STRUCTURES & FOUNDATIONS SUPPORTING VIBRATING MACHINES

Case study: Pile cap supporting a reciprocating machine

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ABSTRACT

Foundations and structures supporting vibrating machines require a specific design in order to minimize the negative effects of vibrations. The performance (as well as safety and stability) of machines depend largely on their design, manufacturing and ultimately on the interaction with the environment. Therefore, machine foundations shall be designed in such a way that the dynamic forces caused by the machines are transmitted to the soil through the foundation avoiding all kinds of harmful effects. Risk mitigation of excessive vibrations foresees the control of the frequency and amplitude of the machine vibrations. The source of excitation, in this case mechanical vibration, should be properly characterized, regarding operating speed, magnitude of the dynamic forces and nature of the excitation. It's up to the design engineer to evaluate, in line with the machine design parameters and the geotechnical context at the location of the machine foundation, the best design to avoid excessive vibration, beyond the limits of acceptance. Limits of acceptance are properly defined, either by national standards, suppliers of equipment and ultimately, good practice. Such guidelines impose boundaries to avoid any damage of the machine and any of its components as well as people discomfort.

1 CASE STUDY – PILE CAP SUPPORTING A RECIPROCATING MACHINE

In order to better understand the approach for design of foundations supporting vibrating machines, a case study is presented. The object of analysis and design is a foundation supporting a reciprocating machine. A driver – electrical engine, a driven machine (compressor) and a coupling device compose the machine. The poor local soil resistance characteristics demand the consideration of a foundation supported on piles.

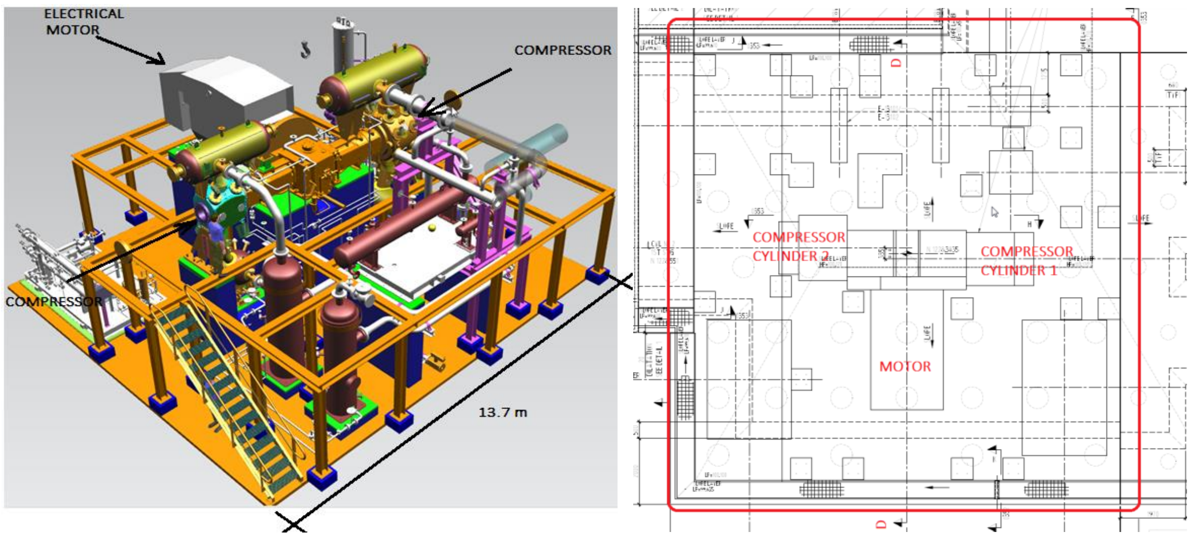

Figure 1 –a) Layout arrangement – Reciprocating machine, Compressor – 3D View; b) Planview – Geometry definition of pile cap and equipment plinths

1.1 GEOTECHNICAL CONSIDERATIONS

In order to define the pile impedances, certain local geotechnical parameters need to be determined based on in situ tests. In this case a Seismic Cone Penetration Test (SCPT) was performed at the piling location. The following results were obtained regarding the parameter *Vs*, shear wave velocity. Other parameters such as the soil density and Poisson ratio were assessed by other means.

Table 1-1 – Parameters determined by Soil Investigation –SCPT & Parameters computed to determine the dynamic impedances

Parameters determined by Soil Investigation - SCPT					Parameters computed to determine the dynamic impedances				
		V_S	ρ	G_{max}	h_i/v_i	$\Sigma h_i/v_i$	ρ_{avg}	$V_{s\ avg}$	$G_{max\ avg}$
depth	depth	shear wave velocity	soil density	dynamic shear modulus			average soil density	average shear wave velocity	average dynamic shear modulus
[m] mv	[m] TAW	[m/s]	[t/m3]	[MPa]			[t/m3]	[m/s]	[MPa]
1,5	0,2	97	1,6	15,1	0,002	0,002			
9,5	-7,8	191	1,7	63,5	0,003	0,072	1,8	111,42	22,5
17,5	**-15,8**	**411**	**2,1**	**357,0**	**0,001**	**0,098**	**1,9**	**163,35**	**50,7**

The shear wave velocity, V_S, and Dynamic Shear Modulus, G_{max}, for a certain depth/pile length were determined according to the following expressions:

$$^{1}V_{S,16} = \frac{L}{\sum_{i=1}^{N} \frac{h_i}{V_i}} = \frac{16}{0,098} = 163,35\ m/s \quad (1\text{-}1)$$

$$G_{\max 16} = \rho_{L\ avg} V_{s,L}^2 = 1,9 * 163,35^2 = 50,7\text{MPa} \quad (1\text{-}2)$$

The definition of the length of the pile was done according to resistance and stiffness requirements. The later was more decisive in the choice of reaching deeper soil layers.

1.1.1 MACHINE PARAMETERS AND UNBALANCED FORCES

Most of the machine parameters are indicated by the compressor manufacturer. The following information is provided:

- General arrangement drawings of all the equipment, indicating self-weight and operation weight, position of the center of gravity, layout of hold down anchor bolts;
- Static loading diagram with all the equipment mass and relative distance to a reference point;
- The dynamic forces resultant from the operation of the compressor (steady-state excitation);
- Frequency of operation of the compressor and motor;
- Power and rotor weight of the motor.

Based on the information provided the dynamic forces are computed and then included in the detailed dynamic analysis – in this case a finite element analysis (in the time domain). The following information (relevant for the dynamic analysis) is provided by the equipment manufacturer:

[1] Expression from Eurocode 8 - average shear wave velocity $v_{s},30$ (for 30 m depth) - adapted for the pile length

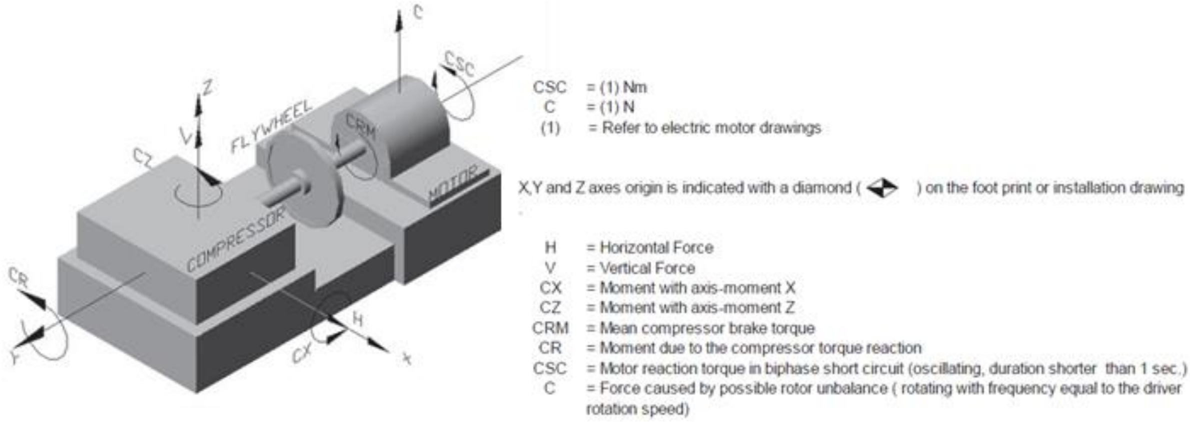

Figure 2 – Manufacturer input – Dynamic and Static forces due to operation and emergency shutdown of the machine

1.1.2 DYNAMIC FORCES - UNBALANCED FORCES AND MOMENTS

The dynamic forces shown in Figure 2 characterize the rotating and oscillatory motion of the steady-state excitation generated by the reciprocating machine (compressor). The primary forces (or of 1st order) are due to the rotating motion and have the same frequency of operation as the driver/compressor. On the other hand, the secondary forces (or of 2nd order) are due to the oscillatory (or reciprocating) motion of the piston.

Table 1-2 – Dynamic forces (unbalanced forces) due to operation of the reciprocating machine (steady-state excitation)

Unbalanced Forces, F_x (H)		Unbalanced Forces, F_z (V)		Unbalanced Moment, M_z (Cz)		Unbalanced Moment, M_x (Cx)	
1st Order	2nd Order	1st Order	2nd Order	1st Order	2nd Order	1st Order	2nd Order
F_x = 19.07 * cos(ωt -180) kN	F_x = 4.09 * cos(2ωt - 0,01) kN	F_z = 0.70 * cos(ωt - 0,01) kN	F_z = 0 * cos(2ωt-0), kN	M_z = 55.69 *cos(ωt - 180) kNm	M_z = 12.87 *cos(2ωt - 0) kNm	M_x = 4.35 *cos(ωt -90) kNm	M_x = 0 *cos(2ωt -0) kNm

The motor unbalanced force caused by possible rotor unbalance (rotating with frequency equal to the driver rotation speed) is defined assuming the mass of the rotor, an eccentricity (mass unbalance) corresponding to a balance quality grade G16 (eω = 16 mm/s) and a Service Factor equal to 2:

$$F = \frac{m_r Q \omega S_f}{1000} = \left(5081 * 16 * \frac{370}{60} * 2\pi * 2\right)/1000 = 6,30\ kN \qquad (1\text{-}3)$$

$$F_z = 6.30 * \cos(\omega t)\ (kN) \qquad (1\text{-}4)$$

1.1.3 DYNAMIC FORCES – TORQUE LOAD VARIATIONS

Since the drive mechanism is non-integral (electric motor), it produces a net external drive torque on the driven machine. The torque is equal in magnitude and opposite in direction on the driver and driven machine. The following values define the moment due to the compressor torque reaction varying in time according to the manufacturer's input:

Table 1-3 – Dynamic forces (Moment) due to the compressor torque reaction

Moment due to the compressor torque reaction (CR)					
My = 4.51 *cos(ωt -139.3), kN-m	My = 18.59 *cos(2ωt +157.1), kN-m	My = 3.53 *cos(3ωt +66.6), kN-m	My = 7.55 *cos(4ωt +166.7), kN-m	My = 2.81 *cos(5ωt -20.4), kN-m	My = 2.07 *cos(6ωt -39.1), kN-m

On the other hand, the motor develops a torque moment (also called drive torque) as defined below:

$$NT = \frac{9550P_S}{f} = \frac{9550 * 990}{370} = 25{,}552\ kNm \quad (1\text{-}5)$$

Considering: *NT*, normal torque (kNm); *PS*, power being transmitted by the shaft at the connection (kilowatts) and *f*, operating speed (rpm). The drive torque moment has opposite direction regarding the torque moment developed in the compressor.

$$My = 25.55 * \cos(\omega t)\ (kNm) \quad (1\text{-}6)$$

1.1.4 SHORT CIRCUIT FORCES

Short circuit in motors causes short circuit forces of a considerable magnitude. It should only be considered for strength design not being considered for the dynamic analysis.

1.1.5 PRELIMINARY DESIGN

Based on the layout operation requirements, the machine characteristics regarding mass and its distribution and the *in situ* geotechnical characteristics a first attempt is performed to define the foundation geometry. The soil stratigraphy at the location of this equipment is of poor resistance to allow direct foundations. Thus, deep foundations (piles) are defined. According to the rules of thumb, the mass of the pile cap for a reciprocating machine shall be at least four times the mass of the reciprocating machine. At the same time, the length and width of the foundation and the piling layout is defined such that the combined center of gravity of the foundation-machine system coincides with the center of stiffness of the pile group with a margin of 5%. A minimum width/length in plan of at least 1.5 times the vertical distance from the machine centerline to the bottom of the foundation block is considered for the plan dimensions. Besides the above stated rules, care is taken in the definition of the piling layout and pile diameter in such a way that 50% of the pile capacity is not exceeded in static design conditions, allowing low pile stresses. The thickness of the pile cap is defined such that the piles are properly anchored to the pile cap. The pile cap is kept isolated from the remaining production unit by an expansion joint of 30 mm, avoiding any propagation of vibration to the surrounding equipment. Considering the type of machine (reciprocating) and the operation speed, the foundation is defined such that its frequency is considerably above the excitation frequency. Therefore, the pile cap is over-tuned regarding the vibrating machine. Considering the operation speed of the machine, isolation is not desirable. The ratio of mass of the foundation to the mass of the machine is higher than the minimum good practice values and therefore is not object of concern. This results from the enlargement of the foundation in plan due to operation requirements. The pile cap is defined with a geometry of 12.9m by 13.7 m and 1.5m thickness. Thirty-six piles are disposed within this area with minimum spacing of $3*\Phi_{pile}$. A pile diameter bigger than 660 mm is defined according to stiffness requirements.

1.2 PILE IMPEDANCES (STIFFNESS AND DASHPOT)

The definition of the pile impedances in this case study is done following the approximate procedures developed by Novak [7]. Despite being an approach where both spring and damping constants are frequency dependent, simplified expressions were developed as well by Novak [7], that under certain conditions, are frequency independent. Since this case study fits in that domain of validity, decision is taken to use those expressions, for simplicity. Few aspects are considered for the computation of the impedances:

- The shear dynamic modulus is diminished in about 30% for the computation of the impedances for horizontal motion;
- Torsional stiffness is disregarded according to Arya, O'Neill, Pincus [8] : "*torsional moments applied to the structure are resisted almost completely by couples produced by lateral reactions at the pile heads*";
- Impedances due to the pile cap embedment are considered for vertical, horizontal and rocking motion;
- Pile group interaction is considered using static interaction coefficients, referenced by Arya, O'Neill, Pincus [8] and developed by Poulos [16]. According to ACI 351-3R [4] "*If the dimensionless frequency a_0< 0.1 (…) then this approach should provide a reasonable estimate of pile group stiffness*." – about the static interaction coefficients;
- Group Interaction factors are not considered for rocking motion according to Arya, O'Neill, Pincus [8]: "*group action for rocking motion is not as prevalent as in the translational modes*";
- Horizontal motion and rocking motion are defined for one direction of motion and for the smaller plan dimension (conservative assumption) for simplicity (the pile cap is close to a square shape and the center of stiffness of the pile group is almost coincident with the center of gravity of the pile cap);
- Piles are considered as end bearing piles for computation of vertical stiffness; according to geotechnical design: 70% tip resistance and 30% friction resistance (shaft). As per Arya, O'Neill, Pincus [8]: if combined friction and end bearing piles, fixed tip piles impedance factors apply;
- Piles are considered flexible, for computation of pile group interaction factors for horizontal motion.

The following geotechnical, machine and foundation parameters are used for the calculation of the impedances.

Table 1-4 – Foundation parameters (Pile and Pile Cap) for computation of impedances (stiffness and dashpot)

Foundation parameters - Pile			
Pile length	L_p	16	m
Pile diameter	Φ_{Pile}	660	mm
r_0 - equivalent pile radius	L_p/r_0	48,48	OK - L_p/r_0>25
Young modulus of the pile material	E_p	35,9	GPa
Specific weight of the pile material	γ_p	25,00	kN/m^3
Compression wave velocity in pile	V_C	3751,45	m/s
Poisson's ratio of the pile material	μ_p	0,20	
	Piles subjected to vertical vibration	end-bearing piles	
	Piles subjected to horizontal motion	flexible piles	
Foundation parameters - Pile Cap			
Longitudinal development in x	Lx	12,9	m
Longitudinal development in y	Ly	13,7	m
Area of pile cap	A	177	m^2
Young modulus of the cap material	E	35,9	GPa
Mass of pile cap and plinths	$m_{pile\ cap\&plinths}$	967,39	ton
Equivalent radius of the pile cap	r_0	7,50	m
	x_r	6,57	m
	z_c	1,38	m
	Nr Piles	36	
Backfill	G_s	18000	kPa
Specific weight of the backfill	γ_s	18	kN/m^3
Height of embedment	D_f	0,75	m

Table 1-5 – Machine parameters for computation of impedances (stiffness and dashpot)

Machine Parameters			
	operating speed	370	rpm
Operating frequency	f	6,2	Hz
operation frequency of the machine	$\omega=2\pi f$	38,75	rad/s
dimensionless frequency parameter	a_0	0,0783	OK - $0,05>a_0>0,8$
Mass of the machine	$m_{machine}$	74,69	ton

Table 1-6 – Geotechnical parameters for computation of impedances (stiffness and dashpot)

Geotechnical parameters			
Density of soil	ρ	1,900	$kN.s^2/m^4$
Soil Poisson's ratio	μ_s	0,3	
Dynamic shear modulus	G_{max}	50707	kPa
Shear wave velocity	V_s	163,35	m/s

Table 1-7 – Foundation-Machine parameters for computation of impedances (stiffness and dashpot)

Foundation-Machine parameters	
V_s/V_p	0,044
γ_s/γ_p	0,75
E_p/G	707,517
$m_c=m_{machine}+m_{pile\ cap}=$	1042,078 ton

Following Arya, O'Neill, Pincus [8], the pile impedances are computed using the parameters defined in Table 1-4, Table 1-5, Table 1-6 and Table 1-7:

Table 1-8 – Pile impedances – Single pile: Stiffness and damping (after Novak (1974) [7])

Motion	Spring K_i^1		Damping c_i^1	
Vertical	$K_z^1 = \frac{E_p A}{r_0} f_{18,1} =$	1270,934 MN/m	$c_z^1 = \frac{E_p A}{V_s} f_{18,2} =$	3,261 MN.s/m
Horizontal	$K_x^1 = \frac{E_p I}{r_0^3} f_{11,1} =$	282,788 MN/m	$c_x^1 = \frac{E_p I}{r_0^2 V_s} f_{11,2} =$	1,378 MN.s/m
Rocking	$K_\varphi^1 = \frac{E_p I}{r_0} f_{7,1} =$	415,592 MN.m/rad	$c_\varphi^1 = \frac{E_p I}{V_s} f_{7,2} =$	0,592 MN.m.s/rad
Cross-stiffness/damping	$K_{x\varphi}^1 = \frac{E_p I}{r_0^2} f_{9,1} =$	-259,211 MN/rad	$c_{x\varphi}^1 = \frac{E_p I}{r_0 V_s} f_{9,2} =$	-0,762 MN.s/rad

Table 1-9 – Embedded cap Impedance: Stiffness and damping (after Novak and Beredugo [13])

Motion	Spring K_i^f		Damping c_i^f	
Vertical	$K_z^f = G_s D_f \overline{S_1} =$	36,450 MN/m	$c_z^f = D_f r_0 \sqrt{G_s \gamma_s / g}\, \overline{S_2} =$	6,850 MN.s/m
Horizontal	$K_x^f = G_s D_f \overline{S_{u1}} =$	54,450 MN/m	$c_x^f = D_f r_0 \sqrt{G_s \gamma_s / g}\, \overline{S_{u2}} =$	9,816 MN.s/m
Rocking	$K_\varphi^f = G_s r_0^2 D_f \overline{S_{\varphi 1}} + G_s r_0^2 D_f [(\delta^2/3) + (z_c/r_0)^2 - \delta(z_c/r_0)] \overline{S_{u1}} =$	1967,375 MN.m/rad		
	$c_\varphi^f = \delta r_0^4 \sqrt{G_s \gamma_s / g} \{ \overline{S_{\varphi 2}} + [(\delta^2/3) + (z_c/r_0)^2 - \delta(z_c/r_0)] \overline{S_{u2}} \} =$	115,930 MN.m.s/rad		

The pile group interaction is considered according to the static solution of Poulos [16], for vertical and horizontal motion. In both cases an interaction factor is calculated assuming any of the 36 piles as reference pile. The average value of the interaction factor is considered for the computation of the pile group stiffness (corner piles and side piles have less stiffness/damping reduction (interaction)).

With: α_{Aj}, the interaction factor for vertical motion describing the contribution of the jth pile to the displacement of the reference pile (that is, α_1 =1); α_{Lj}, the interaction factor for horizontal motion describing the contribution of the jth pile to the displacement of the reference pile (that is, α_{L1} =1). The values of the pile group impedances are determined assuming the average static interaction factors defined in Table 1-10:

Table 1-10 – Pile group static interaction factors for vertical and horizontal motion

Total nr of piles	36		
Reference Pile	$\Sigma\alpha_A$	$\Sigma\alpha_{Lx}$	$\Sigma\alpha_{Ly}$
Σ	437,62	126,03	127,34
Average	**12,16**	**3,50**	**3,54**

Table 1-11 – Pile group impedances for vertical and horizontal motion: stiffness and damping

Motion	Spring K_i^G	Damping c_i^G
Vertical	$K_z^G = \frac{\sum_1^N K_z^1}{\sum_1^N \alpha_r} + G_s\, D_f \bar{S_1} =$ 3800,255 MN/m	$c_z^G = \frac{\sum_1^N c_z^1}{\sum_1^N \sqrt{\alpha_r}} + D_f\, r_0 \sqrt{G_s \gamma_s / g}\, \overline{S_2} =$ 16,507 MN.s/m
Horizontal	$K_x^G = \frac{\sum_1^N K_x^1}{\sum_1^N \alpha_L} + G_s\, D_f \overline{S_{u1}} =$ 2932,570 MN/m	$c_x^G = \frac{\sum_1^N c_x^1}{\sum_1^N \sqrt{\alpha_L}} + D_f r_0 \sqrt{G_s \gamma_s / g}\, \overline{S_{u2}} =$ 23,844 MN.s/m

As stated previously, pile group interaction is not considered for the rocking motion. The individual stiffness and damping are assigned for the individual piles. For vertical and horizontal motion, the values calculated in Table 1-11 are divided by the number of piles and assigned to the viscous dampers supports of the FEA.

1.3 DETAILED ANALYSIS (FEA) AND RESULTS

A detailed dynamic analysis is performed by means of a finite element analysis. The software used for this calculation is Robot Structural Analysis from Autodesk. The finite element analysis is done resorting to solid finite elements (cuboid elements, in particular) to facilitate the inclusion of eccentricities resulting from the large thicknesses of the structural elements. Solid finite elements have only translation degrees of freedom. Restraining rotation or modelling rotation stiffness requires the definition of rigid links or fictitious rigid bars, connecting at least 3 non-collinear nodes of the solid and subsequent application of rotation stiffness to the master node of the rigid link (or a selected node of the fictitious bars). The solid finite elements dimensions are limited to 0,50 m per face. The mass and stiffness are correctly distributed according to the geometry of the pile cap. Following the recommendation from ACI 351 3R [4] the concrete is defined with a modified modulus of elasticity. Thus, a higher dynamic modulus of elasticity is used, instead of the static modulus of elasticity following a formula from ACI 318. The piles are defined as elastic viscous-damper supports. The impedance (stiffness and dashpot) is defined in 1.2 and is modelled at the pile head connected to the pile cap. The

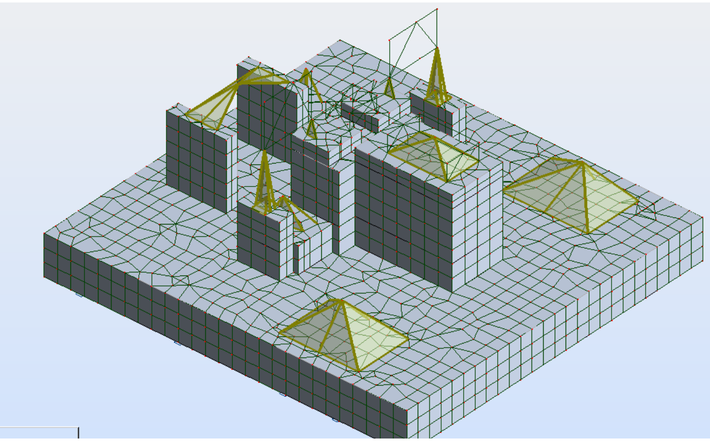

Figure 3 – Finite Element Analysis – Volumetric finite elements - Pile cap and equipment plinths supporting a reciprocating a machine

supports are modelled with rigid links connecting the solid (rotation free nodes), in the limits of the pile diameter, and a master node (pile head) where the rotation restriction is applied (due to the fixation of the pile in the pile cap). The static and dynamic equipment is modelled with rigid links connecting the supports of the equipment to its center of gravity (master node). Therefore, the mass is lumped at its center of gravity and the equipment is considered infinite stiff. For the dynamic equipment, compressor and motor, the axis of the rotor is modelled at its centerline as defined in the manufacturer drawings (regarding the top of concrete of the plinth). The bearing pedestals of the rotor are modelled with rigid links.

1.3.1 RESULTS: FREE VIBRATION RESPONSE

A modal analysis is performed, for which a fundamental frequency of 7,62 Hz is obtained. The fundamental mode of vibration corresponds to an horizontal motion in direction y. The 2nd and 3rd mode of vibration correspond to horizontal motion in x (7,77 Hz) and vertical motion (10,87 Hz).

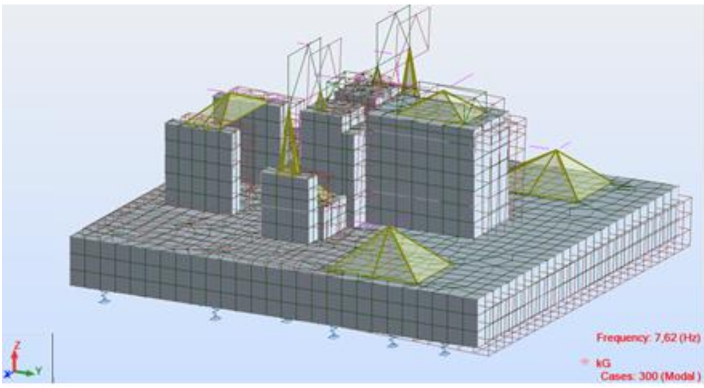

Figure 4 – Finite Element Analysis – Modal Analysis: Vibration Mode 1 – Translation in Y

1.3.1.1 Check of resonance

With the natural frequencies of the free vibration response it is possible to compute the frequency ratio (p/ω) by relating the operating speed of the equipment (dynamic excitation frequency) to the natural frequencies of the foundation. As shown in Table 1-12 the frequency of the foundation differs from the operating speed of the equipment by a margin of more than 20%. This limitation is applied to prevent resonance conditions.

Table 1-12 – Vibration modes, frequencies, mass participation and frequency ratio

Modal Analysis /Mode	Freq, *p* (Hz)	Per, T (s)	Cur.mas.UX (%)	Cur.mas.UY (%)	Cur.mas.UZ (%)	p / ω	
300/1	7,62	0,13	3,03	84,42	0,03	1,236	OK
300/2	7,77	0,13	89,57	3,16	0,03	1,260	OK
300/3	10,87	0,09	0,16	0,18	98,59	1,763	OK

1.3.2 RESULTS: FORCED VIBRATION RESPONSE

1.3.2.1 Steady State Response

Dynamic forces defined in 1.1.2 and 1.1.3 are applied at a steady state operating frequency as a time history function. The dynamic forces derived from the operation of the compressor and the motor are applied simultaneously. The amplitudes of vibration are computed at the compressor bearing levels and at the

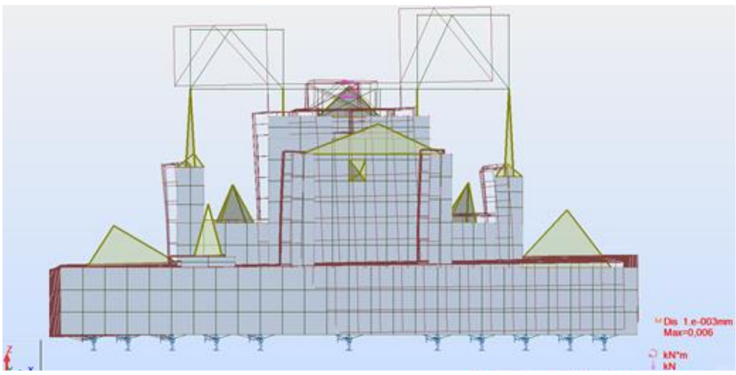

Figure 5 – Time history analysis – Deformed shape at a random time step – Side View XZ

base of the pedestals (top of concrete of the plinths). The resulting amplitudes of vibration and velocities in the time domain are plotted below for the singular nodes.

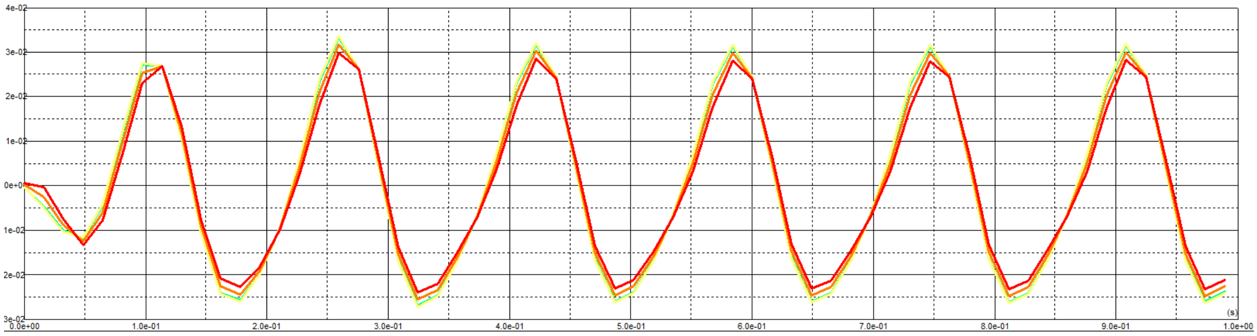

Figure 6 – Time history analysis – Amplitude of vibration (mm)– Direction X : Max displacement ~30 micron

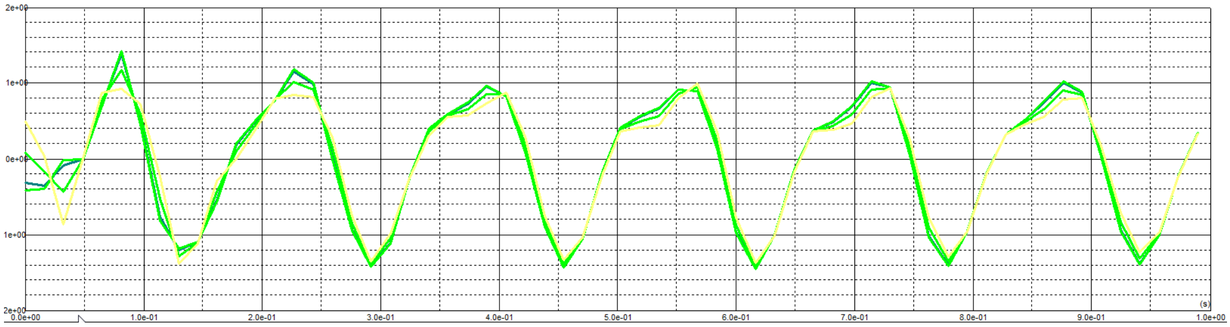

Figure 7 – Time history analysis – Velocity (mm/s) – Direction X: Max velocity ~1.4 mm/s

1.3.2.2 Transient Vibration Response

During the start-up and shut-down of the reciprocating machine, this transient excitation crosses the natural frequencies of the pile cap. At each foundation frequency, the machine foundation system remains in transient resonance till passing the transient excitation frequency. This results in enhanced amplitudes that should be checked as well. In the absence of a function defining the start-up and shut-down of the machine in the time domain, a sweep analysis in the frequency domain can be performed. In such case, the dynamic forces characterizing the steady-state excitation can be used for a frequency response analysis, in a range of frequency from 1 Hz to 30 Hz (with increment of 0.25 Hz). Since the magnitude of the forces used derive from an operation frequency, the amplitudes computed for the different frequencies shall be scaled by the square of the ratio of the resonant frequency to the operating frequency. The transient resonant amplitudes for a specific location (bearing of the compressor) are plotted below for direction X (worst case according results from the analysis).

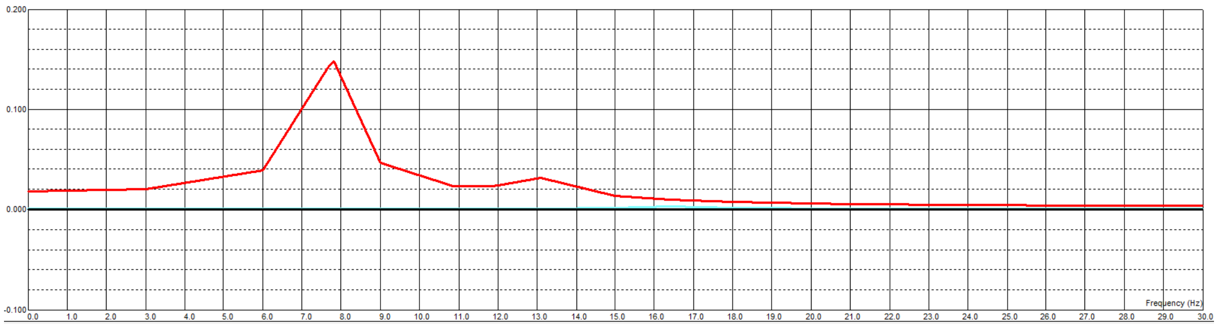

Figure 8 – Frequency response functions – transient response – Amplitude vibration (mm) – Direction X: Max displacement ~145 micron

The maximum displacement is obtained for a frequency of ~7.6 Hz - matching the natural frequency of the pile-supported foundation, as expected.

1.4 ACCEPTANCE CRITERIA

1.4.1 MACHINE LIMITS AND PHISIOLOGICAL LIMITS

Machine limits: The limits of vibration are normally defined by the machine manufacturer. In this case, recommendations from Blake (1964) are followed. According the time history analysis the maximum displacements and velocities occur for the direction X. The maximum peak displacement for this direction is around 30 microns and the maximum velocity for the same direction is around 1.4 m/s. Baxter and Bernhard's chart defines limits for peak to peak displacements. For that reason, the determined displacement values from the time history analysis shall be multiplied by 2 to assess the vibration performance (plotted in Figure 9 a)).

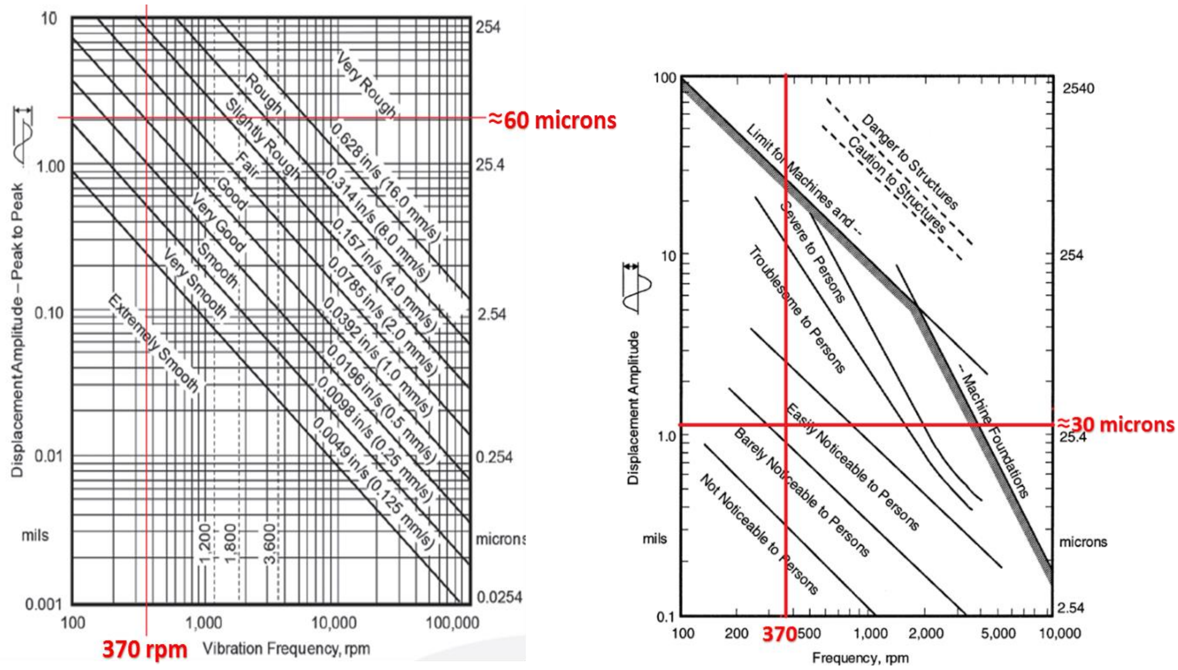

Figure 9 – a) Vibration performance criteria from Baxter and Bernhard 1967 [28], General Machinery Vibration Severity Chart) – plot of case stud; b) Reiher-Meister chart (Richart et al. 1970 [12])– plot of case study

The amplitude vibrations of the case study reciprocating machine almost fit in the boundary of the "very good" vibration criteria according to Baxter and Bernhard's chart. The velocity is slightly above the recommended to fit within "very good" classification. Regarding the transient vibration response, looking at the values of the peak amplitude displacement shown in Figure 8 of around 145 micron one would say that the pile-supported foundation does not meet any of the vibration criteria used for the steady-state verification. However, since the operating speed of the machine is below the natural frequencies of the pile-supported foundation-machine system, it is certain that the start-up and shut-down of the machine will not go above the operating speed of the machine, corresponding to 6.17 Hz (or 370 rpm) thus not posing a problem.

Physiological limits: The Reiher-Meister chart plotted in Figure 9 b) is used to evaluate the human perception and sensitivity to vibration. The maximum displacement obtained from the time history analysis corresponds to direction X. Accordingly, a peak displacement of around 30 microns is plotted in the Reiher-Meister chart (the chart considers peak displacements). As shown for this case study the source of vibration from the reciprocating machine is almost "Easily Noticeable to Persons", which is acceptable.

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