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INFLUENCE OF SOIL STRUCTURE INTERACTION ON THE FOUNDATION OF EQUIPMENT SUBJECT TO DYNAMIC FORCES

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Abstract. In the last decades, analytical solutions based on simplified assumptions commonly used in project offices have been replaced by sophisticated and precise mathematical methods based on finite element modeling, bringing more reliability to the calculations. However, the finite element method may have its results strongly influenced by the parameter values adopted in the simulation of the dynamic behavior of the system equipment-foundation-foundation soil. The definition of parameters for dynamic analysis of foundations with complex geometry, buried in excavated and compacted soil, supported by a terrain with diversified stratification has significant importance on the accuracy of results, when faced to the uncertainties of the actual parameters of the foundation soil. To circumvent such uncertainties, the use of conservative parameters for soil has been the practice adopted, preventing high costs and long time required for the development of assessment surveys on the characteristic parameters of the foundation soil. Aiming to a customized project, it is therefore necessary to assess the influence of Soil Structure Interaction upon the displacements from the dynamic loads. In this article, the influence of soil rigidity in displacements of the foundation of a ball mill subject to dynamic loading is assessed. The main objective is assuring that the vibration amplitudes of the foundation occur within allowable values for both the equipment and people in its surroundings

1 INTRODUCTION

One of the aims of the project of foundation for mechanical equipment consists of limiting vibration amplitudes within allowable values for the machine and also for people and equipment in its surroundings Bathia, K. G., 2008. Excessive movement of the mechanical equipment can break connections, damage bearings and auxiliary equipment and endanger equipment operation. When transmitted to the soil, they prevent people's work and may cause damage to structures due to vibration or repression. Then, the foundation design for a machine as shown in Figure 1, below, must consider, besides the static loads, dynamic forces produced by the operation of the machine and transmitted to the foundation. For adequate accuracy of the applied loads onto equipment foundations, correct assessment of the parameters adopted in the simulation of the dynamic behavior of the system equipment-foundation-foundation soil becomes necessary.

Figure 1: Ball Mill: Source (http:// www.metso.com.br)

The definition of parameters for dynamic analysis of foundations with complex geometry, buried in excavated and compacted soil, supported upon a terrain with varied stratification has significant importance on the accuracy of results, considered the uncertainties of the actual parameters of the foundation soil.

Many machinery foundations are designed based on not always justified "empirical rules" provided by manufacturers. Most of them establish that the mass of the foundation must be n times the mass of the moving parts, or n times the mass of the machine itself, disregarding important characteristics as the soil parameters. This procedure is no longer justified based on the advances in the Structural Dynamics and Dynamics of Soils areas which allow to predict - with relative accuracy - the behavior of a machine foundation subject to dynamic excitations.

In general, dynamic analysis of a machine foundation includes (Mcneill, R. L., 1969):

- the definition of the performance criteria for the foundation;
- the determination of dynamic forces generated by the machine;
- the collection of soil profile information and assessment of its parameters;
- the calculation of the dynamic response of the foundation and subsequent checking based on the performance criteria.

The foundation engineer must be aware that his responsibility does not end after the foundation is built. The last phase of the project is monitoring the foundation performance in order to assess if the values provided in the analysis are confirmed by the values measured. Information collected in this phase is essential for the development of new projects. It allows for, together with the help the machine designer, establishing performance criteria for given types of foundation.

2 DYNAMIC ANALYSIS OF REINFORCED CONCRETE STRUCTURES

2.1 Influence of Soil Structure Interaction (SSI)

Although not all design offices consider the effects of soil structure interaction (SSI) in their calculations for the concrete foundations subject to dynamic action, the fact is that soil rigidity significantly affects the values of speed, displacement, acceleration and natural frequency of the structure.

Usually, soil rigidity, also called the modulus of rigidity or modulus of vertical reaction is calculated by correlation with the Standard Penetration Test SPT. It is, however, known that this correlation is only valid to static loading, in most cases.

The aim of this paper is to show the influence of the value of the modulus of rigidity (k) on two points of a concrete foundation of a ball mill.

2.2 Project Considerations

Empirical correlations which are not always 100% reliable, in terms of structural dynamic analysis, become necessary for a correct assessment of soil rigidity. Relations among soil displacements and soil reactions are determined through the definition of the elastic constants of the soil. Due to establish these constants, Chaves (2004) shows a correlation between soil stiffness and the number of strokes of SPT report. Below we can see expressions adopted by Chaves apud Tepedino (1980) to determine the vertical reaction modulus Ks^v (N/cm^3).

- For clay and clayey soils: Ksv = 3Nspt
- For sand and sandy soils: Ksv = 5Nspt

In addition, to understand the study that was done in this paper the VDI 2056 was used. This document provides allowable reference values of speed, displacement and acceleration for concrete structures subjected to dynamic forces. From these reference values, it is possible to analyze if the structure is acceptable or not in terms of limit state of service.

3 CASE STUDY

3.1 Generalities

We present below the numeric analysis of the concrete foundation of a real ball mill, made by varying the soil rigidity coefficient, in order to assess the speed, displacement and natural frequency of the structure.

3.2 Considerations on the numeric model - methodology

Modal and frequency domain response analyses were carried out to make it possible to check the dynamic influences present. Finite element modeling technique was used in this development.

The following input data of the analyses were used for the performance of the studies:

- geometric information by 2D drawings of the shapes in their first version
- the engine revs
- properties of the foundation concrete

Regarding soil parameters, the following estimates for the Reaction Modulus (ks), in Table 1 below, were used:

Model	Rigidity (t/m3)
Model 1	k = 500
Model 2	k = 5000
Model 3	k = 500000

Table 1: Models Analyzed

The values of k presented above (Table 1) represent three different types of soils: one very flexible (Model 1), an intermediate rigid soil (Model 2), and one that is very hard (Model 3).

The flexibility of the soil (modulus of rigidity) was added to the base of the ball mill using the model of Winkler, with springs evenly spaced in accordance with the considered mesh. The finite element adopted for the numerical modeling using the Finite Element Method was the 3D solid, presenting for each node three degrees of freedom (translation in X, Y and Z axis). Furthermore, the dimensions of the solid elements respect the bulb of pressure proposed by Bowles (1988), which one is based on the equations of Boussinesq.

The development of this study starts with information survey (geometry, operation data and others) with data capable of feeding the analyses to be performed. See below the 3D model of the mill base in reinforced concrete, in Figure 2 below.

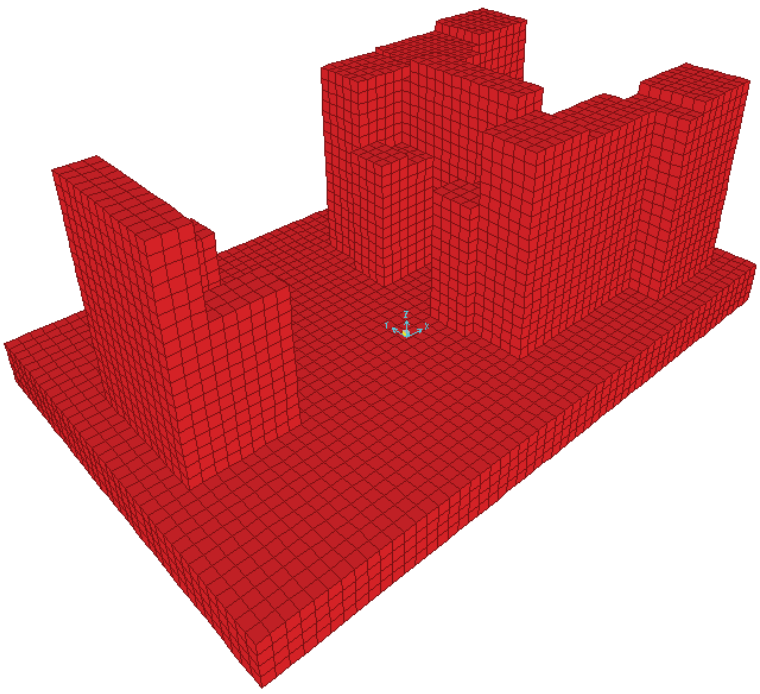

Figure 2: 3D Numeric Model of the Mill Foundation - SAP 2000

Modal analysis' aim is to inform the natural frequencies and the vibration modes of the system under study. With this information it is possible forecasting, in what operation conditions the foundation may face dynamic instability, through the use of coupling (resonance) of natural and work frequencies.

3.3 Soil parameters

When preparing a draft project, all soil properties must be taken into account for the analysis of the location, which includes its geological formation and composition features, as well as the knowledge of its layers and the variation of properties according to its depth. Unfortunately, the only variable for soil representation by springs is the vertical reaction modulus (K). An incorrect estimate of this parameter can cause serious errors in the structural analysis of the model at hand.

In cases where there are no changes in soil resilience capacities and in their structure due to dynamic action, and where there are extremely small amplitude of displacements, the use of a soil with an elastically linear system can be used in the calculation model, having satisfactory results been demonstrated.

3.4 Equipment data

Below we can see a schematic representation of the mill and the mill foundation in the study.

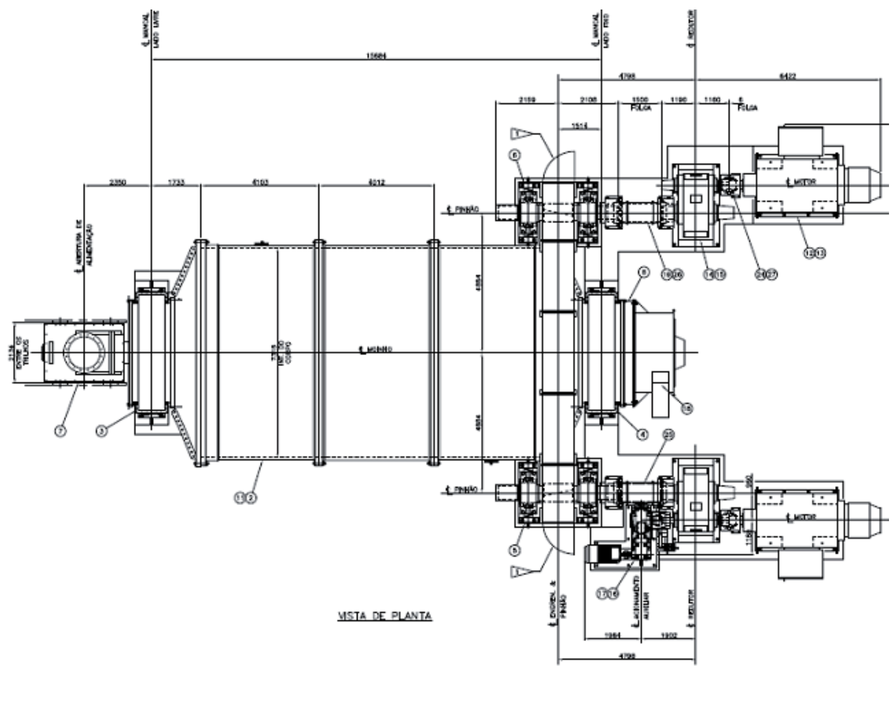

Figure 3: Ball Mill Plan View

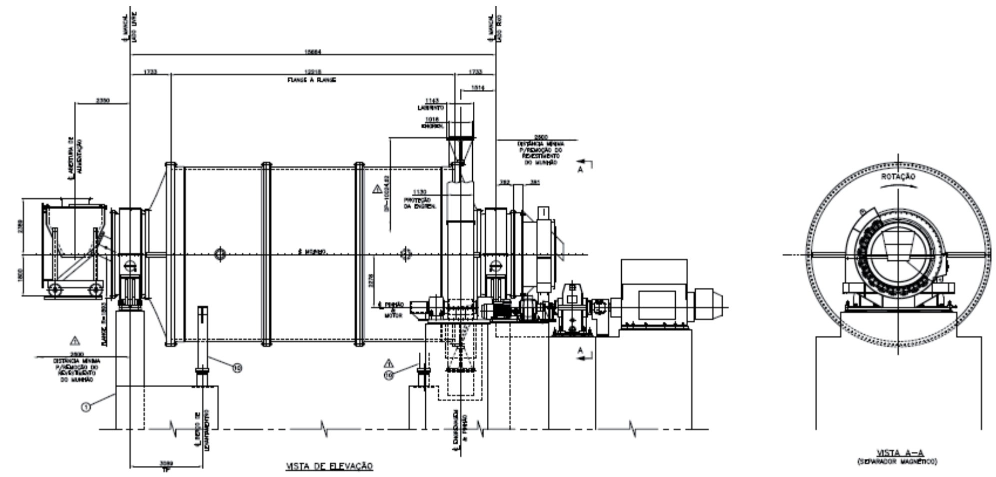

Figure 4: Ball Mill Side View

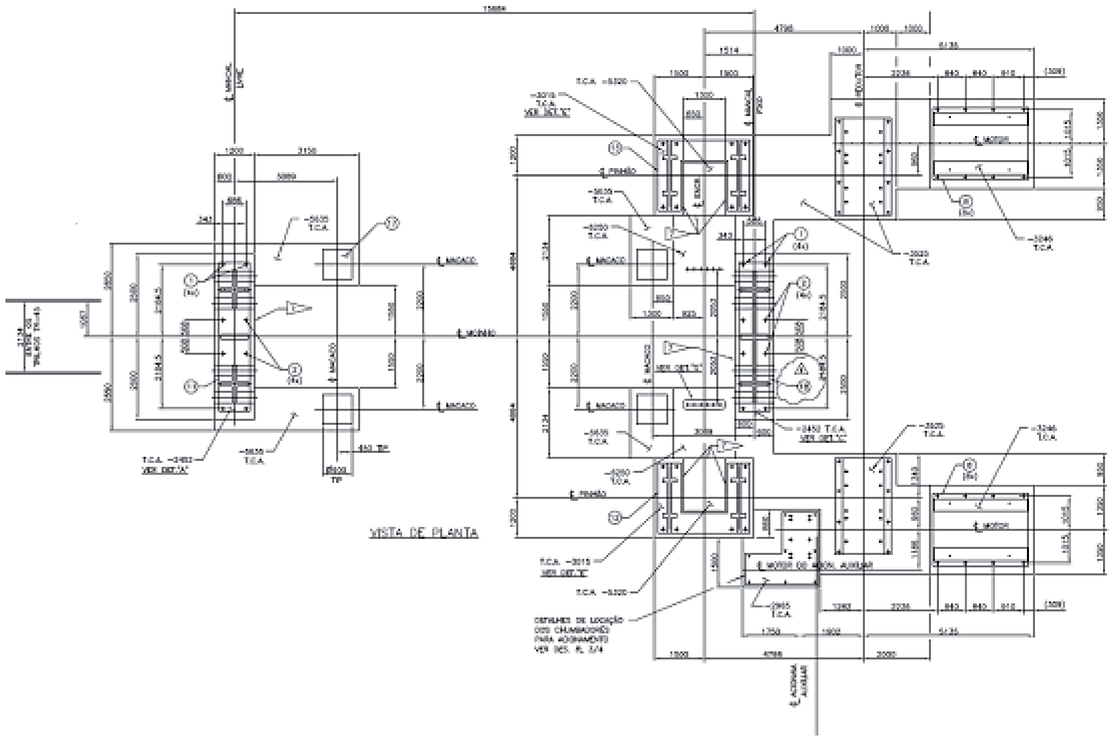

Figure 5: Dimensions of the construction foundations of the ball mill

3.5 Loads considered in the model

The effects of loads from the most representative efforts were considered to calculate the static and dynamic models, in this case:

- Dead Load - from the weight of the volume of concrete of the model
- Weight of the Mill (loaded) - free support
- Weight of the Mill (loaded) - static support
- Weight of the pinions no.1 and no.2

- Weight of the motor
- Weight of the reducer
- Dynamic loads from the mill and pinion

We adopted the following frequencies of operation for the mill and pinion

- MILL rotation speed: 15 rpm = 0.25 Hz
- PINION rotation speed: 150 rpm = 2.50 Hz

These are then "low speed rotation" equipment (less than 5-7 Hz).

4 RESULTS

4.1 Modal Analysis

Below are presented the results found in modal analysis for the project under study. The following table identifies the relative frequency of each of the modes studied in the three models at hand.

Table 2 illustrates each one of these modes of vibration, as it follows.

Modes of Vibration	Frequency (Hz)		
	Model 1	Model 2	Model 3
1	1.4898	2.9699	4.0038
2	1.6581	3.8688	6.5699
3	2.0873	4.7687	6.9386
4	2.6149	4.8449	12.709
5	3.0309	8.3402	14.634
6	3.2712	9.0089	15.745
7	3.6458	9.544	18.97
8	4.9392	9.7512	19.027
9	7.1333	11.206	19.206
10	10.416	13.009	19.365
11	13.775	15.604	19.436
12	16.85	17.292	20.758

Table 2: Modes of vibration and their natural frequencies

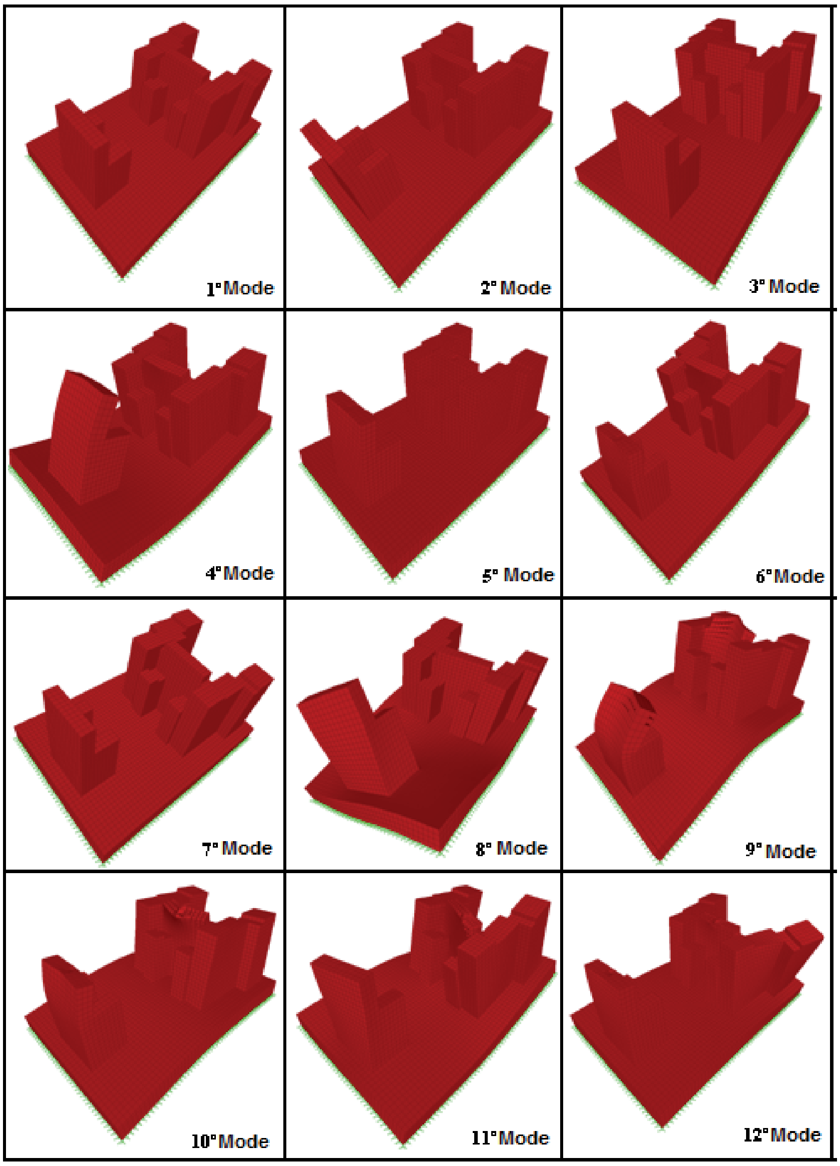

Figure 6: Vibration modes (1-12)

4.2 Result analysis from modal analysis

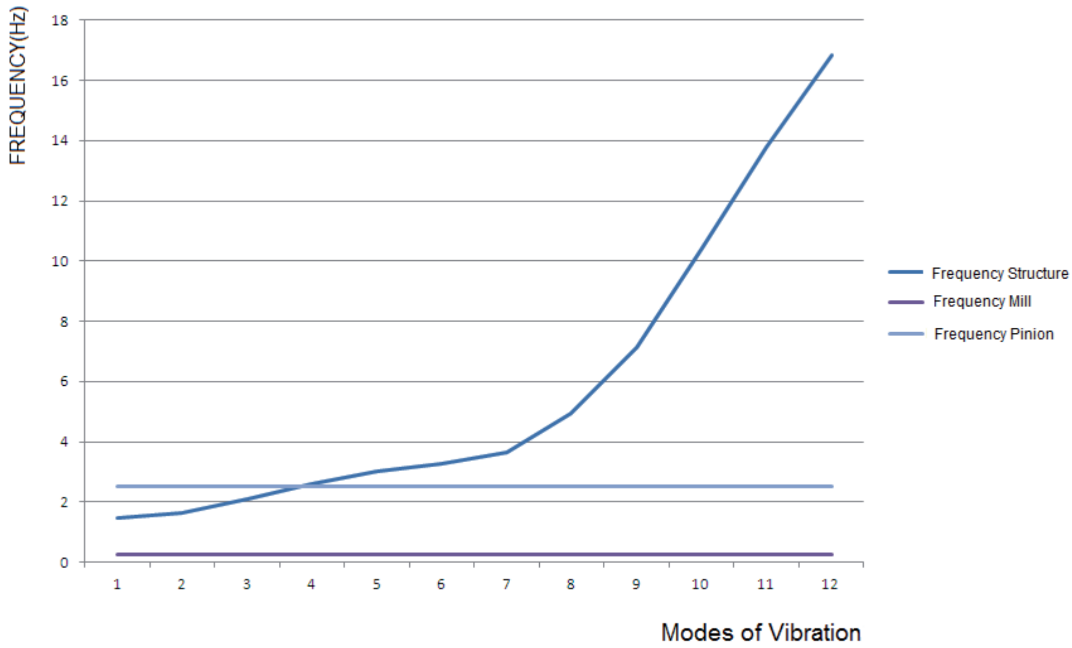

Figure 7: Analysis of modal response (Model 1)

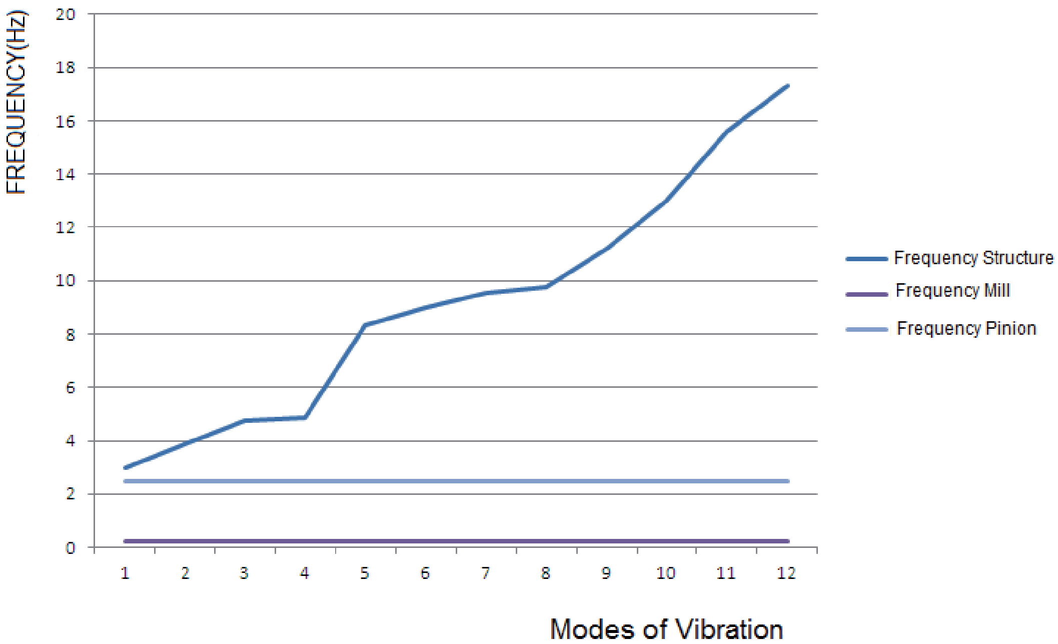

Figure 8: Analysis of modal response (Model 2)

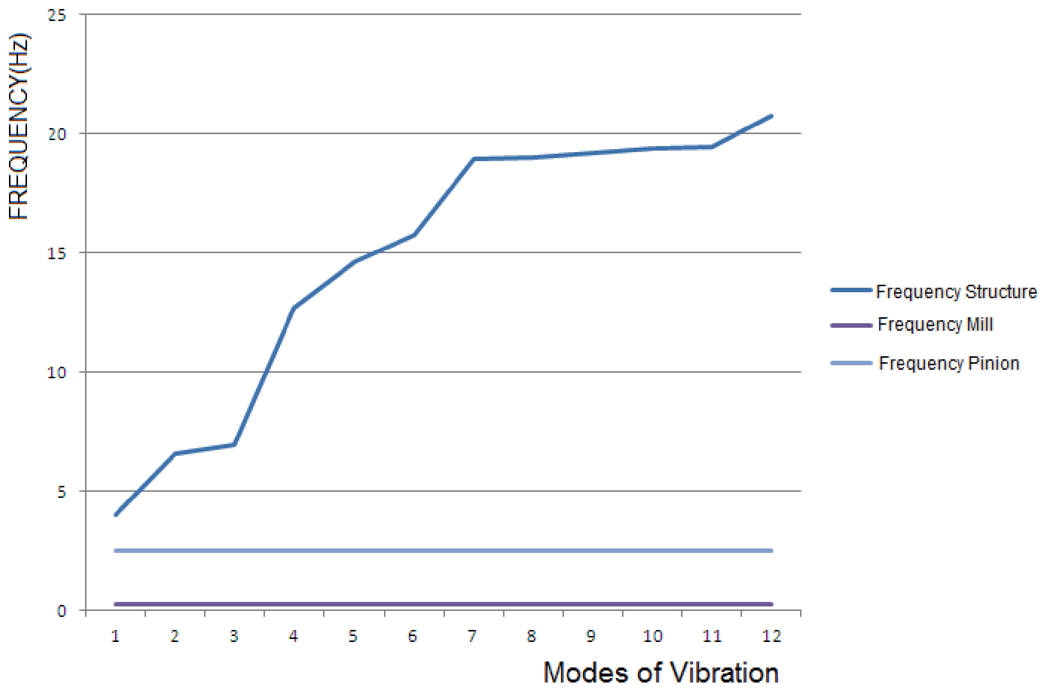

Figure 9: Analysis of modal response (Model 3)

As evidenced by the previous diagrams, the first natural frequencies of the mill foundation, in model 1, couple with the working frequencies of the pinion. Then, if the vertical reaction modulus of the soil was actually 500 t/m3, we would certainly have a problem in the resonance structure.

4.3 Speed and displacement assessment

We assessed the speeds and displacements of the model in analysis in two critical points of the mill operation platform:

- At point 11501: one of the points of the Mill foundation (Power/Movable)
- At point 13065: one of the points of the Mill foundation (Download/Static)

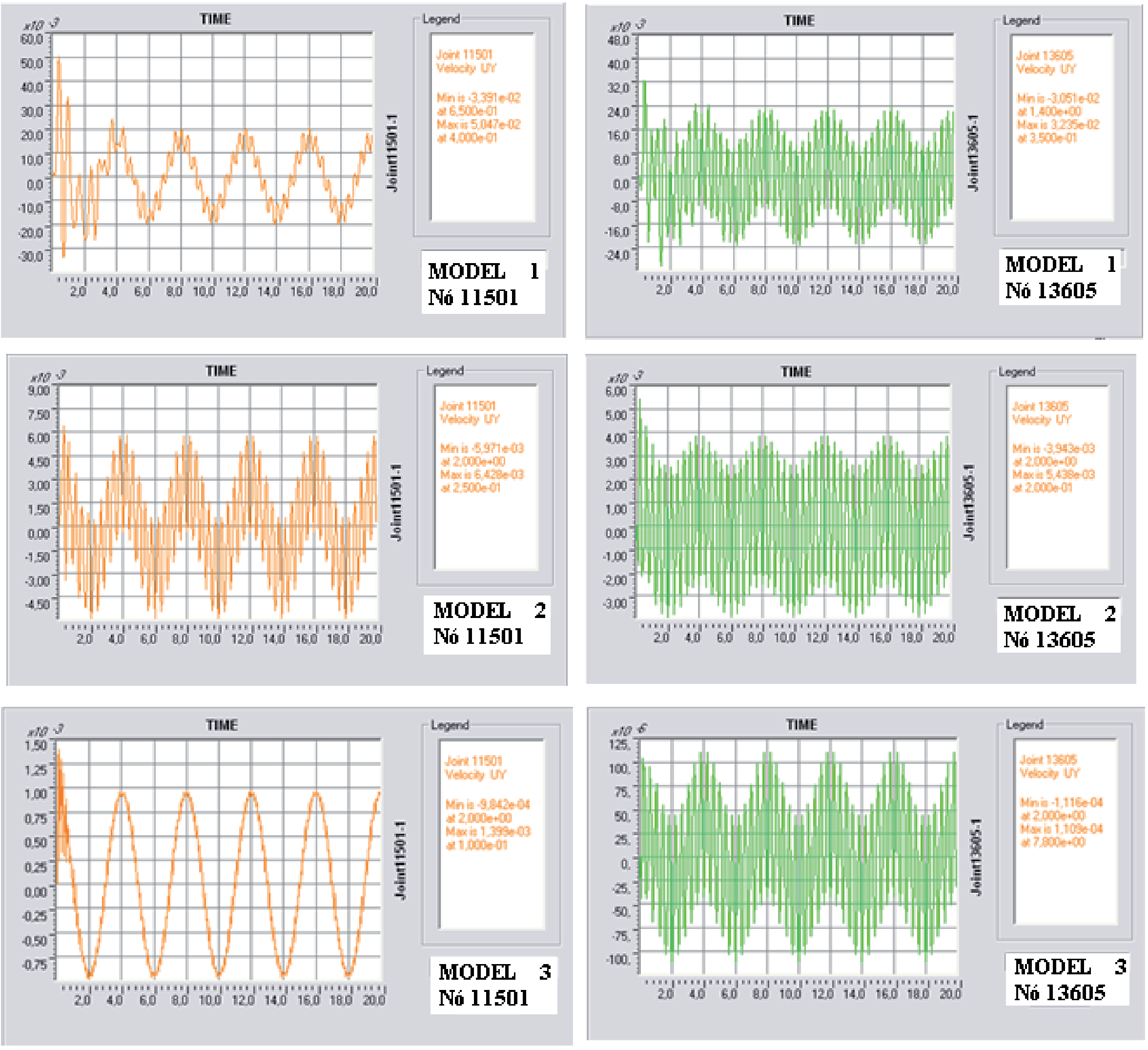

Figure 10: Analysis of Vyy speeds (mm/s) in points 11501 and 13605

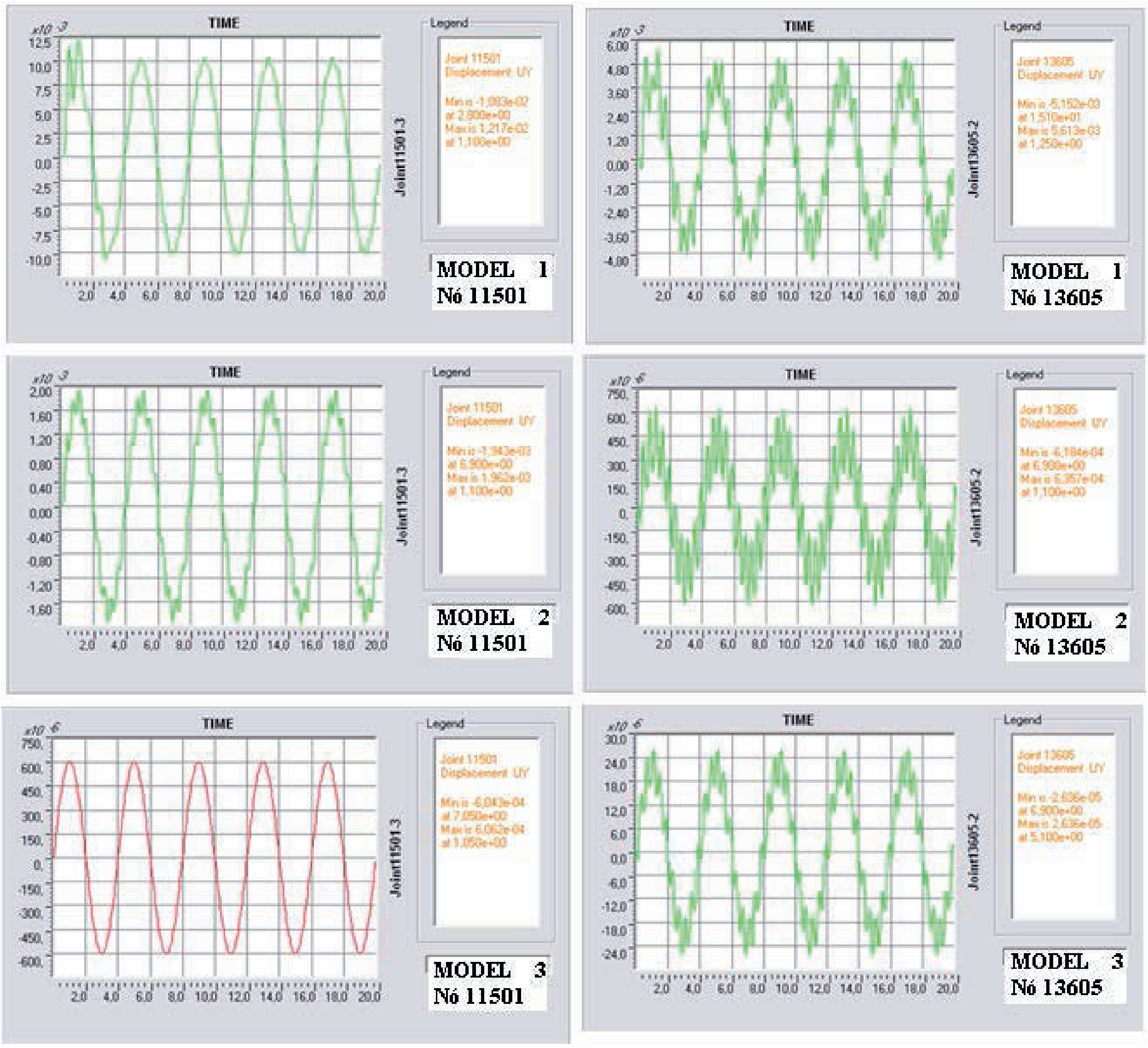

Figure 11: Analysis of Uyy displacement (m) in points 11501 and 13605

A summary of the maximum speeds and displacement per model is presented in the Table 3 and Table 4, below.

Vyy Speed (mm/s)			
Model	Rigidity (t/m3)	Node 11501	Node 13605
Model 1	k = 500	50.47	32.35
Model 2	k = 5000	6.428	5.438
Model 3	k = 500000	1.399	0.1109

Table 3: Vyy Speed (mm/s)

Dyy Displacement (mm)			
Model	Rigidity	Node 11501	Node 13605
Model 1	k = 500	12.17	5.613
Model 2	k = 5000	1.962	0.6357
Model 3	k = 500000	0.6062	0.02636

Table 4: Dyy Displacement (mm)

5 CONCLUSION

From the results found it is concluded that soil rigidity has significant influence on the results of displacement, speed and the natural frequency of the structure in study.

It can be seen, then, that an incorrect estimate of the vertical reaction modulus K can cause serious problems in the structure. As can be noted in the tables above, the differences among the models under study are very significant. In some cases, the difference between a model and the other lies in the power of base ten.

Ultimately, a rigorous analysis of soil parameters becomes necessary to prevent incorrect analysis of the structure at hand.

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