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# Permanent deformation estimates of dynamic equipment foundations: Application to a gas turbine in granular soils

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ABSTRACT

Permanent displacements of a gas turbine founded on a fine, poorly graded, and medium density sand are studied. The amplitudes and modes of vibration are computed using Barkan´s formulation, and the "High-Cycle Accumulation" (HCA) model is employed to account for accumulated deformations due to the high number of cycles. The methodology is simple: it can be easily incorporated into standard mathematical software, and HCA model parameters can be estimated based on granulometry and index properties. Special attention is devoted to 'transient' situations at equipment´s start-up, during which a range of frequencies – including frequencies that could be similar to the natural frequencies of the ground – is traversed. Results show that such transient situations could be more restrictive than stationary situations corresponding to normal operation. Therefore, checking the stationary situation only might not be enough, and studying the influence of transient situations on computed permanent displacements is needed to produce a proper foundation design.



## 1. Introduction

Cyclic loads acting on a foundation element are transmitted to the ground, producing strains that may induce settlements. Such settlements need to be controlled for an adequate functionality of foundations and of their overlaying equipments. Previous research on the cyclic behavior of sands has mainly considered seismic loading: i.e., short and intense cyclic-loads that may produce liquefaction, permanent deformations, or both. But machine foundations are different, since vibration amplitudes are usually small and do not produce substantial short-term deformations. For instance, in foundations on non-saturated soils, appreciable permanent deformations could occur as a result of dynamic amplifications due to matching of the natural vibration frequencies of the soil and the equipment; or, as indicated by Okur and Ansal [1], to 'stiffness degradation' –the rapid growth of deformation that occurs when a certain number of cycles of a given amplitude act on the soil [2]– produced by the high number of load cycles.

To avoid resonance problems, it is common that manufacturers suggest that the mass of the foundation is 2–3 times the mass of the vibrating machine. However, such approach is often heuristic, as a larger foundation mass does not necessarily imply smaller vibrations [3]. Building on previous research, Anyaegbunam [3] has recently proposed methods to select foundation mass to limit vibrations. Such solutions, however, assume the damped vibration of a single degree of freedom (SDOF) analog, hence neglecting cyclic soil behavior.

In this work, permanent deformations (displacements) of a gas turbine founded on granular soils are studied, considering both normal 'steady-state' operation and 'transient-states', such as those occurring during start-up and switch-off. (A recent similar analysis is presented by Francois et al. [4], who considered accumulated foundation settlements in granular soils due to traffic loading.) The explicit "High-Cycle Accumulation" (HCA) model [5,6] is used to estimate deformations in this work. Since the model is simple to program and use, with parameters that can be estimated using common geotechnical information – mainly, granulometry (grain size, uniformity), and index properties (minimum void ratio) [7] – it can be employed, even at initial stages of a project, for simple settlement estimations of foundations for vibratory equipment, such as those commonly employed for turbines in energy projects.

## 2. Project description

### 2.1. Geotechnical characterization and geometry of the gas turbine foundation

We study the foundation of a gas turbine – and its auxiliary equipments – in a combined-cycle energy plant. The turbine

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foundation is constructed using a concrete block with weight $W$=24,699 kN. The block is symmetric along its longitudinal axis, with $L$=43 m length, and with variable width, $B$, with $B$=8 m below the control units and the generator, and with $B$ reaching $B$=12.8 m under the turbine. (The average width is $B_{av}$=9.07 m). See Fig. 1 for a schematic representation of the foundation layout, and Fig. 2 for a cross section.

Available geotechnical data, including SPT measurements, show that the turbine is founded on a fine, poorly graded, and medium density sand, which is homogeneous with depth. It has a uniformity coefficient of $C_u$=4.2, a coefficient of curvature of $C_c$=0.92, and an average grain size $d_{50}$=0.32 mm. Its minimum void ratio, corresponding to 'maximum density' conditions, is $e_{min}$=0.40, and the maximum is $e_{max}$=0.70, with an in-situ void ratio of 0.50, critical friction angle of 30° and a bulk density of 18 kN/m$^3$. The water table is deep enough so as not to affect the foundation performance.

A cross-hole test was conducted to characterize the ground´s dynamic elastic parameters. Results are presented in Fig. 3, which suggests an approximately linear increase with depth. Given such data, representative average values for the dynamic 'stress bulb' below the foundation, corresponding to approximately 1.5 times the foundation width (1.5$B$=13.5 m), are selected. Thus, the following parameters, that correspond to the arithmetic average of available field data, will be adopted as representative for dynamic design: Poisson ratio 0.3, elastic Young´s modulus 729 MPa, and Shear modulus 279 MPa. Due to the small strain amplitudes generated in the soil by the gas turbine, an amplitude dependence of these dynamic parameters is not considered in the present study. In addition, on the side of safety, the increase of the stress in the subsoil due to the weight of the vibratory equipment, and of its foundation, is not considered to obtain such representative elastic values.

### 2.2. Vibration of the gas turbine

The eccentricity of a rotating mass with respect to its rotation axis produces dynamic loads that depend on the mass, and on the angular velocity, of the rotating device. In our case, the dynamic loads are due to the turbine and the generator; since they have the same rotation velocity, they can be considered as a unique dynamic load, and they will jointly referred to as the 'turbine' load.

The manufacturer provides the 'equivalent' magnitude of the (centrifugal) force produced by the turbine in the stationary regime. It can be computed as:

$$P_0 = \frac{\pi W_L N_m}{980} \tag{1}$$

where $P_0$ is the magnitude of the equivalent centrifugal force (kN), $W_L$ is the weight of the rotating mass (kN) and $N_m$ is the rotation frequency (Hz). (See Table 1 for values corresponding to the equipments considered herein).

However, gas turbines can also produce transient situations with variable rotation frequency. As an example, Fig. 4 shows the evolution with time of the turbine´s vibration frequencies during 'start-up': first, there is a fast frequency increase, reaching approximately 600 rpm after 100 s; then, there is a 360 s period with constant vibratory frequency that corresponds to the 'purging' or 'cleaning' of the turbine; and, finally, the frequency increases almost linearly until it reaches, after approximately 28 min (1680 s), its steady-state (normal operation) value of 3600 rpm (60 Hz). Below, it is shown that these transient situations can have a significant contribution to permanent deformations.

## 3. Dynamic analysis of the foundation

To study the dynamic behavior of the ground, we first need to compute its response – amplitudes and modes of vibration – as a result of the (harmonic) dynamic loads introduced by the vibratory equipment. Traditionally, such analyses have been conducted using Barkan´s formulation [8], which assumes a vibratory mass on elastic ground, *as neglecting damping is simpler and on the side of safety*.

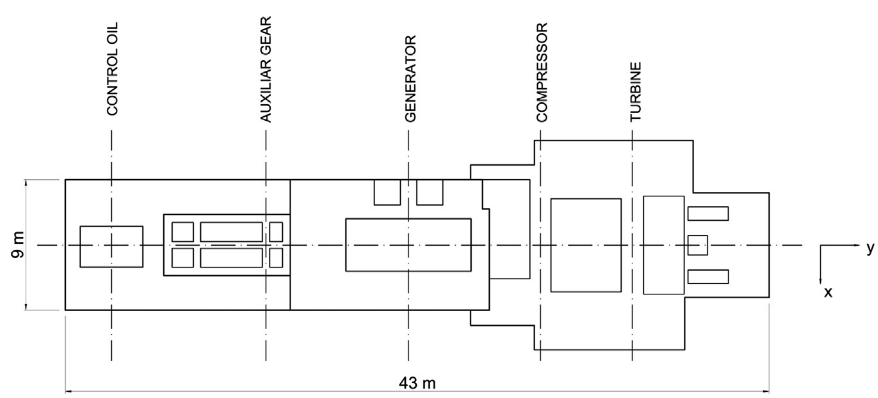


**Fig. 1.** Simplified geometry of the gas turbine foundation (plan view).

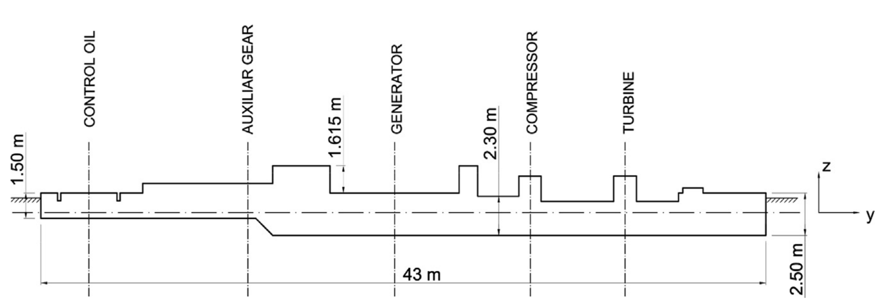


**Fig. 2.** Cross section of the turbine foundation.