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STRUCTURE-SOIL INTERACTION FOR FRAMED STRUCTURES UNDER DYNAMICS LOADING CAUSED BY RECIPROCATING COMPRESSOR

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Abstract. *Gas compressors are key components of industrial plants in oil refining, mainly acting as mechanical energy suppliers to chemical processes. Among the types of compressors, the reciprocating ones are highlighted. Due to mandatory demands of chemical process and industrial arrangement, such equipment is commonly installed on framed structures. This condition and the typical movement of mechanical parts of the compressors generate dynamic loads which frequently cause unacceptable vibrations. The work aim at evaluate the dynamic behavior of a system consisting of a framed structure, a reciprocating compressor, foundation in piles and the soil itself. For this purpose, parametric study is developed from a finite element model and field measurements. The parametric study goal is to establish ranges of local soil parameters within which the dynamic behavior of a system can be understood and measured. The parameters so-called constant coefficient of horizontal reaction (n_h) of natural soil which typically occurs in an industrial area located in Araucária, Paraná state, Brazil, are then evaluated. The evaluation of the dynamic behavior of the system through the developed models is benchmarked by field measurements of effective velocity of vibration in the actual structure, obtained by instrumentation. The soil parameters are obtained by back analysis of tests results by using a model widely used in design offices: model proposed by Miche[1]. It takes into account the variation of the soil parameters with depth. Yet the other goal is to evaluate the influence of the soil parameters obtained by static and cyclic horizontal loading tests, the later ones being proposed to simulate the dynamic effect on the soil. Finally, the article presents comparisons of the results provided by the finite element model in terms of natural frequencies of vibration.*

1 INTRODUCTION

During the first studies of vibrations in structures and machine foundations, simple calculation methods considered the dynamic effects simply as an amplified static loading, that is, a factor known as Dynamic Factor was applied over the value of static loads, which often led to larger loads than the actual dynamic loading and thus the design became very conservative.

By the increasing size of equipments as the ones found at an industrial plant, which began operating under conditions more and more severe, a deeper analysis regarding dynamic loads became necessary and fundamental. Among these equipment, we highlight the large reciprocating compressors, which have as main function to provide mechanical energy to chemical processes. Reciprocating compressors, due to requirements of chemical process and industrial arrangement, are commonly installed on framed structures, which are no rarely under unacceptable vibrations caused by dynamic loads. This condition motivates special attention during design phase.

Furthermore, the cost associated with equipment shutdowns in industrial plants due to mechanical failures and poor performance is significantly higher than the cost associated with a well developed design, which justifies every effort to ensure that the appropriate behavior during the future operation be achieved.

The dynamic interaction between soil and structures embedded in it is still a field where researchers are looking for answers to various problems. As an example, the soil is modeled as a linear spring on the theory of elastic half-space, which by hypothesis is considered as a linear isotropic medium, which indeed is not.

In the analysis of the dynamic response of foundations, soil can be treated in several ways. These treatments include finite element method, boundary element method, analytical solutions developed from the solution of the wave equation and simplified mechanical models. The finite element method allows the evaluation of the underground complex configurations, but requires significant computational effort. Yet analytical solutions are generally limited to very simple conditions and are not always applicable to real conditions, especially when nonlinearities and complex boundary conditions are involved [2].

In this work, we studied the typical soil parameters of an industrial area, located in Araucaria, Paraná state, Brazil, which in general belongs to the geological formation so-called Guabirotuba.

This parametric study aimed at establishing ranges of local soil parameters within which the dynamic behavior of a framed piled structure supporting a reciprocating compressor could be completely understood.

The numerical evaluation of the dynamic behavior of the system was fitted by measured values of velocities in the actual structure obtained by data acquisition. The spring coefficient km and the horizontal reaction constant n_h were assessed.

These parameters were obtained by back analysis from field loading tests considering a model widely used in design offices, which was proposed by Miche [1]. It considers the soil parameters varying along depth.

The article also seeks to evaluate the influence of soil parameters obtained by testing static load and obtained through cyclic static loading tests on piles, the last one proposing to simulate the dynamic effect on the soil.

Finally, comparisons between the results provided by the simplified models and the finite element model in terms of natural frequencies of vibration were done.

2 INTERACTION AMONG MACHINE, STRUCTURES AND SOIL

In general, a problem of machine foundations corresponds to an interaction among machines, supporting structures and underground, all of them directly or indirectly subjected to dynamic loads.

The dynamic interaction between a reciprocating compressor, a concrete supporting structure, its foundation and subsoil is covered in this paper. As will be shown, the movement of the pistons inside the cylinders of the compressor generates transient forces and moments on the structure and, consequently, on its foundations.

2.1 Machines

Typically, the basic oscillating mechanism shown in Figure 1 consists of a piston moving in a cylinder guide, a connection bar fixed at a piston and the rotating element (crank), which rotates around its axis (crankshaft) with angular frequency ω. The piston movement can be horizontal or vertical depending on the design of the equipment.

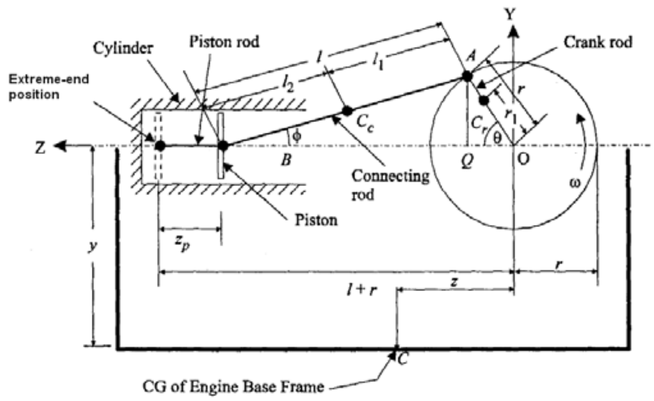


Figure 1: Typical arrangement of reciprocating compressor 1 cylinder [4]

The components of the mechanical system of the reciprocating compressor shown above are described in table 1.

Crank mass	m_r
Crank lengh	r
Crank gravity center	C_r
Conection rod gavity center	C_c
Rotational axis	O
Lengh between C_r and O	r_1
Rotational velocity	ω
Conection point at crank	A
Conection point at piston	B
Concetion rod mass	m_c
Concetion rod lengh	l
Distance between C_c and A	l_1
Distance between C_c and B	l_2
Piston mass	m_p

Table 1: Mechanical elements of a reciprocating compressor

The force generated at point B can be expressed by the following equation.

$$F_B = m_B r\omega^2(\cos\omega t) + m_B r\omega^2\left(\frac{r}{l}\cos 2\omega t\right) \quad (1)$$

The term m_B in equation *1* can be written as $m_B = m_r(\frac{l_1}{l}) + m_p$.

2.2 Structure and soil

The complete understanding of a problem of dynamic loading on a structure and its foundation due to a mechanical equipment or even due to earthquakes can be achieved only when it is analyzed as a whole unique system. For instance, by ignoring the effect of the soil, treating it as undeformable, the response of the structure can vary significantly.

The consideration of soil as a deformable elastic element leads to the coupling between soil and structure stiffness, which changes the overall behavior of the system. Also, what if the foundation of a structure is placed directly on the ground, what if it is supported on piles, what if it is embedded in the soil, what if the soil layers are laminated, all these features are capable of influencing the behavior of a system.

3 PHYSICAL MODEL

This chapter presents all the physical characteristics of the problem of soil-structure interaction-equipment studied, namely geometry and material of the structure-foundation system, soil physical properties and mechanical equipment operating data.

There are also shown the results of the horizontal loading test conducted in the field, the values of the soil physical property (spring coefficient) obtained through the test results and back analysis, besides the results of field measurements of vibration velocities at specific points of the structure.

3.1 Structure

The supporting system is formed by a concrete framed structure over block-pile foundation, as shown in figures below.

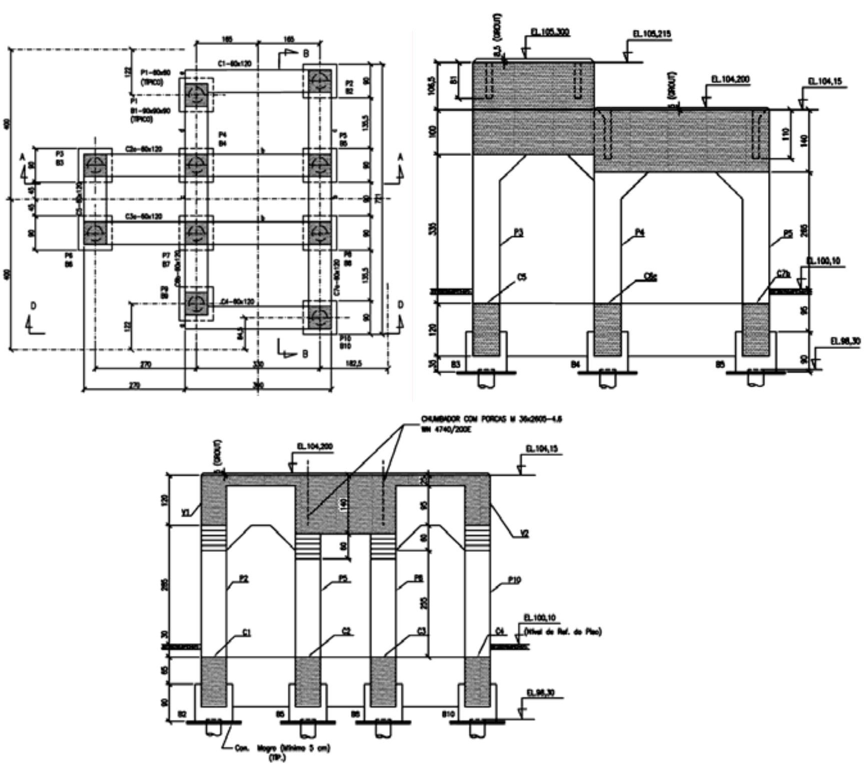


Figure 2: Assessed structure – Plan and Views

3.2 Equipment

The set of equipment that belongs to the mechanical system consists primarily of gas compressor, electric motor and accessories in general.

The compressor is reciprocating with horizontal cylinders, manufactured by the *Neuman & Esser*, operating at frequency of 590 *rpm*. The following images show some of its components.

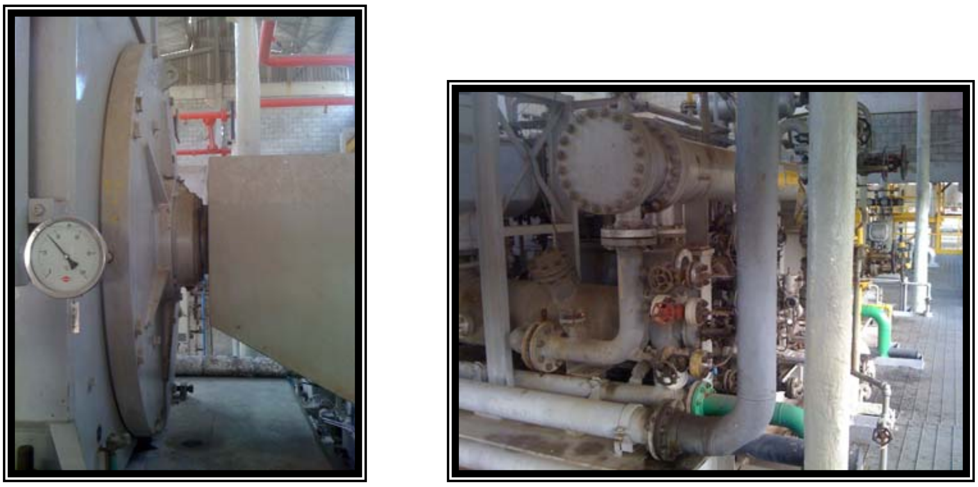


Figure 3: Overview of motor-compressor coupling and parts of mechanical system

Amplitude of dynamic loadings transmitted by the compressor is shown on the table below.

Direction	Dynamic forces (N)	Dynamic torsion (N.m)
Horizontal	20788	35287
Vertical	0	9542

Table 2: Mechanical elements of a reciprocating compressor

The magnitude of the dynamic forces generated by the electric motor is small and hence its contribution to the dynamic response of the system is negligible [5]. Therefore, in the developed model, the electric motor only participates with its mass.

In this case, the allowable vibrating velocity on the top of the supporting structure (settling of skids) was limited to 2.00 mm/s.

3.3 Soil constitutive model

The typical geological formation of the region where the assessed equipment is installed consists of two phases well highlighted. The first and most superficial is known as Tinguis formation. The second and deeper is known as Guabirotuba formation, consisting generally the layer in which foundations elements are embedded.

Figure 4 shows a typical geotechnical profile obtained through two SPT tests. On this figure, the horizontal lines are spaced one meter along the depth of the borehole.

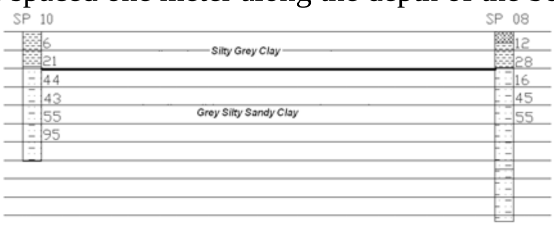


Figure 4: Geotechnical profile of the local subsoil

In this study, the soil was considered as a discrete component, linear, mass less, acting independently in two orthogonal horizontal directions as a spring coefficient km. Each spring is applied at one point (node) of foundations (piles).

Considering the data above and in order to define the constitutive model of soil, field test (horizontal static loading) was performed on two piles of the same diameter (40.0 cm) and close to the region where the compressors are installed. The tests followed the Brazilian standard ABNT NBR 12131 [3] and American standard ASTM D3966 [6].

The following table summarizes the test results.

Pile tag	E-16	E-3
Bore-hole	SP-13	SP-10A
Max load test (kN)	84	65
Max displacement (mm)	20,4	31,31

Table 3: Results of horizontal static loading test

Also, cyclic loading tests were performed, whose applied load versus displacement curves for each cycle are presented below.

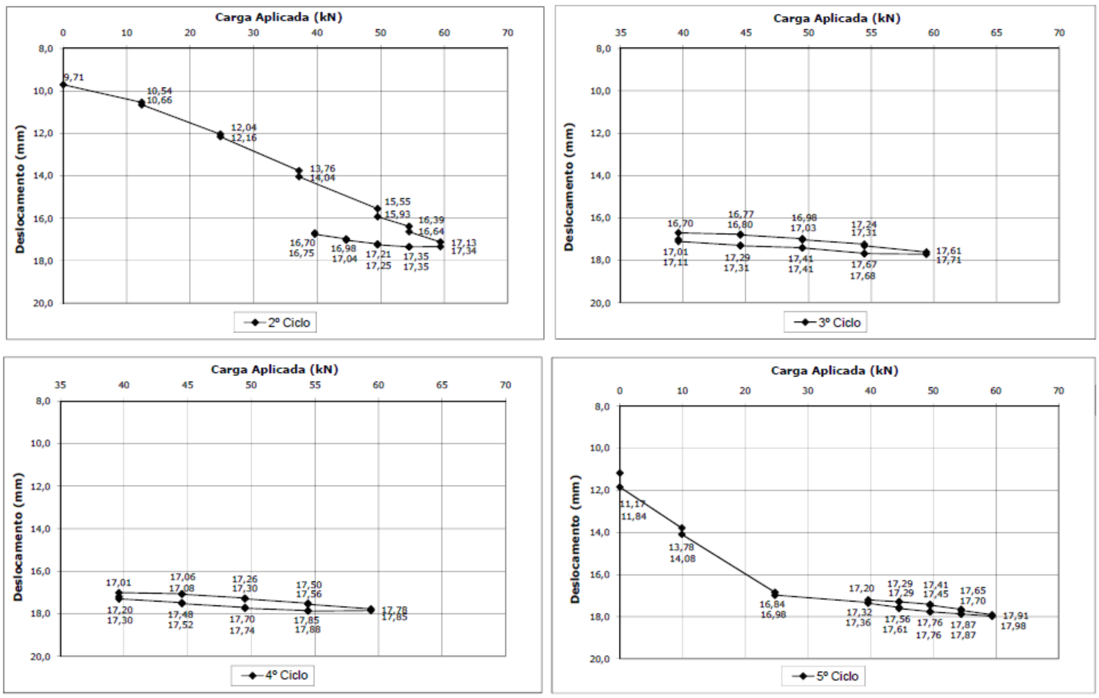
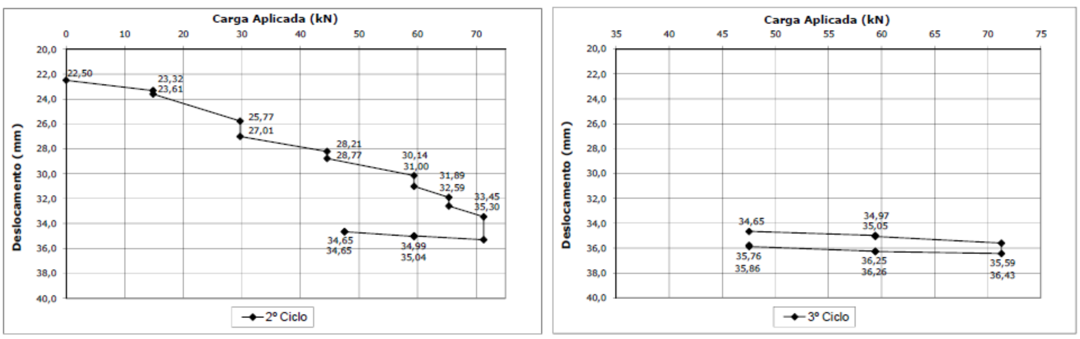


Figure 5: Cyclic loading test results – Pile E-16



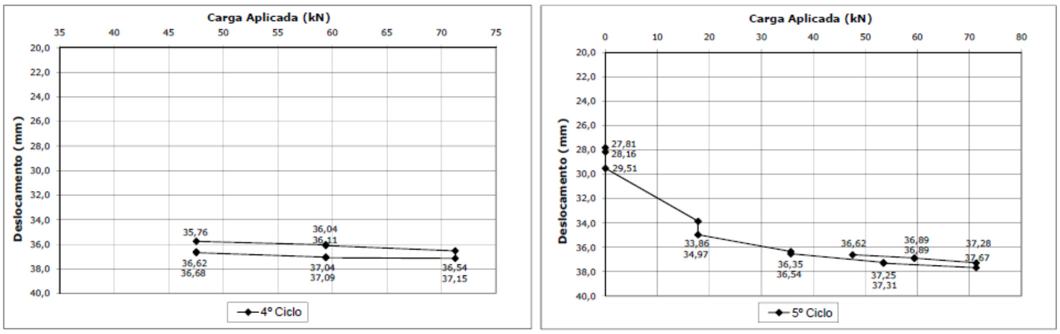


Figure 6: Cyclic loading test results – Pile E-03

The results of these cyclic tests were used to calculate the soil dynamic parameters.

In order to obtain soil parameters values (static and cyclic), a back calculation procedure was used by means of Miche [1] method. This method deals with horizontal interaction between a pile element embedded in subsoil and subjected to horizontal loads.

Miche [1] analyzed the problem of piles immersed in an elastic medium with horizontal soil parameter growing linearly with depth, subjected to a horizontal force on its top. The constant of this linear behavior is called n_h and can be written as follows.

$$n_h = \sqrt[3]{\left(\frac{2{,}4F}{y}\right)^5 (EI)^2} \tag{2}$$

In this equation parameters E and I are known, which depend on the material of the pile and its geometry, and the values F and y, which are obtained from the horizontal loading test cited above.

For the static case, considering pile E-16, the soil parameter n_h achieved 5087.99 kN/m^3.

For the cyclic case, also considering pile E-16, the results are shown below for each cycle.

	Cycle 1	Cycle 2	Cycle 3	Cycle 4	Cycle 5	Cycle 6	Cycle 7
n_h (kN/m^3)	170776,2606	69712,6988	166058,8790	94779,7101	191974,2753	107239,9283	157227,3290
n_h/D	426940,6515	174281,7471	415147,1976	236949,2751	479935,6882	268099,8206	393068,3226

Table 4: Soil parameter n_h for cyclic loading – Pile E-16

Considering Pile E-03, for the static case, the soil parameter n_h achieved 1624.98 kN/m^3.

For the cyclic case, also considering pile E-03, the results are shown below for each cycle.

	Cycle 1	Cycle 2	Cycle 3	Cycle 4
n_h (kN/m^3)	34222,4094	183437,5885	82482,4884	326398,0336
n_h/D	85556,0235	458593,9713	206206,221	815995,084

Table 5: Soil parameter n_h for cyclic loading – Pile E-03

4 ACTUAL VIBRATION DATA

Figure below shows the amplitude of vibration (*rms* – root means square) in terms of velocity (mm/s). The measurements were taken on the support structure of the compressor. The data collection points were located in all columns of the structure, more precisely at 2.00 m from ground level. The following rectangles represent columns cross section and containing the amplitude values of vibration velocity.

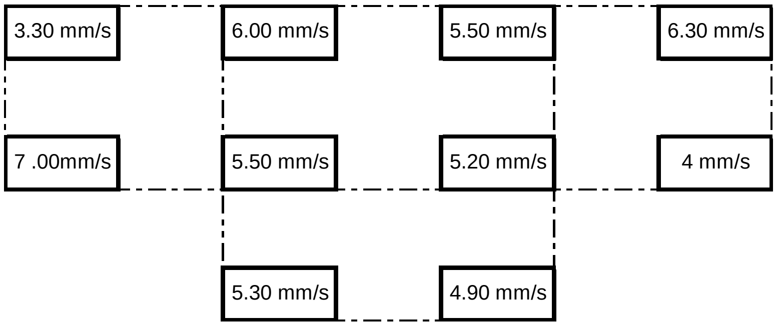


Figure 7: Velocities amplitude of vibration in columns (mm/s)

In the present work, the model had the root mean square of velocity as a parameter of calibration.

5 NUMERICAL MODEL

5.1 General

This chapter aim at presenting the numerical model used to understand the structure-soil-equipment behavior under dynamics loading. For this purpose, a computational 3D Finite Element model was developed by using ABAQUS® software, which was calibrated by field measurements.

A modal superposition was driven in the dynamics analysis.

The structure was modeled with two distinct elements. Once they have massive aspect, bases were modeled with C3D4 type elements (linear tetrahedral solid with 4 nodes). Columns and beams were modeled with linear beam elements (B31).

Pile foundations and its interaction with the soil were modeled considering the piles as linear beam elements and the soil as a set of linear springs (SPRING 1) acting in both perpendiculars directions to the pile.

The modeling of equipment takes into account the concentration of masses in their respective centers of gravity and its connection to the structure by rigid mass less beam elements [7]. Besides acting as dynamic loading, the mechanical system also affects the dynamic behavior of the model since it contributes to the mass matrix of the equations of motion. Figure 8 shows the FE Structure-Foundation-Soil-equipment model.

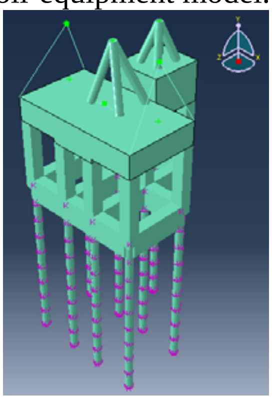


Figure 8: FE model on ABAQUS®

The main model input data are shown on tables 6 and 7 below.

Sub Systems	Elements	Geometry (m)			Type of Finite Element
		Section		Diameter	
		a	b		
Structure	Beam underground	0,6	1,2	-	Beam
	Columns	0,6	0,6	-	Beam
	Bases	-	-	-	Solid 4 nodes linear
Foundation	Piles	-	-	0,4	Beam
	Soil	-	-	-	Linear spring

Table 6: Model data (a)

Sub Systems	Elements	Material	Physical Properties			
			Elasticity Modulus (N/m^2)	Poisson Coefficient	Specific Weight (N/m^3)	Spring Constant (N/m)
Structure	Beam underground	Reinforced concrete	21287367145,8	0,2	25000	-
	Columns					
	Bases					
Foundation	Piles					
	Soil	-	-	-	-	See tests

Table 7: Model data (b)

5.2 Loadings

The static loading is considered herein to be the weight of all components of the system.

The forces and torsion generated by reciprocating compressor are provided by the equipment manufacturer. The amplitudes of the primary and secondary excitation loads, as well as corresponding excitation frequencies are presented below.

Forces	F0x1	17865	N
	F0x2	2923	N

Torsion	T0x1	31667	N.m
	T0x2	3620	N.m
	T0y1	9542	N.m
	T0y2	0	N.m

Excitation	w	9,83	Hz

Table 8: Machine loading data

Either forces or torsions act in direction x and y under the same excitation frequency.

6 PARAMETRIC ANALYSIS

This chapter describes the parametric studies conducted from the finite element model of the interactive system structure-soil-foundation and analyzes the influence of the soil parameter in the dynamic behavior of such system, that is, vibration velocity and natural frequencies (eigenvalues). The constant of horizontal reaction coefficient n_h obtained by back analysis is then used as the soil parameter.

6.1 Assessment 1 - n_h static case

From figure 9, it is observed that the calculated velocities fall into two distinct narrow limits, the first between the actual speed of 3.2 mm/s and 4.0 mm/s, and the second between 5 mm/s and 5.5 mm/s, whereas values of n_h between 1600 kN/m^3 and 65000 kN/m^3. For lower values of n_h , approximately between 1600 and 5000 kN/m^3, the velocities behave more in a random pattern, and for values above 5000 kN/m^3, there is a tendency for smaller influence of n_h on the system dynamic response.

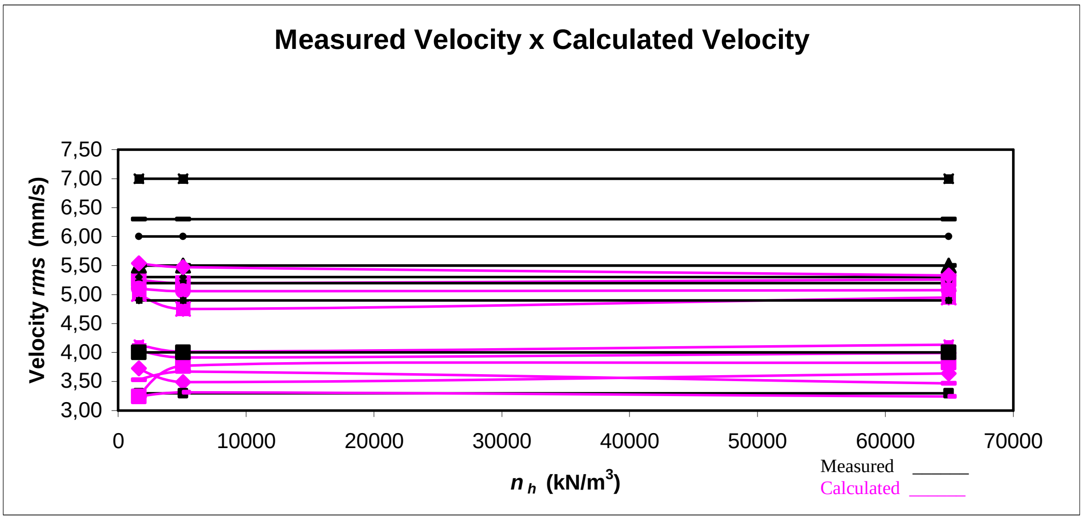


Figure 9: Comparisons between measured and calculated velocities

For the n_h values within the typical range of these soils, it is observed that the natural frequencies exhibit significant variation. Practically, only the natural frequencies corresponding to modes 8 and 9 showed variation less than 20%, thus inferring that the parameter nh obtained under static conditions is not suitable to represent the soil models when one wishes to obtain the eigenvalues of the structure- foundation-soil interactive system.

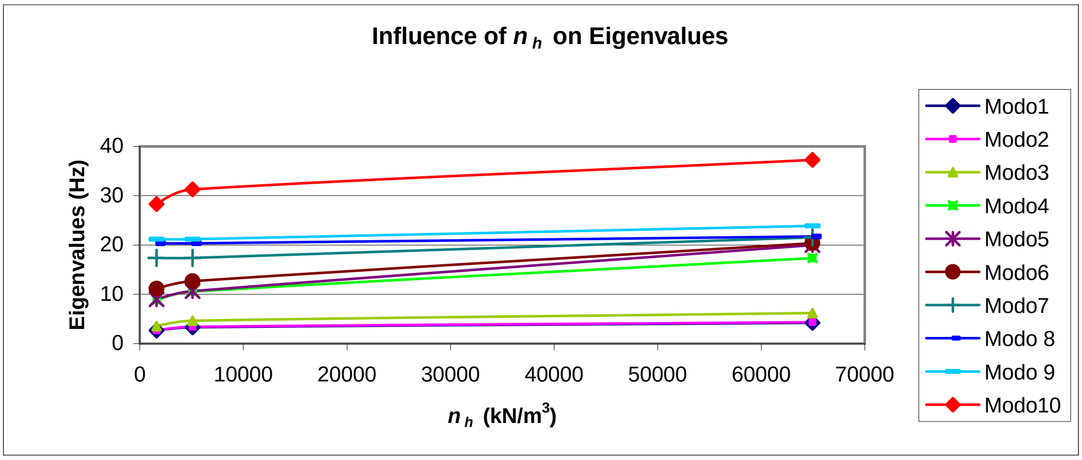


Figure 10: Curves eigenvalue versus n_h

6.2 Assessment 2 - n_h cyclic case

From figure 11, it is noted that the calculated velocities are predominantly underestimated for n_h parameter values within the range of 34000 to 326,000 kN/m^3.

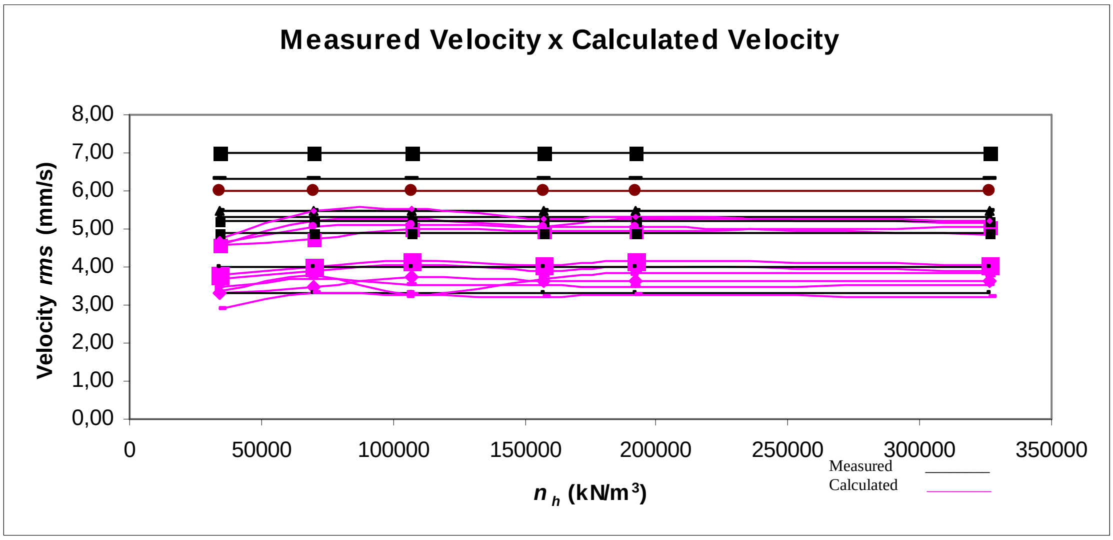


Figure 11: Comparisons between measured and calculated velocities

For the first six modes of vibration, the percentage deviation was no greater than 3.5% when varying the n_h value of approximately 64% (n_h between 69,000 kN/m^3 and 192,000 kN/m^3). In contrast, the percentage deviation of the natural frequencies from the seventh vibration mode, when varying the value of n_h, was approximately 28%.

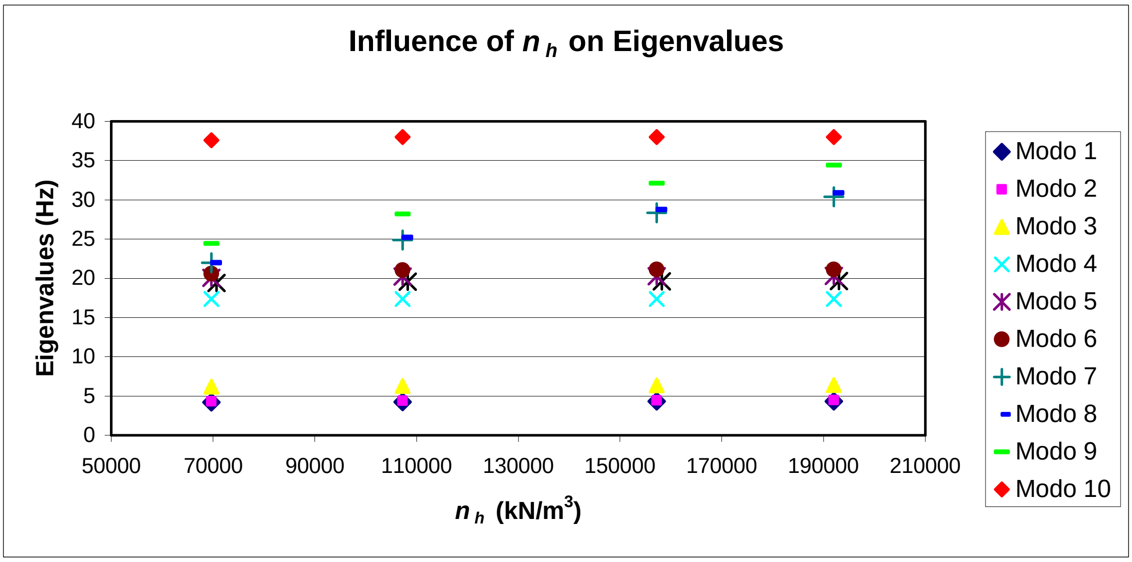


Figure 12: Curves eigenvalue versus n_h

7 CONCLUSIONS

When using soil parameters obtained under static conditions, there is distinct ranges of n_h where the dynamic response of the system is sometimes overestimated and sometimes underestimated. For values of static n_h within the typical range of these soils, it is observed that the natural frequencies exhibit significant variation. Practically, only the natural frequencies corresponding to modes 8 and 9 showed variation less than 20%, thus alerting on the need for careful choice of soil parameter so as not to provide misinterpretation of the system resonance condition.

When using soil parameters obtained under cyclic conditions, there is also distinct ranges of n_h where the dynamic response can be underestimated or overestimated. In relation to natural frequencies, it appears that from the seventh mode of vibration, there is significant variability in its magnitude as a function of n_h. For cases of compressors with high operating frequency, the choice of soil parameter must be careful to avoid misinterpretation of the resonance condition. However, the first six vibration modes undergo little variation due to the increased stiffness caused by dynamic loading. This fact motivates the completion of field trials with a larger number of charge cycles.

The study of the interaction between equipment, structures, foundations and soil is a vast field and inherently with many uncertainties, which often forces the specialists involved in the design to assume parameter values that can lead to either success or failure of machine performance.

In this context, complementary studies have been carried out in order to improve knowledge in this subject, for example: testing the effect on the dynamic response of the system by using non-linear spring as a representative parameter of soil; testing the effect on the dynamic response of the system in relation to the use of springs associated with viscous dampers and evaluating the effect of the soil stiffness degradation due to the dynamic loading.

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