtained by using a three-dimensional finite element method. The study indicated that the embedded foundation can reduce the amplitudes of vibration.

Hinton (1988) analyzed reinforced concrete plates and shells under dynamic loading. Three dimensional isoparametric brick elements with 20 nodes were used to simulate the concrete. A modified elastic-plastic constitutive model was adopted to represent the concrete behavior. Newmark implicit time scheme was used to solve nonlinear dynamic equations. Results were compared with other models and were found in a good agreement.

Anteneh (2003) concluded that as the mass or mass moment of inertia of the foundation block increases, the damping ratio and the natural frequency of the foundation get smaller. Therefore, if small-frequency machines are constructed on a bigger foundation block, the probability of the natural frequency of the foundation and the operational frequency of the machine to coincide is big. In other words, a foundation having big mass or mass moment of inertia could fail with small frequency machines due to resonance conditions. From the numerical examples and discussions, one can generalize that embedding a foundation, whether it is in a homogeneous half space or a homogeneous stratum over bedrock reduces the amplitudes of all modes of oscillations. In other words, waves generated by the machine are highly damped in the embedded foundations than surface foundations. Therefore, embedding a block-type machine foundation is always helpful to reduce the vibration amplitude.

Prakash and Puri (2006) studied the methods of analysis for determining the response of foundation subjected to harmonic excitation. Analogs based on the elastic-half space solutions were used, and soil stiffness considered frequency independent for design of machine foundations. They found that the embedment of a foundation strongly influences its dynamic response.

Bhatia (2006) concluded that machines of higher ratings gave rise to considerably higher stresses thereby posing problems with respect to performance and safety. This called for development partly in the field of vibration technique and partly in that of soil mechanics. Hence, new theoretical procedures were developed for calculating the dynamic response of foundations.

Bhatia (2008) established that it is not enough to base the design only on the vertical loads multiplied by a dynamic factor, even if this factor introduces a dynamic load many times greater than the original one. It should be remembered that the operation of the machines generates not only vertical forces, but also forces acting perpendicular to the axis; it is thus not enough to make into account the vertical loads only and to multiply those by a selected dynamic factor.

Livshits (2009) showed that a modal analysis is required for frequencies separation verification. Very strict limits for amplitude of vibrations at machine bearings shall be checked by a harmonic forced vibration analysis. Response spectrum analysis gives an estimation of internal forces and displacements due to seismic excitation. Structural design of the turbine generator foundation, made of reinforced concrete, requires a series of static analyses on various static and quasi-static loads. And he concluded that ANSYS/CivilFEM software provides an efficient tool for dynamic analysis and structural design of the turbine-generator foundations.

Abou Alsaoud (2011) studied the finite element modeling and dynamic analysis of massive and elevated foundation of steam turbine generator, using three dimensional solid elements model available in ANSYS finite element package. It was concluded that the damping ratio has significant effect on the structural response in the harmonic analysis of the foundation. And the difference in response due to the changes in the compressive strength is minor.

Numerical Modeling Principles:

All design procedures have to be based on simple but adequate models reflecting the real behavior of the structure. For first estimation and principal studies spring-mass-systems can be used, for more detailed investigations numerical (finite element) models are required. In any case of dynamic calculations/ modeling the following aspects have to be considered properly:

Mass: Machine and foundation masses have to be right in size and position. Machine masses (e.g. rotor masses) have to be placed at their center of gravity and be connected to the foundation by bars. In general, these bars are modeled as rigid connections.

Stiffness: position and size of foundation and subsoil stiffness as main parameters have to be considered properly. Additional stiffness due to the machine itself and their fixation to the foundation and non-bearing elements have to be implemented for slender foundation. The subsoil stiffness is often modeled by elastic springs (pile supported foundations) or bedding modulus (directly soil supported foundations).

Damping: The total energy dissipation is based on several phenomena, mainly on nonlinear material damping of the structure and the subsoil. For constructional engineering studies the damping ratio ξ is used and applied as one value for the whole system. A total system damping factor is considered, implying all damping phenomena.

Description of the Computer Program:

ANSYS (V 11) is used for analysis throughout this study. ANSYS is a general-purpose finite-element modeling package for numerically solving a wide variety of engineering problems. These problems include static/dynamic, structural analysis (both linear and nonlinear), heat transfer, and fluid problems, as well as acoustic and electromagnetic problems. In general, a finite-element solution may be broken into the following three stages:

1. Preprocessing: defining the problem. The major steps in preprocessing are (i) define key points /lines/areas/volumes, (ii) Define element type and material/geometric properties, and (iii) mesh Lines/areas/ volumes as required. The amount of detail required will depend on the dimensionality of the analysis, i.e., 1D, 2D, axisymmetric, and 3D.
2. Solution: assigning loads, constraints, and solving Here, it is necessary to specify the loads (point or pressure), constraints (translational and rotational), and finally solve the resulting set of equations.
3. Post processing: further processing and viewing of the results. In this stage one may wish to see (i) lists of nodal displacements, (ii) element forces and moments, (iii) deflection plots, and (iv) stress contour diagrams or temperature maps.

ANSYS Structural Harmonic Analysis:

When a structure is subjected to cyclic loading, the resulting response is expected to be cyclic as well. ANSYS can solve this class of problems through the Harmonic analysis option. The strictions on a harmonic analysis are: all loads must be sinusoidal functions of time, and all loads must have the same frequency. Sinusoidal loads are specified through the parameters amplitude, phase angle and forcing frequency range. Amplitude is the peak value of the load, and phase angle is the time lag between multiple loads that are out of phase with each other. On the complex plane, it is the angle measured from the real axis. Finally, forcing frequency range is the frequency range of the Harmonic load (in cycles/time).

Definition of real constants:

Element real constants are properties, which depend on the element type, such as cross-section, area, moment of inertia, initial strain and thickness…etc. In this analysis, real constant set 1 is used for solid65 element, which requires real constants for smeared reinforcement in the three directions x, y and z. The input data for this set of real constants is volume ratio, as shown in Table (3). The volume ratio refers to the ratio of reinforced steel in the element.

Description of the Problem:

The machine foundation studied has the dimensions shown in Figure (1) and (2). In this problem, the element solid65 was used for modeling the concrete foundation (2.2x5.2x4.5) m and the element solid45 was used for modeling the foundation soil (15.4x18.2x11) m (some authors (Bhatia, 2008) considered soil domain equal to 3 to 5 times the lateral dimensions in plan on either side of the foundation and 5 times along the depth should work out to be reasonably correct). The interface is modeled by using three-dimensional surface-to-surface (Target170 and Contact174) contact elements connected with concrete and soil.

Input Data and Discussion of Output Results:

Input data for machine foundation are given by (K.G. BHATIA 2008) (table 1). According to ANSYS program, the entered material properties are listed in table (2). Unbalance Forces F_1 =0.404 kN and F_2 = 0.808 kN are considered acting in vertical as well as in lateral direction. These forces are considered acting: (a) in-phase and (b) out of phase, see (Figure 3).

From figures (4), (5), (6), and (7) it can be noted that the finite element analysis results agree with the analytical results and the difference in the ultimate displacement is about (7.14, 4.6, 27.6 and 12.5)% when the dynamic force (along X direction (in-phase), along X direction (out of phase), along Y direction (in phase) and along Y direction (out of phase)) respectively as shown in table (4). Figures (8) and (9) show the relationship between the vertical displacement and the distance (from beginning of the left side of foundation) at elevation (3.7, 4.5) m respectively.

From the illustrated relationships between the vertical displacements along a distance, it can be stated that the variation of vertical displacement reveals a response similar to the behavior of structural concrete subjected to static loads. At the point of loads, the greatest displacement generated, and then the values for each of the displacement are decreasing towards the other nodes.

CONCLUSION:

1. It can be noted that the finite element analysis agrees with the analytical results, and the difference in the ultimate displacement is about (7.14, 4.6, 27.6 and 12.5)% when the dynamic force (along X direction (in-phase), along X direction (out of phase), along Y direction (in phase), along Y direction (out of phase)) respectively
2. The finite element analysis through ANSYS is valuable tool for evaluating the structural dynamic characteristics of machines and structures during the design stage.
3. The method can be used to estimate operating stress levels and to estimate the natural frequencies and mode shapes for equipment and supporting structures.

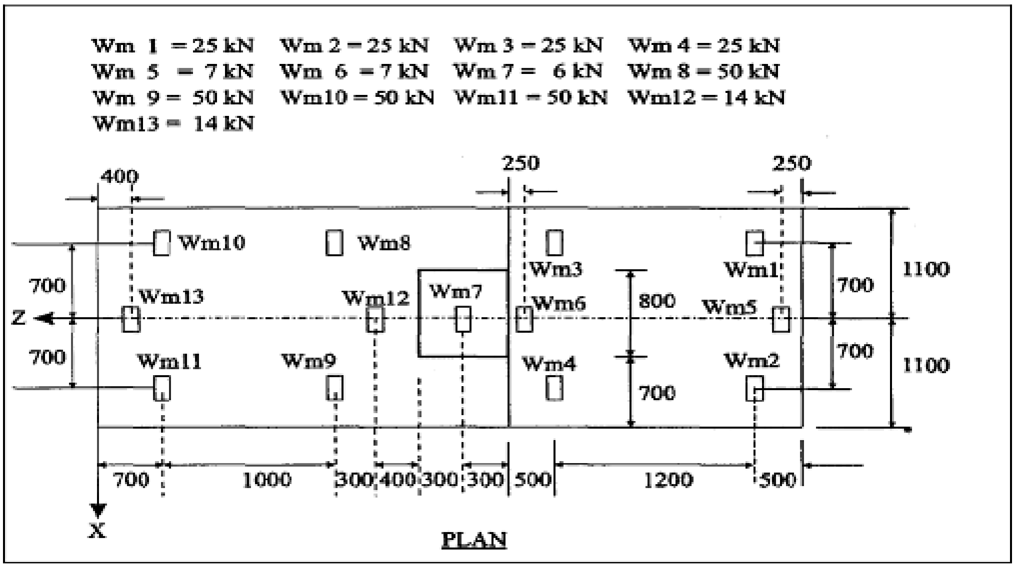

Figure (1) Details of machine foundation of the problem (Bhatia,2008)

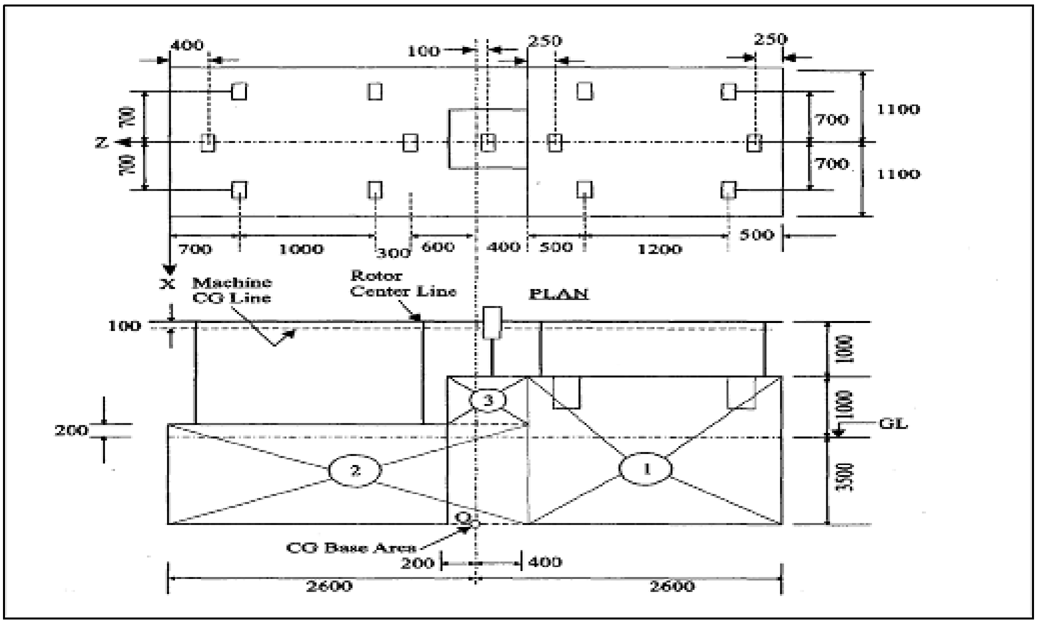

Figure (2) Machine layout with respect to CG of base area O (Bhatia,2008)

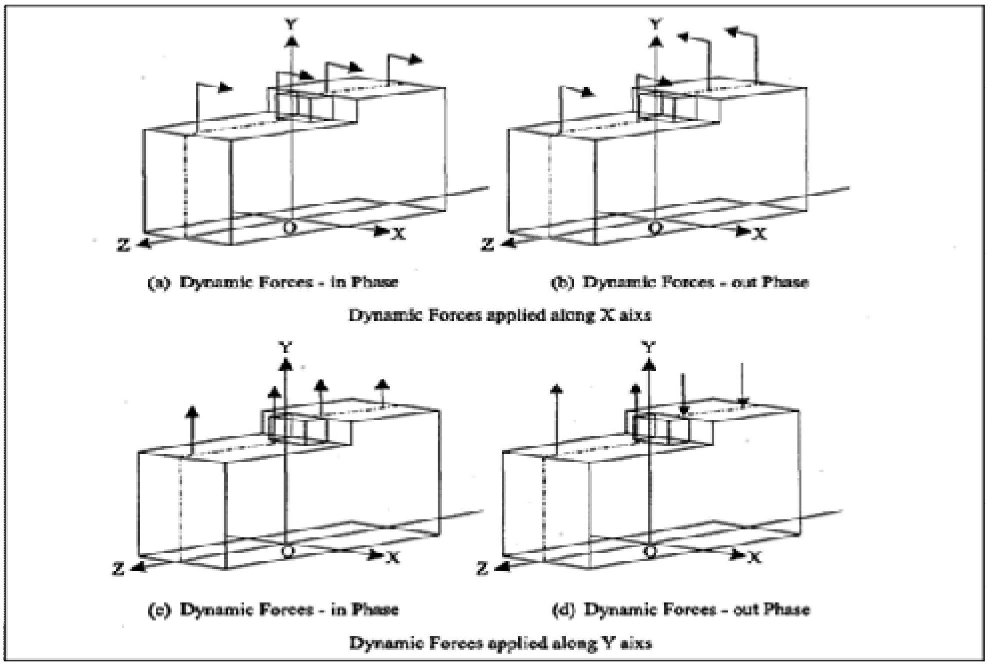

Figure (3) shows dynamic forces applied at bearing location.

Table (1) input data are as given by (K. G. BHATIA 2008)

Machine Data:

- Weight of Drive Machine (excluding Rotor) 100 kN
- Weight of the Non-Drive Machine (excluding Rotor) 200 kN
- Weight of Drive Machine Rotor 10 kN
- Weight of Non-Drive Machine Rotor 20 kN
- Bearings: Both the rotors have Pedestal bearings
- Weight of bearing pedestal
  - Drive machine 2 kN (each pedestal)
  - Non-drive machine 4 kN (each pedestal)

Consider CG of bearing pedestals and coupling at rotor Centre Line level.

- Weight of Coupling 6 kN
- Rotor Speed 600 rpm
- Balance Grade for both the rotors $G6.3$
- Height of Rotor Centerline above Ground level 2000 mm
- Height of Machine Centroid below rotor centerline 100 mm

Foundation Data

- Length of Foundation Block 5200 mm
- Width of Foundation 2200 mm
- Height of Foundation block is above ground level
  - Drive end side 1000 mm
  - Non drive end side 200 mm
- Mass Density of concrete $\rho_c = 2500$ kg/m^3

Soil Data

- Mass Density $\rho_s = 1800\ \text{kg/m}^3$
- Poisson's Ratio $\nu = 0.25$
- Damping constant $\zeta = 0.1$
- Site Coefficient of Uniform Compression normalized to 10 m^2 Area
  $C_{u01} = 4.6\times10^4\ \text{kN/m}^3$
- Site Static Stress $\bar{\sigma}_{01}$ @ 3.5 m depth 100 kN/m^2
- Net Bearing capacity at 3.5 m depth 250 kN/m^2

Table (2): Input data for the foundation of problem

	Symbol	Definition	Value
Concrete	f_c'	Cylinder compressive strength (MPa)	25
	E_c	Young's modulus (MPa)	23500
	ν	Poisson's ratio	0.15*
	ρ_c	Density (kg/m^3)	2500
Interface	μ	Coefficient of friction	0.5*
Soil	Es	Young's modulus (MPa)	30**
	ν	Poisson's ratio	0.25
	ρ_s	Density (kg/m^3)	1800

Notes: *Assumed value, = 4700 (ACI 318M-code) , and * * This value corresponds to loose-medium sand according to the guide line of Bowles, 1996.

Table (3): Real constant for concrete

Real constant	Element type	Constant	
1	Solid65	Volume ratio	0.002

Table (4): The result of amplitudes for analytical and finite element method through ANSYS computer software.

Amplitudes in microns		
Dynamic Force	Analytical Method(Bhatia, 2008)	FE Analysis(ANSYS Program)
Along X In-phase	8.4	9.0
Along X out of phase	15.2	15.9
Along Y In-phase	5.8	4.2
Along Y out of phase	2.4	2.7

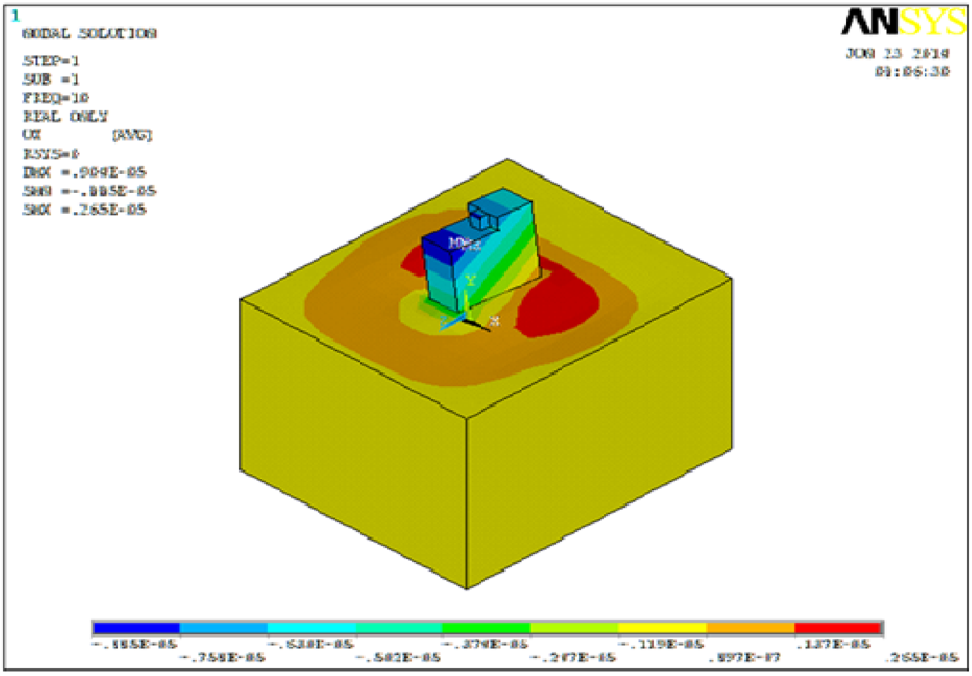

Figure (4): Displacement of foundation (m) when applied dynamic forces along X direction (In phase)

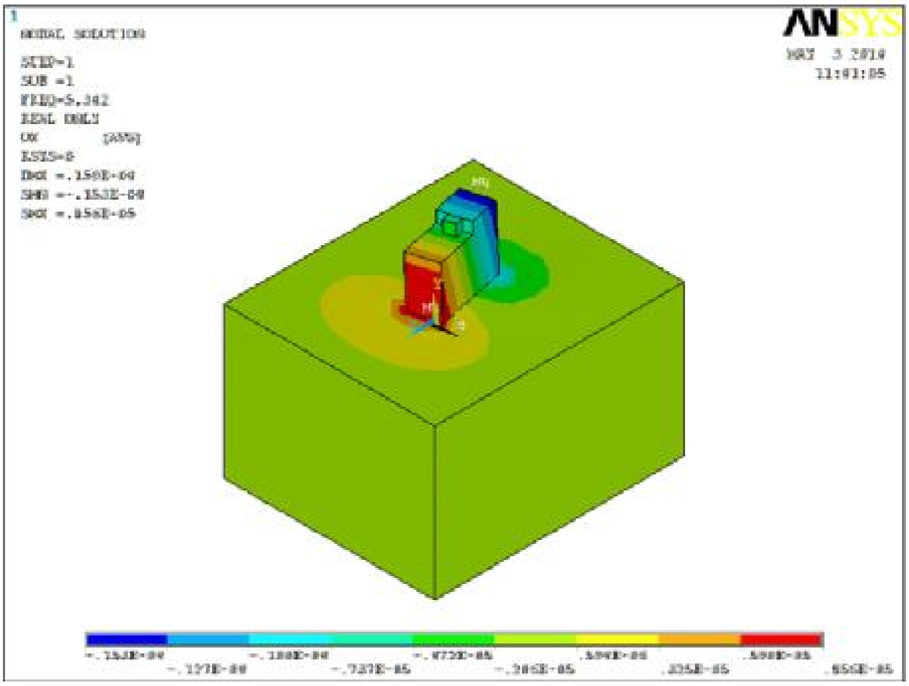

Figure (5): Displacement of foundation (m) when applied dynamic forces along X direction (out of phase)

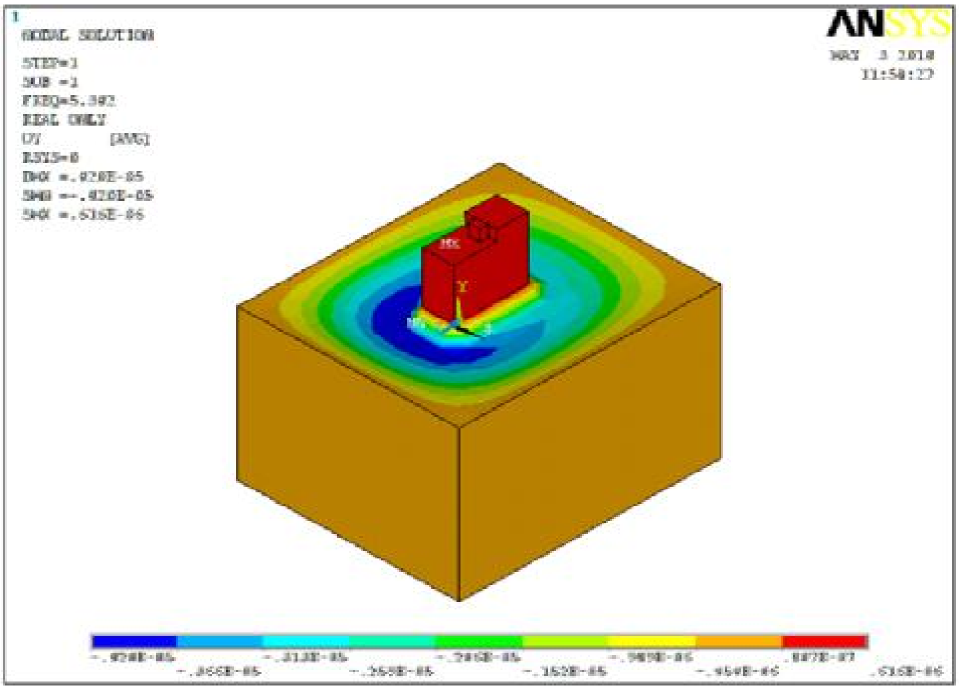

Figure (6): Displacement of foundation (m) when applied dynamic forces along Y direction (In phase)

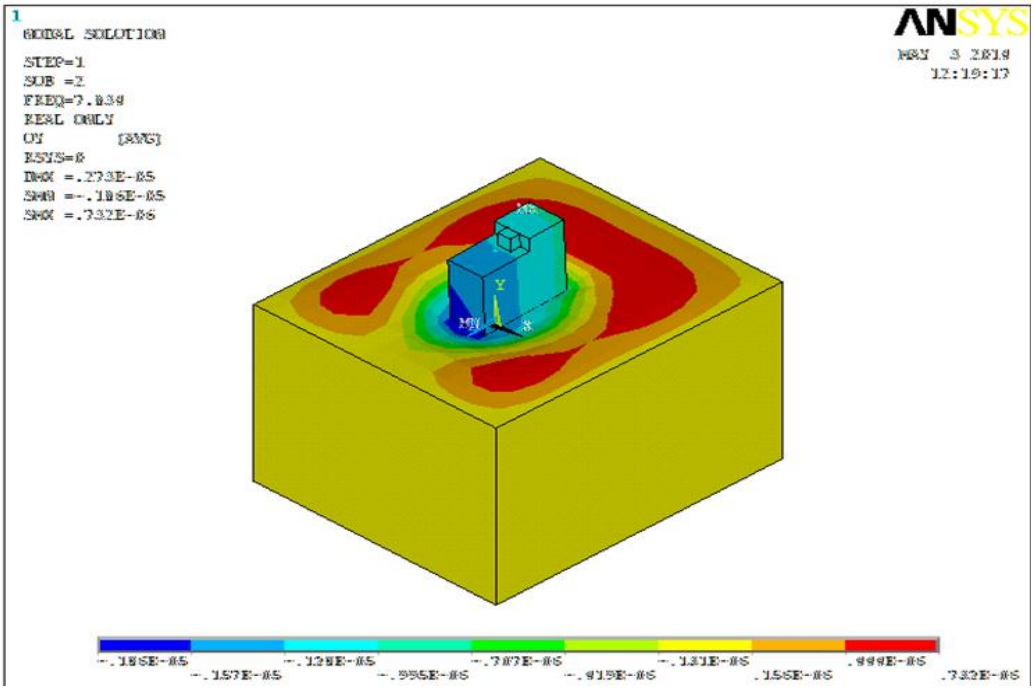

Figure (7): Displacement of foundation (m) when applied dynamic forces along Y direction (out of phase)

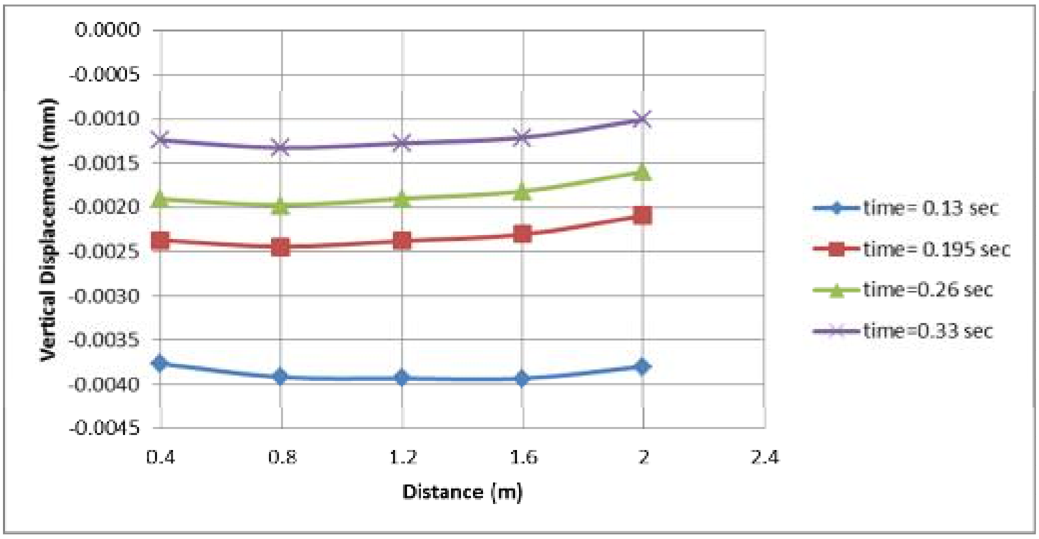

Figure (8): Variation of vertical displacement with distance (from beginning of the left side of foundation) for the machine foundation at elevation 3.7m

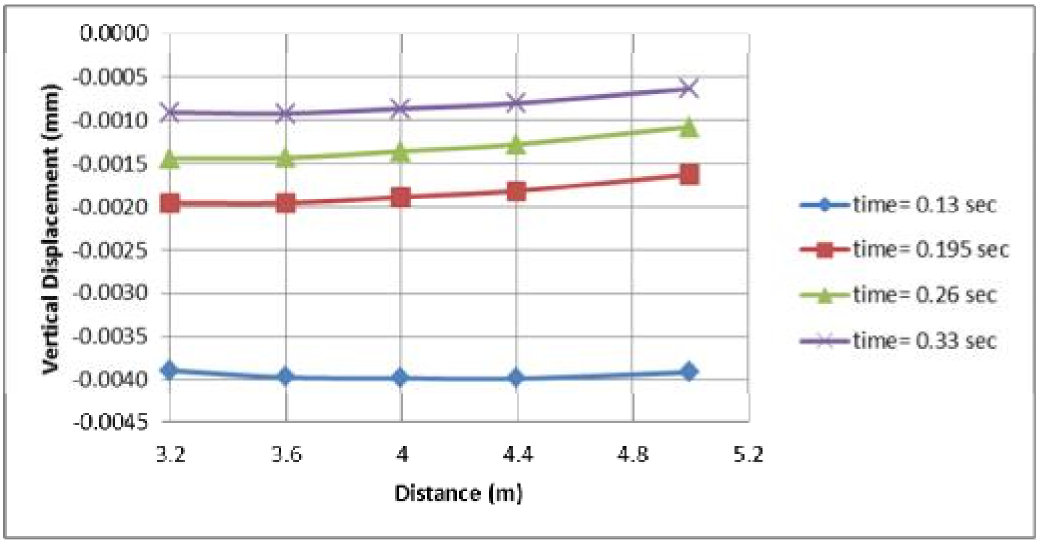

Figure (9): Variation of vertical displacement with distance (from beginning of the left side of foundation) for the machine foundation at elevation 4.5m

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