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Comparative analysis of solutions in shallow foundations or in pile foundations for an industrial machine

Análise comparativa de soluções em fundações direta e sobre estacas para um equipamento industrial



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Abstract

This paper presents a methodology for the analysis of reinforced concrete rigid block foundations subjected to the vibrations due to the operation of machines. This analysis is important in the design of great industrial plants, where equipment of great size and high cost is present, and in which an adequate structural behavior is essential for the plant operation. The analysis methodology is initially presented, based on two computer programs, BLOCKSOLVER and PILAY. This methodology is applied in a comparative analysis of solutions in shallow foundations and in pile foundations for a Flue Gas Blower, equipment present in a petrochemical plant. The dynamic analysis is done for the two types of foundation, and also for a parametric variation in the shear modulus of the soil (G). The design of the foundation is done considering the geometrical limitations for the location of the equipment, consequent of the plant layout. The most important results are the maximum displacements, checked against the stringent limitations imposed by the design standards.

Keywords: machine foundations, dynamic analysis.

Resumo

Apresenta-se uma metodologia para a análise de fundações de concreto armado em bloco rígido, submetidas a vibrações decorrentes da operação de máquinas. Esta análise é fundamental no projeto de grandes instalações industriais, em que estão presentes fundações para equipamentos de grandes dimensões e custo elevado, e onde o comportamento estrutural adequado é essencial para a operação destas instalações. É apresentada inicialmente a metodologia de análise, baseada em dois programas computacionais, o BLOCKSOLVER e o PILAY. Esta metodologia é aplicada na análise comparativa de soluções em fundações diretas e sobre estacas de um soprador de gás, equipamento que integra os arranjos das refinarias petroquímicas. A análise dinâmica é feita para os dois tipos de fundação, fazendo também uma variação paramétrica do módulo de deformação transversal do solo (G). O dimensionamento da fundação é feito considerando o espaço limitado para a locação do equipamento determinado pelo arranjo da refinaria. Os resultados mais importantes são os deslocamentos máximos da fundação, que são verificados considerando as rigorosas limitações impostas pelas normas de projeto.

Palavras-chave: fundação de máquinas, análise dinâmica.

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1. Introduction

The knowledge of the effects of the dynamics loads in structures is nowadays even more necessary, due to the crescent investments and the construction of new refineries with the purpose of aggregating crescent value to the production of Brazilian oil and gas, leading to the development of new technologies is several areas of technological knowledge.

The study of the effects of these loads supposes the specific knowledge of concepts of Dynamics Analysis, to be found in classical books, such as the ones from CLOUGH and PENZIEN [1], as well as in books recently published in Brazil, such as the ones authored by SOUZA LIMA and SANTOS [2] and BRASIL and SILVA [3], these two last ones specifically dedicated to the Civil Engineering. In the last one, valuable specific information for the design of Machine Foundations can be found, theme in which the technical bibliography is scarce, even in an international level. Objecting to complete this summary frame of references in this area, the already classical book from ARYA et al. [4] and the more recent one, from BHATIA [5], can be cited.

As examples of relevant normative recommendations, frequently followed in the design of machine foundations in Brazil, the German standards DIN 4024-1[6] e DIN 4024-2 [7] and the specifications from PETROBRAS N-1848 [8] and from the American Concrete Institute ACI 351.3R-04 [9] can also be cited.

This paper intends to present a comparative analysis of solutions in shallow and deep foundations for a gas blower, equipment present in the layouts of petrochemical refineries. The study of the foundations behavior will be done varying some of the parameters for the analyses, such as the type of foundation (shallow or deep) and the soil shear moduli (G).

The foundation models are analyzed using a specific computer program for the dynamic analysis of machine foundations, the BLOCKSOLVER (COUTINHO and MENDES [10]). This program determines the maximum displacements in the frequency of operation, allowing for the calculation of the maximum vibration velocity of the foundation. For the analysis of the pile foundations, the program PILAY (NOVAK and ABOUL-ELLA [11]) will be also used. This program determines the stiffness coefficients (K_x, K_y e K_z), as well as the damping coefficients (C_x, C_y e C_z) of the piles, according to the characteristics of these piles and of the soil. These coefficients are used as input data for characterize the foundation in the BLOCKSOLVER program. The check of maximum allowed velocities is done following the criteria of Standard ISO 2372 [12].

The main conceptual objective in this machine foundation design is to find out a solution in which the operational frequencies are far enough from the frequencies of the foundation, in order to minimize the displacements caused by the application of the dynamic loads. The foundation design is done considering the limited available space for the location of the equipment, determined by the stringent plant layout. This design will consist in the definition of the geometric dimensions of the foundation block and in the selection of the best solution in the dynamic point of view, in shallow or deep foundations. This paper summarizes the Graduation Project (MACABÚ [13]) presented by the first author, under the orientation of the two other authors.

2. Method of analysis

The methodology of analysis in based on the programs BLOCKSOLVER, for the dynamic analyses of the shallow and deep foundations for the equipment and PILAY, for the evaluation of the stiffness and damping coefficients of the piles in the vertical and horizontal directions. These programs are described in the following.

2.1 The program BLOCKSOLVER

In the specific case of rectangular shallow foundations over homogeneous soil, the BLOCKSOLVER (COUTINHO and MENDES [10]) performs the whole analysis in a totally automatized way. In this case, the formulation of Wolf and Gazetas, found in WOLF [14], is applied.

In more general cases, impedance coefficients (springs and dampers), concentrated in the geometric center of the inferior face of the foundation block, shall be furnished to the program, as input data. In the specific case of pile foundations, these impedance coefficients shall be initially determined for isolated piles, by the PILAY program.

The dynamic analysis of rigid blocs, under harmonic loads, can be represented by a system of six differential equations of movement. This equations system can be written in the complex form, allowing for its solution in a matrix form, see CLOUGH and PENZIEN [1]:

$$M\ddot{u}(t) + C\dot{u}(t) + Ku(t) = F.e^{i\omega t} \quad (1)$$

The system machine-foundation presents the matrices M, C and K, of mass, damping and stiffness, respectively. The vector F corresponds to the amplitudes of applied forces and moments. The vector u(t) collects the variations in time of displacements and rotations in the six degrees of freedom; i is the imaginary unity and ω is the excitation circular frequency. As the problem is harmonic, u(t) can be written as a function of U, that corresponds to the unknown amplitudes of displacements and rotations, in the form:

$$u(t) = U.e^{i\omega t} \quad (2)$$

The problem is solved using the complex matrix algebra:

$$(-\omega^2 M + i\omega C + K).Ue^{i\omega t} = F.e^{i\omega t} \quad (3)$$

$$U = (-\omega^2 M + i\omega C + K)^{-1}.F \quad (4)$$

The mass matrix M is assembled from the geometric characteristics of the block and from the equipment masses. The damping and stiffness matrices C e K of the system are assembled from the elastic soil properties and from the type of foundation.

Figure 1 – Transversal section of the blower

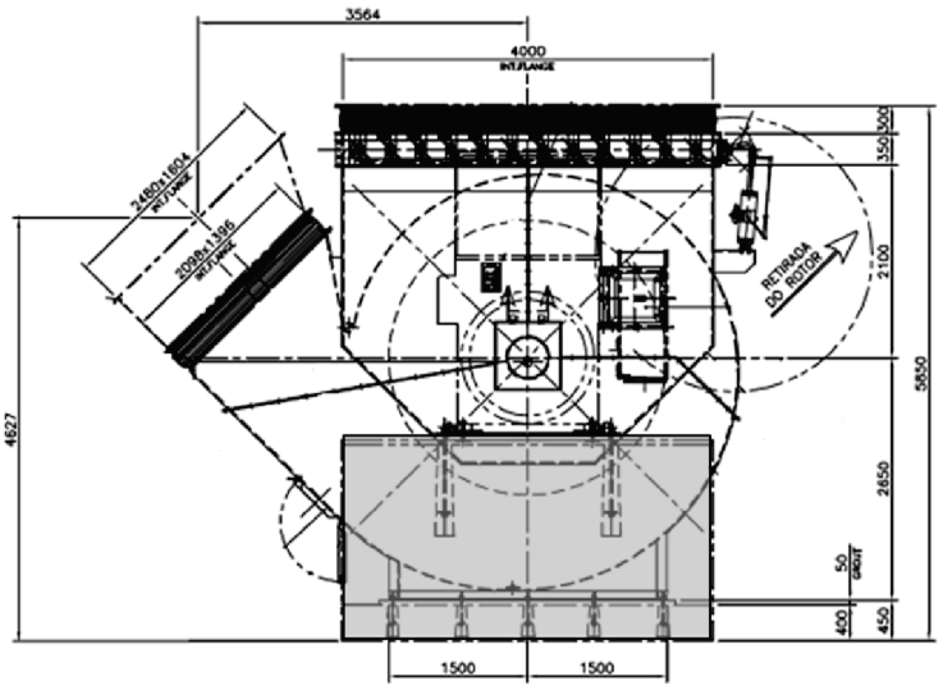


Figure 2 – Longitudinal section through the axis of the blower showing the fixation points of the equipment in the foundation concrete block

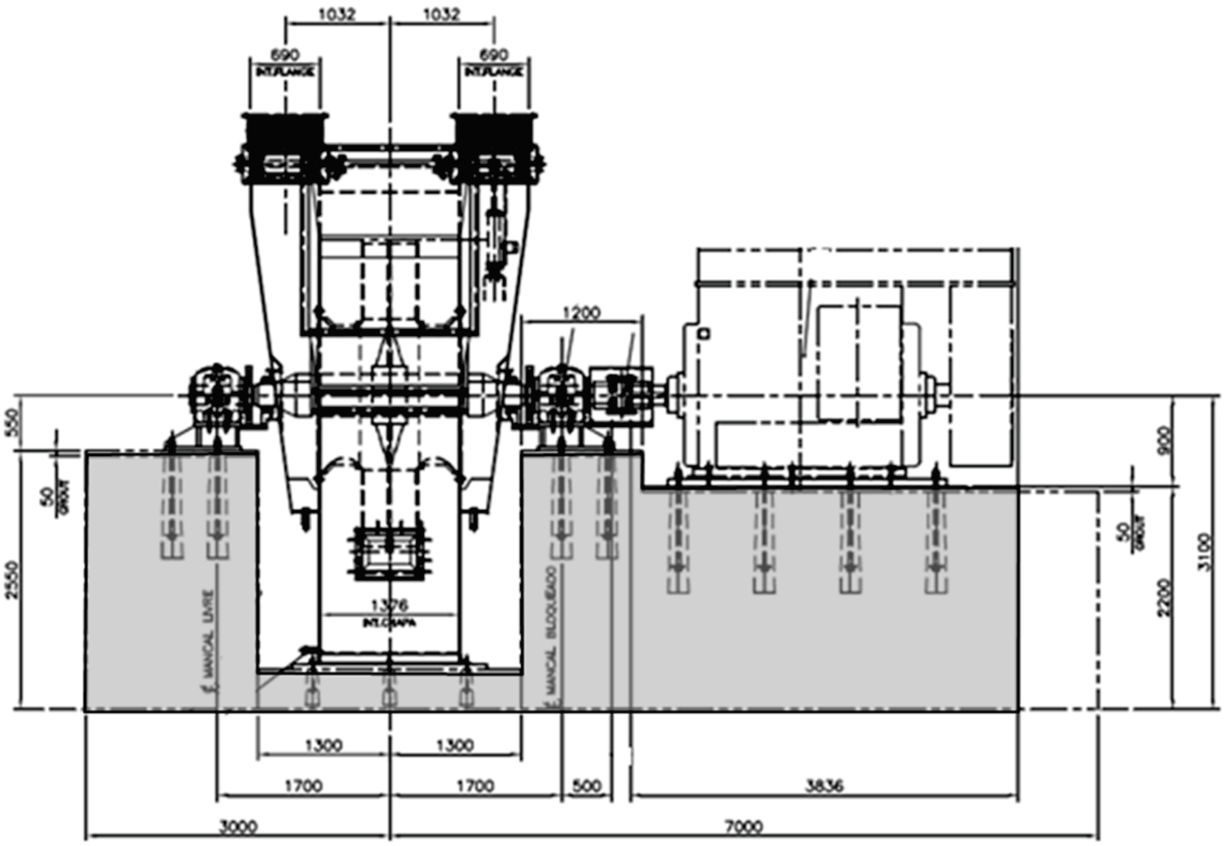


Table 1 – Static loads

Area	I	II	III	IV	Total
Static load (N)	-38073	-38073	-209254	-171381	-456781

Table 2 – Dynamic loads in the foundation

Area	Normal dynamic load (N)		Maximum dynamic load (N)		Axial load (N)
	Y	Z	Y	Z	X
I	2660	2660	4688	4688	0
II	2660	2660	4468	4468	0

Further details on the consideration of soil-structure interaction effects can be found in the original Graduation Project (MACABÚ [13]).

2.2 The program PILAY

The program PILAY (NOVAK and ABOUL-ELLA [11]) evaluates the stiffness and damping coefficients for an isolated pile. From these coefficients, the stiffness and damping coefficients for the whole foundation are determined, considering the total number and position of the piles (considering the group effect). These coefficients are input data for the analysis of the deep foundation in the BLOCKSOLVER program.

The PILAY was developed from the Nowak's approach, considering that the soil layers are elastic and continuous, that the pile is circular and with solid transversal section, the pile material is linear elastic and the pile is perfectly linked to the soil, do not occurring separation between piles and soil.

For the calculation of the stiffness and damping coefficients, it is necessary to define the velocity of the shear waves corresponding to each soil layer. Characteristics of the pile and soil are also input parameters, such as: specific weight, Poisson coefficient, length, radius, transversal area and moment of inertia of the piles, Young modulus of the piles material, as well as thickness of the soil layers.

Figure 3 – Points of application of loads

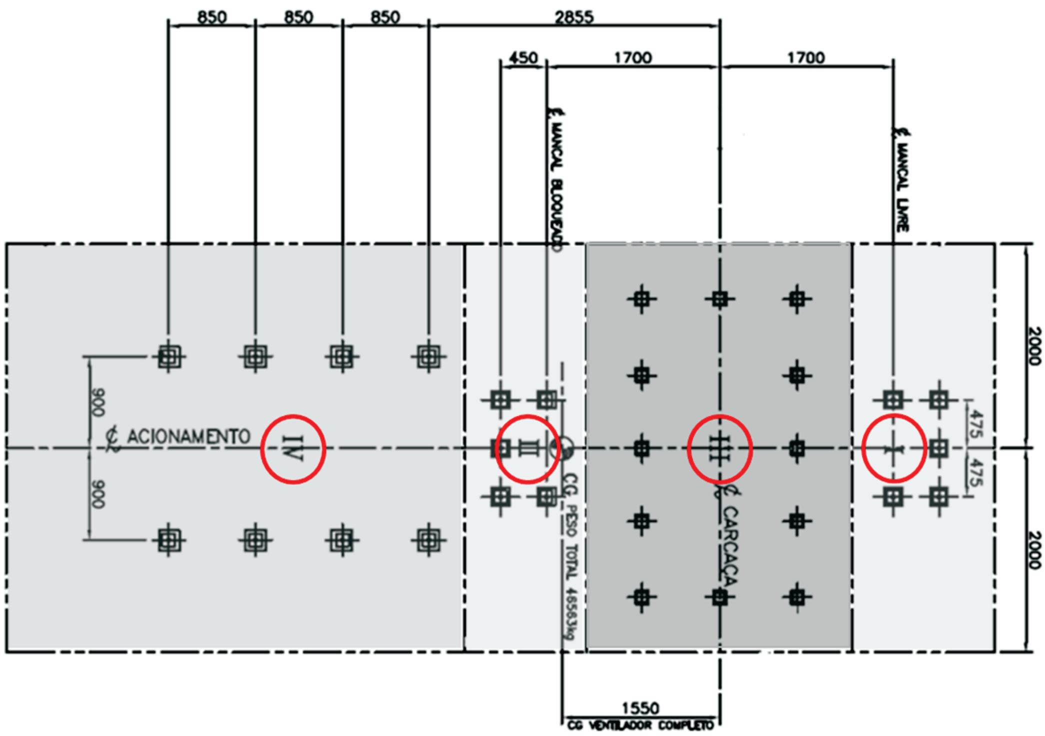
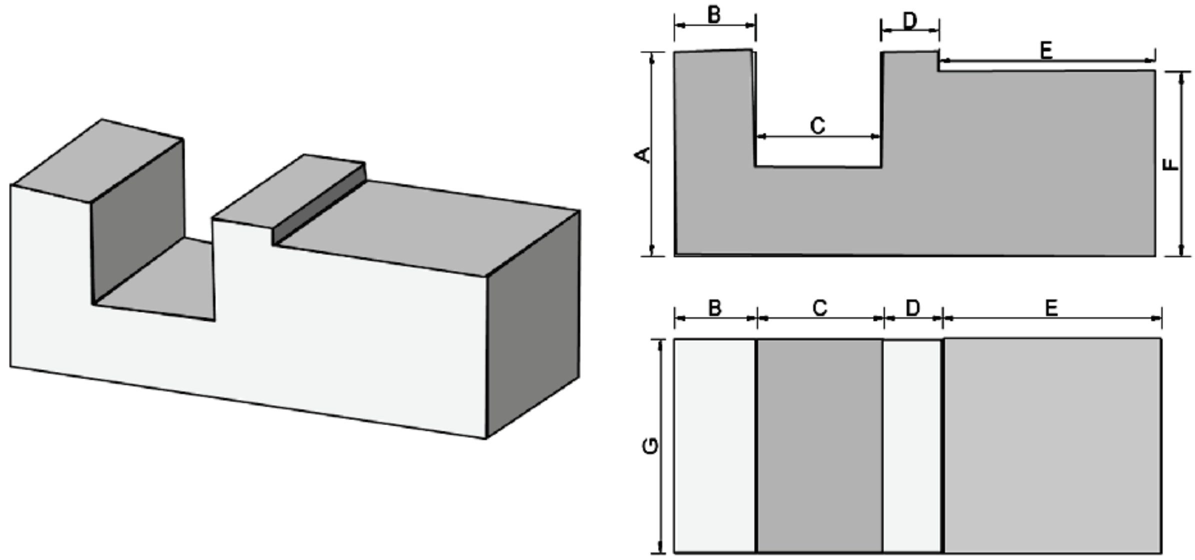


Figure 4 – Sketch of dimensions of the concrete block



3. Analyzed foundation

A comparative analysis between the two foundation solutions is presented, for an equipment mounted on a rigid reinforced concrete block, one on shallow foundation and the other one on deep foundation composed by eight concrete piles (with diameter Φ=25 cm).
A parametric variation for the soil shear moduli was considered. The two solutions are analyzed for the same loads, being the block on piles bigger in plant that the block in shallow foundation. This increase in dimensions was necessary in order to accomplish with the limitations in displacements, as explained in the sequel.

3.1 Characteristics of the equipment – Gas blower

The geometric dimensions of the equipment are shown in transversal and longitudinal sections in Figures 1 and 2, respectively. The loads and their respective application points are defined by the equipment supplier. In Table 1 the static loads applied in equipment areas I, II, III e IV and dynamic loads applied in areas I e II are defined in Table 2, and shown in Figure 3.
The analyses were done for two different values of frequencies: in the blower frequency (19.75 Hz) and in the motor frequency (60 Hz). The results corresponding to these two frequencies were further combined following the criteria defined by ISO 2372 [12], applying the square root of the sum of the squares of the effective velocities obtained in the two frequencies.

3.2 Characteristics of the concrete block

The concrete block was designed following the recommendations of PETROBRAS document N-1848 [8]. The block centroid and the gravity center of the assemblage machine-block shall be in the same vertical line, being allowed a maximum eccentricity of 5% with relation to the corresponding dimension, according to these recommendations.
The block height was determined in order to be at least 1/5 of the

Table 3 – Dimension of the blocks

Dimension of the blocks (m)			
Shallow foundation		Pile foundation	
A = 3.70	E = 4.50	A = 3.70	E = 5.50
B = 1.70	F = 3.35	B = 2.70	F = 3.35
C = 2.60	G = 4.00	C = 2.60	G = 4.00
D = 1.20		D = 1.20	

Table 4 – Variation of G – shallow foundation

Soil shear modulus (kPa)		
Shallow foundation NSPT = 10		
Model 1	~50% G	30000
Model 2	100% G	72500
Model 3	~150% G	108000

Table 5 – Variation of G – pile foundation

		Soil shear modulus (kPa) pile foundation		
		1st layer - NSPT = 10	2nd layer - NSPT = 26	3rd layer - NSPT = 53
Model 1	~50% G	30000	80000	135000
Model 2	100% G	72500	160000	270000
Model 3	~150% G	108000	240000	405000

smaller block dimension in plan, nor smaller than 1/10 of the block bigger plan dimension. The block is in reinforced concrete, with f_{ck} = 30 MPa. The block dimensions were determined in order to be adequate to the equipment geometry, and are shown in Figure 4 and Table 3. Adopting for the pile foundation the same block dimensions considered for the shallow foundation, obtained displacement amplitudes became inadmissible. It was necessary to increase the dimensions of this pile foundation, in order to have more mass, reducing in this way the displacements to admissible values.

3.3 Characteristics of the soil

The soil, under the action of the forces produced by the operation of the equipment, presents a very small level of deformations, in the order of some micra (*μ*m). This corresponds to a very small level of strains, allowing to the consideration of the soil behavior as linear and elastic. The several regions of the soil were considered as homogeneous.
The several considered soil parameters are defined as follows.

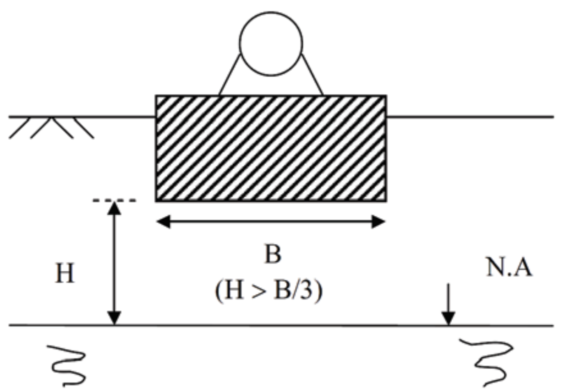
3.3.1 Shear modulus (G), Poisson coefficient (ν) e specific mass (ρ)

The soil shear modulus was empirically defined, due to the lack of specific tests for its determination. This parameter was evaluated as a function of the number of blows in the Standard Penetration Test (SPT), according to OHSAKI and IWASAKI [15]:

$$G = 11{,}5 \times (N_{spt})^{0{,}8} \quad (5)$$

The number of blows in the SPT varies with the soil depth. These values were defined from the test report more representative for the analyzed foundation. Due to the imprecision of the adopted empirical formula and also due to the process of uniformization of the soil properties, a parametric variation of 50% of increase/decrease in the value of G was considered. The G values used in the three soil conditions are presented in Tables 4 and 5.
The value of n = 0.35 was adopted for the Poisson coefficient. The eventual variation in the numerical value of this parameter has an influence in the results much smaller than the variation in the values of G. For the specific mass the value of ρ = 1.8 t/m³ is considered.

Figure 5 – Minimum distance between the foundation block and the water level



3.3.2 Consideration on the phreatic water level

The presence of high phreatic water lever leads to an amplification on the vibrations, propagating them to long distances, and also can lead to the compactation in saturated sand layers. In this way, in order to make possible a solution in shallow foundation, it is recommended that the distance between the bottom of the block and the water level shall be at least three times the smaller horizontal dimension of the block, as shown in Figure 5.

4. Results of the analyses

4.1 Shallow foundation

The maximum foundation displacements in the directions X, Y and Z for each excitation frequency and according to each value of the soil shear modulus are presented in Table 6.
The maximum velocities can be evaluated from the values of the displacements obtained by the program, using the following formula (CLOUGH and PENZIEN [1]):

$$v = 2 \times \pi \times f \times d \quad (6)$$

Table 6 – Maximum displacements in directions X, Y and Z for each G value

f (Hz)	G (kN/m^2)	Translation X (10^{-3} mm)	Translation Y (10^{-3} mm)	Translation Z (10^{-3} mm)
19,75	30000	5.2	19.8	18.8
	72500	5.1	28.2	20.1
	108000	5.1	32.6	20.6
60,0	30000	0.2	1.9	1.9
	72500	0.3	1.9	1.9
	108000	0.4	2.0	2.0

Table 7 – Effective velocities in directions X, Y and Z for each G value

G (kN/m^2)	Effective velocities		
	Velocity X (mm/s)	Velocity Y (mm/s)	Velocity Z (mm/s)
30000	0.46	1.81	1.73
72500	0.46	2.53	1.84
108000	0.46	2.91	1.88

where:
v = velocity (mm/s)
f = frequency of operation (Hz)
d = displacement (mm)

As there are two different frequencies of operation, the effective velocities are defined as a function of the above determined velocities, with the following equation:

$$v_{rms} = \sqrt{\left(v_1^2 + v_2^2\right)/2} \quad (7)$$

In this way, the effective velocity is obtained by the combination of the velocities for the frequencies of 19.75 Hz e 60 Hz, as presented in Table 7.
According to ISO 2372 [12], the analyzed equipment can be classified as a Heavy Machine (Class III). Velocities up to 1.8 mm/s are classified in the optimal range, between 1.8 and 4.5 mm/s are in the acceptable range, between 4.5 a 11.2 mm/s in are the tolerable range and the velocities superior to 11,2 mm/s are non-tolerable. The maximum obtained velocity was 2.91 mm/s, occurring in the

Figure 6 – Frequency x Translation Y (solution in shallow foundation)

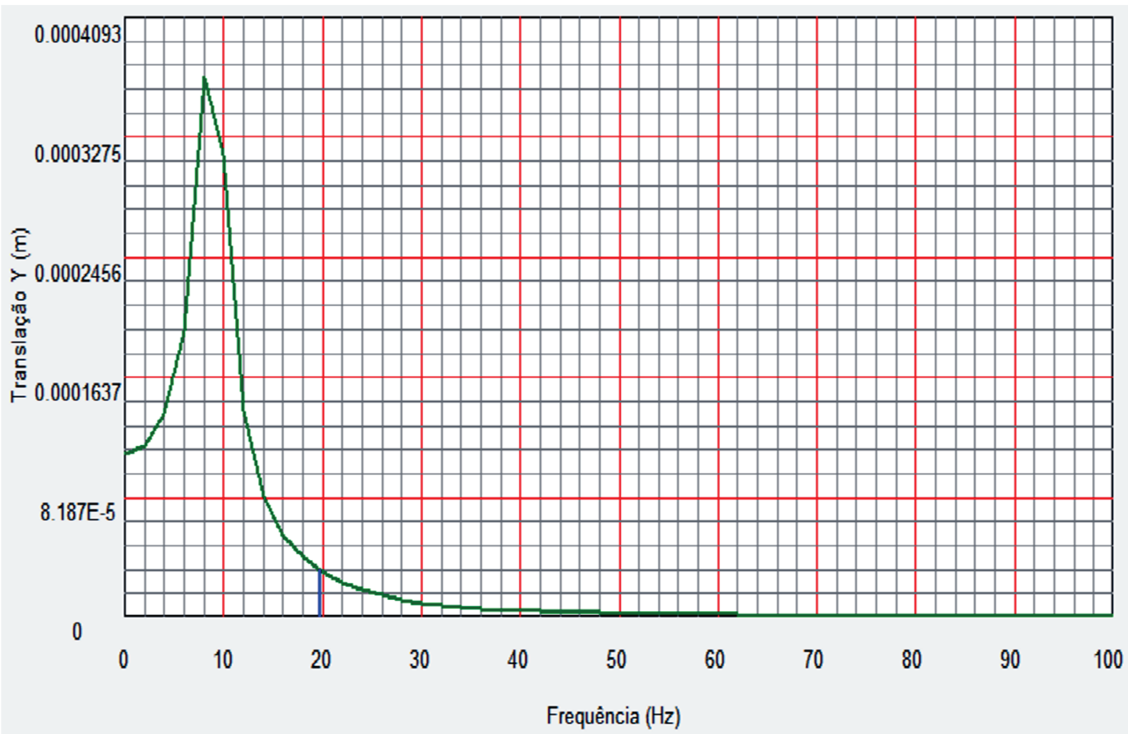


Table 8 – Stiffness and damping coefficients – Model 1

Model 1							
Frequency = 19.75 Hz				Frequency = 60 Hz			
PILAY output							
Stiffness coefficient		Damping coefficient		Stiffness coefficient		Damping coefficient	
KWW	343660	CWW	407	KWW	355180	CWW	383
KUU	62683	CUU	163	KUU	64855	CUU	150
Considering the 8 piles							
Stiffness coefficient		Damping coefficient		Stiffness coefficient		Damping coefficient	
KZ	27492805	CZ	3255	KZ	2841440	CZ	3063
KX = KY	01464	CX = CY	1305	KX = KY	518840	CX = CY	1201
KZZ	5004611	CZZ	13023	KZZ	5178023	CZZ	11983
KXX	2749280	CXX	3255	KXX	2841440	CXX	3063
KYY	24688534	CYY	29227	KYY	25516131	CYY	27505

horizontal direction (Y), for the bigger value of shear modulus (G). This velocity is then in the acceptable range. Therefore, according to the criteria established in ISO 2372 [12], and also considering that the eigenfrequency of the foundation is far from the exciting frequency, as shown in Figure 6 (obtained with the program BLOCKSOLVER), the proposed solution is acceptable.
In the other hand, considering the most representative SPT report, it can be seen that the water lever is in a distance closer than three times the smaller dimension of the block, it can be concluded that a solution in piles shall be also analyzed.

4.2 Pile foundation

For the three considered conditions of soil stiffness (Models 1, 2 and 3) the values of the stiffness and damping coefficients obtained by the program PILAY, as well as condensed coefficients in the center of the block, are presented in Tables 8, 9 and 10 for each one of the frequencies of operation. In this evaluation, considering the distance between piles, the group effect was disregarded.
The displacements of the foundation in directions X, Y and Z for each frequency of excitation and according to each value of soil shear modulus are presented in Table 11. The effective velocities, resulting from the combination of the velocities for the different frequencies, are presented in Table 12. The maximum found effective velocity was 4.20 mm/s, occurring in the vertical direction (Z) for the bigger value of the shear modulus (G), and is in the acceptable classification range. In this case, the eigenfrequency is still far from the frequency of excitation, as shown in Figure 7.
As for the pile foundation there are not restrictions regarding the water level, this solution becomes more adequate relatively to the shallow foundation.

5. Conclusions

In this paper, the procedure followed for making possible the foundation for a typical equipment with dynamic loads in an industrial plant is presented. For this, a comparative analysis was done between solutions in shallow and pile foundations. Through the use of the programs PILAY and BLOCKSOLVER it was possible to evaluate the foundation displacements caused by the dy-

Table 9 – Stiffness and damping coefficients – Model 2

Model 2							
Frequency = 19.75 Hz				Frequency = 60 Hz			
PILAY output							
Stiffness coefficient		Damping coefficient		Stiffness coefficient		Damping coefficient	
KWW	472230	CWW	425	KWW	481210	CWW	417
KUU	117830	CUU	200	KUU	121030	CUU	196
Considering the 8 piles							
Stiffness coefficient		Damping coefficient		Stiffness coefficient		Damping coefficient	
KZ	3777840	CZ	3401	KZ	3849680	CZ	3335
KX = KY	942640	CX = CY	1598	KX = KY	968240	CX = CY	1568
KZZ	9407547	CZZ	15949	KZZ	9663035	CZZ	15652
KXX	3777840	CXX	3401	KXX	3849680	CXX	3335
KYY	33925003	CYY	30537	KYY	34570126	CYY	14084

Table 10 – Stiffness and damping coefficients – Model 3

Model 3							
Frequency = 19.75 Hz				Frequency = 60 Hz			
PILAY output							
Stiffness coefficient		Damping coefficient		Stiffness coefficient		Damping coefficient	
KWW	559250	CWW	428	KWW	566940	CWW	422
KUU	156710	CUU	216	KUU	160120	CUU	213
Considering the 8 piles							
Stiffness coefficient		Damping coefficient		Stiffness coefficient		Damping coefficient	
KZ	4474000	CZ	3421	KZ	4535520	CZ	3372
KX = KY	1253680	CX = CY	1731	KX = KY	1280960	CX = CY	1705
KZZ	12511726	CZZ	17273	KZZ	12783981	CZZ	17015
KXX	4474000	CXX	3421	KXX	4535520	CXX	3372
KYY	40176520	CYY	30722	KYY	40728970	CYY	30284

Table 11 – Displacements in directions X, Y and Z for each G value

f (Hz)	G (%)	Translation X (10^{-3} mm)	Translation Y (10^{-3} mm)	Translation Z (10^{-3} mm)
19,75	50%	3.46	13.42	25.50
	100%	3.13	11.26	35.26
	150%	3.15	8.73	47.46
60,0	50%	0.03	1.58	1.67
	100%	0.05	1.57	1.70
	150%	0.21	1.87	2.17

namic loads. In this way, the foundation displacements can be well controlled and limited.

From the obtained values of displacements, the corresponding effective velocities were determined. Considering that the analyzed equipment presents two frequencies of excitation, the effective velocities were determined through the combination of results. In the analysis of the shallow foundation, the maximum obtained velocity was 2.91 mm/s, occurring in the horizontal direction (Y). In the analysis of the pile foundation, the maximum obtained velocity was 4.20 mm/s, occurring in the vertical direction (Z). Although the velocity in the pile foundation is 40% bigger than the one in the shallow foundation, both are in the acceptable range, according to the criteria established by ISO 2372 [12].

Table 12 – Effective velocities in directions X, Y and Z for each G value

G (%)	Effective velocities: Velocity X (mm/s)	Velocity Y (mm/s)	Velocity Z (mm/s)
50%	0.30	1.25	2.28
100%	0.27	1.07	3.13
150%	0.28	0.91	4.20

Analyzing the reports of the more representative SPT test, it can be observed that the water level is a distance closer than three times the smaller block dimension. Therefore, the pile foundation is considered as the best solution.

In order to obtain satisfactory results for the solution in piles, it was necessary to increase the foundation mass, increasing the horizontal block dimensions, in order to reduce displacements and separate the eigenfrequencies from the frequency of operation. The difficulty for this increase of the mass was the restriction imposed by the adjacent foundations, in order to avoid interferences with them.

6. References

[01] CLOUGH, R.W.; PENZIEN, J. Dynamics of Structures, McGraw-Hill Book Co – Second Edition, Singapore, 1993.

[02] SOUZA LIMA, S.; SANTOS, S.H.C. Análise Dinâmica das Estruturas, Editora Ciência Moderna, Rio de Janeiro, 2008.

[03] BRASIL, R.M.L.R.F; SILVA, M.A. Introdução à Dinâmica das Estruturas, Editora Edgard Blücher, São Paulo, 2013.

[04] ARYA, S.; O'NEILL M.; PINCUS, G. Design of Structures and Foundations for Vibrating Machines, Gulf Publishing, Houston, 1979.

[05] BATHIA, K.G., Foundations for Industrial Machines, D-CAD Publishers, New Delhi, 2008.

[06] DEUTCHES INSTITÜT FOR NORMUNG. DIN 4024-1 – Machine Foundations; Flexible Structures that Support Machines with Rotating Elements. 1988.

[07] DEUTCHES INSTITÜT FOR NORMUNG. DIN 4024-2 – Machine Foundations; Rigid Foundations for Machinery with Periodic Excitation. 1991.
[08] PETROBRAS. N 1848 – Projeto de Fundações de Máquinas. 2008.
[09] AMERICAN CONCRETE INSTITUTE. ACI 351.3R-04 - Foundations for Dynamic Equipment, 2011.
[10] COUTINHO, D.S.A.; MENDES, C.H.F. Projecto Automatizado de Fundações de Máquinas. Projeto Final de Curso, Rio de Janeiro, DME/POLI/UFRJ, 2007.
[11] NOVAK, M.; ABOUL-ELLA, F. PILAY – A Computer Program for Calculation of Stiffness and Damping of Piles in Layered Media. Systems Analysis Control and Design Activity (SACDA), The University of Western Ontario, London, Canada, 1977.
[12] INTERNATIONAL ORGANIZATION FOR STANDARDIZATION. ISO 2372 – Mechanical Vibration of Machines with Operation Speeds from 10 to 200 rev/s, 1974.
[13] MACABÚ, L.P. Análise Comparativa de Soluções em Fundação Direta e Sobre Estacas para um Equipamento em uma Instalação Industrial. Projeto de Graduação, Departamento de Estruturas, Escola Politécnica da UFRJ, Setembro de 2011.
[14] WOLF, P.J. Foundation Vibration Analysis Using Simple Physical Models, Prentice Hall, 1994.
[15] OHSAKI, Y.; IWASAKI, R. On dynamic shear moduli and Poisson's ratio of soil deposits. Soil and Foundations, JSSMFE, v.14, nº4, p. 59-73, Dec. 1973.

Figure 7 – Frequency x Translation Z (solution in pile foundation)