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DYNAMIC BEHAVIOUR OF SOILS IN MACHINE–FOUNDATION–SOIL INTERACTION

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ABSTRACT

This paper analyzes the dynamic behavior of cohesionless soils within the machine–foundation–soil interaction system from a mechanical engineering perspective. The types of dynamic loads generated by industrial equipment are presented together with the mechanical modeling of the system using a single-degree-of-freedom approach. The influence of vibration amplitude on dynamic shear strength and soil stiffness is highlighted. The reduction of soil dynamic parameters may modify the system's natural frequency and promote resonance phenomena. Therefore, the design of foundations for vibrating machinery must be based on a comprehensive dynamic analysis that accounts for the nonlinear behavior of cohesionless soils.

KEYWORDS: mechanical vibrations, dynamic loading, dynamic shear strength, vibration stability

1. INTRODUCTION

In the context of the development of high-power industrial equipment and the increasing dynamic performance of such systems, the analysis of the vibration behavior of mechanical systems becomes an essential component of the design process. The operation of equipment such as rotating machines, turbogenerators, compressors, or compaction equipment generates dynamic loads. This transmitted to the foundation and, subsequently, to the supporting soil, therefore, influencing the stability and durability of the entire system.

Traditional approaches have considered the soil as an ideal rigid support. However, experimental and theoretical research in soil dynamics has shown that the supporting soil behaves as a deformable medium. This is characterized by elastic and dissipative properties, with a pronounced nonlinear behavior depending on the level of dynamic loading [5,7]. Consequently, the soil must be integrated into the mechanical model of the machine–foundation–soil system and treated as an active element that influences the overall vibration response.

The present paper aims to analyze the dynamic behavior of cohesionless soils within the machine–foundation–soil system. It also focuses on the variation of shear strength under dynamic conditions and on its implications for the natural frequency and vibration stability of mechanical equipment. In this context, analyzing the interaction between the machine, the foundation, and the supporting soil becomes

essential for a correct evaluation of the dynamic behavior of the system.

2. CLASSIFICATION OF DYNAMIC LOADS

Dynamic are time-varying actions that produce vibrations or oscillatory motion in mechanical systems [6]. In the case of machine foundations, these loads are generated either by the operation of industrial equipment or by external phenomena that transmit vibrational energy to the supporting soil. The analysis of dynamic loads is essential for evaluating the behavior of the machine–foundation–soil system and for preventing vibration instability phenomena.

From the point of view of time variation, dynamic loads can be classified into several categories. Each type of loading produces a different response of the mechanical system and requires specific analysis methods.

Harmonic loads are characterized by a sinusoidal variation in time and are frequently encountered in rotating machines or equipment generating periodic vibrations. In these situations, the excitation force can be expressed by relation (1):

$$F(t) = F_0 \sin(\omega t) \quad (1)$$

where F_0 represents the amplitude of the force and ω is the angular frequency.

Periodic composite loads are characterized by the repetition of a certain motion pattern after a specific time interval. These loads can be decomposed into harmonic components using Fourier analysis and are frequently encountered in industrial machinery operating in cyclic regimes.

Random loads do not present deterministic variation and are characteristic of phenomena such as earthquakes or dynamic loads generated by heavy vehicle traffic. In such cases, system response analysis is performed using statistical methods.

Transient loads are generated by short-duration actions such as impacts or mechanical shocks. These loads produce a temporary system response, with vibration amplitudes gradually decreasing until equilibrium conditions are restored. Dynamic loads can be classified according to the time variation law as follows:

Harmonic loads – characterized by a sinusoidal variation in time, expressed by the relation $F(t)=F_0\sin(\omega t)$. These loads are typically generated by rotating machines and may lead to resonance phenomena.

Composite periodic loads – represent periodic excitations that can be decomposed into harmonic components using Fourier series. Such loads are encountered in equipment like turbogenerators and may produce multi-frequency vibrations.

Random loads – non-deterministic loads whose variation does not repeat in time. Typical examples include external excitations such as earthquakes or traffic-induced vibrations. Their analysis generally requires probabilistic methods.

Transient loads – loads produced by short-duration impulses such as shocks or impacts. These loads generate a temporary vibration response that gradually decreases due to damping.

These categories of dynamic loads must be considered when analyzing the vibration response of the machine–foundation–soil system.

3. MECHANICAL MODELING AND DYNAMIC SHEAR STRENGTH

3.1 Mechanical modeling of the machine–foundation–soil system

For the analysis of dynamic behaviour, the machine–foundation–soil system can be represented by a simplified mechanical model shown in Fig. 1, in which the soil is modelled as an elastic element characterized by stiffness k and a dissipative element defined by the damping coefficient c.

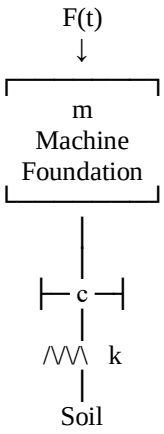

Fig. 1. Simplified mechanical model of the machine–foundation–soil system used in vibration analysis of machine foundations.

The machine–foundation–soil system can be modelled as a single-degree-of-freedom system described by the differential equation of motion [6]:

$$F(t) = m\ddot{x} + c\dot{x} + kx \quad (2)$$

where m represents the equivalent mass of the machine–foundation system, k the dynamic stiffness of the soil, c the damping coefficient, and F(t) the excitation force generated by the machine.

The parameters k and c depend on the dynamic properties of the soil and on the vibration level.

3.2 Shear strength under static and dynamic conditions

Under static conditions, the shear strength of cohesionless soils is mainly governed by the internal friction between soil particles and can be expressed according to the Mohr–Coulomb failure criterion by relation (3):

$$\tau_s = \sigma \tan \phi_s = \mu_s \sigma \quad (3)$$

where: σ represents the normal stress and φ_s is the internal friction angle under static conditions, μ_s - coefficient of internal friction determined under static conditions.

According to the results obtained by the researchers, in the case of dynamic shear, the dependence relationship between shear stress and normal stress remains linear as in static shear (fig. 1). As a result, the dynamic resistance can be expressed as follows (4):

$$\tau_d = \sigma \tan \phi_d + \tau_0 = \mu_d \sigma + \tau_0 \quad (4)$$

where: τ_d -dynamic shear strength; σ- normal stress; φ_d - angle of internal friction determined under dynamic conditions; μ_d - coefficient of internal friction determined under dynamic conditions; τ_o - initial shear strength due to possible cohesive forces.

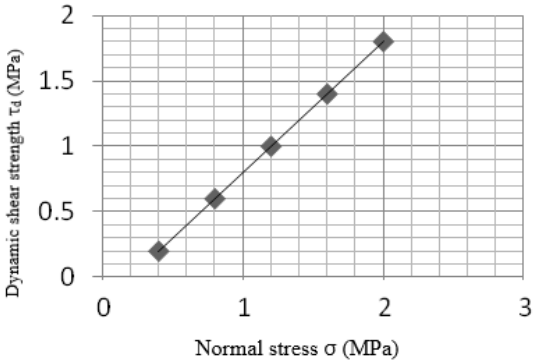

Fig. 2. Variation of dynamic resistance depending on stress

The main differences between the static and dynamic behaviour of soils can be summarized as follows:

a/. The internal friction angle under static conditions is denoted by φs, while under dynamic conditions it becomes φ_d. Experimental observations show that φdis generally smaller than φ_s, as vibration reduces the interparticle contact forces.

b/. The friction coefficient under static conditions is $\mu_s = \tan\varphi_s$, while under dynamic loading it becomes $\mu_d = \tan\varphi_d$. In dynamic conditions, this parameter may vary depending on the intensity and amplitude of the vibrations.

c/. The stiffness of the soil under static loading can be considered almost constant. However, under dynamic loading the stiffness becomes variable and depends on the level of vibration

d/. The stability under static conditions is mainly determined by the balance of forces. Under dynamic conditions, the stability of the system becomes sensitive to resonance phenomena, which makes dynamic analysis necessary.

3.3 Resonance and vibration stability

In mechanical systems subjected to dynamic loads, one of the most important phenomena is resonance. This occurs when the excitation frequency approaches the natural frequency of the machine–foundation–soil system.

The natural frequency of the system is given by relation (5):

$$\omega_n = \sqrt{\frac{k}{m}} \quad (5)$$

where k represents the dynamic stiffness of the soil and m the equivalent mass of the machine–foundation system. When the excitation frequency ω approaches the natural frequency ω_n, vibration amplitudes may increase significantly. This phenomenon is known as resonance and can lead to amplification of displacements and mechanical stresses in the system [3]. The vibration stability of the system depends directly on the stiffness and damping of the supporting soil. The presence of damping leads to energy dissipation and reduces vibration amplitudes, contributing to the dynamic stability of the machine–foundation–soil system.

4. IMPLICATIONS FOR THE DESIGN OF FOUNDATIONS SUBJECTED TO DYNAMIC LOADS

The design of foundations for machinery generating dynamic loads must consider the complex interaction between the machine, the foundation, and the supporting soil [1,4]. Unlike foundations subjected to static loads, in this case, the effects of vibrations on the stability and dynamic behaviour of the system must be carefully analyzed. An essential aspect is the accurate determination of the dynamic parameters of the soil, particularly the dynamic stiffness and the damping coefficient. These parameters influence the natural frequency of the system and its ability to dissipate vibration energy. In the case of cohesionless soils, the dynamic stiffness may decrease as the vibration amplitude increases, which may lead to changes in the operating conditions of the machinery. During the design process, it is necessary to avoid coincidence between the operating frequency of the machinery and the natural frequency of the machine–foundation–soil system. Approaching this condition may lead to the occurrence of resonance,

characterized by a significant amplification of vibration amplitudes and an increase in mechanical stresses. This acts on both the foundation structure and the equipment. Furthermore, the mass and dimensions of the foundation must be selected so as to contribute to the reduction of vibration amplitudes and to increase the dynamic stability of the system. In general, a foundation with a larger mass leads to lower displacement amplitudes and improved vibration performance.

In certain situations, vibration isolation systems such as elastic pads, dampers, or layers of granular material are used in order to limit the transmission of vibrations to nearby structures. These solutions reduce the vibrational energy transmitted to the soil and help protect adjacent structures.

Therefore, the design of foundations for vibrating machinery must be based on a rigorous dynamic analysis that includes the real characteristics of the soil and its nonlinear behaviour under vibration loading. The dynamic behaviour of foundations for machinery is influenced by several factors related both to the characteristics of the machinery and to the properties of the supporting soil. The main factors influencing the vibration response of the machine–foundation–soil system are summarized in Table 1.

Table 1. Factors influencing the dynamic behaviour of the machine–foundation–soil system

Factor	Description	Effect on dynamic behavior
Machine mass	Total mass of the equipment and foundation	Influences the natural frequency
Soil stiffness	Deformation modulus of the soil	Determines system stiffness
Vibration amplitude	Intensity of dynamic excitation	May reduce dynamic stiffness
Operating frequency	Frequency of vibrations generated by the machine	May lead to resonance
System damping	Capacity for energy dissipation	Reduces vibration amplitude

5. CONCLUSIONS

The analysis highlights that the supporting soil represents an active element of the machine–foundation–soil system and directly influences its dynamic behaviour. The reduction of shear strength under dynamic conditions and the decrease in equivalent stiffness caused by increasing vibration amplitude may modify the natural frequency of the system and lead to resonance conditions.

Under these circumstances, the design of foundations for vibrating machinery must rely on rigorous dynamic analysis that considers the real properties of the soil and its nonlinear behaviour under dynamic loading.

The integration of soil dynamics principles into the analysis of mechanical systems contributes to improving vibration stability and increases the operational safety of industrial equipment.

A proper evaluation of soil dynamic parameters also allows the optimization of foundation design and the reduction of vibration transmission to surrounding structures. Furthermore, understanding the interaction between machinery, foundations, and the supporting soil is essential for the development of reliable engineering solutions for modern industrial installations subjected to dynamic loading.

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