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Case History of the Malfunctioning of a “Compressor - Foundation - Supporting Soil” System

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ABSTRACT

The paper presents a case history related to the interaction of a compressor, its concrete block foundation and the supporting soil system. The owner of the compressor asked the Romanian National Center for Earthquake Engineering and Vibrations to solve the problem of the excessive vibration amplitudes that put the compressor out of service at a short time after starting to operate. The first step that was made was the *in situ* performance of measurements, in order to establish the dynamic properties of the compressor foundation, as well as the amplitudes of the vibrations at the operating speed. The design of the foundation was then checked, in order to determine if it has been designed taking into account the demands of the manufacturer. It should be stressed here that the poor performance of the compressor was due to a faulty design of the foundation, to a faulty construction, and to inadequate geotechnical information, that led to unrealistic soil data used in estimating the foundation response. The purpose of the evaluation was to establish whether remedial measures were to be taken to reduce the foundation's vibration amplitudes to permissible levels, or to redesign the foundation completely.

INTRODUCTION

"*An essential requirement for adequate design of a machine foundation is that the motion amplitudes under operating conditions do not exceed the specified value. The vibration amplitudes depend upon the natural frequency of the vibrating system, the operating frequency, and the magnitude of the applied dynamic forces and moments. The information on magnitude and characteristics of the dynamic loads imposed by the machine on the foundation is thus vital for a satisfactory design of the machine foundation system. This information is generally supplied by the manufacturer of the machine and should be procured from him. This presents difficulty sometimes since the interests of the client and the manufacturer of the machine are not in unison, and the manufacturer of the machine may not like to admit that large unbalanced forces may occur from operation of the machine supplied by him*".

These aspects were presented by professors Shamsher Prakash and Vijay Puri in the beginning of Chapter 5 of their book "*Foundations for Machines: Analysis and Design*" and I consider that they perfectly characterize the subject of this paper, that is the excessive vibration case history of a new ensemble consisting of a compressor, its concrete block foundation and the supporting soil, encountered in Romania.

In fact, when the compressor was placed in operation, the foundation and its surroundings started vibrating excessively and, as a result, the excessive vibration amplitudes put the machine out of service short time after it started to operate.

The owner did not know whom to blame for the unsatisfactory performance of the facility and started accusing all parties involved: the manufacturer of the compressor, the designer of the foundation and the builder of the machine foundation. This case is another situation when a "vibration problem" occurred "after the fact", and the machine foundation became "target of blame". However, as it will be seen further on, in the case of this ensemble "compressor – concrete block foundation – supporting soil", only the manufacturer of the compressor that was out of blame.

SOME INFORMATION ON THE INITIAL DESIGN OF THE COMPRESSOR FOUNDATION

A compressor (type 06-NK3) that was installed in an oil refinery was supported on a concrete block foundation that has been built to match the dimensions suggested by the supplier of the machine. The manufacturer of the compressor also imposed the requirement that the foundation should be designed in such a manner that the "peak-to-peak" displacement amplitudes at operating speed, at the top of the foundation, do not exceed 63.5 μm (microns), which is an extremely severe condition.

In the design of a compressor foundation the knowledge of the dynamic soil properties and the proper understanding of the dynamic soil moduli (with the corresponding elastic spring constants), together with damping, are frequently required. Though the designer knew these aspects he preferred to use the results of an existing geotechnical study, performed at approximately 60 m from the site where the compressor 06-NK3 was to be placed. Before starting the construction of the machine foundation the designer asked to the owner to clear the foundation medium by removing a sewerage pipe (∅ 600mm), an outlet nozzle, a recirculating water chamber, an electric cable canal and a water processing canal, that existed on site. The soil consisted of brown, dry plastic, silty clay, over which was laid a compacted soil padding (compacting degree 98%). At the time when the construction of the compressor's foundation began no water infiltrations existed in the general digging.

When the compressor was placed in operation, the foundation vibrated excessively. It was the foundation-related problem that was held responsible for the malfunctioning of the ensemble "compressor – foundation – supporting soil". In order to solve this situation, the first step was to perform geotechnical investigations on the site of the compressor foundation. Two drills near the compressor foundation were performed (at a distance of 3.15 m on both sides of the transversal axis of the compressor foundation, as shown in Fig.1).

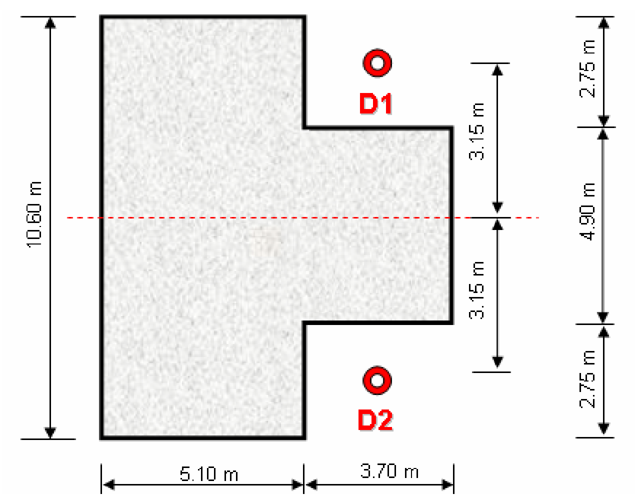
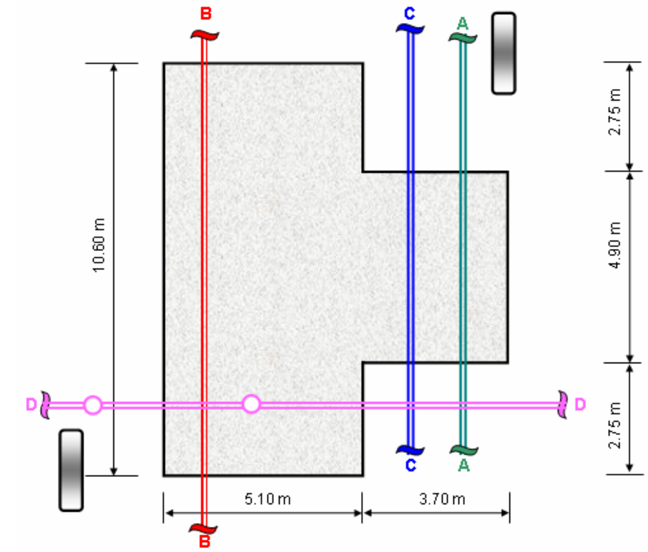


Fig. 1. Layout of the foundation and positioning of the drills

The first results of the geotechnical study pointed out the presence of water infiltrations and water-saturated soil, at the following depths: 0.90m÷1.60m (D1) and 1.30m÷2.0m (D2). A temporary solution to get rid of the water consisted of two drain pipes operating near the compressor foundation. The existing situation of the pipes below the foundation is presented in Fig. 2.



LEGEND

- existing sewerage pipe ∅600 mm in soil; the designer asked the owner to remove it but the owner didn't do that; the designer was not informed about that fact;
- existing canal; the designer asked the owner to demolish it, and the owner pulled it down;
- ∅300 mm pipe, discovered during the digging process for the new foundation;
- pipe, discovered during the digging process for the new foundation (-0.90m); the designer wasn't notified about it;
- holes performed in the ∅1200 mm pipe; through these holes concrete was cast in place;
- drain water chamber.

Fig. 2. The existing pipes below the compressor foundation.

It is obvious that the first geotechnical study did not contain the necessary basic elements for the analysis of the foundation to dynamic actions. The second one confirmed the fact that one couldn't count on any elastic coefficients for the site. None of the two geotechnical studies furnished values of elastic soil moduli obtained either in static or dynamic conditions, for the site. At the time of the technical assessment it was ascertained that there were water infiltrations at the bottom of the compressor foundation, situation in which the behavior of the "compressor–foundation –supporting soil" system was strongly influenced by them.

STAGE I: INSTRUMENTAL INVESTIGATION PROGRAM

Introductive elements

The first step that was made during the technical assessment was the *in situ* performance of measurements, having in mind to establish the dynamic properties of the compressor foundation, together with the vibration amplitudes at the top of the foundation, at idle operating speed.

Proposed objectives – Stage I

The main objectives of the instrumental data acquisition were the following:

- identifying the eigen dynamic characteristics of the compressor foundation, when the equipment does not operate, considering as action the microtremors together with the ambient vibrations due to industrial traffic and to the functioning of other facilities in the vicinity;
- identifying of some functioning characteristics of the installation;
- identifying of the dynamic characteristics of the compressor foundation, during idle functioning of the compressor, in the following operation stages: starting moment, idle functioning and stopping moment;
- clarifying the technical causes of excessive vibrations (annoying) generated by the functioning of the equipment;
- establishing the degree of transmissibility of the vibrations through the foundation medium to the vicinity;
- recommending, if possible, the most appropriate solutions in order to avoid the vibration problems.

Methodology adopted for data acquisition

The acquisition of the instrumental data was achieved with highly sensitive modern equipment, consisting of eight SS-1 Ranger seismometers, widely recognized as excellent short-period field instruments and VSS-3000, a fully portable acquisition system designed for ambient and forced vibration field measurements (KINEMETRICS). The first step when performing experimental investigations is to select the locations where motion will be recorded. The number of measuring points will depend on the type and complexity of the experiment and on the type of the structure.

With the complete cooperation of the owner, the author of this paper recorded the vibrations of the ensemble "compressor – foundation – supporting soil". For this stage, the transducer locations are presented in Fig. 3. In all the instrumented locations there were measured velocities, on both horizontal directions (transversal – "T"; longitudinal – "L") and on the vertical one ("V").

The signal analysis was carried out with the DASYLab 5.5 program, the following typical types of analysis having been carried out:

- numerical integration in time domain, obtaining in this manner from the basic signal (velocities) the vibration displacements;
- Fast Fourier Transform (FFT) of the real signal, both for velocities and displacements (Fourier Amplitude Spectra);
- auto-correlation functions (cross-correlation of an input signal with itself), by means of which it is possible to detect an inherent periodicity in the signal itself and to determine the damping ratio;
- computation of maximum displacement values at the top of the foundation.

The time domain representations (velocities and displacements) were performed in view of getting an overall image of the spatial motion of the foundation subjected to dynamic actions.

The Fourier Amplitude Spectra and the auto-correlation functions emphasized the frequency content of the recorded motions, as well as the increase of the dominant compounds. This led to an accurate identification of the natural frequencies of the foundation and of the maximum displacement values at the top of the compressor foundation.

Typical time domain velocities and the corresponding amplitude Fourier spectra are shown in Fig. 4÷Fig. 10.

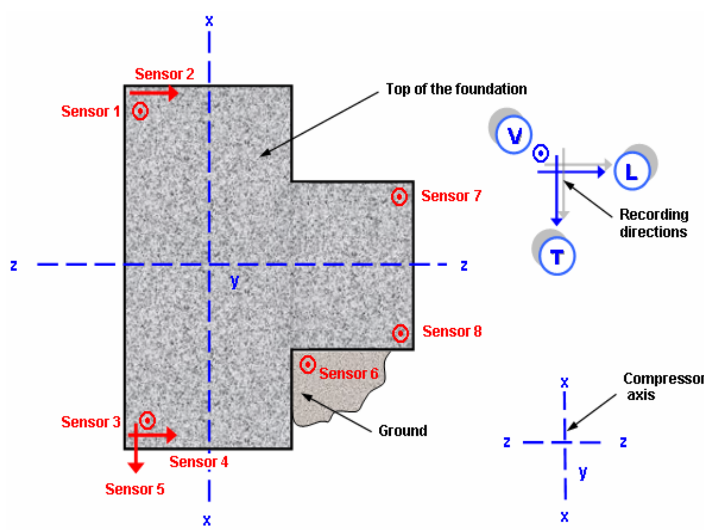


Fig. 3. Location of sensors – Stage I

After performing the program of instrumental investigations for this stage, a set of useful information was obtained.

In Tables 1 are summarized the resulted values, in the case of idle functioning of the compressor, for the direction parallel to the "z" – "z" axis of the compressor.

Table 1

Recording direction	Functioning of the compressor	Measured values			
		v_{max} (μm/s)	f (Hz)	d_{max} (μm)	f (Hz)
Parallel to z – z axis	starting	4158	10.25	71.25	10.25
	"idle"	4225	12.45	60.50	12.45
	stopping	4178	10.25	78.30	10.25

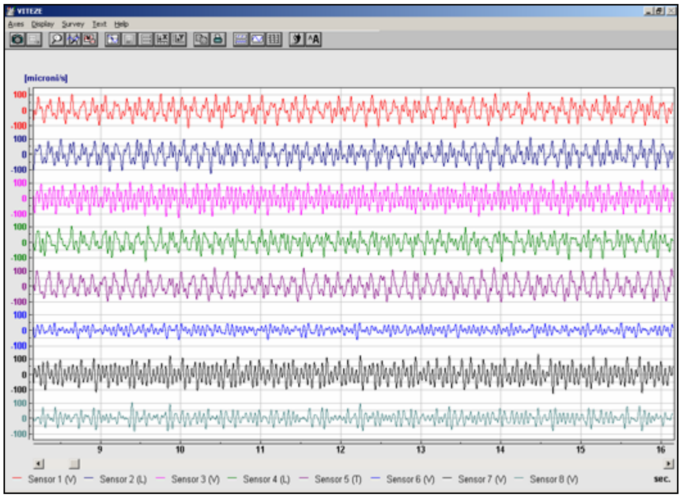


Fig. 4. Ambient vibration data acquisition. Time domain; velocities.

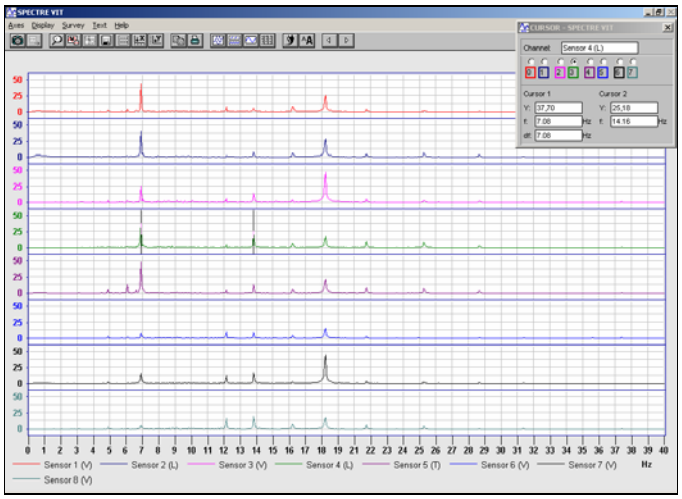


Fig. 5. Ambient vibration data acquisition. Amplitude Fourier spectra; velocities.

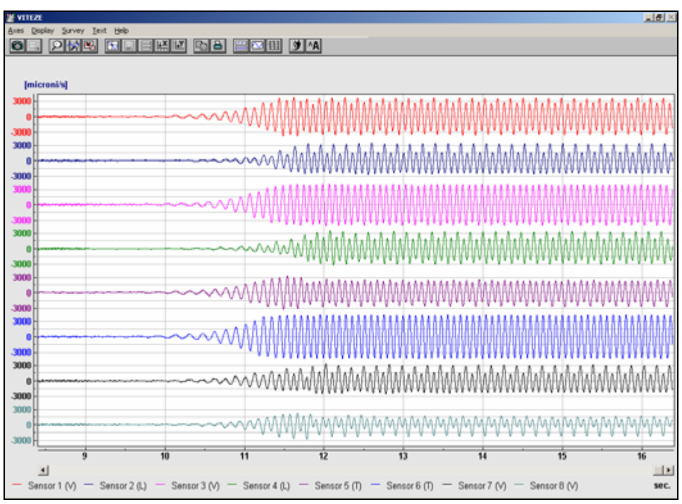


Fig. 6. Functioning of the compressor – starting moment. Time domain; velocities.

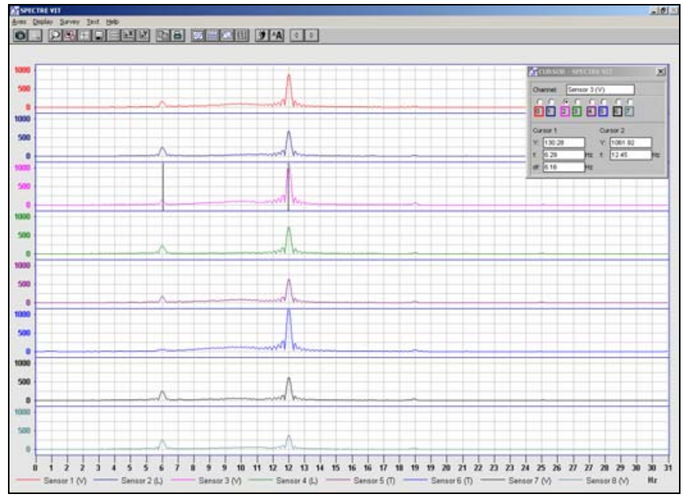


Fig. 7. Functioning of the compressor – starting moment. Amplitude Fourier spectra; velocities.

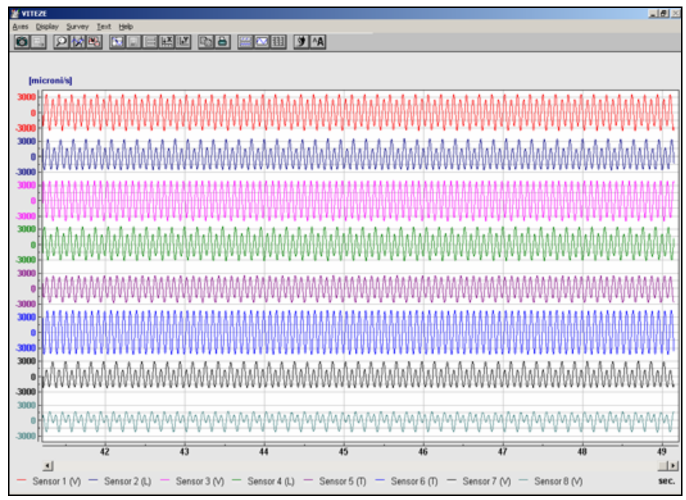


Fig. 8. Functioning of the compressor – idle functioning. Time domain; velocities.

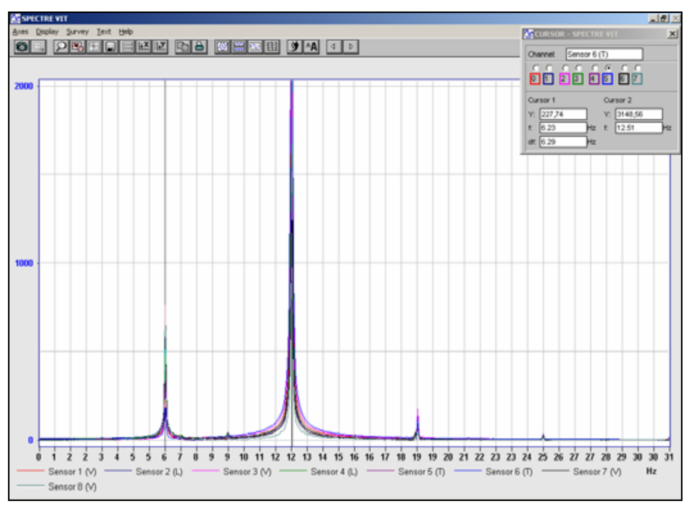
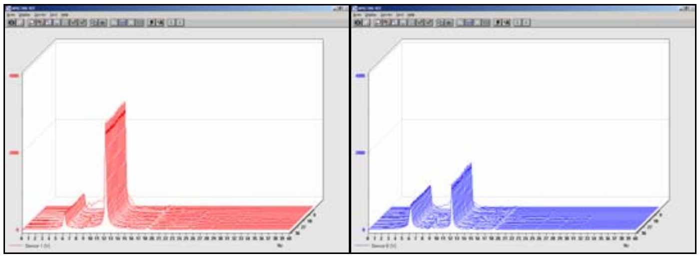


Fig. 9. Functioning of the compressor – idle functioning. Amplitude Fourier spectra; velocities.



(a) (b)

Fig. 10. Functioning of the compressor – idle functioning. Running Fourier spectra; velocities.
(a) – sensor placed on the top of the compressor foundation;
(b) – sensor placed on the ground, at the bottom of the foundation

Some results after performing stage I

1. The manufacturer of the compressor specified the unbalanced forces and moments on the foundation. He provided the following requirements: *the primary unbalanced forces and moments vary from maximum values on one direction to maximum values on the other direction, for each complete rotation of the shaft corresponding to the functioning frequency of the reference compressor operating speed (f_1 = 6.18 Hz; n_1 = 371 rpm); the secondary unbalanced forces and moments vary from maximum values on one direction to maximum values on the other direction (performs this cycle) twice for each rotation of the shaft, at a double functioning frequency of the compressor (f_1 = 12.36 Hz).* The aspect that had to be considered by the designer was that the secondary unbalanced forces and moments occur at the second order frequency of the compressor, equal to 12.36Hz.
2. The rigid foundation of the compressor 06-NK3 was thus designed and resulted "high tuned" with respect to the first operating frequency of the compressor, which was equal to 6.18 Hz (the eigenfrequencies of the ensemble "compressor – foundation – supporting soil" were greater than the first operating frequency of the compressor).
3. The design had to be made in a manner so that the eigenfrequencies of the ensemble "compressor – foundation – supporting soil" are not a whole number multiple of the operating frequency of the compressor, to avoid resonance with higher harmonics. The excessive vibrations observed during the idle functioning of the compressor were the result of the closeness of certain eigenfrequencies of the ensemble to the second order frequency of the compressor.
4. The eigenfrequencies of the ensemble "compressor – foundation – supporting soil" that were identified by measurements were close to the first and second frequency of the exciting force (6.23 Hz and 12.45 Hz). The eigenfrequencies corresponding to coupled translation and rotation vibrations of the dynamic system, taking into account the different sources of vibration already mentioned (ambient vibrations and steady state vibrations), were: 5.0 Hz; 7.08 Hz; 12.45 Hz; 14.16 Hz; 16.60 Hz; 18.70 Hz; 21.25 Hz.
5. The maximum vibration amplitude values obtained were given in Table 1. In comparison to a "peak-to-peak" value of the displacement at the top of the block foundation specified by the compressor's manufacturer, equal to 63.5 microns, after performing the instrumental recordings, a value equal to 121 microns was obtained. So, the "peak-to-peak" amplitude of the motion at the idle operating frequencies exceeded the permissible value.
6. In conclusion, when the instrumental investigations were performed during stage I, a lack of "*frequency calibration*" together with a lack of "*maximum dynamic response calibration*" was highlighted.
7. Remedial measures were proposed, but the owner didn't entirely consider them.

STAGE II: INSTRUMENTAL AND THEORETICAL INVESTIGATIONS

After performing the first set of instrumental investigations the following additional aspects have occurred:

- the change of the soil parameter characteristics on the site of the foundation because of the appearance of water at its bottom;
- the decision of the owner and of the designer to enlarge the footing of the foundation, by casting in place reinforced concrete completions at the two corners of the compressor foundation (modification of spatial geometry of the compressor foundation, Fig. 11).

When performing the instrumental investigations (stage II) the sensors were mounted at the same locations as previously (sensors 1÷8). Two more RANGER seismometers were placed on the extensions of the compressor foundation (sensors 9 and 10, on the vertical direction), as a result of the change of its initial geometrical configuration. Sensors 11 and 12 were placed at a distance of about 40 m from the foundation, on the ground, as shown in Fig. 11.

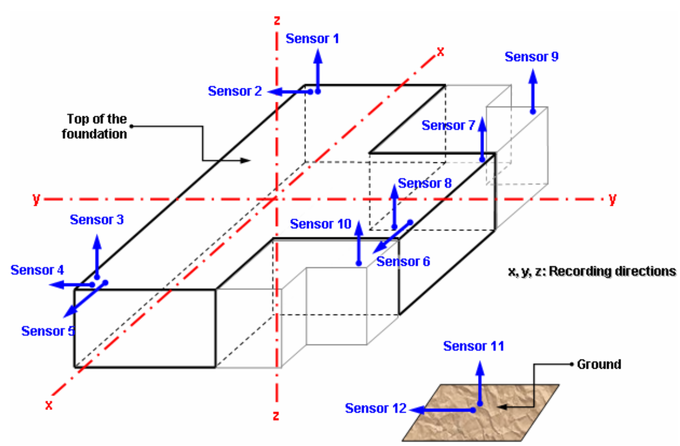


Fig. 11. Location of sensors – Stage II

It was aimed to see the influence of the two reinforced concrete completions on the response of the ensemble “compressor – foundation – supporting soil”.

The same types of analysis as in stage I have been performed. Samples of the time domains and amplitude Fourier spectra are presented in Fig. 12÷15. In Fig. 16 are given the maximum displacement values for all the considered directions at the starting, idle functioning and stopping of the 06-NK3 compressor. Table 2 shows the maximum displacement values corresponding to the frequencies identified by instrumental measurements.

Together with the second stage of the instrumental investigations an analytical study based on these results was performed. The main objectives of this study were:

- finding the characteristics of the foundation motion taking into account its six degrees of freedom, as a result of considering the foundation as a solid rigid body;
- deriving from the motion parameters (associated with the six degrees of freedom) the motions corresponding to the measurement directions, in order to verify the validity of the numerical analysis and to estimate the range of the possible measurement errors;
- obtaining of supplementary information in view of finding an accurate proposal for solving the existing situation.

To obtain useful data there was performed filtering of the recorded signals, on certain bands of frequency. In the case of idle functioning of the compressor, two narrowband filtering procedures in the vicinity of 6.2 Hz and 12.4 Hz were performed. There was also performed a narrowband filtering around 7.08 Hz, frequency corresponding to the functioning of another compressor in the vicinity of the 06-NK3 compressor.

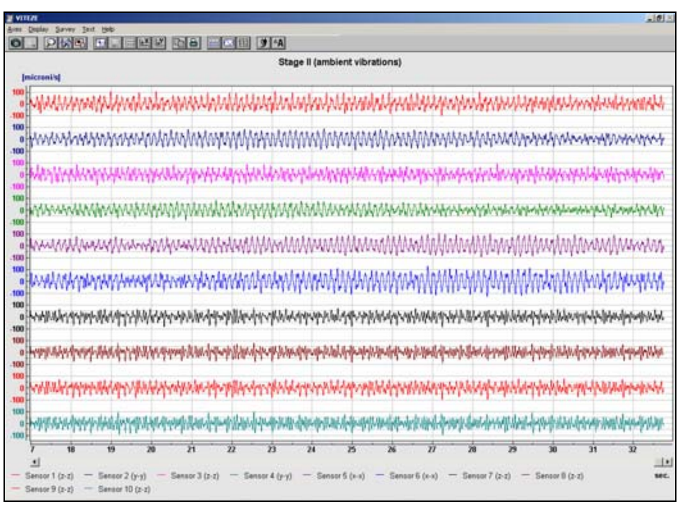


Fig. 12. Stage II - ambient vibration data acquisition. Time domain; velocities.

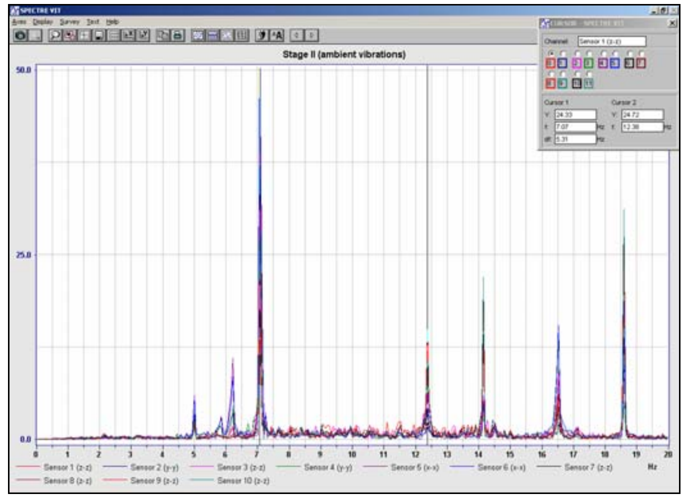


Fig. 13. Stage II – ambient vibration data acquisition. Amplitude Fourier spectra; velocities.

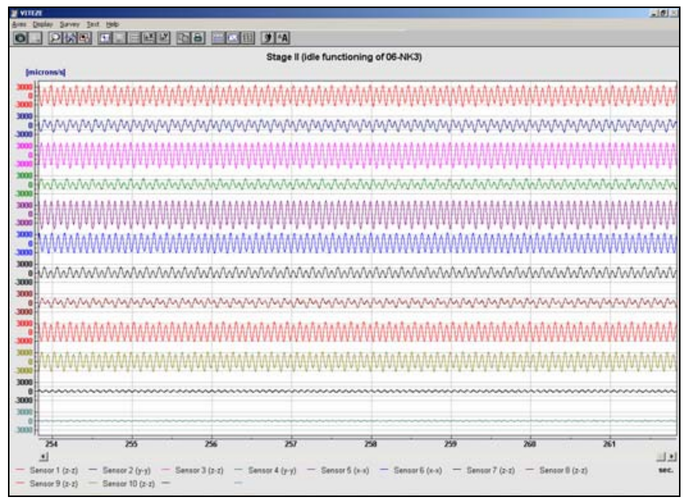


Fig. 14. Stage II – idle functioning of the compressor. Time domain; velocities.

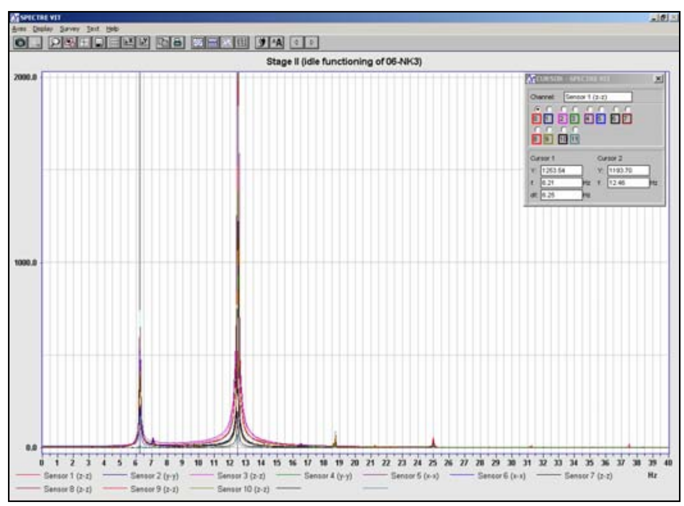


Fig. 15. Stage II – idle functioning of the compressor. Amplitude Fourier spectra; velocities.

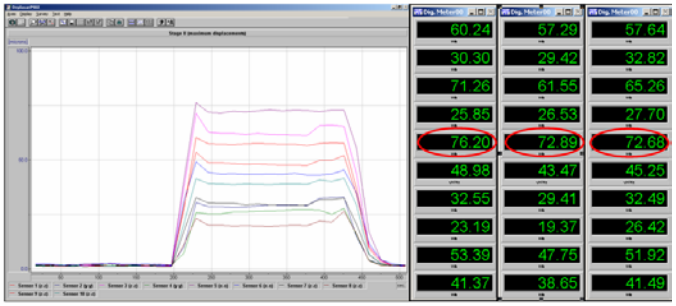


Fig. 16. Stage II – idle functioning of the compressor. Maximum recorded displacement values [microns].

Table 2

Recording direction	Functioning of the compressor	d_{max} (μm)
Parallel to x – x axis	starting	76.20
	“idle”	72.89
	stopping	72.68

METHODOLOGICAL ELEMENTS AND BASIC RELATIONS FOR THE VIBRATION ANALYSIS OF THE ENSEMBLE “EQUIPMENT – FOUNDATION”

General elements

The following developments are concerning the estimate of characteristics of rigid body motion (sinusoidal) for a foundation of industrial equipment. There were two different kinds of disturbances: microtremors and forces applied during the idle functioning of the equipment which applies periodic, almost sinusoidal forces. Motion records were obtained along four points/directions (at two points for the Ox direction and at two points fort the Oy direction, respectively) in the horizontal plane, and along the vertical direction again, at four points. Since it was assumed that the records are affected by some errors, it was decided to derive the amplitudes and phases of motion along the six DOF of the foundation block, idealized as a rigid body, on the basis of a least quadratic error approach. As an explanation, on the vertical direction, the four measurement points lead to data that might imply a slight out-of-plane of the block foundation; the four horizontal components lead to data that might imply a slight slippage deformation in the horizontal plane (Fig. 17 and Fig. 18). Analytical developments in this sense are presented further on. Deterministic and stochastic approaches both were kept in view. Detailed developments are presented for the deterministic approach only, since the stochastic approach leads to non-linear, hard to handle, equations.

As preliminary needed elements the following ones appear to be necessary:

1) Required data

- masses (including the equipment), masses center;
- disturbing forces (application points, directions, phases, amplitudes);
- Fourier analysis of microtremors;
- narrowband filtered oscillations in the vicinity of the spectral peaks (time magnifying glasses in order to observe the phase differences, and ordinates magnifying glasses in order to better understand the amplitudes ratio).

2) Proposed analysis

- identification of the oscillation characteristics for the frequencies corresponding to spectral peaks obtained from the combination of recorded and filtered data (as the recorded data are redundant it appears to be necessary to find the optimal solutions to minimize the quadratic errors);
- comparison elements between the oscillation in idle operation conditions of the compressor, respectively at rest, when motions are determined by industrial noise, and taking into account both stages of the technical assessment (before and after performing the extension of the foundation).

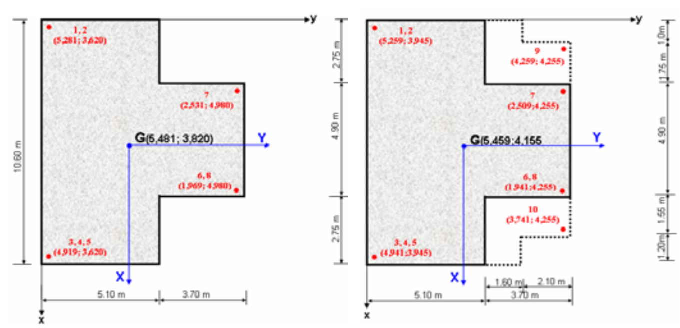


Fig.17. Mass center of the compressor foundation. (a) – stage I; (b) – stage II.

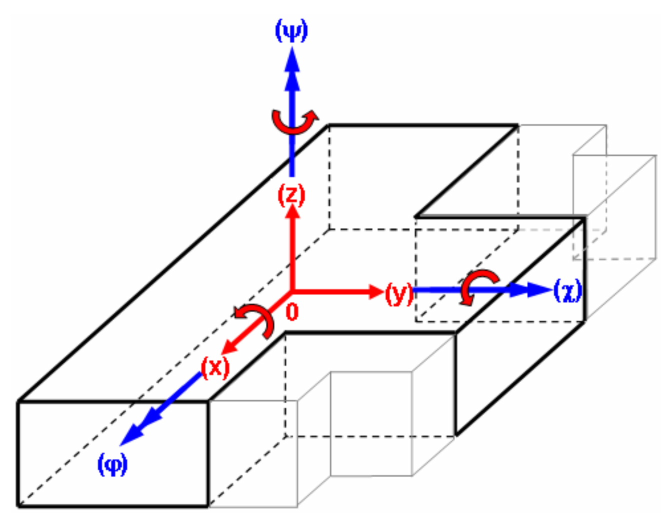


Fig.18. Stage II – system axis

Basic symbols

The following symbols were used:

- φ:: frequency (Hz);
- ω: angular frequency (rad/s);
- $u^*(\omega)$ or $u_k^*(\omega)$: vector of the Fourier amplitudes (complex) of the displacements, along the measuring directions/points (marked with "k" index);
- $v_r^*(\omega)$ or $v_{lr}^*(\omega)$: complex eigenvectors of order "r", corresponding to the adopted general reference system (axes of index "l") and to the angular frequencies ω;
- M: mass matrix of the ensemble "compressor–foundation", considered rigid body;
- $K^*(\omega)$: impedance matrix (complex, variable) corresponding to the soil subsystem, respectively to the soil – foundation interface, related to the two system axis;
- $f^*(\omega)$: vector of the external forces (disturbing).

Motion equations and their solutions

Motion equation (for the complex Fourier images):

$$\left[-\omega^2 M + K^*(\omega)\right] v^*(\omega) = f^*(\omega) \tag{1}$$

The homogeneus equation for the nonclassical problem of eigenvalues (depending upon parameter ω):

$$\left[-\lambda_r^*(\omega) M + K^*(\omega)\right] v_r^*(\omega) = 0 \tag{2}$$

Properties of the eigenvalues solution:

$$v_r^{*T}(\omega) M v_s^*(\omega) = \delta_{rs} \tag{3a}$$

$$v_r^{*T}(\omega) K^*(\omega) v_s^*(\omega) = \left[\lambda_r^*(\omega)\lambda_s^*(\omega)\right]^{1/2} \delta_{rs} \tag{3b}$$

Spectral expansion of the rigidity, impedance and transfer matrices:

$$K^*(\omega) = \sum_r \lambda_r^*(\omega) M v_r^*(\omega) v_r^{*T}(\omega) M \tag{4a}$$

$$Z^*(\omega) = \left[-\omega^2 M + K^*(\omega)\right] = \sum_r \left[-\omega^2 + \lambda_r^*(\omega)\right] M v_r^*(\omega) v_r^{*T}(\omega) M \tag{4b}$$

$$Z^{*(-1)}(\omega) = \left[-\omega^2 M + K^*(\omega)\right]^{(-1)} = \sum_r \left[-\omega^2 + \lambda_r^*(\omega)\right]^{(-1)} v_r^*(\omega) v_r^{*T}(\omega) \tag{4c}$$

Passing from vectors $v^*(\omega)$, or $v_l^*(\omega)$, to vectors $u^*(\omega)$, or $u_k^*(\omega)$:

$$u^*(\omega) = A v^*(\omega), \tag{5a}$$

where "A" is a real, constant, matrix, having kinematic significance, or

$$u_k^*(\omega) = \sum_l a_{kl} v_l^*(\omega), \tag{5b}$$

where a_{kl} are the terms of the matrix "A".

Matrix "A" is rectangular, and the instrumental data are redundant. The system (5b) cannot be solved by the classical method; however the quadratic error sum must be minimized (for each angular frequency ω that corresponds to a spectral peak):

$$\varepsilon_k^*(\omega) = u_k^*(\omega) - \sum_l a_{kl} v_l^*(\omega) \tag{6}$$

The involved vectors are represented with real, as well as imaginary parts (for which the ascertainment of the angular frequency "ω" as argument is abandoned).

$$u_k^* = u_k' + i u_k'' \qquad v_l^* = v_l' + i v_l'' \tag{7}$$

The condition of minimizing the error:

$$E = \sum_k \left|\varepsilon_k^*\right|^2 = \sum_k \left\{ \left[u_k' + i u_k'' - \sum_l a_{kl}\left(v_l'^* + i v_l''^*\right)\right]^2 + \left[u_k' - i u_k'' - \sum_l a_{kl}\left(v_l'^* - i v_l''^*\right)\right]^2 \right\} = min \tag{8}$$

Thus, the annulment conditions for the partial derivatives are:

$$\frac{\partial E}{\partial v_l'^*} = \sum_k \left\{ - a_{kl}\left[u_k' - i u_k'' - \sum_{l'} a_{kl'}\left(v_{l'}'^* - i v_{l'}''^*\right)\right] - a_{kl}\left[u_k' + i u_k'' - \sum_{l'} a_{kl'}\left(v_{l'}' + i v_{l'}''^*\right)\right]\right\} = 0 \tag{9a}$$

$$\frac{\partial E}{\partial v_l''^*} = i \sum_k \left\{ - a_{kl}\left[u_k' - i u_k'' - \sum_{l'} a_{kl'}\left(v_{l'}' - i v_{l'}''^*\right)\right] + a_{kl}\left[u_k' + i u_k'' - \sum_{l'} a_{kl'}\left(v_{l'}'^* + i v_{l'}''^*\right)\right]\right\} = 0 \tag{9b}$$

After reducing the like terms, the following equation system results:

$$\sum_{k,l'} a_{kl} a_{kl'} v_{l'}'^{*} = \sum_{k} a_{kl} u_k' \qquad (10a)$$

$$\sum_{k,l'} a_{kl} a_{kl'} v_{l'}''^{*} = \sum_{k} a_{kl} u_k'' \qquad (10b)$$

from where the solutions $v_{l'}'^{*}(\omega), v_{l'}''^{*}(\omega)$, respectively the complex solutions $v_l^{*}(\omega) = v_l'^{*}(\omega) + i\, v_l''^{*}(\omega)$, are derived, for various angular frequencies "ω" that correspond to certain spectral peaks (it is expected that the different $v_l^{*}(\omega)$ components be out of phase). After finding the solutions of the equation systems (10), the results will be examined in a critical manner, following that certain corrections be accomplished, together with gathering the conclusions regarding the studied dynamic system.

For computation, the auxiliary (symmetrical) matrix $b_{ll'}$ is brought in:

$$b_{ll'} = \sum_{k} a_{kl} a_{kl'} \qquad (11)$$

and its inverse $b_{ll'}^{-1}$, which is as well symmetrical, is also considered. The solution for the equation systems (10) will be:

$$v_l^{*'} = \sum_{kl'} b_{ll'}^{-1} a_{kl'} u_k' = \sum_{k} c_{lk} u_k' \qquad (12a)$$

$$v_l^{*''} = \sum_{kl'} b_{ll'}^{-1} a_{kl'} u_k'' = \sum_{k} c_{lk} u_k'' \qquad (12b)$$

where the matrix $''c_{lk}''$ occurs:

$$c_{lk} = \sum_{l'} b_{ll'}^{-1} a_{kl'} \qquad (13)$$

For checking, the values $u_k^{*'}$ and $u_k^{*''}$ given by the following expressions are computed:

$$u_k^{*'} = \sum_{l} a_{kl} v_l'^{*} \qquad (14a)$$

$$u_k^{*''} = \sum_{l} a_{kl} v_l''^{*} \qquad (14b)$$

The values $u_k^{*'}$ and $u_k^{*''}$ derived from these relations differ from the input homologues values u_k', u_k'', as the experimental input values are redundant and affected by errors, while the solutions $u_k^{*'}$ and $u_k^{*''}$ correspond to computation that had in mind to obtain minimum quadratic errors, based on condition (8). The previous relations are to be used in the following manner:

- the optimal solutions ($v_l^{*'}$, $v_l^{*''}$) are determined based on the relations (12);
- in view of comparing and checking, the measures $u_k^{*'}$, $u_k^{*''}$ are determined by means of relations (14), and further on they are compared with the input measures u_k' , u_k'' .

Using the expressions (12) was easy and led to a quite credible outcome. Checking this outcome by means of the comparison of the outcome by applying the relations (14) against direct experimental data, put to evidence nevertheless non–negligible deviations, due to the possible imperfect idealization of the dynamic system, as well as to measuring errors.

<u>Some conclusions resulted from numerical verifications of instrumental data</u>

(a) It was considered that the adopted methodology is the only one capable to lead to results accurate enough in what concerns the real motion of the ensemble "compressor – foundation", taking into account the uncertainty of the characteristics of the soil beneath the foundation. The design of such foundation taking data from technical literature must be carried out with much care, in order to avoid "after the fact" excessive vibrations.

(b) Studying the motion of the foundation based on the above mentioned methodology, a series of useful information on the nature of the vibrations of the ensemble "compressor – foundation" was obtained.

(c) The results obtained by numerical analysis led to the following remarks:

   - the recorded motions have always a spatial character, non-zero components "v_l" occurring on all six degrees of freedom of the ensemble "compressor – foundation";
   - the spatial character of the recorded motions is more significant at the low frequency spectral components, while at the components with frequencies around 12.5Hz a marked dominant oscillation occurs in the longitudinal-vertical plane (xOz).

(d) By changing the in-plane configuration of the initial foundation, by adding the two lateral wings, it was proved that the measure was not sufficient. Some minor changes in the amplitude of the displacement of the block foundation were observed:

   - for the frequency equal to *6.20 Hz*, on the direction "x – x", the displacement amplitude increased more that twice (from 2.704 μm to 6.483 μm), as shown in Tables 3 and 4; on the "y – y" direction the displacement amplitude decreased to more that half (from 8.044 μm to 3.729 μm), as shown in Tables 3 and 4 ; for the same frequency, the rotation about the vertical axis "z – z" increased its value more than three times (from 0.702 μrad to 2.24 μrad; 1 μrad = 10^{-6} rad). One can state that even though the amplitudes of the motions along the six degrees of freedom have changed in a significant manner, the differences between amplitudes in the points and along the directions of measurements, obtained by instrumental investigations, respectively by numerical analysis, are minor. This fact represents a checking of the validity of the performed computation, as well as of the measured values by means of instrumental investigations.

Table 3 – Initial configuration of the foundation (stage I)

Degrees of freedom	$v_l^{*\prime}$	$v_l^{*\prime\prime}$	v_l^{*0}	$\Delta\alpha_l^*$
1 (x)	2.375	-1.293	**2.704**	-28.571
2 (y)	-6.518	-4.714	**8.044**	215.876
3 (z)	-0.805	1.085	1.351	126.563
4 (φ)	-2.207	-0.628	2.295	195.886
5 (χ)	0.419	-1.111	1.188	-69.328
6 (ψ)	-0.184	0.677	**0.702**	105.226

Table 4 – Modified configuration of the foundation (stage II)

Degrees of freedom	$v_l^{*\prime}$	$v_l^{*\prime\prime}$	v_l^{*0}	$\Delta\alpha_l^*$
1 (x)	5.862	-2.770	**6.483**	-25.291
2 (y)	2.689	2.584	**3.729**	43.852
3 (z)	0.392	0.290	0.488	36.447
4 (φ)	-2.041	-1.036	2.289	206.915
5 (χ)	0.371	-0.725	0.814	-62.9145
6 (ψ)	1.136	-1.931	**2.240**	-59.5385

- for the frequency equal to *12.40 Hz*, as a numerical example shown in Tables 5 and 6, one can emphasize that for component 1 there is no sensitive change in the second stage, for the second component a decrease of about 60% of the initial value is noticed, while for component 4 the decrease is about 50% (from 16.81 μm to 8.08 μm).

Table 5 – Initial configuration of the foundation (stage I)

	u_k'	u_k''	$u_k'^0$	$\Delta\alpha_k$	$u_k^{*\prime}$	$u_k^{*\prime\prime}$	u_k^{*0}	$\Delta\alpha_k^*$
1	18.41	0.00	**18.41**	0.00	18.86	-0.56	18.87	-1.70
2	0.00	15.37	**15.37**	90.00	-7.33	2.76	7.84	159.4
3	-21.21	-6.89	22.30	197.99	-21.67	-6.32	22.57	196.25
4	-2.63	-16.61	**16.81**	261.00	4.70	-3.99	6.17	-40.35
5	-15.21	0.00	15.21	179.99	-6.51	14.96	16.31	113.52
6	12.34	24.22	27.18	63.00	3.64	9.26	9.95	68.54
7	11.80	0.00	11.80	0.00	10.77	1.28	10.86	6.78
8	-8.18	0.00	8.18	179.99	-7.14	-1.29	7.26	190.27

Table 6 – Modified configuration of the foundation (stage II)

	u_k'	u_k''	$u_k'^0$	$\Delta\alpha_k$	$u_k^{*\prime}$	$u_k^{*\prime\prime}$	u_k^{*0}	$\Delta\alpha_k^*$
1	18.43	0.00	**18.43**	0.00	18.25	0.51	18.26	1.59
2	8.12	-4.14	**9.11**	-27.0	8.22	-3.94	9.12	-25.64
3	-23.41	0.00	23.40	179.9	-23.23	-0.51	23.23	181.25
4	-7.68	2.49	**8.08**	161.99	-7.78	2.31	8.12	163.5
5	26.17	8.51	27.52	18.00	26.04	8.27	27.32	17.61
6	13.05	13.05	18.46	45.00	13.18	13.29	18.72	45.24
7	7.72	-2.51	8.12	-18.00	9.83	-1.56	9.95	-9.02
8	-6.14	-1.99	6.46	198.01	-8.27	-2.01	8.51	193.61
9	17.88	0.00	17.88	0.00	16.94	-1.39	16.99	-4.68
10	-16.56	-2.62	16.76	188.99	-15.59	-2.18	15.74	187.99

FINAL CONCLUSIONS

The unsatisfactory behavior of the ensemble "compressor 06-NK3 – foundation – supporting soil" was due to a complex set of factors, each factor's influence being difficult to be quantified.

Aspects regarding the emplacement of the compressor

The emplacement of the compressor 06-NK3 had been chosen in the immediate vicinity of two other compressors in operation, one of them having the same speed of rotation and the other one having a speed of rotation very close to the first one. One can state that the presence of these two compressors has had a certain influence on the unsatisfactory behavior of the new ensemble "compressor 06-NK3 – foundation – supporting soil", due to several potential factors hard to be identified. Among these factors, the following ones can be mentioned:

- the interaction between the three compressor foundations due to vibration transmissibility (reciprocal influences);
- the generation of a "dynamic asymmetry" of the overall "*ensemble of the three compressor foundations – soil medium*", as a result of the presence in the near vicinity of significant masses (masses of the two existing compressor foundations), much more bigger than the mass of the excavated soil for the 06-NK3 foundation; for a more complete understanding it is needed to imagine the fact that if the 06-NK3 compressor foundation would be placed in the middle of a natural soil massive, the behavior conditions to dynamic actions would be much more favorable, ensuring a symmetry in dynamic behavior on any direction;
- the two sets of the performed instrumental investigations put to evidence both spectral peaks and amplifications in the bands of frequency associated to the functioning of the existing ensembles "compressor – foundation – supporting soil".

Aspects regarding the foundation medium

The designer of the 06-NK3 foundation has used a geotechnical study performed at another location, which had as a result inadequate geotechnical information. He hasn't had the necessary data for an accurate evaluation of the behavior of the supporting soil to dynamic actions as well as for the design of the compressor foundation based on dynamic concepts. The coefficients of elasticity of the soil have been taken from literature, not from a well-planned geotechnical site investigation that could have furnished realistic soil properties for the design of the compressor foundation. The excessive vibrations of the new ensemble imposed the necessity of performing geotechnical investigations on the site. These were also incomplete, but new information about the site condition was revealed: excessive humidity, water infiltration, and the presence of different pipes under the compressor foundation. An aspect that still remains unclear is why the above mentioned elements were not remarked and emphasized, or were hidden, during the excavation of the soil for the new foundation.

In conclusion, the designer has used unrealistic soil data for estimating the foundation response. It is important to recognize that without adequate and meaningful data from the site investigation the engineering analysis will be of doubtful value and may even lead to erroneous conclusions. Unfortunately this paper dealt with such a situation.

Aspects regarding the initial design of the foundation

In the design process of the 06-NK3 compressor foundation it couldn't be avoided that the eigenfrequency of the ensemble "compressor – foundation – supporting soil" is a integer number multiple of the operating frequency of the compressor, in order to keep away from resonance with higher harmonics. The excessive vibrations generated by the idle functioning of the compressor (in addition to all the other causes above mentioned) are the result of the approach of some frequencies corresponding to some coupled motions of the ensemble to the second order frequency of the excitation (given by the manufacturer of the compressor), or to other higher order frequencies.

Aspects regarding the instrumental investigation results, after the change of the spatial configuration of the foundation

After performing the instrumental investigation program, a large number of frequencies, corresponding to coupled translation and rotation vibrations of the ensemble "compressor – foundation – supporting soil", to the idle functioning of the compressor and to the operating of the two other compressors placed in the vicinity, have resulted.

The motion amplitudes, expressed in terms of kinematic measures (displacements "0–peak" and not "peak-to-peak"), at starting, idle operation and at stopping of the compressor, have already been specified (in Table 2). It can be noticed that the global value of the motion amplitude, in the case of idle functioning of the compressor, has significantly increased (with about 20%), fact that can be accredited on the much higher closeness of the frequency of the coupled motion of the block foundation ($f_{stage\ II}$ = 10.44Hz, towards $f_{stage\ I}$ = 10.25Hz) to the second order frequency of the excitation ($f_{excitation}$= 12.4Hz). The signal processing of the signal (in stage II) highlighted the fact that the two reinforced concrete extensions have a coupled motion with the initial foundation, information that proved that there was a good connection between the reinforced concrete of the existing block foundation and the one cast in place for the extensions.

A positive effect of the change of the spatial configuration of the compressor foundation (by increasing its footing) was the increasing of the overall damping of the ensemble "compressor – foundation – supporting soil".

In what concerns the vibration transmissibility in the vicinities (more significant in stage II), this was the result of a much stronger coupling of the translation and rotation motions in the plane "xOz" (Fig. 18). Vibrations due to by the compressor idle operation resulted annoying to persons working in an adjoining building.

Remedial measures

The change of the geometrical layout of the compressor foundation, decided exclusively by the designer and the owner, didn't solve the excessive vibration problem. The purpose of the technical assessment by instrumental investigations and checking of the validity of the entire process was to determine which remedial measures were to be taken in order to reduce the foundation's vibration amplitudes to permissible (severe) level given by the manufacturer.

The entire process of investigations led to the following remedial measure, having in mind to obtain a "*dynamic response*" calibration (trying to respect the severe condition given by the manufacturer for an amplitude at the bottom of the foundation equal to 62.5 μm): completely redesign the foundation, process that should have in mind the increase of the total weight of the foundation and whose effect would be the change, in a favorable manner, of the eigencharacteristics of the compressor foundation. The owner completely agreed with the proposed solution and decided to redesign the foundation.

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