11th International Conference on Vibration Problems
Z. Dimitrovová *et al.* (eds.)
Lisbon, Portugal, 9-12 September 2013

SENSITIVITY ANALYSIS OF SOIL-FOUNDATION-MACHINE INTERACTION ON LAYERED SOIL

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Keywords: Soil, Foundation, Machine, Interaction, Probability, Sensitivity, RSM, ANSYS.

Abstract. *This paper deals with the possibility of the sensitivity and probabilistic analysis of the reliability of the machine foundation depending on variability of the soil stiffness, structure geometry and machine operation. During the structural design process, an engineer has to consider problems of the soil-foundation and foundation-machine interaction from the safety, reliability and durability of structure point of view. The simple spring soil model and detailed solid FEM model is considered. The advantages and disadvantages of the deterministic and probabilistic analysis of the machine foundation resistance are discussed. On the example of compressor foundation the affectivity of the probabilistic design methodology was presented. The Response Surface Method (RSM) for the analysis of the compressor foundation reliability was used on program ANSYS. The 151 simulations for five load cases were calculated in the real time on PC. The sensitivity of the machine foundation to the uncertainties of the soil properties due to long-time rotating movement of machine is not negligible for design engineers. The probabilistic analysis gives us more complex information about the soil-foundation-machine interaction as the deterministic analysis.*

1 INTRODUCTION

The seismic load impacts to the building structures and technology as well as to the human comfort [1, 2, 3, 5, 8 to 11]. The requirements to design of the foundation under rotating machines increased due to development of calculation method and computer tools. The Eurocodes and national standard define much of these requirements [6 and 14]. During the structural design process, an engineer has to consider problems of the soil-foundation and foundation-machine interaction in the point of view of the safety, reliability and durability of the structures.

During the structural design process, an engineer has to consider problems of the safety, reliability and durability of machine foundations from the point of view of its planned life cycle. Recent advances and the general accessibility of information technologies and computing techniques give rise to assumptions concerning the wider use of the probabilistic assessment of the reliability of structures through the use of simulation methods [4, 7, 8, 9, 10, 11 and 12]. Much attention should be paid to using the probabilistic approach in an analysis of the reliability of structures [4, 6, 10, 12 and 13].

2 OPTIMAL DESIGN OF THE MACHINE FOUNDATION

From the point of view of Eurocode [6] the engineer-designer has take into account following influences

- Impact of machine vibration to structures
- Impact of machine vibration to the people and operation (mechanic, acoustic, optic)
- Impact of machine vibration to the technology (requirements of manufacturer)

Sensitivity class of the machine or equipment	Characteristics	Limit value for the frequency f	
		a_{max}[mm.s^{-2}] $f < 10$Hz	v_{max}[mm.s^{-1}] $f > 10$Hz
I	High	6,3	0,1
II	Middle	63,0	1,0
II	Low	250,0	4,0
IV	None	>250.0	>4.0

Table 1: Limit values of the machine vibration and the production facilities by STN 730032

On the base of the evaluation of all influences it is necessary to check following assessment:

- criterion of limit state design of structures,
- physiological criterion,
- functionality criterion,

The design forces and displacements are calculated using the harmonic response analysis of the structures for normal and extreme operation. The maximum displacements and velocities must be checked to the criterion of the standards STN 730032 [14] and DIN 4024.

3 SOIL-FOUNDATION INTERACTION

The dynamic response is other in the case of stiff and soft soil [1, 2, 3, 5 and 8] due to soil-foundation interaction effects. There are following aspects:

- Soil move can affect the rotation of foundation about its horizontal axis,
- First period of foundation under soft soil will be longer as in the case of stiff soil,
- Eigenvalues and a participation factors will be different in the case of soft and stiff soil,

- No proportional damping is depend on the radial and reflex damping of soil under foundation and different damping of foundation structure

The consideration of SSI effects is very important. The influence of stiffness and damping characteristic of the soil to the structure are not negligible. There are many ways of mathematical representation of the soil. The soil can be represented by a set of equivalent springs or a continuum.

Mode of Vibration	Mass Ratio B	Damping Coefficient C	Damping Ratio $D = C/\sqrt{K_m}$	Spring Constant K
Vertical $(u_v \equiv u_z)$	$B_v = \frac{1-\nu}{4}\frac{m}{\rho.r_o^3}$	$C_v = \frac{3,4.r_o^2}{1-\nu}\sqrt{\rho.G}$	$D_v = \frac{0,425}{\sqrt{B_v}}$	$K_v = \frac{4Gr_o}{1-\nu}$
Horizontal Sliding $(u_h \equiv u_x, u_y)$	$B_h = \frac{7-8\nu}{32(1-\nu)}\frac{m}{\rho.r_o^3}$	$C_h = \frac{4,6.r_o^2}{2-\nu}\sqrt{\rho.G}$	$D_h = \frac{0,288}{\sqrt{B_h}}$	$K_h = \frac{32(1-\nu)Gr_o}{7-8\nu}$
Rocking $(\varphi_\psi \equiv \varphi_x, \varphi_y)$	$B_\psi = \frac{3(1-\nu)}{4}\frac{I_\psi}{\rho.r_o^5}$	$C_\psi = \frac{0,8.r_o^4}{(1-\nu)(2+B_\psi)}\sqrt{\rho.G}$	$D_\psi = \frac{0,15}{(1+B_\psi)\sqrt{B_\psi}}$	$K_\psi = \frac{8Gr_o^3}{3(1-\nu)}$
Torsional $(\varphi_\theta \equiv \varphi_z)$	$B_\theta = \frac{I_\theta}{\rho.r_o^5}$	$C_\theta = \frac{4.\sqrt{B_\theta}}{1-2B_\theta}\sqrt{\rho.G}$	$D_\theta = \frac{0,5}{1+2B_\theta}$	$K_\theta = \frac{16Gr_o^3}{3}$

m – machine and foundation mass, *G* – shear modulus , ν - Poisson ratio, ρ - unit soil masses, I_ψ - mass moment of inertia around axis of rotation for rocking, I_θ - mass moment of inertia around axis of rotation for torsion, r_o – effective radius, which is

$$r_o = \sqrt{B\frac{L}{\pi}} \text{ for translation,} \quad r_o = \left(\sqrt{B\frac{L^3}{3.\pi}}\right)^{1/2} \text{ for rotation,} \quad r_o = \left(\sqrt{B.L\frac{B^2+L^2}{6.\pi}}\right)^{1/2} \text{ for torsion}$$

where *B* is the width of foundation, *L* – length of foundation

Table 2: Stiffness and damping characteristics of the machine foundation [1].

For FE modelling, it is well known that a narrow domain with fixed boundaries is not likely to represent realistic soil behaviour, whereas a very large domain would result in an increased problem size. It is, therefore, necessary to find an optimum value that reflects the realistic behaviour of soil without significant loss in accuracy.

The embedment of foundation causes the reduction in the amplitudes. This effect could be on account of change in stiffness, change in damping, change in soil mass participation, or their combinations. In the case of the simple soil model the effect of soil-foundation interaction can be considered by the relation in tab. 1.

In the case of the layered soil the effective soil modulus can be determined using the simple 1D model of soil or 3D FEM model of the soil below foundation.

4 PROBABILISTIC AND DETERMINISTIC RELIABILITY METHODS

Most problems concerning the reliability of building structures are defined today as a comparison of two stochastic values, loading effects *E* and the resistance *R,* depending on the variable material and geometric characteristics of the structural element.

The variability of those parameters is characterized by the corresponding functions of the probability density $f_R(r)$ and $f_E(e)$. In the case of a deterministic approach to a design, the deterministic (nominal) attributes of those parameters R_d and E_d are compared.

The deterministic definition of the reliability condition has the form

$$R_d \geq E_d \tag{1}$$

and in the case of the probabilistic approach, it has the form

$$RF = R - E \geq 0 \tag{2}$$

where *RF* is the reliability function, which can be expressed generally as a function of the stochastic parameters X_1, X_2 to X_n, used in the calculation of *R* and *E*.

The various forms of analyses (statistical analysis, sensitivity analysis, probabilistic analysis) can be performed. Most of these methods are based on the integration of Monte Carlo (MC) simulations [10]. Three categories of methods have been presently realized - direct, modified and approximation methods.

The approximation methods (Response Surface Methods) are based on the assumption that it is possible to define the dependency between the variable input and the output data through the approximation functions in the following form:

$$Y = c_o + \sum_{i=1}^{N} c_i X_i + \sum_{i=1}^{N} c_{ii} X_i^2 + \sum_{i=1}^{N-1} \sum_{j>i}^{N} c_{ij} X_i X_j \tag{3}$$

where c_o is the index of the constant member; c_i are the indices of the linear member and c_{ij} the indices of the quadratic member, which are given for predetermined schemes for the optimal distribution of the variables or for using regression analysis after calculating the response [10]. Approximate polynomial coefficients are given from the condition of the error minimum, usually by the "Central Composite Design Sampling" (CCD) method or the "Box-Behnken Matrix Sampling" (BBM) method.

5 MODEL OF MACHINE FOUNDATION

The analysis of the soil-foundation-machine interaction was realized on the case of compressor foundation type 13K401 fy. DEMAG DELAVAL using in the building RAYTHEON Slovnaft Bratislava.

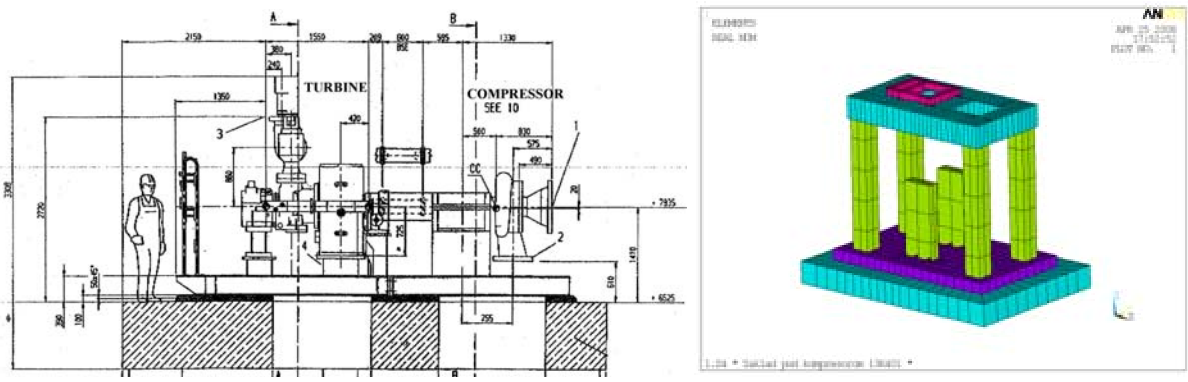

Figure 1: Scheme of compressor 13K401 and foundation FEM model.

Compressor 13K401 (with total masses 5,8t) and turbine GK 22/28 fy. Siemens AG (with total masses 7,5t and pipe system 22t) is put on the reinforced concrete foundation in the form of invert table on the level +6,52m. This structure consists the foundation plate (with dimension 5000x8250x1000mm) on level -1,45m, four columns (with dimension 400x400x5875mm) and horizontal reinforced concrete frame, resp. plate (with dimension 3050x7250x800mm) on level +6,52m. The mass of foundation frame is 192,44t. The subsoil consist the gravel. The material properties were taken from the geophysical test in this locality. We considered three

FEM models Z4L, Z4M and Z4H (with various soil models -low, medium and high). FEM model consist 888 elements (shell, solid, beam) and 1001 nodes.

The comparison of the dynamic characteristics of the subsoil and published values is presented in the table 3. On the base of measured data three soil models – low, medium and high were incorporated in the FEM model. The stiffness of soil has the considerable influence to the modal characteristic and the eigenvalue of entire structure (see table 4).

Soil type	Depth [m]	v_s[m/s]	G_d[MPa]	E_d[MPa]
Clay	1	180-400	54-320	600-1280
Gravel	3	280-300	150-180	670-720
Sand and gravel	2	250-550	90-600	700-2000
Claydstone	14	700-1200	800-2000	2100-5200

Table 3: Material properties of soil

Model		Direction X		Direction Y		Direction Z	
Foundation	Soil	Frequency [Hz]	Prop. ratio [%]	Frequency [Hz]	Prop. ratio [%]	Frequency [Hz]	Prop. ratio [%]
13K401L	Low	15,02	48,9	12,06	53,9	14,66	65,8
13K401M	Medium	18,18	51,7	14,69	55,1	16,47	54,8
13K401H	High	22,04	52,5	17,91	55,4	17,78	41,8

Table 4: Comparison of foundation principal frequencies

The dynamic loads were defined by intensity of forces in the point of anchor and rotation velocity. In the case of normal operation the velocity of turbine (resp. compressor) rotor is equal to 12500 r.p.m (resp. 10998 r.p.m) and for extreme condition the velocity of turbine (resp. compressor) rotor were defined by manufacturer as 4700 r.p.m (resp. 17200 r.p.m).

6 HARMONIC RESPONSE ANALYSIS

The harmonic response analysis solves the time-dependent equations of motion for linear structures undergoing steady-state vibration [2]. The equation of motion for a structural system is defined in the following form

$$[M]\{\ddot{u}\}+[C]\{\dot{u}\}+[K]\{u\}=\{F\} \tag{4}$$

where $[M]$, $[C]$ and $[K]$ are the structural mass, damping and stiffness matrices, $\{\ddot{u}\},\{\dot{u}\}$ and $\{u\}$ are the nodal acceleration, velocity and displacement vectors, $\{F\}$ is applied load vector.

The displacement and applied force vector may be defined in the form

$$\{u\}=\left\{u_{max}e^{i\Phi}\right\}e^{i\Omega t} \quad \text{and} \quad \{F\}=\left\{F_{max}e^{i\Psi}\right\}e^{i\Omega t} \tag{5}$$

where u_{max} and F_{max} are the maximum displacement and force, i – square root of -1, Ω - imposed circular frequency (2πf), f – imposed frequency, t – time, Φ - displacement phase shift, ψ - force phase shift.

Substituting relations (16) into (15) gives

$$\left[[K]-\Omega^2[M]+i\Omega[C]\right]\left(\cos\Phi+i\sin\Phi\right)\{u_{\max}\}=\left(\cos\Psi+i\sin\Psi\right)\{F_{\max}\} \tag{6}$$

where time term $e^{i\Omega t}$ is removed from the left and right side of the equation. The equation may be solved directly as the complex system of the equations.

7 UNCERTAINTIES OF INPUT VARIABLES

The effect of soil-structure interaction can be investigated in the case of probabilistic assessment by sensitivity analysis of the influence of variable properties of soil. A soil stiffness variability in the vertical direction is defined by the characteristic stiffness value k_z from the geological measurement and the variable factor $k_{z.var}$. The random distribution of the soil stiffness under foundation plate is approximated with bilinear function on the slab plane in dependency on three parameters $k_{z.var}$, $k_{xx.var}$, $k_{yy.var}$

$$k(x,y)=\left\{k_{z.var}+2\frac{(x-x_o)}{L_x}k_{yy.var}+2\frac{(y-y_o)}{L_y}k_{xx.var}\right\}k_{z,k} \tag{7}$$

where $k_{z.k}$ is characteristic value of soil stiffness, x_o, y_o are coordinates of foundation structure gravity centre, L_x and L_y are the plane dimensions of the slabs in directions x and y.

The variability of geometric characteristics is defined with $h_{.var}$ (column dimension), $d_{1.var}$ (foundation plate thickness), $d_{2.var}$ (compressor plate thickness).

The stiffness of the structure is determined with the characteristic value of Young's modulus E_k and variable factor e_{var}. A load is taken with characteristic values G_k, F_k, $F_{r.k}$ and variable factors g_{var}, f_{var} and $f_{r.var}$.

The uncertainties of the calculation model are considered by variable model factor θ_R and variable load factor θ_E for Gauss's normal distribution.

Name	Quantity	Charact. value	Variable paramet.	Histogram	Mean	Standard deviation	Min. value	Max. value
Soil	Stiffness	$k_{z,k}$	k_z_var	Uniform	1,085	0,240	0,67	1,5
		$k_{xx,k}$	k_{xx_var}	Uniform	0	0,580	-1	1
		$k_{yy,k}$	k_{yy_var}	Uniform	0	0,580	-1	1
Material	Young's modulus	E_k	e_var	Lognormal	1	0,050	0,868	1,149
Load	Dead	G_k	g_var	Normal	1	0,100	0,719	1,281
	Live - amplitude	F_k	f_var	Lognormal	1	0,100	0,752	1,317
	-frequency	Fr_k	fr_var	Normal	1	0,100	0,719	1,281
Geometric	Height	h_k	h_var	Normal	1	0,050	0,860	1,140
	Thickness	$d1_k$	d1_var	Normal	1	0,010	0,972	1,028
		$d2_k$	d2_var	Normal	1	0,010	0,972	1,028
Model	Model uncertainties	θ_E	Te_var	Normal	1	0,100	0,719	1,281
	Resistance uncert.	θ_R	Tr_var	Normal	1	0,100	0,719	1,281

Table 5: Probabilistic model of input parameters

The results of the probability analysis of the foundation model present that the principal frequencies are variable in the direction X (from 4,32HZ to 6,37Hz), Y (from 13,05HZ to 17,61Hz) and Z (from 16,84HZ to 21,68Hz). These frequency intervals have the important influence to response from the harmonic compressor excitation.

8 RELIABILITY OF THE MACHINE FOUNDATION

Reliability of the foundation structures is analyzed in accordance of national and Eurocode standard requirements [6 and 14] for ultimate and serviceability limit state.

The horizontal reinforced structures are designed on the bending and shear loads for ultimate limit state function (2) in the next form

$$g(M) = 1 - M_E / M_R \geq 0, \qquad g(V) = 1 - V_E / V_R \geq 0 \tag{8}$$

where M_E, V_E are design bending moment and design shear force of the action and M_R, V_R are resistance bending moment and resistance shear force of the structure element.

The vertical plane reinforced concrete structures are designed to the tension or pressure and shear resistance for function of failure [10] in the form

$$g(N) = 1 - N_E / N_R \geq 0, \qquad g(V) = 1 - V_E / V_R \geq 0 \tag{9}$$

where N_E, V_E are normal and shear design forces of action and N_R, V_R are resistance normal and shear forces to unit length.

The serviceability of compressor foundation is limited by maximum displacement amplitude and velocity amplitude in dependency on operation frequency of compressor.

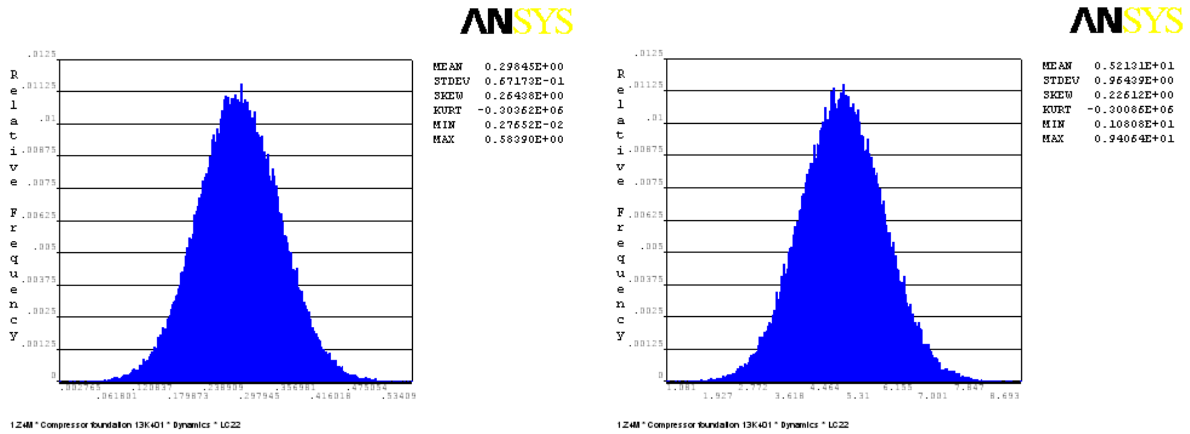

Figure 2: Reliability density function of horizontal and vertical velocity.

The failure function of the amplitude of horizontal displacement u and velocity v is defined in the form

$$g(u) = 1 - u_E / u_R \geq 0, \qquad g(v) = 1 - v_E / v_R \geq 0 \tag{10}$$

where u_E, v_E are maximum amplitude of displacement and velocity from action and u_R, v_R are limit displacement and velocity.

9 SENSITIVITY ANALYSIS

Sensitivity analysis of the influence of the variable input parameters to the reliability of the structures depends on the statistical independency between input and output parameters.

Matrix of correlation coefficients of the input and output parameters is defined by Spearman in the form

$$r_s = \left[\sum_{i=1}^{n} \left(R_i \bar{R} \right) \left(S_i \bar{S} \right) \right] \Bigg/ \left[\sqrt{\sum_{i=1}^{n} \left(R_i \bar{R} \right)^2} \sqrt{\sum_{i=1}^{n} \left(S_i \bar{S} \right)^2} \right] \tag{11}$$

where R_i is rank of input parameters within the set of observations $[x_i]^T$, S_i is rank of output parameters within the set of observations $[y_i]^T$, $\bar{R}, \bar{S}$ are average ranks of the parameters R_i and S_i respectively.

The results of the sensitivity analysis of the vertical displacement of the compressor foundation are presented in the Fig.3. Variability of three input quantities (velocity of the turbine rotor, load amplitudes, foundation mass and stiffness) is important to the displacement of compressor foundation due to normal performance of rotor. In the case of extreme loads the variability of the five input quantities (velocity of the turbine rotor, soil stiffness, foundation dimension and mass, structure stiffness, and load amplitudes) is important to the displacement of compressor foundation.

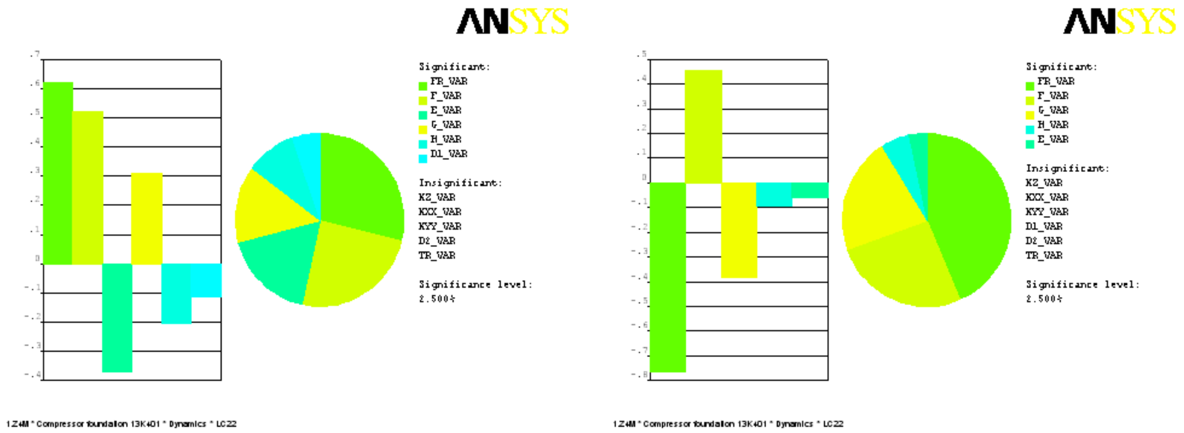

Figure 3: Sensitivity analysis of the horizontal and vertical displacement for compressor impact.

The frequency of rotor movement is lower in the case of extreme performance than the normal performance. It is the reason of the higher sensitivity of foundation to the variability of material and geometry input parameters. The sensitivity analysis gives the valuable information about the influence of uncertainties of input variables (load, material, and model) to engineer for optimal design of the structures.

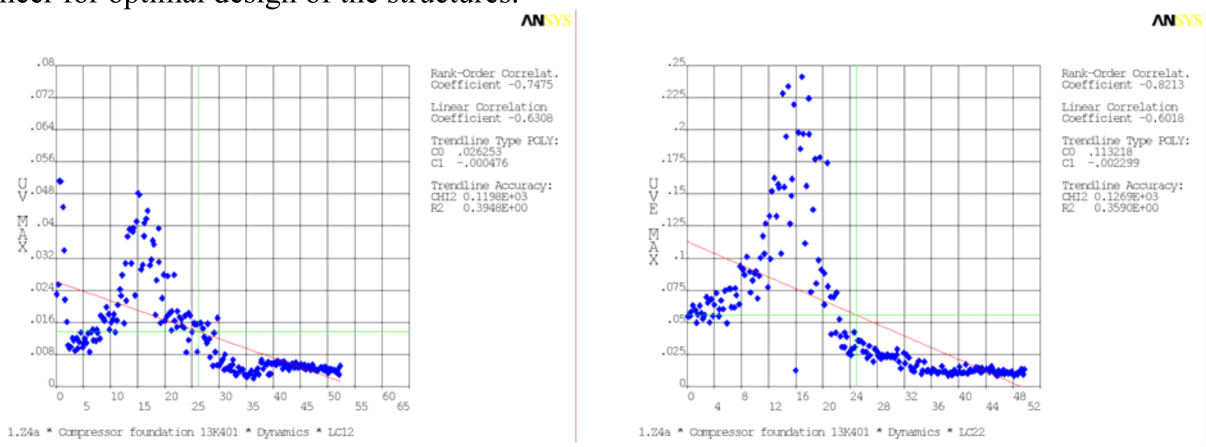

Figure 4: Sensitivity analysis of the vertical displacement through frequency for normal and extreme performance

The sensitivity of the vertical displacement over the compressor operation frequencies is demonstrated in the Fig.4a for normal performance and in the Fig.4b for the extreme performance. The horizontal displacements of the compressor foundation are higher for the lower frequency as 5Hz. In the case of vertical displacements their peaks are about the frequency 15Hz for both performances normal and extreme (Fig.4).

10 COMPARISON OF DETERMINISTIC AND PROBABILISTIC ANALYSES

The comparison of deterministic and probabilistic solution of the safety and reliability of the compressor foundation is documented in the table 6.

The differences between deterministic and probabilistic results are equal about to 5-33% (or 50-100%) for mean (or maximum) displacement amplitude values. In the case of normal forces and bending moment these differences are lower.

Method	Model	Maximum displacement amplitude [mm]				Maximum velocity amplitude [mm/s]			
		$P_{0.05}$	$P_{0.95}$	$P_{0.50}$	St.dev	$P_{0.05}$	$P_{0.95}$	$P_{0.50}$	St.dev
Normal operation of turbine and compressor									
Deterministic	Z4L	-	0.09220	-	-	-	1.08290	-	-
Probabilistic		0.06113	0.18119	0.12110	0.03651	0.56067	1.69163	1.12545	0.34365
Deterministic	Z4M	-	0.07874	-	-	-	1.68280	-	-
Probabilistic		0.05685	0.11783	0.08719	0.01855	0.67532	2.59868	1.63442	0.58289
Deterministic	Z4H	-	0.07357	-	-	-	1.49000	-	-
Probabilistic		0.05425	0.10153	0.07767	0.01439	1.32758	1.90912	1.60778	0.17649
Extreme operation of turbine and compressor									
		Maximum normal force [kN]				Maximum bending moment[kNm]			
Deterministic	Z4L	-	215.18	-	-	-	258.50	-	-
Probabilistic		180.30	256.90	218.47	23.27	216.50	308.85	262.62	28.05
Deterministic	Z4M	-	213.72	-	-	-	256.67	-	-
Probabilistic		179.30	250.42	214.77	21.62	215.54	300.49	257.95	25.79
Deterministic	Z4H	-	213.16	-	-	-	255.94	-	-
Probabilistic		178.74	248.77	213.69	21.26	215.00	298.28	256.58	24.27

Table 6: Comparison of deterministic and probabilistic analyses.

11 CONCLUSIONS

This paper deals with the possibility of the sensitivity and probabilistic analysis of the reliability of the machine foundation depending on variability of the soil stiffness, structure geometry and machine operation. The optimal design of the machine foundation pursues the minimization of the dynamic effects of the machine to the structure. The sensitivity of the machine foundation to the uncertainties of the soil properties due to long-time rotating movement of machine is not negligible for design engineers. On the example of foundation of compressor 13K401 and turbine GK22/28 fy. SIEMENS AG the affectivity of the probabilistic design methodology was presented. The simulation method RSM for the analysis of the compressor foundation reliability was used on program ANSYS. The 151 simulations for five load cases were calculated in the real time on PC (CPU=626sec). The differences between deterministic and probabilistic results are equal about to 5-33% (or 50-100%) for mean (or maximum) displacement amplitude values. The probabilistic analysis gives us more complex information about the soil-foundation-machine interaction than the deterministic analysis.

Acknowledgement

The project was realized with the financial support of the Grant Agency of the Slovak Republic. The project registration number is VEGA 1/1039/12.

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