

DYNAMIC ANALYSIS AND REINFORCEMENT OF A KILN FOUNDATION UNDER EXCESSIVE VIBRATIONS

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ABSTRACT

This paper presents the case of a footing belonging to a kiln reported to be vibrating beyond reasonable levels at an industrial facility in Avelar, Portugal. The vibration was characterized through several measurements using accelerometers placed on different locations on the column and footing, identifying the principal vibration modes. Given the results of former surveying campaigns, which included Standard Penetration Tests, it was possible to model and calibrate the system through the use of a three-dimensional finite element program. A reinforcement solution to decrease the level of vibration based on performance requirements and parametric studies was then proposed consisting in the use of micro-piles. The solution has been implemented and the foundation behavior has improved dramatically.

Keywords: dynamic analysis, foundations, reinforcement, micro-piles, vibration

INTRODUCTION

Excessive vibration is a problem that often affects industrial equipment due to inadequate foundation. The usual approach consists in guaranteeing that the dynamic excitation, which is a known characteristic of the machine, has a frequency that is significantly different from the vibration modes that the structure exhibits. Although this procedure is generally enough to limit the appearance of excessive vibration problems, the process still involves numerous difficulties in quantifying the effects of the complex soil-structure interaction because it depends, not only on the geometry of the structure itself, but also on the geotechnical conditions. This implies that the design process must include the relevant data to characterize the soil and the analysis method must be able to model it conveniently so the vibration modes are realistically determined. This last aspect has known great improvement during the last years due to the development of several software packages that use the Finite Element Method (FEM) to produce reliable estimates of the expected behaviour.

In the present paper, a foundation of a column that supports a kiln is analyzed. High levels of vibration had been reported and the maintenance team responsible for this industrial facility had already identified some damage in various components of the machinery leading to increasingly long stoppage periods to perform repair operations. Considering this context, the complete process leading to a solution is described, starting with the gathering and treatment of relevant data. This phase was fundamental since the interpretation of the obtained results provided insight into the dynamic

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performance of the structure, allowing its behaviour under the dynamic excitation to be quantified, not only in direction and nature, but also in terms of magnitude. A 3D-FE model was then created in order to reproduce the observed behaviour, being the main concern of this stage the evaluation of the parameters of the non-linear springs used to introduce the effect of the soil. This was done by comparing the computed vibration modes with the ones measured in the field and good agreement was reached. The next step involved the conception of a reinforcement that would be able to increase the difference between the frequency of the dynamic excitation and the frequency of the vibration modes, thus reducing the probability of resonance. Among all the available options, the installation of a reinforced concrete ring with micro-piles was the selected one due to its easiness of construction. A parametric study, which accounted for the uncertainties of the geotechnical profile in terms of the position of the bearing stratum, was then conducted in order to establish the most balanced solution by computing the change in the model's vibration modes for different quantities and types of micro-piles to be used. The final stage was to use the final model to evaluate the design forces that would be expected in the micro-piles under the measured dynamic excitation and to prescribe the adequate constructive dispositions.

COLLECTED DATA

Geological/Geotechnical model

The existence of 12 boring logs with SPT tests, executed in the factory area, provided some insight about soil properties. However, since none of the borings was executed near the column (hereon designated P2 column), the adopted geological profile is a cautious interpretation of the available data. The majority of the borings revealed an upper fill layer with a thickness between 1 to 3 m, composed by brown silty clay with lithic fragments and $9 < N_{SPT} < 12$. An underlying layer, composed by silty clays and marl clays from Jurassic period is the actual bearing stratum of foundation columns. This layer exhibits a great heterogeneity of N_{SPT} values on the several borings, varying in a wide interval of $5 < N_{SPT} < 32$. A boring at the new silo location showed worst soil properties, with a medium consistency marl clay of $N_{SPT} = 5$ below water table. In the following analyses of vibrations and solution achievement, a cautious average value of $N_{SPT} = 12$ was considered. The bedrock is composed by strongly fissured calcareous marls ($F_{4.5}$) at depths between 4 to 11 m. The ground water table depth varies between 3 to 6 m.

Based on the borings data, the profile shown in Figure 1 was adopted as the geological/geotechnical model.

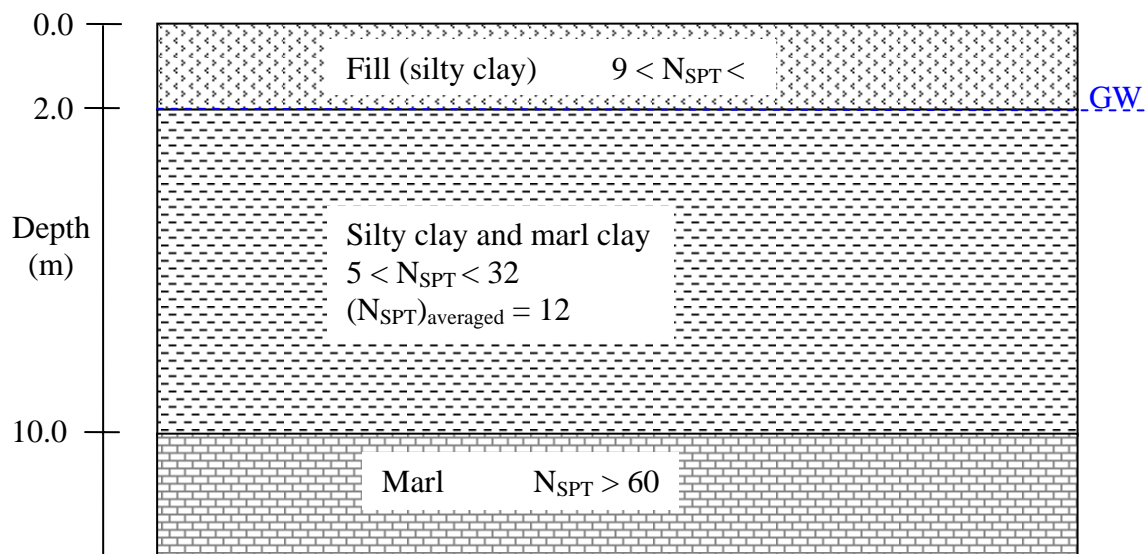


Figure 1. Assumed Geological/geotechnical model

2.2 Kiln and column

Figure 2 presents a global view of the rotary kiln. It is used to produce expanded clay pellets, a light weight construction product. The kiln is supported by four columns. Column P2 presented serious vibration problems. It is a massive block of concrete, with the geometry depicted in Figures 3 and 4 (dimensions are in meters). It is supported by a shallow foundation and was designed for a vertical static load of 1200 kN.



Figure 2. Global view of the kiln



Figure 4. Views of the column P2

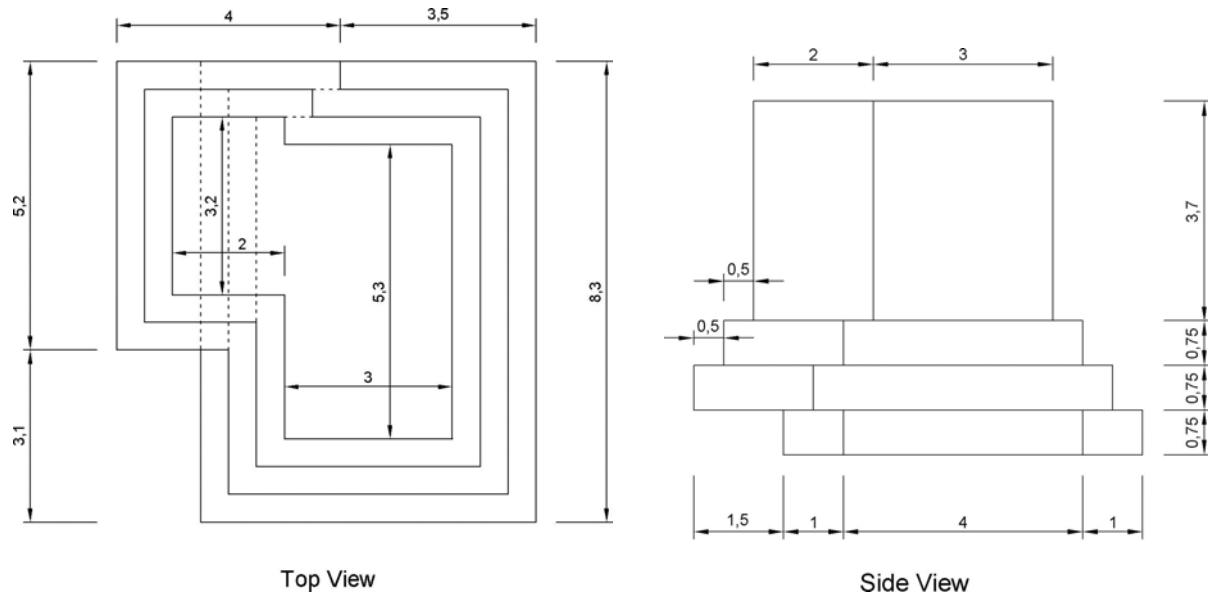


Figure 4. Geometry of column P2

2.3 Vibration measurement

The measurements were carried out during kiln operation. A frequency analyzer from Bruel & Kjaer using the software PULSE and 7 unidirectional accelerometers of B&K4370 and B&K4378 type were used for this purpose. The measurements were taken at 6 different points at the top and at the footing level (Figure 5) and, whenever possible, in 3 orthogonal directions at each point: one vertical and the others longitudinal and transversal to the kiln axis. Four accelerometers were kept fixed in their positions and directions in order to be used as reference signals and the other three accelerometers were moved by changing their location or measurement direction. This procedure results in a total of three setups exclusively for measurements of the studied column. With the 4th setup a comparison of the vibration's spectra of the studied column with those of an adjacent one is sought. From these last measurements no important vibration amplitudes were detected in the adjacent column.

The results after numerical integration are summarized by their acceleration and displacement maximum spectral peak values in Table 1. After analyzing the auto and cross spectra it was identified the very probable existence of 2 fundamental vibration modes of rigid body (column + foundation) movement: 1st mode – $f_1 = 5.56$ Hz representative of a rotation around an axis close to the kiln's longitudinal axis; 2nd mode – $f_2 = 11.12$ Hz representative of a vertical displacement.

The excessive vibration noticed results from a resonant phenomenon in the 1st mode. This conclusion was confirmed by the analysis of the data collected from the adjacent column, which showed also a first spectral peak at about 5.56 Hz. This value may correspond to the excitation caused by the rotation of the kiln and induces the resonance phenomenon responsible for the large amplitudes detected. At this nearby column, another spectral peak at 8.4 Hz was detected, which may represent the vibration in the first mode of this column.

Displacements were obtained by integrating the accelerations. For the highest spectral peak at the frequency of 5.56 Hz, the maximum displacement was observed at Point A (top of the column). Considering an harmonic movement at that frequency, a conservative value for the displacement amplitude can be obtained from the RMS spectral value (0.122 mm), that is: $1.41 \times 0.122 = 0.172$ mm. These values are clearly excessive and fall on a range where intervention is required (Milititsky et al, 2005).

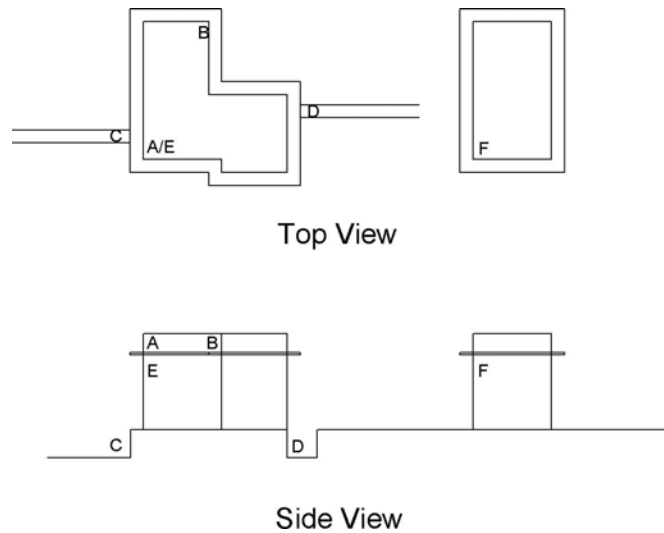


Figure 5. Localization of measured points

Table 1. Peak spectral (RMS) values of accelerations and displacements

Accelerometer / direction / point	Peak of acceleration spectrum (m/s^2)	Peak of displacement spectrum (mm)	Measurement setups
1 (transv.) A	0.148	0.122	1
2 (vertical) A	0.056	0.046	1
3 (longit.) A	0.031	0.026	1
4 (transv.) B	0.138	0.114	1
5 (vertical) B	0.068	0.056	1
6 (longit.) B	0.049	0.038	1
7 (vertical) footing C	0.031	0.026	1
1 (transv.) A	0.205	0.168	2
2 (vertical) A	0.077	0.063	2
3 (transv.) footing C	0.089	0.073	2
4 (longit.) footing C	0.007	0.006	2
5 (vertical) B	0.094	0.077	2
6 (longit.) B	0.067	0.055	2
7 (vertical) footing C	0.043	0.036	2
1 (transv.) A	0.161	0.132	3
2 (vertical) A	0.050	0.050	3
3 (transv.) footing C	0.057	0.057	3
4 (longit.) footing C	0.005	0.005	3
5 (vertical) B	0.060	0.060	3
6 (vertical) footing D	0.015	0.015	3
7 (vertical) footing C	0.028	0.028	3
1 (transv.) A	0.132	0.108	4
2 (longit.) A	0.027	0.021	4
3 (transv.) footing C	0.078	0.064	4
4 (transv.) adjac. column F	0.003	0.002	4
5 (longit.) adjac. column F	0.006	0.005	4
6 (longit.) footing D	0.021	0.017	4
7 (vertical) footing C	0.038	0.031	4

($\Delta f=0.03125$ Hz; $\Delta t=0.0078125$ sec.)

NUMERICAL MODELLING OF VIBRATION MODES

The development and analyses of numerical models was performed with SAP 2000 (v.9) software. Due to the highly complex geometry of the system constituted by the footing, the column and the kiln, a 3D model had to be created. For this purpose, the referred version of the program includes tridimensional, eight noded elements (known as “Solid”) that have three translational degrees of freedom associated to each of its nodes. The integration scheme adopted is a $2 \times 2 \times 2$. To obtain improved accuracy, the complete geometry was modeled (Figure 6.a)) including the column, the three steps of the footing and the soil placed above (mainly to incorporate its mass on the system).

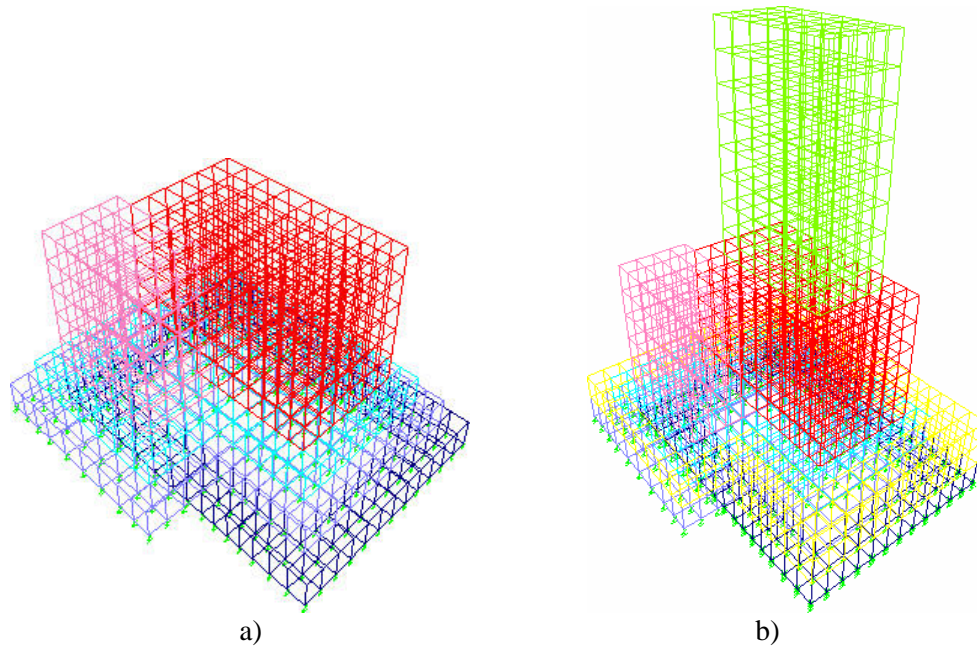


Figure 6. Tridimensional FE model a) without kiln, b) with kiln

Furthermore, the kiln itself had to be introduced in the model so that its presence (load, weight and stiffness) was also taken into account when computing the vibration modes. This was accomplished by placing a volume on top of the column with dimensions that would guarantee that its centre of gravity would coincide with the position of the axis of the kiln (Figure 6.b)). Additionally, very stiff springs, usually considered as having a stiffness at least one order of magnitude larger than the rest of the materials, were placed along the two faces of this volume normal to the longitudinal direction to restrain the movement of the kiln along its axis.

Being linear-elastic elements, the only properties which need to be defined are the self-weight and the elastic characteristics. Table 2 presents the values used during the analyses. Note that for the kiln an equivalent weight was estimated by guaranteeing that for the given volume the static load would be accurately reproduced.

Table 2. Weight and stiffness of the materials

Component	γ (kN/m ³)	E (MPa)
Column	25.0	29×10^3
Footing	25.0	29×10^3
Kiln	26.1	100×10^3
Soil above footing	17.0	10

To introduce the soil-structure interaction, non-linear springs were placed on the bottom face of the model and, taking into account that in this program it is possible to define the link/support property through multi-linear segments, zero stiffness was chosen if and when these elements were subjected to tension forces (Figure 8).

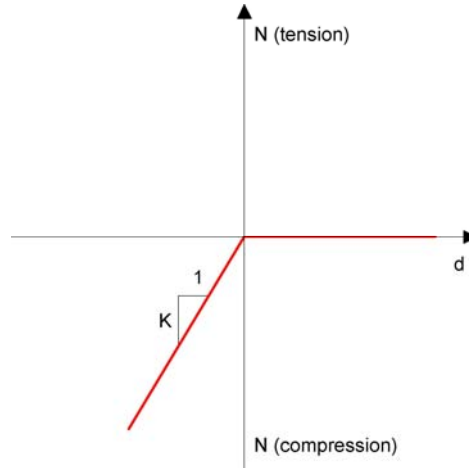


Figure 8. Stress-strain relation for springs

For compression forces, the stiffness adopted was determined by the product of the subgrade reaction modulus by the area of influence of each spring. If the latter was dictated by geometry only, the former was estimated using a correlation with the available results of the Standard Penetration Test.

For an average value of N_{SPT} between 12 and 16, the undrained shear strength, s_U , can be expected to vary from 60kPa to 80kPa. Estimating the distortion to which the soil is subjected under the observed circumstances to be between 10^{-5} and 10^{-4} it is possible, according to Seed and Idriss (1970), to assume a ratio of G/s_U of about 1000 to 1300. Using these relations and Equation 1 with the Poisson's ratio set to 0.5, the Young's modulus can be estimated for the considered range. The obtained values are presented in Table 3.

$$E = 2 \cdot G \cdot (1 + \nu) \quad (1)$$

Table 3. Young's modulus

	$s_U = 60\text{kPa}$	$s_U = 80\text{kPa}$
$G/s_U = 1000$	$E = 180 \text{ MPa}$	$E = 240 \text{ MPa}$
$G/s_U = 1300$	$E = 230 \text{ MPa}$	$E = 310 \text{ MPa}$

The subgrade modulus can then be determined by the elastic settlement formulae:

$$k_s = \frac{E}{2B \cdot (1 - \nu^2) \left(I_1 + \frac{1 - 2\nu}{1 - \nu} I_2 \right) \cdot 0.93 \cdot I_f} \quad (2)$$

which, for the geometry of the analyzed footing, results in:

$$k_s = \frac{E}{3.43} \quad (3)$$

For the extreme values determined for the Young's modulus (180 MPa and 310 MPa), the subgrade modulus can be estimated to assume a magnitude from 52 MN/m³ to 90 MN/m³. In the analyses, an average value of 70 MN/m³ was used.

Having defined the model (geometry, materials and restraints), the vibration modes and the respective frequencies were determined by SAP 2000 (v.9): the first consisted in a rotation about the longitudinal

axis of the kiln with a frequency of 5.52 Hz and the second in a vertical translational movement with a frequency of 12.13 Hz. The model was considered to be successfully calibrated since these results agree well with the measured data which, as referred previously, revealed a rotating movement of the same nature as the one computed with a frequency of 5.56 Hz and a vertical one with a frequency of 11.12 Hz.

ANALYSIS WITH REINFORCEMENT

Prior to evaluate the changes in structural behaviour due to the installation of the micro-piles, a static calculation was performed with the presented model. The main purpose was to evaluate the magnitude and distribution of the stresses transmitted to the soil, caused by the self weight of the structure and the kiln. The results revealed that the average stress on the base of the intermediate level of the foundation (notice that the deepest step is just a strip around the perimeter of this area) was of about 110 kPa, which is an adequate value for the studied situation. Underneath the deepest step of the footing the stresses were relatively higher, reaching the magnitude of 180 kPa, the largest value yielded by the calculation.

Conception of the reinforcement

As demonstrated by the measurements and the numerical analyses, the existence of an overlap between the 1st natural frequency of the system and the excitation frequency is very likely. Therefore, in order to mitigate the resonant phenomena and, consequently, reduce the vibrations level, the 1st natural frequency of the system should be diverted from the currently existent. Alteration of the natural frequencies is possible, mainly, using one of the following procedures: modification of the structure mass and foundation area; foundation soil improvement (using cement injections, jet-grout, etc); modification of the foundation stiffness or a mixed solution of the former. As the system mass is very large, any change of this property would be unprofitable unless very large quantities of concrete were to be used. This solution should imply an exaggerated construction volume incompatible with the column's placement. Thus, the solution here described intends to establish an improved foundation performance by modifying its stiffness. The proposed method consists in the construction of micropiles that allow the transmission of stresses to the deep bearing stratum. Naturally, the success of this solution depends on the bearing stratum depth, but, in the case of column P2, and according to the borings, the expected depth is compatible with this method.

When this kind of solution is adopted, the micropiles connection to the already existent structure should deserve special attention. For this purpose, a concrete ring involving the footing over the 2nd step should be constructed, to make a reliable connection and allowing an adequate transmission of forces. After the selection of the most efficient zone to connect micropiles, a parametric analysis is required to determine the number and diameter of micropiles that will be able to modify significantly the natural frequencies. Some previous analyses showed that diameters smaller than $D_{ext}=139.7$ mm and $t=10$ mm, where D_{ext} is the outer diameter of a pipe pile and t its thickness, are inefficient. Several cases with different number and spatial distribution were considered: 4, 8, 13, 17 and 24 micropiles (Figure 9 and Table 4). Because of the uncertainty of bearing stratum depth, 3 cases were studied with different depths: 6 m, 10 m and 14 m. The results are presented in Figure 10.

As Figure 10 shows, a further increase in the number of micropiles leads to a decreasing gradient of the 1st frequency mode improvement. This is caused by the proximity of the last micropiles to be installed to the rotation axis. In other way, Figure 10 shows a consistent increasing of 2nd frequency mode with number of micropiles because this movement is purely vertical and the micropiles stiffness contributes equally, whatever their placement is.

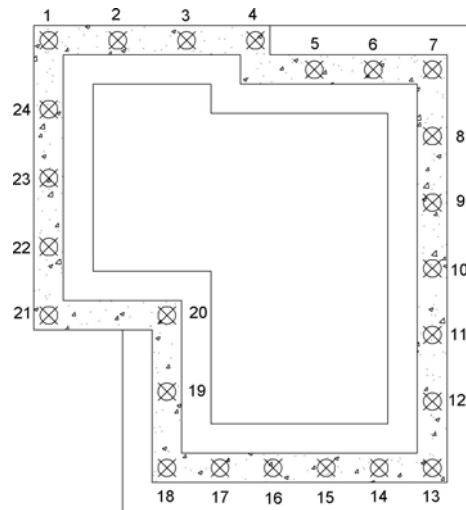


Figure 9. Plan view of the micropile location

Table 4. Configurations studied

Number of micropiles	Micropiles used
4	1, 7, 18, 13
8	1, 3, 5, 7, 13, 15, 16, 18
13	1 – 7, 13 – 18
17	1 – 8, 12 – 19, 24
24	1 - 24

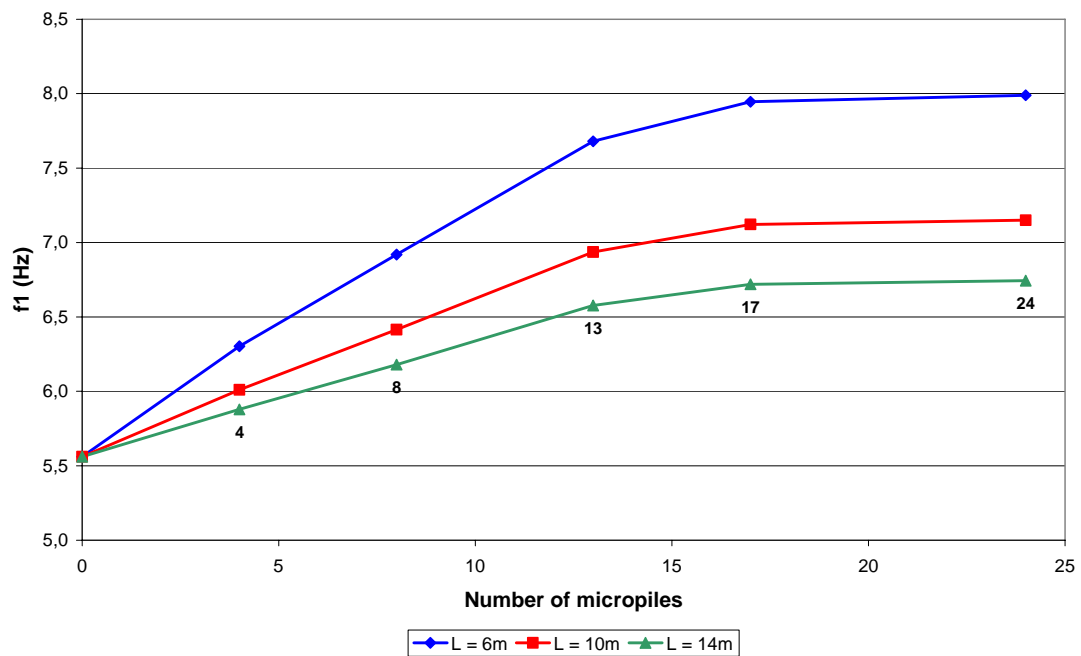


Figure 10. Number of micropiles vs 1st natural frequency

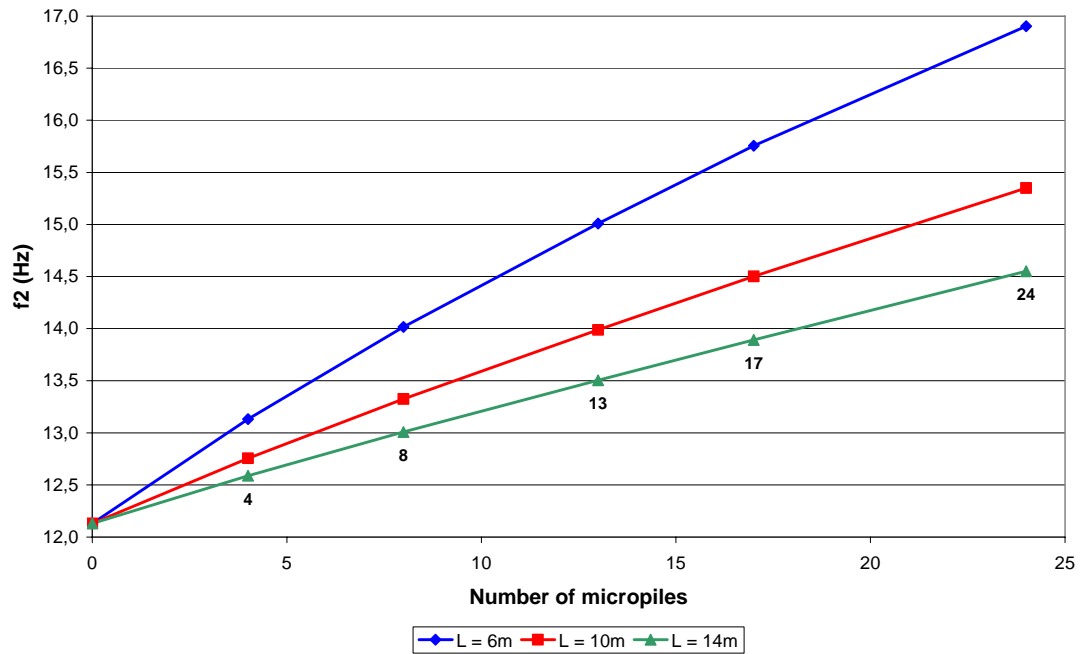


Figure 11. Number of micropiles vs 2nd natural frequency

Calculation of the natural frequencies

Regarding the equilibrium between efficiency and costs, the use of 13 micropiles seems to be the best solution. The proposed reinforcement is therefore 13 micropiles arranged around the 2nd step of the footing. A concrete ring should be built over the 2nd step and with the top at the 1st step of the footing, to connect effectively the micropiles to the existent structure. At the other 11 placements, holes in the ring should be left, to allow posterior introduction of micropiles if local geotechnical conditions reveal to be worse than expected. The micropiles will be placed with 1 m average spacing, pipe section of $D_{ext} = 139.7 \text{ mm}$ / $t = 10 \text{ mm}$ in St52 ($f_y = 355 \text{ MPa}$ and $E = 200 \text{ GPa}$) steel. The manufacturer establishes a service limit load of 826 kN (with FS=1.75). The geotechnical design of the micropiles was performed using Bustamante's (1985) method.

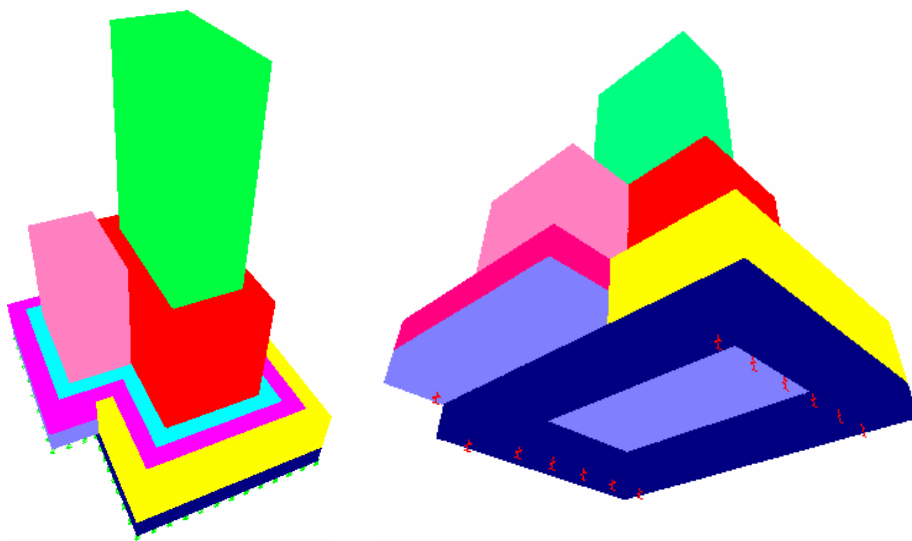


Figure 11. Calculation's model with 13 micropiles

In order to model the micropiles, 13 springs were introduced at the model's base (Figure 11), with a stiffness of 92746 kN/m each (corresponding to an elastic length of 10 m, a steel section of 40.75 cm² with E = 200 GPa and a cement grout section of 112.53 cm² with E = 10 GPa).

The system's new natural frequencies were then determined and the results of the analysis with reinforcement yielded the first mode as a rotation around the longitudinal axis of the kiln with $f_1 = 6.94$ Hz (measured 5.56 Hz), and a second as a translation in vertical direction with $f_2 = 13.99$ Hz (measured 11.12 Hz).

These new values were thought to guarantee that the resonance phenomenon would now be limited after installing the preconized reinforcement. Ideally, the improvement should provide a natural frequency double or half of the excitation (Das, 1993). In order to further improve the results, recommendations were provided to the owner to adjust the kiln setup.

The referred procedure was able to identify the most efficient solution that would guarantee that the resonance phenomenon would be limited. The reinforcement through the use of micro-piles was then proposed to the company that owns the industrial facility who accepted its implementation. The structural solution has been constructed and is now being monitored by the University of Coimbra in order to evaluate its effectiveness.

CONCLUSIONS

The design method presented in this paper was able to identify the vibration modes and amplitudes of a complex system of soil-foundation-column-kiln, under excessive vibrations. The finite element model that was developed matched with reasonable agreement the values measured in the field. In order to solve the malfunction of the kiln's foundation, several different stiffening systems were studied and an optimized solution was sought. The number, position, length and mechanical characteristics of micropiles were considered, the final solution consisting of 13 tubular micropiles located at the edge of the existing foundation. This system is expected to have a positive impact on the first vibration mode (rotation) and also on the second (vertical translation), thus achieving the desired relation with the frequency of the dynamic solicitation.

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