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# Investigating the effective factors on the dynamic analysis of foundations located on saturated porous medium under the effect of horizontal and torsional vibrations using the cone model method

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**ABSTRACT:** Seismic analysis of machine foundations located on saturated porous media can be carried out with several methods. Some of these methods are very accurate such as the boundary element method, complex finite element method, and scaled boundary finite element method. Other methods, such as the cone model method, is not only simple and practical but also have appropriate and acceptable accuracy. In the cone model, the soil mass is modeled with incomplete cones and the propagation of waves in these cones is followed until the wave is sufficiently damped and its effect on the foundation response is negligible. In this research study, the application of the cone model method in determining the dynamic stiffness, taking into account the effect of pore water (two-phase approach), has been investigated for different soil conditions. The system of differential equations governing horizontal and torsional vibrations in a porous medium is obtained by considering the effect of soil dilatancy. Also, the effect of different parameters such as layer thickness, porosity, and permeability coefficient has been investigated on the foundation's response under shear and torsional vibrations. The obtained results show that the cone model can provide a good level of accuracy and high computational efficiency for predicting the horizontal and torsional vibrations of foundations resting on saturated porous media. Also, the two-phase environment shows considerable attenuation in low frequencies compared to the one-phase one, and in the case of deep rock bed, there is no significant difference in attenuation. In addition, the greater the thickness of the layer, the closer its performance is to the case where the foundation is based on a half-space, and if the thickness of the first layer is more than 20 times the radius of the disk, the environment can be accurately described as a half-space regardless of other layers. Also, with the increase of the permeability coefficient of the layer, the influence of this parameter in the analysis increases, especially in smaller frequencies, and the decrease of the permeability coefficient leads to an increase in damping. Another part of the results obtained from this research shows that the porosity parameter has a very small effect on the horizontal and torsional stiffness coefficients, although the sensitivity of the dynamic analysis to porosity is significant for high frequencies of vertical alternating load.

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## 1- Introduction

In general, there are two types of methods for foundation vibration analysis: rigorous and approximate. Numerical methods like the finite element method [1-3], boundary element method [4], and scaled boundary element method [5, 6] are examples of rigorous methods that can be used to evaluate the dynamic response of footings when complex analytical solutions are required [7]. Although, the use of new methods of solving differential equations that are expanding every day by researchers in the fields of science and engineering [8] can be considered as an analytical solution for directly solving differential equations related to wave propagation, proposing and improving approximate methods with sufficient accuracy is always be of interest. One of the approximate and simple methods that have been developed as alternatives to rigorous methods to analyze foundations is the cone model method. The cone model method has been developed in recent decades as an alternative to exact methods, which not only has acceptable accuracy but also requires much less computational effort and cost compared to exact methods. This method can be used also for probabilistic analyzes in which a large amount of calculations is required [9, 10]. Numerous studies have compared single-phase and two-phase modeling techniques for soil and fluid, with two-phase techniques being more accurate and closer to reality because they account for the interaction between the water phase and the impermeable probe [11-13].

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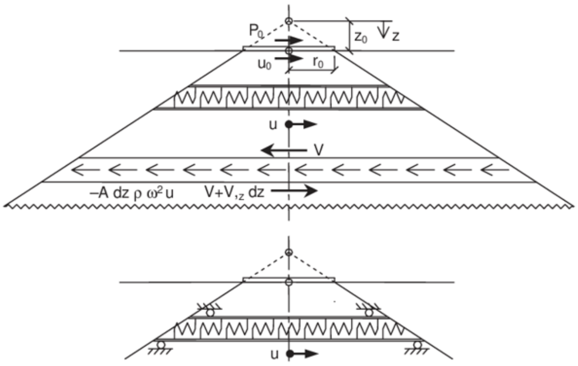


**Fig. 1. Cone model for horizontal degree of freedom**

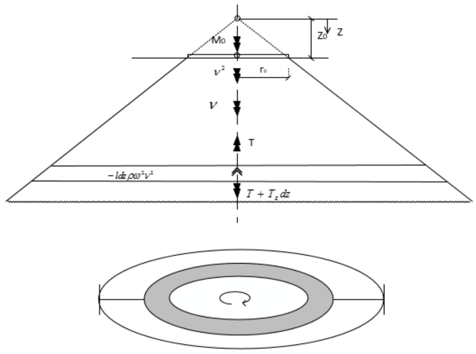


**Fig. 2. Cone model for rotational degree of freedom**

## 2- Methodology

In this study, the validated approximate cone model method is used to investigate the dynamic analysis of foundations rested on saturated porous media under torsional and horizontal vibrations. An effective framework based on the cone model technique has been coded in MATLAB for this purpose. The effect of soil dilatancy is carefully taken into account To obtain the system of differential equations governing horizontal and torsional vibrations in a porous medium. Additionally, the relationships between vertical and horizontal displacements are developed, which leads to the development of vertical stiffness and horizontal stiffness. It has been studied how different parameters, such as layer thickness, porosity, and permeability coefficient, affect how well foundations respond to shear and torsional vibrations.

### 2- 1- Cone model method

The dynamic equilibrium equations and compatibility relations for an incomplete semi-infinite cone should be established by taking into account both the solid and fluid phases To obtain the relations of differential equations under horizontal (Fig. 1) and torsional vibrations (Fig. 2). Full rigidity of foundation, weightless of foundation, dilatation in media, one-dimensional mechanics of materials method, and soil elasticity were presumed meanwhile of seismic analysis with cone model. Furthermore, the uniform stress distribution in the soil layers assumed and soil intended for two-phase media. It should be noted that the one-dimensional mechanics of materials method presumption means that all plates remain plain after stress application.

According to Fig. 1, the horizontal displacement is defined as:

$$-\tau A_x + \left(\tau + \frac{\partial \tau}{\partial x}dx\right)\left(A_x + \frac{\partial A_x}{\partial x}dx\right) = \left(\left[\ 1-n\ \rho_s + n\rho_f\right]\frac{\partial^2 v}{\partial t^2}\right)A_x dx \tag{1}$$

where $n$, $A_x$, $p_s$, $p_f$ and t are porosity, the cross-sectional area of the cone at a distance x from the apex, mass density of the solid, mass density of fluid, and time, respectively. Also, is shear stress and v is the total horizontal displacement. After simplifying the above relation and neglecting the $dx^2$ term, the following relation results:

$$\frac{\partial \tau}{\partial x}A_x + \tau\frac{\partial A_x}{\partial x} = \left(\left[\ 1-n\ \rho_s + n\rho_f\right]\frac{\partial^2 v}{\partial t^2}\right)A_x \tag{2}$$

where $A_x$ is the derivative of A(x) with respect to x ( i. e. $A_x = \frac{\partial A(x)}{\partial x}$). The area at depth x is defined as $A(x) = (x/x_0)^2 A_0$ with $A_0 = \pi r_0^2$, where x is measured from the apex and considered area.

In the case of torsional vibration, according to Fig. 2, the torsional displacement is defined as:

$$\begin{aligned} &-T\ \ x,\omega\ \ +T\ \ x,\omega\ \ +T\ \ x,\omega\ {}_{,x}\ dx+ \\ &\omega^2 I\ \ x\ \ dx\ \ \ 1-n\ \ \rho_s+n\rho_f\ \ \vartheta=0 \end{aligned} \tag{3}$$

The Eq. 3 can be also expressed in the following form:

$$\frac{\partial T}{\partial x} + \omega^2 I\ \ x\ \ \ \ 1-n\ \ \rho_s + n\rho_f\ \ \vartheta = 0 \tag{4}$$

where I(x) is the polar moment of inertia ( $I(x) = \frac{\pi r_0^4}{2} = (\frac{x}{x_0})^4$ ), and T is the torsion which is obtained as a function of rotation as $G\upsilon I(x)$ .

## 3- Results and Discussion

This study examined the dynamic analysis of foundations supported by saturated porous media under horizontal and torsional vibrations using the cone model method. The two-phase medium showed significant damping at low frequencies compared to the single-phase medium. However, for a deep bedrock, there is not much difference in damping. The greater the thickness of the layer, the closer its performance is to the case where the foundation is located on a half-space. The results showed that if the thickness of the first layer is more than 20 times the disk radius, the medium can be analyzed with good accuracy like a half-space, regardless of other layers. In addition, the parameters of the porous medium in the dynamic analysis of the foundation showed that the influence of this parameter in the analysis increases with the increase of the permeability coefficient of the layer. The lower the frequency, the more visible the above effect.

## 4- Conclusions

Given the results, it can be stated that:

• A decrease in the permeability coefficient leads to an increase in damping. From the obtained results, it can be concluded that the effect of the permeability coefficient is significant for values greater than $10^{-4}$.

• Porosity has a very small effect on the horizontal and torsional stiffness coefficients. The sensitivity of the dynamic analysis to porosity is significant for high frequencies of vertical load, although the coefficient of porosity is not very effective in soil dynamic stiffness.

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