Application of the finite element method for analysis of the influence of dynamic loads on a machine foundation on piles

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Abstract. This work presents the fundamental concepts of structural dynamics, applied to the study of machine foundations. It discusses a method of obtaining the representative parameters of the pile-soil set considering the effect of the group acting by the proximity of the piles. In addition, this article is dedicated to preparing a detailed case study with the aid of ANSYS®, software based on finite elements, in order to reach the displacement values incorporated by the foundation element. These results were obtained according to normative criteria in the questions of severity of vibrations, effects on people and damage to the structure, allowing for attesting the capacity of the chosen foundation to resist the dynamic loads caused by the operation of the machine.

Keywords: Machine Foundation; Dynamic Analysis; Synchronous Condenser

1 Introduction

Synchronous condensers are essential rotating machines directly connected to the electrical grid, ensuring the stability and reliability of the Brazilian electrical system. Unlike generators, they do not drive or are driven by other components; instead, they provide inertia, improve short-circuit handling, and manage reactive power to maintain voltage stability. With the growth of renewable energy sources like solar and wind, which lack inertia, synchronous condensers have become crucial for integrating these energies and maintaining grid stability. They help regulate grid frequency, compensating for the fluctuations caused by variable renewable generation. As the adoption of renewable energy increases and environmental regulations tighten, the demand for synchronous condensers has risen, prompting detailed studies of these machines and their supporting structures. The design of their concrete foundations is especially important due to the cyclic vibrations generated during operation.

The foundation design is typically suggested by the manufacturer, requiring modal and harmonic analysis to validate dimensions. ANSYS® Workbench, a finite element modeling tool, was used to validate the design by analyzing the effects of dynamic loads. The study involves defining the component geometry and dynamic geotechnical parameters, obtaining natural frequencies, displacements, and vibration velocities. The Pilay program provides stiffness and damping coefficients of the foundation, which are input into ANSYS® for analysis. The main goal is to distance the operating frequency from the structure's natural frequencies to minimize dynamic load impacts. This article summarizes the Graduation Project by Rodrigues, under the guidance of the co-author.

2 Analysis Method

The analysis methodology relies on Ansys® for the dynamic analysis of the equipment's pile foundation and Pilay for evaluating the stiffness and damping coefficients of piles in vertical and horizontal directions.

2.1 The Pilay Program

The program, developed by Novak and Aboul-Ella (1977), is designed for vertical piles in stratified soils with negligible material damping. It calculates dynamic stiffness, damping, internal forces, and displacements for all vibration modes, including torsion. In this work, the program is used only to determine the stiffness and damping of an isolated pile. These values are then used to calculate the stiffness and damping coefficients of the foundation, considering the pile group effect. These coefficients are input data for foundation analysis in Ansys®.

2.2 The ANSYS® Program

Ansys® is a finite element-based software used to solve various engineering problems, including dynamic issues that encompass modal and harmonic analysis. Thus, modal analysis is used to calculate the frequencies and modes of vibration, while harmonic analysis is useful for determining the response of a structure subjected to time-varying harmonic loads.

2.3 The numerical modal analysis – Ansys®

Modal analysis in Ansys® calculates the natural frequencies and vibration modes of a structure. This analysis can be conducted on structural systems with materials that have linear mechanical properties and without any force acting on the system. This system of equations can be written in complex form, which allows for matrix treatment, see Clough and Penzien [2]. The solution developed by the software begins by:

$$[M]\{\ddot{u}\} + [C]\{\dot{u}\} + [K]\{u\} = \{F\} \tag{1}$$

Starting from the premise that there is no external loading acting, disregarding the damping and assuming that the displacements occur in a harmonic regime:

Thus, it follows:

$$(-\omega_i^2[M] + [K])\{\phi\}_i = \{0\} \tag{2}$$

The equality is satisfied if $\{\boldsymbol{\phi}\}_{\boldsymbol{i}} = \mathbf{0}$ or if:

$$\det(-\omega_i^2[M] + [K]) = \{0\} \tag{3}$$

2.4 Numerical Harmonic Analysis – Ansys®

Harmonic analysis determines the response of a structure to time-varying harmonic loads. In this stage, cyclic loadings are applied to the structure, enabling the determination of harmonic displacements for each degree of freedom, the stresses developed by the component, among various other pieces of information. The analysis begins from equation 1, assuming that $\{F\}$ and $\{u\}$ vary harmonically at a specific frequency ω. Thus:

$$[M]\{\ddot{u}\} + [C]\{\dot{u}\} + [K]\{u\} = \{Fe^{i\omega t}\} \tag{4}$$

The machine-foundation system is described by the matrices $[M]$, $[C]$ and $[K]$, which represent mass, damping, and stiffness, respectively. The vector $\{F\}$ indicates the amplitudes of the applied forces and moments. The vector $\{u\}$ records the time variations of displacements and rotations across the six degrees of freedom. The circular frequency of excitation is represented by ω. As the problem is harmonic, $\{u\}$ can be represented in terms of $u_{máx}$, which are the unknown amplitudes of displacements and rotations, in the following manner:

$$\{u\} = \{u_{máx}\}e^{i\omega t} \tag{5}$$

The problem is solved using complex matrix algebra:

$$u_{máx} = (-\omega^2[M] + i\omega[C] + [K])^{-1}F \tag{6}$$

In synchronous condensers, dynamic forces primarily stem from mass eccentricity, where the center of mass of rotating parts does not align with the center of rotation. This misalignment, caused by imperfections, transport issues, wear, or clearances, is a common source of vibration in rotating machinery. Even minor irregularities in mass distribution can lead to significant vibrations. The mass matrix [M] is constructed based on the equipment's geometry and mass, while the damping [C] and stiffness [K] matrices are derived from the soil's elastic properties and the foundation type. For more details on soil-structure interaction, refer to Rodrigues' original Graduation Project. At the rotor's center of gravity, the harmonic forces act in any direction perpendicular to the longitudinal axis of rotation are, $F_{din} = m_{rot} Q\omega$. The parameter Q represents the balancing quality of the machine. This value is found in ACI 351.3R-18 [1] where it relates the type of equipment to the necessary fine-tuning. For this case, Q was adopted as 6.3 mm/s. m_{rot} indicates the mass of the rotating parts, and ω represents the angular operating frequency of the machine, $\omega = 2\pi f$, where f is the nominal frequency of the equipment, 15 Hz (900 rpm). Very strict limits for the amplitude of vibrations at the machine base must be verified through harmonic forced vibration analysis.

3 Foundation Analyzed

An analysis is presented for a machine foundation on piles. This includes a step-by-step dynamic evaluation for the foundation of equipment mounted on a rigid reinforced concrete base. The proposed solution, taking into account all the conditions and limitations of the project, consisted of a foundation block and piles with the following characteristics: length of 10.006 m, width of 8.0 m, and height of 3.20 m. The total weight of the block is 620.70 Mg. The piles have a length of 10.50 m and a diameter of 1.0 m. Fourteen piles were used for this solution.

3.1 Soil Characteristics

The soil, when subjected to forces induced by the operation of machines, exhibits extremely small deformations, on the order of a few microns (μm). These specific deformations are so small that they allow the soil's behavior to be considered elastic and linear. Different regions of the soil are treated as homogeneous. The various soil parameters are considered as defined below. The soil's transverse deformation modulus was determined empirically, due to the absence of specific tests for its measurement. This parameter was evaluated based on the number of blows obtained in the SPT test, according to the methodology of Ohsaki and Iwasaki [5], $G = 11500\ N^{0,8}$. The local subsoil has predominantly clayey characteristics with the presence of soft soil. The impenetrable layer is located at approximately 14 m depth. The Poisson's ratio was adopted as $\nu = 0.35$. The variation of this parameter has a much lesser influence on the results compared to the variation of G values. For the specific gravity, a value of $\rho = 1.8$ t/m³ was assumed.

3.2 Concrete Base Characteristics

The base was designed according to Petrobras N-1848 [6] guidelines, ensuring the centroid of the base and the center of gravity of the foundation-machine assembly are vertically aligned, allowing up to 5% eccentricity. The foundation block height accommodates the full length of the anchor, approximately three meters, and must be at least 1/5 of the smallest base dimension and no less than 1/10 of the largest dimension. Made of reinforced concrete with a compressive strength of fck = 25 MPa, the base's dimensions are tailored to the equipment's geometry. Results were calculated based on ISO 2372 [3] criteria, using the effective velocity obtained at the single operating frequency.

3.3 Equipment Characteristics – Synchronous Condensers

The synchronous condenser is a large-scale piece of equipment. The loads and their application points are defined by the equipment manufacturer. The harmonic analyses were conducted at the operating frequency of the synchronous condensers (15 Hz). For this case study, specific conditions were imposed to ensure the avoidance of certain frequencies, as required by the equipment manufacturer. The natural frequency of the foundation must not coincide with multiples of 60 Hz (N x 60 Hz, where N = 1, 2, 3, 4, 5, etc.) and with multiples of 15 Hz (N x 15 Hz, where N = 0.5; 1, 2, 3, 4). Additionally, the first harmonic of any critical speed of the foundation must not coincide with 15 Hz, considering a variation of ± 20%, i.e., between 12 Hz and 18 Hz.

3.4 Model Characteristics

The model was developed in ANSYS® 2021 R1 Academic Workbench, incorporating a hole for equipment maintenance. Each pile was represented by a spring-dampener system in the x, y, and z directions. Stiffness and damping values, calculated in the Pilay program, were used as input data. The machine was modeled as a mass at the equipment's center of gravity. This model, shown in Fig. 1, was used for modal and harmonic analyses.

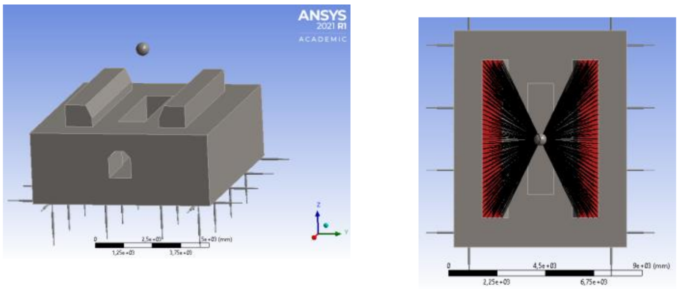

Figure 1. Finite element model for the machine foundation

4 Analysis Results

4.1 Calculation of Dynamic Geotechnical Parameters (K and C)

The values of vertical and horizontal stiffness and damping for the group of 14 piles are presented at Tab. 1. The Pilay software was used for this calculation.

Table 1. Vertical and Horizontal stiffness (K_v and K_h) and damping (C_v and C_h) for each pile considering the group effect.

Piles	K_v (kN/m)	C_v (kN.s/m)	K_h (kN/m)	C_h (kN.s/m)
1, 4, 11 e 14	1.1334×10^6	4.8672×10^3	2.0820×10^5	1.6004×10^3
2, 3, 12 e 13	9.2300×10^5	3.9636×10^3	1.4224×10^5	1.0934×10^3
5, 7, 8 e 10	8.7285×10^5	3.7483×10^3	8.5921×10^4	6.6046×10^2
6 e 9	8.1460×10^5	3.4981×10^3	5.7160×10^4	4.3938×10^3

4.2 Estimation of the Exciting Force

Considering the balancing quality as Q=6.3 mm/s as recommended by ACI 351.3R-18, the result of the dynamic force (F_{din}) under the commissioning condition, with a safety factor (S_f) of 1, is $F_{R,1}$ = 98kN. At the end of the service life, we have a safety factor of 2,5 (S_f), resulting in a loading of $F_{R,2,5}$ = 245kN.

4.3 Modal Analysis

The vibration modes that will be excited in each direction are those that mobilize most of the mass, and these are summarized in Tab. 2.

Table 2 - Excited Modes in Each Degree of Freedom

Translation Degree of Freedom	Excited Modes	Natural Frequencies (Hz)	Rotation Degree of Freedom	Excited Modes	Natural Frequencies (Hz)
x (translation)	2	6.15	xx (rotation)	1	6.15
y (translation)	1	6.02	yy(rotation)	2	6.15
z (translation)	4	17.98	zz(rotation)	3	10.32

4.4 Harmonic Analysis

This stage of the analysis was conceived by applying two forces, one horizontal and one vertical of the same magnitude, and considering a phase difference of 90 degrees between them associated with a harmonic function. Both forces were applied at the external mass point of the block base, representing the rotor axis. Additionally, the program was provided with the load transfer surface from the machine to the block. Moreover, for verifying vibration levels, forced analyses were conducted considering the dynamic forces $F_{R,1}$ and $F_{R,2,5}$. The verification of vibration severity was performed through a direct comparison between the limits established in ISO 2372 [3] and the velocity results extracted from the program converted into effective velocity (rms), presented in Tab. 3.

Table 3 - Effective velocities (vrms) developed – ANSYS®

v_{rms}	Result for $F_{R,1}$	Result for $F_{R,2,5}$	Description
$v_{rms,x}$ =	0.01 mm/s	0.04 mm/s	Velocity in rms for the direction x
$v_{rms,y}$ =	1.16 mm/s	2.90 mm/s	Velocity in rms for the direction y
$v_{rms,z}$ =	1.22 mm/s	3.04 mm/s	Velocity in rms for the direction z

According to ISO 2372, the equipment is classified as heavy machinery (Class III). Velocities up to 1.8 mm/s are optimal, 1.8 to 4.5 mm/s are acceptable, 4.5 to 11.2 mm/s are tolerable, and above 11.2 mm/s are unacceptable. The maximum velocities found were 1.22 mm/s and 3.04 mm/s, both within the acceptable range. Based on these results and the natural frequency being far from the excitation frequency, the adopted solution is deemed feasible.

5 Conclusions

This article presented the systematic approach employed to enable the foundation of a typical piece of equipment, in this case, a synchronous condenser, which generates dynamic loads in an electrical substation. An analysis was conducted using the Pilay and Ansys® programs. This evaluation confirmed that the proposed foundation is ±20% away from the operating frequency as required by the manufacturer, ensuring that resonance is not an issue for this case. Additionally, with the results of the real velocities, the effective velocities were calculated, with the maximum values found being 1.22 mm/s for $F_{R,1}$ and 3.04 mm/s for $F_{R,2,5}$, occurring in the vertical direction (Z) for the analyzed shear modulus G. These results fall within the acceptable classification range according to the criteria established by ISO 2372 [3]. Thus, it is concluded that this foundation solution is applicable as the displacements experienced by the foundation are well controlled and limited, adhering to regulatory restrictions.

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