TURBO GENERATOR MACHINE FOUNDATIONS SUBJECTED TO EARTHQUAKE LOADINGS

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ABSTRACT :

For industrial partners, actual simplified design rules in line with the growth of knowledge regarding earthquake engineering are essential for competitiveness. As turbo generators are placed all over the world, i.e. in different seismic hazard zones, not only machine sets but also the foundations have to be standardised and able to resist certain earthquake loading levels. Prior to the release of new or revised turbo generators (foundations), extensive static and dynamic calculations are carried out to confirm the foundation outline and basic dimensions, and also verifying the resistance against unfavourable load combinations. Based on gained knowledge of detailed seismic analyses, practical design approaches have been elaborated for different kind of foundation types (mainly spring mounted, table mounted and raft foundations); and, for some machine manufacturers, summarised in specific design criteria.

This paper focuses on the a.m. investigations and studies, proposes simplified design principles for large machine foundations and will show specific requirements for turbo generators, which are sometimes in contradiction to seismic design demands. For practicable design of pedestals, foundation supports and machine anchorages, it is preferred to transfer seismic loads to static equivalent forces. Here, apart from local parameters such as ground acceleration and soil amplifications, the main concern is the load distribution over the height. Especially for compact raft foundations, the soil-structure-interaction is an eminent attribute, as first eigenfrequencies are in strong dependence to the bedding situation, and are often situated within the critical earthquake frequency range with regard to the soil amplification.

KEYWORDS: Life Line Systems, Machine Foundations, Turbo Generators, Simplified Design Rules, Static Equivalent Force Method, Numerical Modelling Techniques

1. MACHINE FOUNDATIONS

1.1. Introduction

Despite of the limited numbers of large turbo generators, the machine industry puts enhanced efforts not only to standardise their machines, but also the corresponding foundations. The increasing requirements for machine efficiency reasons have lead to a demand of high quality, standardised machine foundations fitting the manufacturer's demands and becoming more and more often to be delivered / sold together with the machines themselves. Although the costs of machine foundations are only a small fraction of the total costs, they have to be designed properly; costs due to outages (e.g. machine failures and shutdowns) may exceed easily the total costs of design and construction of foundations.

Prior to the release of new or revised turbo generators foundations, extensive static and dynamic calculations are carried out to confirm outline and basic dimensions, and also to verify the resistance against unfavourable load combinations. Later, for each foundation / pedestal, separate static and dynamic design calculations have to be performed (to prove the local conditions, e.g national codes, building material qualities, subsoil properties, etc.) and

summarised within a site specific document to be handed over to local authorities for approval. Here simplified calculation methods can be applied based on the first 'basic design' studies. No new complete design process is necessary, only the fulfilment of requirements has to be proven. In general, eigenforms and -values over the full frequency range will be studied. The foundation behaviour under dynamic loading situations will be shown by performing sweep calculations, and the foundation resistance will be proven by applying the static equivalent force method.

The analogue procedure as described above is valid for seismic loading situations. As turbo generators are placed all over the world, i.e. in different seismic hazard zones, standardised foundations have to be able to resist certain earthquake loading levels, which have to be defined by the client for the 'basic design' studies. Based on gained knowledge of such detailed seismic analyses, practical design approaches are elaborated and summarised in specific design criteria. This paper treats the following reinforced concrete foundation types in regard to earthquake loadings: spring mounted, table mounted and raft foundations.

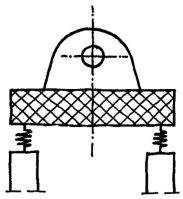
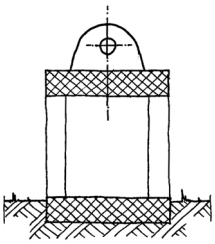
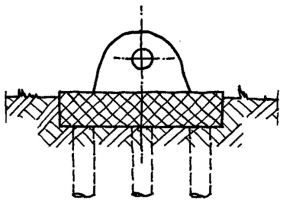
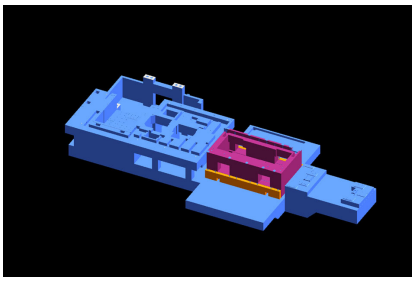
Spring Mounted Foundation	Table Mounted Foundation	Raft Foundation
		
Battle River 400 MW, Canada Erection State	Meishi, China, Steam Turbine Table Erection State	 ALSTOM Power KA26-1 SS, PDMS-Model Turbo Set Foundation

Fig.1: Machine Foundations Types

1.2. Design Aspects

The design has to provide detailed knowledge of the static and dynamic behaviour of the foundation and of the load transfer mechanisms (e.g. from the machine to the foundation and further to the substructure / soil). It has also to provide a deeper understanding of the governing excitation forces and associated frequencies for studies of the machine performance. Design requirements on turbo generator machine foundation can be summarised as following: The foundation has to guaranty smooth running during normal operation, and foundation integrity for possible accidental loading situations. For this, aspects as eigenfrequencies, operational vibration velocities, bearing stiffness, accidental loadings (especially dynamic amplifications), foundation section forces, loads on the foundation supports (soil/piles), overall stability, foundation deformation (e.g. rotor axis curvature during normal operation), vibration propagation, etc. have to be checked separately. The main aspects of dynamic design studies may be summarised as follows:

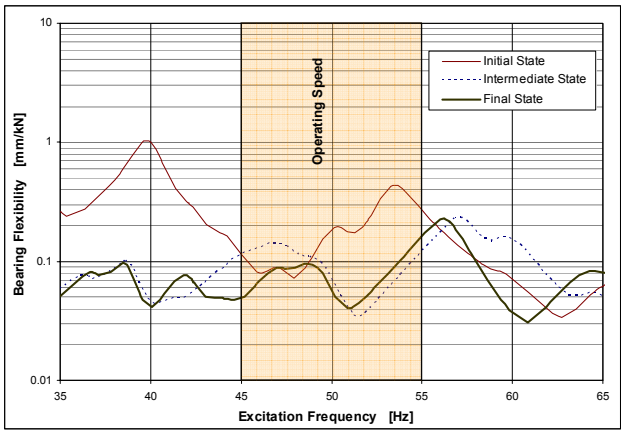
Eigenfrequencies: Avoiding main structural resonances is starting point of every dynamic investigation. If governing structural eigenfrequencies can be tuned out of the critical frequency range (range next to the operation speed), the dynamic design will of less importance, meaning simplified design principles can be applied. The number of eigenfrequencies to be calculated has to be in accordance with the operating speed: highest eigenfrequency has to be

at least 10% higher than the operating speed.

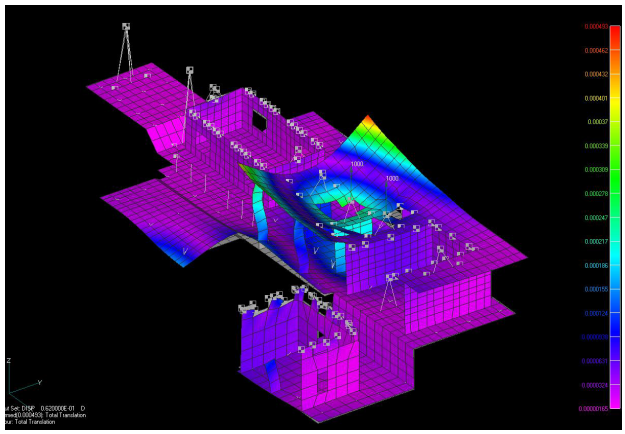
Dynamic stiffness of the foundation (flexibility of the bearing supports): In general no calculation regarding the shaft - foundation interaction will be performed. Instead machine manufacturers are defining dynamic foundation stiffnesses to be achieved on basis of their own design data, assumptions (e.g. when designing the shaft the stiffness and damping of the oil film and the bearing structure has to be considered) and calculations. Other than the static stiffness, the dynamic stiffness implies the mass inertia and describes the dynamic behaviour under harmonic loading situations. Such resonance plots are showing in detail the participation of the numerous eigenfrequencies for a selected point and direction and are used to judge the vibration sensitivity (mainly for the range next to the operational speed).

Operational vibration velocities: Forced vibrations of the foundation itself as well as of the machine bearing supports have to be within certain limits, defined by machine manufacturer or codes. If no specific requirements are present, the vibration situation can be judged based on ISO 10816 „Mechanical vibration - Evaluation of machine vibration by measurements on non-rotating parts“. For rotating machines the excitation is given in regard to the balancing quality (e * Ω): Good balanced machines lead to relative small movements on the bearing supports.

Accidental load cases: Dynamic accidental loads, e.g. blade loss or generator short circuit, can be simplified to static equivalent forces. In general, i.e. without detailed investigation of the excitation of the foundation, a dynamic amplification factor of 1.7 can be assumed (increase of the dynamic force due to resonance nearness). However, it is recommended to study accidental loads in detail as they become governing for most parts of the foundation, especially for machine anchorages.



Example ‘System Tuning’:
Vertical Bearing Flexibility of a TG Machine



Accidental Load Case ‘Blade Loss ST HP’
(Accidental Unbalance Steam Turbine High Pressure)

Fig.2 Example Plots ‘Design Aspects’

Summarised, including further design aspects as vibration isolation, differential settlements, temperature effects, overall foundation stiffness, fatigue aspects, etc. it can be stated that: **Foundations have to be very stiff, as heavy as possible and preferably soft supported**!

1.3. Numeric Modelling Principles

Within this chapter, main aspects regarding numerical modelling principles are summarised. All design procedures have to be based on simple but adequate models reflecting the real behaviour of the structure, including earthquake design studies. For first estimations and principal studies spring-mass-systems can be used, for more detailed investigations numerical (FE-)models are required. In any case of dynamic calculations / modelling the following aspects have to be considered properly:

Mass: Machine and foundation masses have to be right in size and position. Machine masses (e.g. rotor masses) have to be placed at their centre of gravity and be connected to the foundation by bars. In general, these bars are modelled as rigid connections.

Stiffness: Position and size of foundation and subsoil stiffness as main parameters of the fundamental eigenfrequencies have to be considered properly. Additional stiffness due to the machine itself and their fixation to the foundation and non-bearing elements have to be implemented for slender foundations. The subsoil stiffness is often modelled by elastic springs (pile supported foundations) or bedding modulus (directly soil supported foundations).

Damping: The total energy dissipation is based on several phenomena, mainly on nonlinear material damping of the structure and the subsoil. For constructional engineering studies the damping ratio ζ is used and applied as one value for the whole system: A total system damping factor is considered, implying all damping phenomena.

2. SEISMIC LOADING SITUATIONS

2.1. Requirements

Seismic safety of structures means to ensure withstanding a possible intensity of earthquake with a clearly defined return period, e.g. of 1 in 10,000 years. Very rare earthquakes are termed as Safe Shutdown Earthquakes (SSE). All structural members have to be designed to withstand the full seismic loading and to allow a safe shutdown of the plant; the structure must not remain fully operational after the event. Machine foundations normally have to keep their integrity, even after a considerable earthquake, so called Operating Base Earthquake (OBE).

Static equivalent force methods are primarily used for such safeguard against major structural failures and loss of life (i.e. not to limit damage or maintain function). For turbo generator machine foundations, analogue principles can be used but some design factors are not applicable in the full size as for other structures, mainly speaking of ductility (function of earthquake level SSE or OBE).

2.2. Static Equivalent Force Method

Foundation earthquake design procedures and limitations have to consider seismic zoning, site characteristics, functions and importance of structures, structural dynamic behaviour (system and configuration) and height. Moreover, foundations have to be designed with adequate strength to withstand the lateral displacements, considering inelastic response of the structure and the inherent redundancy, overstrength and ductility.

Most codes treating structural earthquake loads do include static equivalent force method guidelines, based on the same principles. For example the determination of the Design Base Shear V is given according UBC 1997 hereafter (similar procedure is given in Eurocode 8):

$$V = \frac{C_v \cdot I}{R \cdot T} \cdot W \qquad V_{\max} = \frac{2.5 \cdot C_a \cdot I}{R} \cdot W \qquad V_{\min} = 0.11 \cdot C_a \cdot I \cdot W$$

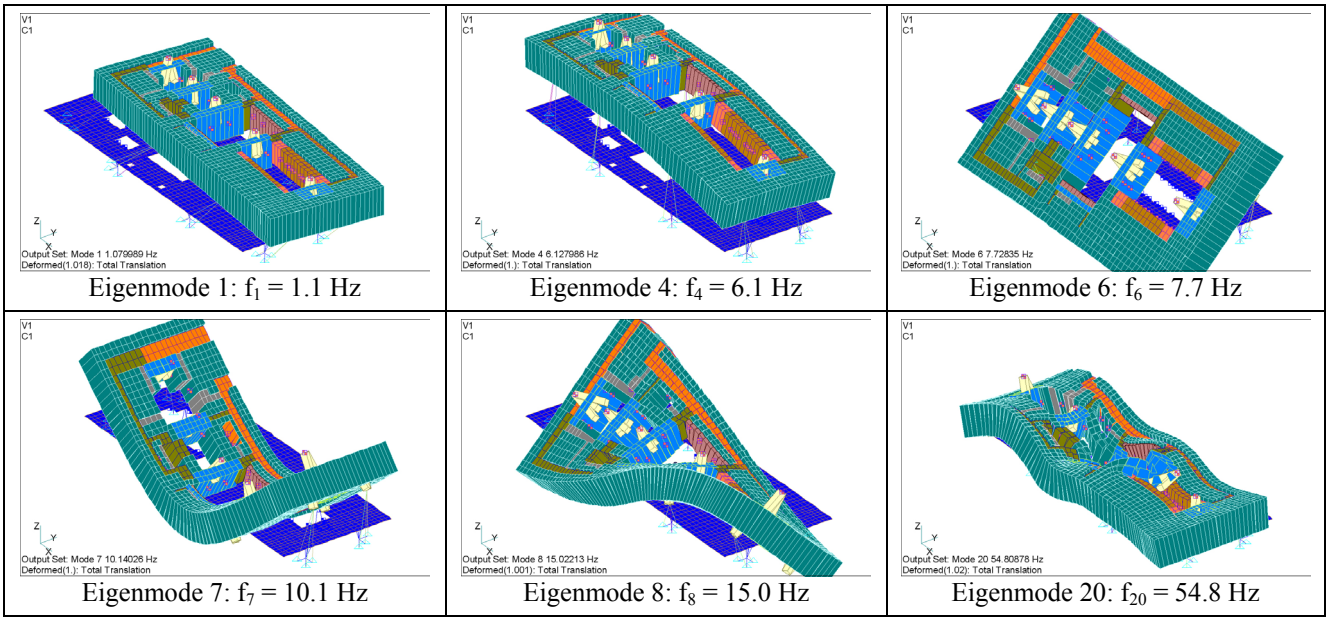
Where:
- C_x = Seismic Coefficients in dependence of the soil type and the seismic zone
- I = Importance Factor
- R = Inherent Overstrength and Global Ductility Capacity Coefficient
- T = Elastic Fundamental Period of the structure in the direction under consideration [s]
- W = Total Seismic Dead Load

Where modes other than the fundamental one affect significantly the response of the structure, modal response spectrum analyses have to be applied. Near source effects will not be treated within this document as the proposed simplified design procedure is only valid to a certain level of peak ground acceleration.

2.3. Dynamic Behaviour of Machine Foundations

2.3.1 Eigenmodes

The principle dynamic behaviour of structures can be described best by their eigenmodes (shape and frequency) and their participation factors. Parametric numerical simulations are performed in order to examine the effects of support conditions (different soil / substructure 'replacements' / FE-elements) on the dynamic response. For raft foundations, such studies have shown that the soil / pile resiliences have only an effect on the basic (low) natural frequencies, whereas the higher vibration modes, governing the operational dynamic behaviour, are virtually not affected. Moreover, the support conditions have only a „square-root"-influence on the natural frequencies, meaning the fundamental eigenfrequencies are not very sensitive to subsoil / bedding differences. The same can be stated for table mounted and spring mounted machine foundations. Whereas for spring mounted foundations mainly the tuning frequency is governing for the fundamental eigenfrequencies (spring characteristics), column properties are predominant for table mounted foundations. For the last named, high tuned and low tuned systems in regard to the operational speed have to be separated.



Eigenmode 1: $f_1 = 1.1$ Hz | Eigenmode 4: $f_4 = 6.1$ Hz | Eigenmode 6: $f_6 = 7.7$ Hz

Eigenmode 7: $f_7 = 10.1$ Hz | Eigenmode 8: $f_8 = 15.0$ Hz | Eigenmode 20: $f_{20} = 54.8$ Hz

Fig.3 Selected Eigenvalues of a Spring Mounted Foundation

Finally, it has to be stated that predominant periods of ground motions are in general close to the eigenperiods of typical machine foundations, meaning due to resonance effects max. base shear has to be considered.

2.3.2 Loading Distribution

Main governing parameter, beside the base shear, is the loading distribution. Extensive, mostly linear time history calculations have been carried out on three-dimensional models, additionally checked by simplified calculations. Main emphasis on these studies has been laid on this aspect. The used, artificially generated soil accelerations to study the foundation behaviour were generally based on design spectrums according to the Swiss Code.

The vertical height distribution of the total force V has to consider the fundamental eigenform (distribution of the mass inertia due to the shape of exited eigenfrequency) and, for example, is often given mainly for story buildings in the form of $V = F_t + \Sigma F_i$ (F_t is a concentrated force at the top and F_i is a concentrated force located to a level, linearly increasing by the height). For machine foundation this height distribution has to be calculated separately in regard to the main directions.

2.3.3 Conclusions

- In general, for all type of foundations maximum design base shear has to be used: $V_{max} = a_{max} \cdot W$. Predominant ground motion frequencies are close to the eigenfrequencies of the foundations. Sometimes, for high tuned table mounted foundations it is reasonable to study a possible reduction of the base shear due to higher fundamental eigenfrequencies.

- Modal superposition has to be considered for table mounted machine foundation, as several eigenmodes can affect the response of the structure significantly.

- Accidental eccentricity of earthquake loads due to uncertainties in the distribution of mass and stiffness is small and can be neglected; this is valid for both, translational and torsional dynamic effects.

- For all foundation types the substructure (piles, soil, columns and springs) can be modelled by spring elements, the dynamic behaviour can be represented accurately. Since today enough computational calculating capacity is normally present in the design offices, it is recommended for table mounted foundations to include the whole structure and replace the soil / piles by spring elements.

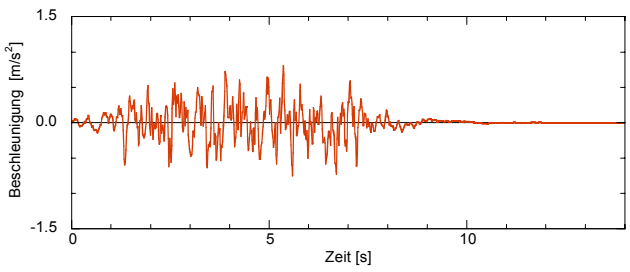
- In regard to the height distribution of the total earthquake load, the linearly increasing distribution can be kept but the base level has to be adapted, e.g. for raft foundation it lays about have of the width beyond the foundation, meaning within the soil.

- The material of the foundation stays (has to stay) mostly within the linear range. Plasticity may occur next to adjacent structures. All machine anchorages have to be designed to withstand the full earthquake loads. This means that the global ductility has to be set to a low value, and the focus on constructive measures for increasing the plastic bearing capacity, if required, has to be laid on pile heads and column connections.

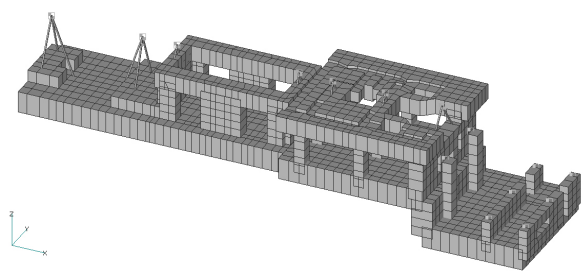
- Machine Fixations: Special care has to be taken to machine anchorages, especially for key points where in horizontal direction higher loads have to be taken compared to the vertical loads.

- For spring and table mounted machine foundation horizontal displacement limitations have to be considered from the beginning as additional measures, e.g. horizontal spring elements, additional horizontal dampers or shear stops can become necessary, which have to be connected to the adjacent structure.

- Substructure of spring mounted foundation has to be stiff enough to avoid interaction of the fundamental eigenfrequencies of the mounted machine foundation and the substructure.



Artificially Generated Soil Acceleration Time History
(based on Swiss Code Design Spectrums)



FE-Model Raft Foundation
(Single Shaft Turbo Set Foundation)

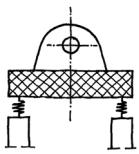
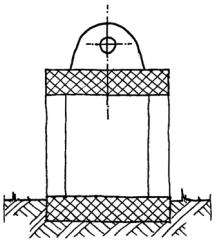
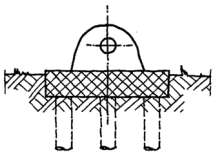
Fig.4 Example Plots Soil Acceleration and FE-Model

3. SIMPLIFIED DESIGN PRINCIPLES

Based on detailed foundation studies for prototype foundations and on experience the following simplified seismic design principles on the basis of the static equivalent force method are proposed.

As eigenperiodes are laying in general between the control periods of design response spectra, V_{max} has to be applied for all foundation types:

$$V_{\max} = \frac{2.5 \cdot C_a \cdot I}{R} \cdot W = a_{\max} \cdot W$$

Type	**Spring Mounted Found.**	**Table Mounted Found.**	**Raft Foundation**
Schema			
System tuning	low tuned	high or low tuned	-
Governing Eigenmodes	Rigid body translations and rotations	Rigid body translations and rotations, column bending	Rigid body translations and rotations
Modal Superposition	No	Yes (to be checked if required)	No
Transversal Load Distribution	$a_{Machine} = 1.2 \cdot a_{max}$ $a_{Foundation} = 0.9 \cdot a_{max}$	$a_{Machine} = 1.2 \cdot a_{max}$ $a_{Toptable} = 1.1 \cdot a_{max}$ $a_{Columns} = 1.0 \cdot a_{max}$ $a_{Baseplate} = 0.8 \cdot a_{max}$	$a_{Machine} = 1.4 \cdot a_{max}$ $a_{Foundation} = 0.8 \cdot a_{max}$
Longitudinal Load Distribution	$a_{Machine} = 1.0 \cdot a_{max}$ $a_{Foundation} = 1.0 \cdot a_{max}$	$a_{Machine} = 1.2 \cdot a_{max}$ $a_{Toptable} = 1.0 \cdot a_{max}$ $a_{Columns} = 1.0 \cdot a_{max}$ $a_{Baseplate} = 0.9 \cdot a_{max}$	$a_{Machine} = 1.2 \cdot a_{max}$ $a_{Foundation} = 0.9 \cdot a_{max}$
System Damping (Soil-Foundation-Machine)	2 %	3 %	4 %
Global Ductility	1.0	1.5	2.0
Horizontal Displacements	have to be limited, if necessary	have to be limited, if necessary	-
Horizontal Earth Pressure	not present	negligible	may be included in some cases

Restriction to the application of simplified design principles using static equivalent force method: The following aspects have to be fulfilled!

Maximum soil acceleration a_{max}	< 0.4 g	< 0.4 g	< 0.5g
Mass Ratio 'Foundation : Machine'	> 2 : 1	> 2 : 1	> 2 : 1
Substructure	'Stiff'	'Soft'	'Soft'
Foundation width : length	< 1 : 2	< 1 : 2	< 1 : 2

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