Evaluation of Different Modeling Options for Seismic Analysis of Large Turbine-Generator Systems and their Foundation

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SUMMARY:
Simplified analysis models are assessed to correctly represent the dynamic behaviour of turbine-generator-foundation-systems considering the interaction between the foundation and the rotating equipment during severe earthquake actions. Different levels of complexity are used to represent the behaviour of the equipment and of the structure, and for that the earthquake action is represented as design response spectrum or records of ground motion. For element forces and accelerations the behaviour of the structures analyzed is not very sensitive to the modelling used; the normal design methodology minimizes interaction effects. Results also confirm that it is possible to make a simplified model of the rotor and the bearings to get a good estimate of the equipment foundation loads. Detailed results show that the displacements in the bearings and the deformation of the rotor tend to be underestimated by the simplified models. This can lead to wrong design decisions if inappropriate models are used.

Keywords: Nonlinear Analysis, Turbine-Generator Foundation System, Response Spectrum Analysis.

1. INTRODUCTION

The dynamic analysis of rotating machines is important considering that these are crucial components for modern industry and in particular for power generation facilities. For the correct operation of the facility during a severe seismic event, the equipment must be able to withstand significant forces from normal operation in addition to the disturbances caused by the earthquake, all of these within very strict limits of operational deformation tolerances.

The dynamic response of the equipment under earthquake excitation is quite complex, mainly due to the presence of rotation dynamic effects (gyroscope effect, rotational inertia, and rotor and bearing non-linear interaction). This is especially relevant for large size equipment, in particular the Turbine - Generator systems for electric power plants in the range of 250MW to 350MW that are commonly used. Several authors have examined the effects of the rotor and bearing interaction in the evaluation of the dynamic response under seismic loading considering a rigid foundation, e.g.: Srinivasan and Soni, (1982), Srinivasan and Soni, (1984), Smith et al, (1992). However, in reality the bearing of the rotor is supported by a foundation-soil system that is flexible, with dynamic properties that cannot be ignored in calculation of the response of the complete system.

Srinivasan and Soni, (1982, 1984) presented an good summary of previous work and developed a model considering the flexibility of the rotor, taking into account the effects of inertia, effect of shear deformation, gyroscope effect, and axial load; in addition to include the stiffness and damping induced by the fluid (oil) of the bearing. They concluded that the gyroscope effect could amplify the seismic response significantly. Later, Suarez, Sign, and Rohanimanesh, (1992) extend the work of Srinivasan and Soni, to predict instability of the system when the rotor achieves a certain rotation speed. They also showed that the effects of nonlinear terms induced by the rotation of the base and the nonlinear force terms that appear in the equation of motion due to the speed of the base are negligible, even when the input motion is intense. Subsequent numerical studies performed by Su and Henried, (1995) confirmed these conclusions.

For large rotating machines oil film bearings are typically used, which play an important role in the dynamic behaviour of the rotor. There are different types: plain cylindrical, four axial grooved, elliptical, multi-lobes, and tilting pads; that correspond to different geometries and configurations of the bearing. In this study, we use the plain cylindrical type for the journal bearings as these are the most used in practice for the bearing of turbines and generators. For defining the dynamic properties of the bearing, the forces generated in the fluid need to be estimated. They can be expressed in terms of hydrodynamic coefficients related to equivalent stiffness and damping. Rao (1983) provides a good summary of how to analytically obtain these coefficients for the approximation of long and short type bearings, by analyzing a perturbation from the equilibrium position.

Among the studies that consider the interaction between the equipment and the foundation, Weiming and Milos (1995) compare different responses under excitation from an imbalance of the rotor and earthquake action. Su, Henried, and Solomon (2000), consider a model for the rotor-structure system where the rotor is supported by flexible bearings, and these are rigidly anchored to the foundation, considering also base isolation at different locations in the structure and the equipment supports.

The aim of the study reported here is to assess the quality of simplified models to correctly represent the dynamic behaviour of turbine-generator foundation system considering the dynamic interaction between the equipment and the foundation. Three types of configurations for the system are discussed, considering Soil Site Class B and C according to the International Building Code IBC 2006. The systems are subjected to 20 artificial ground acceleration records including vertical and horizontal components of motion. For each of these configurations, 5 different manners to model the rotor of the equipment and their journal bearings are considered, which differ in the level of sophistication.

2. PHYSICAL AND MECHANICAL REPRESENTATION OF THE ROTOR

The basic elements to model the rotor are flexible rotating shaft, rigid disk, and their journal bearing system. The shaft is modelled as a Bernoulli-Euler beam with circular cross section and characterized by six degrees of freedom for each end node. Shear deformations are considered negligible. To include the effect of rigid zones of the rotor on the shaft flexible response, a thin rigid disk attached to the nodes is used. This element is considered as a concentrated mass which can be found in one or more places along the shaft. The properties are obtained considering that the whole mass is fixed to a single node. The bearings are considered flexible and they are modelled by their stiffness and damping matrices, which depend on the speed of rotation of the rotor and the vertical load acting on the bearing at any given time.

2.1. Flexible rotating shaft

A flexible element of length l rotating at a constant speed of rotation Ω expressed in radians per second is considered. The displacement and rotation vector for any section of the shaft u^e and $\emptyset^e$ can be expressed in terms of nodal displacements q^e using the interpolation function $N(s)$, where s is a local coordinate measured along the length of a finite element, and $N'(s)$ is the first derivative of $N(s)$ with respect to s. Using the Lagrange formulation, the finite element equations of motion for the flexible rotating shaft can be obtained in terms of the element properties: ρ is the mass density, A is the cross section area, I_x is the moment of inertia of the shaft about the transverse axes, I_p is the mass moment of inertia of the shaft about the normal axis, E is the modulus of elasticity, e_1=[1 0 0] and e_2=[0 1 0] are auxiliary operators. A cubic polynomial interpolation function $N(s)$, can be used as it satisfies the requirements of continuity, boundary conditions, and differentiability needed.

$$u^e(s) = \left[u_x^e(s), u_y^e(s), u_z^e(s)\right]^T = N(s)\cdot q^e \quad \theta^e(s) = \left[\theta_x^e(s), \theta_y^e(s), \theta_z^e(s)\right]^T = N'(s)\cdot q^e \quad (2.1)$$

$$q^e = \left[u_1^e, u_2^e, u_3^e, \theta_1^e, \theta_2^e, \theta_3^e, u_4^e, u_5^e, u_6^e, \theta_4^e, \theta_5^e, \theta_6^e\right]^T \tag{2.2}$$

$$M_s^e \ddot{q}^e + C_s^e \dot{q}^e + K_s^e q^e = f_s^e \tag{2.3}$$

$$M_s^e = \int_0^l \rho A N^T N \, ds + \int_0^l \rho I_x N'^T N' \, ds \tag{2.4a}$$

$$C_s^e = \Omega \int_0^l I_p N'^T (e_1 e_2^T - e_2 e_1^T) N' \, ds \tag{2.4b}$$

$$K_s^e = \int_0^l E I_x N''^T N'' \, ds \tag{2.4c}$$

By inspection, the matrix M_{se} is symmetric, the first term represents the classical mass matrix and the second term includes the effects of rotational inertia. The "damping" matrix C_{se} depends on the speed of rotation, is not symmetric and represents the gyroscopic effect of the rotor. Notably, it does not consider any other damping term associated with the flexible shaft. The matrix K_{se} is the classical stiffness matrix of a flexural element without considering shear stiffness.

2.2. Rigid disk

To include the effect of the rigid disks in the response of the flexible shaft, the entire rigid disk mass is concentrated in one node of the finite element representation of the flexible shaft. The nodal displacements are defined by $q^e{}_d = [u_x, u_y, \emptyset_x, \emptyset_y]^T$. The equations of motion for the rigid disk can be obtained in a similar manner to those for the flexible shaft, resulting in

$$M_d^e \ddot{q}^e + C_d^e \dot{q}^e + K_d^e q^e = f_d^e \tag{2.5}$$

$$M_d^e = m_d A^T \cdot A + I_t A_2^T \cdot A_2 \tag{2.6a}$$

$$C_d^e = \Omega I_0 A_2^T (e_1 e_2^T - e_2 e_1^T) A_2 \tag{2.6b}$$

$$K_d^e = 0 \tag{2.6c}$$

where m_d is the mass of disk, I_t is the mass moment of inertia of shaft about the transverse axes, I_o is the mass moment of inertia of shaft about the normal axes. The matrix M_d^e is symmetric, the first term represents the mass matrix and the second includes the effects of rotational inertia. The "damping" matrix C_d^e depends on the speed of rotation, it is not symmetric and it represents the gyroscopic effect of the rigid disks in the rotor. It does not consider any other damping term associated with rigid disk.

2.3. Journal oil film bearing system

The bearing system is modeled typically through two sets of orthogonal forces coupled with each other (damping and elastic stiffness). These forces depend on the relative displacement and speed of the moving shaft relative to the bearing. Oil film bearings are common in large equipment that operate continuously, as they require little maintenance, provide stiffness and appropriate level of damping to the system. The stiffness and damping properties of the bearing directly affect the critical speed and dynamic stability of the system, and depend upon the type of bearing, its physical dimensions, the viscosity of the fluid, and the rotating speed of the rotor. Several references provide methods to obtain the coefficients of the damping C_{ij} and stiffness K_{ij} matrices. In this study the simple cylindrical type journal bearing, will be used with the approximations of "short bearing", as provided by Rao (1983).

$$K_{ij} = \frac{W \cdot k_{ij}}{c} \quad C_{ij} = \frac{W \cdot c_{ij}}{\Omega \cdot c} \quad S_f s^2 = \left[\frac{\mu N}{P_m}\left(\frac{r}{c}\right)^2\right] = \frac{(1-n^2)^2}{\pi n \sqrt{16 n^2 + \pi^2 (1-n^2)}} \tag{2.7}$$

where W is the weight on the bearing, c is the radial clearance, k_{ij} and c_{ij} are the dimensionless coefficient that are calculated according to Figure 1, S_f is the Summerfield number, μ is the lubricant viscosity, N is the rotational speed in revolutions per second, P_m is the average pressure on the bearing, D is the journal diameter, L is the bearing length, r is the journal radius, n is the eccentricity ratio, and $s=L/D$ is the aspect ratio of the bearing.

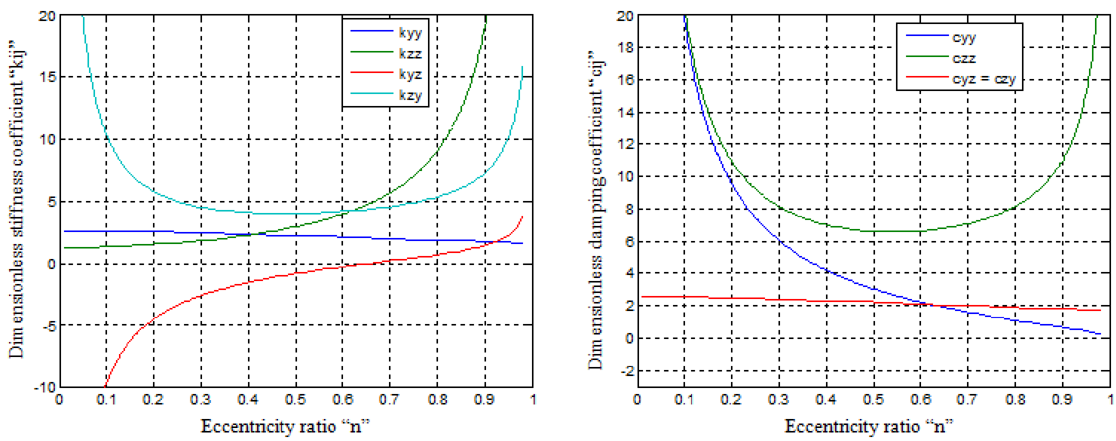

Figure 1. Dimensionless coefficient for oil film bearing using the "short bearing" approximation

In practice, the geometry of the bearing and the fluid properties are defined by the equipment manufacturer, however the average pressure on the bearing will vary over time due to the seismic action. This requires calculating the value of the eccentricity ratio n, as well as the stiffness and damping values, at each integration step.

3. FORMULATION OF THE EQUATION OF MOTION OF THE SYSTEM

To obtain the equation of motion of the entire system the mass, damping, and stiffness matrices for the rotor must be coupled to those of the structural model of the foundation. A coordinate axes system [X,Y,Z] is defined where the degrees of freedom $u_g = [u_{gx}, u_{gy}, u_{gz}]^T$ represent the motion of the base with respect to a fixed inertial system, The degrees of freedom of the nodes of the structure on the base are $q = [q^{(1)}, q^{(2)}, \cdots, q^{(M)}]^T$ ($q^{(j)}$ has 6 degrees of freedom, 3 translations and 3 rotations), and M represents the total number of nodes in the model of the foundation. The effect of the soil is represented by vertical and horizontal linear springs, proportional to the soil stiffness. The degrees of freedom of the nodes where the rotor is connected to the structure are $p = [p^{(1)}, p^{(2)}, \cdots, p^{(s)}]^T$ (3 translations and 3 rotations each), and s is the number of support points of the rotor. The degrees of freedom of the nodes of the rotor, relative to the base, are $r = [r^{(1)}, r^{(2)}, \cdots, r^{(t)}]^T$ and t is the number of nodes in the rotor, regardless of the degrees of freedom of the supports p.

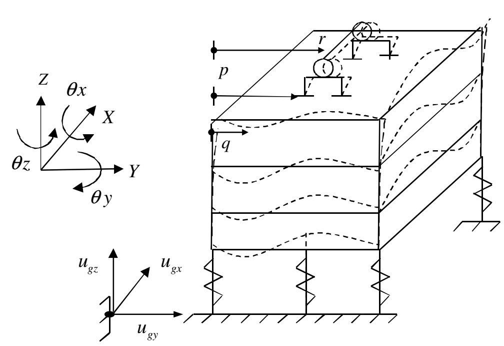

Figure 2. Schematic representation of coordinates (degrees of freedom) used to represent the complete system

Adding up the different components of mass, damping, and stiffness, the equations of motion of the complete system are represented as:

$$\begin{bmatrix} M_q^E & M_{qp}^E & 0 \\ M_{pq}^E & M_{pp}^E + M_p^R & M_{pr}^R \\ 0 & M_{rp}^R & M_{rr}^R \end{bmatrix} \begin{bmatrix} \ddot{q} \\ \ddot{p} \\ \ddot{r} \end{bmatrix} + \begin{bmatrix} C_q^E & C_{qp}^E & 0 \\ C_{pq}^E & C_{pp}^E + C_p^R & C_{pr}^R \\ 0 & C_{rp}^R & C_{rr}^R \end{bmatrix} \begin{bmatrix} \dot{q} \\ \dot{p} \\ \dot{r} \end{bmatrix} + \begin{bmatrix} K_q^E & K_{qp}^E & 0 \\ K_{pq}^E & K_{pp}^E + K_p^R & K_{pr}^R \\ 0 & K_{rp}^R & K_{rr}^R \end{bmatrix} \begin{bmatrix} q \\ p \\ r \end{bmatrix} = -\begin{bmatrix} M_q^E & M_{qp}^E & 0 \\ M_{pq}^E & M_{pp}^E + M_p^R & M_{pr}^R \\ 0 & M_{rp}^R & M_{rr}^R \end{bmatrix} r_g \ddot{u}_g \tag{3.1}$$

The model of the soil and foundation is carried out in SAP2000, and the nonlinear equations that model the rotor are developed using Matlab, therefore the matrices for the foundation system can be obtained from SAP2000, based on the modal analysis parameters: the mass matrix M^E associated with the degrees of freedom of the foundation, the matrix of modes shapes $\Phi=[\phi_1, \phi_2, \cdots, \phi_n]$, which solves the eigen value problem for (M^E,K^E) in the degrees of freedom (q, p), where n is the number of modes considered. Now we can rewrite Eqn. 2.9 as:

$$\begin{bmatrix} \widehat{M}^E & \widehat{M}_{pr}^R \\ \widehat{M}_{pr}^R & M_{rr}^R \end{bmatrix} \begin{bmatrix} \ddot{v} \\ \ddot{r} \end{bmatrix} + \begin{bmatrix} \hat{C}^E & \hat{C}_{pr}^R \\ \hat{C}_{pr}^R & C_{rr}^R \end{bmatrix} \begin{bmatrix} \dot{v} \\ \dot{r} \end{bmatrix} + \begin{bmatrix} \widehat{K}^E & \widehat{K}_{pr}^R \\ \widehat{K}_{pr}^R & K_{rr}^R \end{bmatrix} \begin{bmatrix} v \\ r \end{bmatrix} = -\begin{bmatrix} \widehat{M}^E & \widehat{M}_{pr}^R \\ \widehat{M}_{pr}^R & M_{rr}^R \end{bmatrix} r_g \ddot{u}_g \tag{3.2}$$

where $v = [q\ , p]^T$ are the degrees of freedom of the foundation and supports of the rotor, $\hat{M}^E$ is the mass matrix of the foundation structure, $\hat{C}^E$ is the damping matrix, and $\hat{K}^E$ is the stiffness matrix of ;all three of them consider the effect of the rotor supports. Defining $v = \Phi\eta$, where Φ is the matrix of mode shapes defined above, and η is the vector of modal coordinates associated with these modes and pre-multiplying by Φ^T Eqn. 3.2 becomes the "equation of motion" of the complete system as shown in Eqn. 3.3. This equation can be solved using numerical integration using the Newmark integration for linear systems with β = ¼ and γ = ½. Note that the damping and the stiffness matrices of the bearing vary in time due to the seismic action, therefore the corresponding parts of the matrices must be updated in each step of the integration process. Given this, Newton-Raphson approach was used, solving the equation of motion at each integration step using iteration. The integration step used is the same as that of the ground acceleration record and it corresponds to Δ = 0.01 s.

$$\begin{bmatrix} \Phi^T \widehat{M}^E \Phi & \Phi^T \widehat{M}_{pr}^R \\ \widehat{M}_{pr}^R \Phi & M_{rr}^R \end{bmatrix} \begin{bmatrix} \ddot{\eta} \\ \ddot{r} \end{bmatrix} + \begin{bmatrix} \Phi^T \hat{C}^E \Phi & \Phi^T \hat{C}_{pr}^R \\ \hat{C}_{pr}^R \Phi & C_{rr}^R \end{bmatrix} \begin{bmatrix} \dot{\eta} \\ \dot{r} \end{bmatrix} + \begin{bmatrix} \Phi^T \widehat{K}^E \Phi & \Phi^T \widehat{K}_{pr}^R \\ \widehat{K}_{pr}^R \Phi & K_{rr}^R \end{bmatrix} \begin{bmatrix} \eta \\ r \end{bmatrix} = -\begin{bmatrix} \Phi^T \widehat{M}^E & \Phi^T \widehat{M}_{pr}^R \\ \widehat{M}_{pr}^R & M_{rr}^R \end{bmatrix} r_g \ddot{u}_g \tag{3.3}$$

4. ARTIFICIAL GROUND ACELERATION RECORDS

For this study 20 two component artificially created ground acceleration records were used, one component in the horizontal (transverse) direction and one in the vertical direction. The records were obtained by Fernandez-Davila (2007 from the horizontal components (primary and secondary) of actual ground motions recorded during central Chile earthquake of March 3, 1985. The system is simultaneously subjected to the action of the horizontal principal component of each record action in the transverse direction, and to the action of 2/3 of the secondary component in the vertical direction. In the longitudinal direction of the foundation the rotor can be considered simply as a mass distributed in the structure (rigidly attached), without taking part in the dynamics of the problem. The artificial records are considered to be representative of the motion of the base rock base (fixed base common to the whole model), and different types of site soil conditions are modelled using different vertical and horizontal soil stiffness (modelled as springs). This allows to "filter" the seismic action and to reach the base of the foundation with a seismic input compatible with the type of soil used.

5. TURBINE GENERATION SYSTEM MODELING

Three different configurations of foundation Turbine-Generator system for power plants are considered. They correspond to real projects in the range of 250MW to 350MW, two correspond to steam turbines and the third to a system based on a gas turbine. For each of these configurations five analysis models are created, depending on the level of sophistication of the rotor and bearings model.

The modelling of the structure of the foundation and of the soil remains unchanged for the five models, in order to compare the response without causing distortions in the results. These models are:

- Model 1: This model is called "sophisticated model" since it does not include any kind of simplification and will serve as a base of comparison with other models, assuming it represents the actual system response. The soil-foundation, along with the casing is modelled in SAP2000 and the rotor in MatLab as previously discussed. This allows considering the gyroscope effect and rotational inertia of the rotor due to rotation speed. The existence of rigid disks distributed throughout the rotor length is considered according to their actual geometry. The stiffness and damping matrices of the bearing, which have off-diagonal coupling terms, are considered as variable in time, as there is a significant variation of the vertical load acting on the bearing due to the earthquake action.
- Model 2: This model is similar to the sophisticated model with the difference that the matrices of stiffness and damping of the bearing are considered to be constant over time, disregarding the effect of variation of the vertical load acting on each bearing.
- Model 3: This model is based on Model 2, considering that there are no couplings terms in the stiffness and damping matrices of the bearings.
- Model 4: This model is carried out entirely in SAP2000. To the initial model of the soil-foundation structure a simplified model of the rotor is added. This rotor model has geometry and lateral stiffness properties for bending similar to the sophisticated model. The effects of rotational inertia and gyroscope are not considered. The bearings are modelled by "Link" type elements assigning stiffness and damping values between two points, but the coupling terms and the variation of the coefficients over time are not considered.
- Model 5: This model is equivalent to Model 4 except that the stiffness and damping of the bearing is not considered, i.e. the rotor of the equipment is rigidly connected to the foundation.

The time history of the response for each of the variables of interest is obtained in all cases using special purpose code written for MatLab. All foundations are entirely of reinforced concrete grade H30, with a modulus of elasticity E_c=23.875 *MPa*, and for the rotor of the generator, rotor of the turbine and casing ASTM A-36 steel is used. Additionally, for the five models of the three system configurations it is considered that the foundation is supported by one of two different soil types (site class B and C, IBC 2006). The only load considered in the elements is their own weight, the loads from the rotor due to the speed of rotation and the load produced by earthquake ground motion.

6. FOUNDATION – EQUIPMENT SYSTEM CONFIGURATIONS

Configuration 1 (3 stages Steam Turbine and Generator) is illustrated in Figs. 3 and 4, the equipment total weight is 7531 kN and the weight of the complete foundation model is 67724 kN.

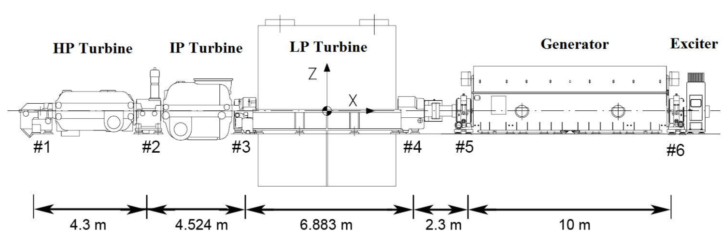

Figure 3. Overview of the equipment for Configuration 1, showing bearing locations #1 to #6.

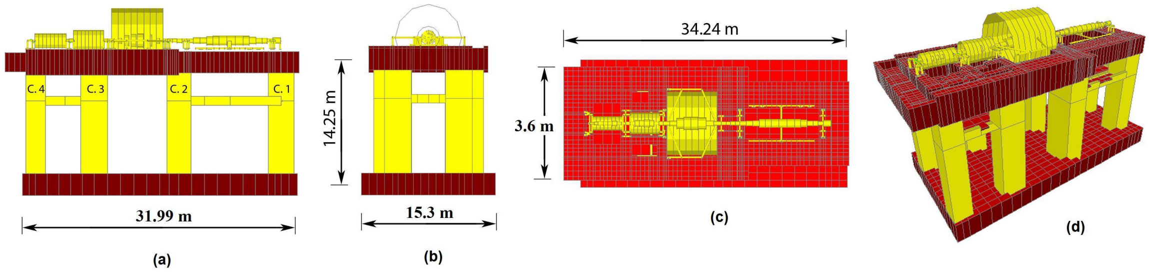

Figure 4. Overview of the foundation model for Configuration 1. (a) Longitudinal Elevation, (b) Transverse Elevation, (c) Plan view from above, (d) 3D Perspective

Configuration 2 (Gas Turbine and Generator) is illustrated in Figs. 5 and 6, the equipment total weight is 6193 kN and the weight of the complete foundation model is 22077 kN.

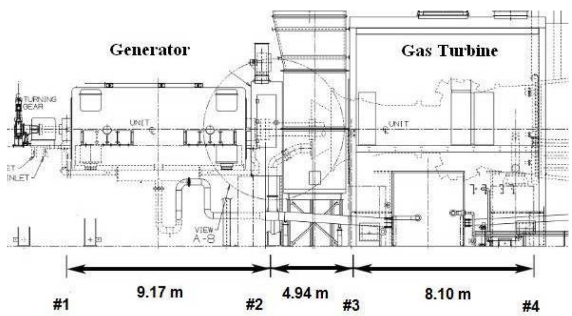

Figure 5. Overview of the equipment for Configuration 2, showing bearing locations #1 to #4.

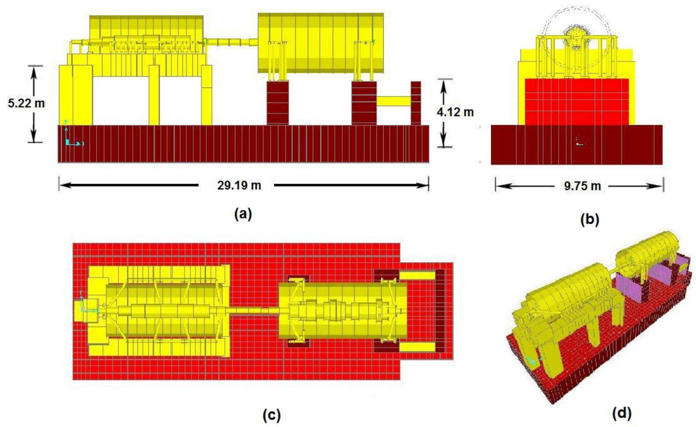

Figure 6. Overview of the foundation model for Configuration 2. (a) Longitudinal Elevation, (b) Transverse Elevation, (c) Plan view from above, (d) 3D Perspective. Vertical Figure shows bearing locations #1 to #4.

Configuration 3 (Steam Turbine and Generator) is illustrated in Figs. 7 and 8, the equipment total weight is 4343 kN and the weight of the complete foundation model is 29900 kN.

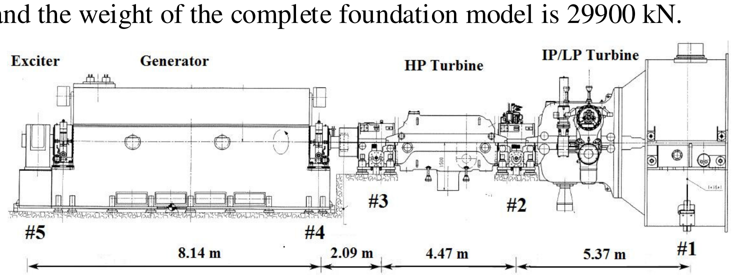

Figure 7. Overview of the equipment for Configuration 3, showing bearing locations #1 to #5.

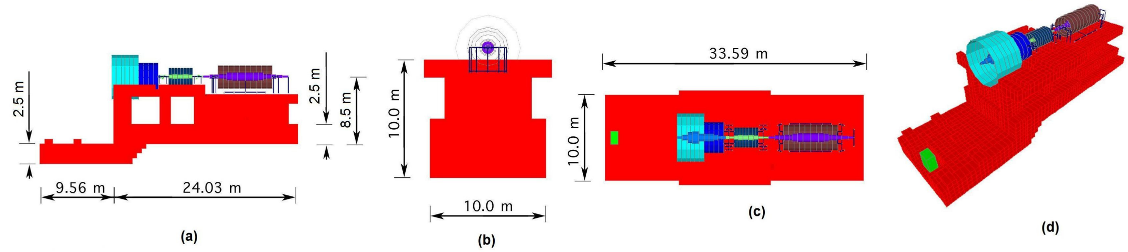

Figure 8. Overview of the foundation model for Configuration 3. (a) Longitudinal Elevation, (b) Transverse Elevation, (c) Plan view from above, (d) 3D Perspective

7. SAMPLE OF RESULTS OBTAINED

For all cases, the results shown correspond to averages over the set of 20 ground motions considered. Given the space restrictions only a sample of the types of results obtained are shown.

Fig. 9 shows the orbit of the bearing (all with the same vertical and horizontal scale) for Configuration 1 and 2, using Model 1, site class C, for one case of ground acceleration (Record No. 2). These orbits represent the relative motion of the rotor into the bearing. It can be seen that the displacements in the horizontal Y and vertical Z are of comparable magnitude and are always less that the clearance that exists in every bearing. The bearings that support the generator have higher displacement amplitudes in all configurations, mainly due to the greater distance between the corresponding bearings.

Table 7.1 shows the differences "*D1ci*" in the maximum and minimum values of the relative displacements of the rotor at the bearings for different configurations and models, where the difference is calculated according to Eqn. 7.1.

$$D_{1cj}(\%) = \frac{\overline{X}_{model1} - \overline{X}_{model"j"}}{\overline{X}_{model\,1}}(\%) \qquad \overline{X} = \left(\sum_{i=1}^{n} X_i\right)/n \qquad j = 1\ldots5 \qquad n = 20 \tag{7.1}$$

Table 7.1. Comparison of differences in extreme values of the relative displacements of the rotor at the bearings.

	Configuration 1 Site class B			Configuration 1 Site class C			Configuration 2 Site class B			Configuration 2 Site class C			Configuration 3 Site class B			Configuration 3 Site class C		
	D_{1c2} (%)	D_{1c3} (%)	D_{1c4} (%)	D_{1c2} (%)	D_{1c3} (%)	D_{1c4} (%)	D_{1c2} (%)	D_{1c3} (%)	D_{1c4} (%)	D_{1c2} (%)	D_{1c3} (%)	D_{1c4} (%)	D_{1c2} (%)	D_{1c3} (%)	D_{1c4} (%)	D_{1c2} (%)	D_{1c3} (%)	D_{1c4} (%)
Displ. Y max. #1	-3	-27	-237	0	-30	-585	32	9	26	-12	-147	-215	-1	-13	-272	-1	-16	-292
Displ. Y min. #1	12	-13	-203	1	-29	-577	81	74	79	31	-50	-95	2	-9	-266	2	-12	-279
Displ. Y max. #2	-3	-26	-117	0	-28	-292	32	26	13	-13	-115	-234	0	-4	-164	0	-5	-173
Displ. Y min. #2	14	-9	-89	2	-26	-285	81	78	76	38	-15	-81	2	-2	-159	2	-2	-167
Displ. Y max. #3	12	4	-61	4	-7	-185	-9	-112	-151	-8	-174	-349	-5	-2	-18	3	-11	-468
Displ. Y min. #3	17	9	-56	3	-10	-189	38	-31	-55	22	-95	-224	12	14	-4	-2	-16	-541
Displ. Y max. #4	12	2	-39	4	-11	-125	3	-58	-83	-14	-180	-367	-3	-13	-246	-2	-15	-344
Displ. Y min. #4	16	5	-38	3	-12	-127	48	7	-10	41	-40	-137	5	-6	-226	3	-9	-333
Displ. Y max. #5	38	37	18	14	15	-74							-1	-6	22	0	-7	-6
Displ. Y min. #5	67	67	56	15	15	-72							3	-3	27	1	-6	-9
Displ. Y max. #6	43	47	22	16	24	-70												
Displ. Y min. #6	51	55	33	11	20	-80												
Displ. Z max. #1	-5	47	40	-8	53	50	48	60	52	-1	18	28	-3	25	-78	-6	10	-67
Displ. Z min. #1	17	61	55	12	61	58	33	48	37	7	20	30	3	28	-65	4	19	-47
Displ. Z max. #2	-5	46	48	-9	52	55	50	60	58	-4	0	22	-3	29	-49	-7	21	-40
Displ. Z min. #2	21	62	63	15	61	64	37	51	49	14	13	33	5	33	-34	5	30	-22
Displ. Z max. #3	2	56	50	-8	60	58	8	50	2	-1	25	-16	10	52	41	-6	24	-17
Displ. Z min. #3	29	71	65	17	68	67	3	46	-3	3	26	-13	-4	48	33	5	32	-5
Displ. Z max. #4	1	56	50	-9	59	57	16	41	-10	-4	-11	-54	0	34	-125	-6	16	-85
Displ. Z min. #4	29	72	66	18	68	67	5	35	-21	9	1	-36	6	35	-110	5	26	-56
Displ. Z max. #5	29	58	55	0	62	59							0	39	-155	-5	27	-110
Displ. Z min. #5	65	78	77	26	71	69							3	39	-147	4	33	-81
Displ. Z max. #6	23	62	58	0	67	64												
Displ. Z min. #6	63	81	79	25	75	73												

It is important to note the very large lateral stiffness (and also axial stiffness) that the rotor has along its length, and hence the need to obtain accurately the deformation that occurs along its axis, because the tolerances for these deformations are only microns given the equipment operational requirements.

To correctly estimate the accelerations at the connection point between the equipment and the foundation is central to obtain the correct design forces for the anchoring systems; which is crucial for achieving good overall system performance. Table 7.2 shows the differences in the extreme values, i.e. maximum positive and maximum negative, of the observed accelerations at the anchor points in Models 2, 3, 4 and 5 compared to Model 1. It is possible to see the small difference between these values (on average 1%), regardless of how the turbine system is modeled.

Table 7.2. Comparison of differences in extreme values of the accelerations at the support points.

	Configuration 1 Site class B				Configuration 1 Site class C			
	D_{1c2} (%)	D_{1c3} (%)	D_{1c4} (%)	D_{1c5} (%)	D_{1c2} (%)	D_{1c3} (%)	D_{1c4} (%)	D_{1c5} (%)
max. #1 Direction Y	0.1	0.0	0.4	0.3	-0.1	-0.1	0.3	0.2
min. #1 Direction Y	0.0	0.0	0.2	0.0	-0.9	-0.9	-0.7	-0.7
max. #2 Direction Y	0.0	0.1	0.2	0.2	-0.2	-0.2	0.2	0.1
min. #2 Direction Y	0.0	0.0	-0.5	-0.6	-0.9	-0.9	-0.7	-0.7
max. #3 Direction Y	-0.1	-0.1	-0.4	-0.4	-0.2	-0.3	0.1	0.0
min. #3 Direction Y	0.0	-0.1	-1.1	-1.2	-0.8	-0.8	-0.6	-0.6
max. #4 Direction Y	0.1	0.0	-1.1	-1.2	-0.2	-0.1	0.1	0.1
min. #4 Direction Y	-0.2	0.0	-0.1	-0.3	-0.8	-0.7	-0.6	-0.6
max. #5 Direction Y	0.0	0.0	-0.9	-0.9	-0.2	-0.1	0.2	0.2
min. #5 Direction Y	-0.2	0.1	0.3	0.1	-0.8	-0.7	-0.6	-0.6
max. #6 Direction Y	-0.2	0.0	-0.7	-0.9	-0.3	-0.3	0.0	0.0
min. #6 Direction Y	0.1	0.3	0.4	0.3	-0.8	-0.6	-0.4	-0.4
max. #1 Direction Z	0.6	0.5	-2.3	-2.4	-0.1	-0.1	-3.3	-3.4
min. #1 Direction Z	0.5	0.8	-1.4	-1.7	-0.3	-0.3	-2.9	-2.8
max. #2 Direction Z	-0.6	-0.8	-3.9	-3.9	0.1	0.1	-2.9	-3.0
min. #2 Direction Z	0.9	1.1	-1.2	-1.4	-0.3	-0.3	-3.0	-2.9
max. #3 Direction Z	-1.0	-1.0	-4.3	-4.2	0.0	0.1	-2.6	-2.7
min. #3 Direction Z	2.1	2.3	-0.1	-0.1	-0.3	-0.3	-3.0	-2.9
max. #4 Direction Z	0.0	0.3	-4.1	-4.3	-0.1	-0.1	-3.4	-3.4
min. #4 Direction Z	0.5	0.8	-2.9	-3.0	-0.2	-0.2	-3.1	-3.2
max. #5 Direction Z	0.2	0.6	-3.5	-3.8	-0.1	-0.1	-3.4	-3.4
min. #5 Direction Z	0.2	0.5	-3.1	-3.2	-0.3	-0.2	-3.0	-3.0
max. #6 Direction Z	-0.3	0.5	-1.9	-2.2	0.0	0.1	-2.8	-2.8
min. #6 Direction Z	0.0	0.4	-0.5	-0.5	-0.1	-0.1	-2.4	-2.4

	Configuration 2 Site class B				Configuration 2 Site class C			
	D_{1c2} (%)	D_{1c3} (%)	D_{1c4} (%)	D_{1c5} (%)	D_{1c2} (%)	D_{1c3} (%)	D_{1c4} (%)	D_{1c5} (%)
max. #1 Direction Y	0.3	1.2	0.2	0.0	0.0	0.1	0.6	0.5
min. #1 Direction Y	0.2	1.0	1.7	1.0	0.0	0.1	0.9	0.8
max. #2 Direction Y	2.6	3.1	2.1	1.8	0.0	0.3	-1.6	-1.6
min. #2 Direction Y	1.7	4.1	-0.9	-0.4	0.0	0.0	-1.4	-1.4
max. #3 Direction Y	-0.2	0.7	-4.3	-5.1	0.0	0.0	-2.2	-2.3
min. #3 Direction Y	-0.2	0.8	-6.0	-6.8	0.0	0.0	-2.3	-2.4
max. #4 Direction Y	-0.1	0.7	-3.5	-4.2	0.0	0.0	-1.4	-1.5
min. #4 Direction Y	0.2	1.5	-0.8	-1.3	0.0	0.1	-1.8	-1.8
max. #1-A Direction Y	4.3	10.4	9.2	0.7	-0.2	0.0	-1.6	-1.7
min. #1-A Direction Y	-2.7	5.5	3.0	-6.3	0.2	0.4	-1.6	-1.6
max. #1-B Direction Y	2.9	6.3	3.4	-6.7	-0.1	0.2	-2.7	-2.8
min. #1-B Direction Y	-2.1	2.0	1.0	-8.0	-0.1	0.1	-2.3	-2.3
max. #2 Direction Y	-0.4	3.5	-7.2	-11.2	-0.1	0.0	-2.5	-2.5
min. #2 Direction Y	0.2	3.6	-5.9	-11.2	0.0	0.2	-2.1	-2.0
max. #3 Direction Y	2.7	5.1	-1.4	-5.4	0.0	0.3	-1.9	-2.0
min. #3 Direction Y	-2.1	-0.4	-8.4	-13.0	-0.1	0.2	-2.9	-3.0
max. #4 Direction Y	1.1	2.7	1.3	-3.1	0.0	0.2	-1.8	-2.0
min. #4 Direction Y	-0.7	0.9	-2.4	-5.8	0.0	0.2	-1.9	-2.1

8. CONCLUSIONS

From the discussion and results presented in this study, the following conclusions are obtained:

- The results from the more simplified models (especially those made entirely in SAP2000) do not provide enough accuracy in predicting the response of the bearings and their stiffness and damping properties. This highlights the importance of using a model that considers the gyroscope effect, rotational inertia, and stiffness and damping coefficients that change in time.
- The estimates of the deformation of the rotor with the simplified models are not good, especially if the distance between the bearings is large, because these effects are amplified, as in the case of the generator rotor. The displacements obtained using the simplified models are smaller in the horizontal direction (in Configuration 1 and 2) thus creating a problem when checking the allowable deformations of the rotor under earthquake loads supplied by the manufacturer. However, for the deformations in the vertical direction, Model 4 overestimates the deformation, giving a conservative value for the design.
- When creating the mathematical model, regardless of the manner in which the turbine-generator system is modelled, it is important to use the correct characteristics of the soil behaviour under the foundation system, because for all the variables studied, particularly for the deformations of the rotor and the accelerations in the anchors, the maximum average values observed are larger for site class B compared to site class C, which can be considered to be an unexpected result.
- The maximum values of the accelerations at the anchor points for the various models and configurations, show small differences (in percentage). Therefore, the details of the model of the

rotor do not significantly affect the observed global behaviour of the system. This result validates the approach normally used for the design of rotating equipment foundation, which seeks to provide large stiffness (and mass) to the foundation to remove their natural frequencies of the critical speeds of the turbine and minimize the interaction between the equipment and the foundation. By providing a correct distribution of the mass of the rotor along its axis and properly connecting these masses to the foundation (overturning effects), it was possible to get results close to those obtained with a sophisticated model, in terms of the forces in the anchors and overall foundation loads.

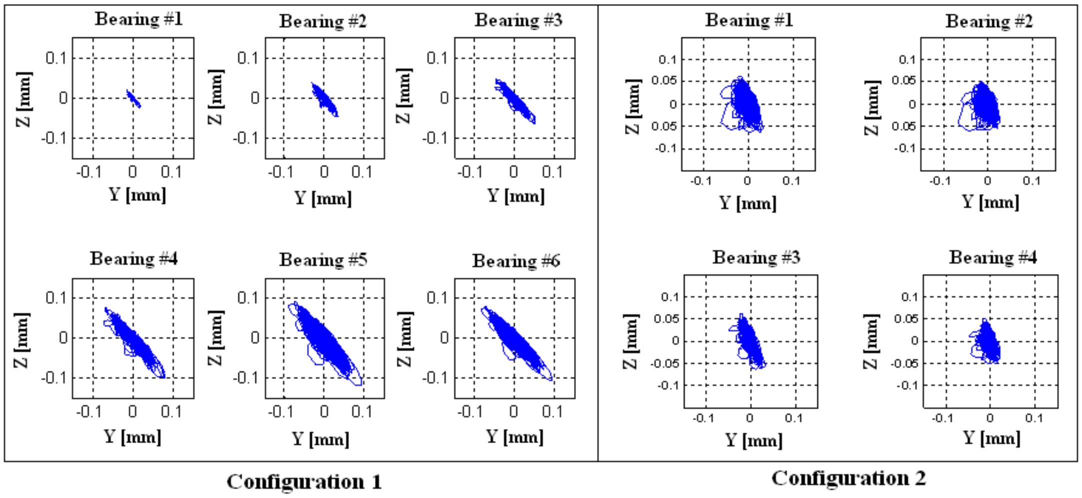

Figure 9. Relative displacement orbits of the rotor in the bearing, Configuration 1 and 2

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