

Machine Foundation Design

Procedure

This Standard replaces and cancels its previous revision.

The CONTEC - Authoring Subcommittee provides guidance on the interpretation of this Standard when questions arise regarding its contents. The Department of PETROBRAS that uses this Standard is responsible for adopting and applying the sections, subsections and enumerates thereof.

Technical Requirement: A provision established as the most adequate and which shall be used strictly in accordance with this Standard. If a decision is taken not to follow the requirement ("non-conformity" to this Standard) it shall be based on well-founded economic and management reasons, and be approved and registered by the Department of PETROBRAS that uses this Standard. It is characterized by imperative nature.

Recommended Practice: A provision that may be adopted under the conditions of this Standard, but which admits (and draws attention to) the possibility of there being a more adequate alternative (not written in this Standard) to the particular application. The alternative adopted shall be approved and registered by the Department of PETROBRAS that uses this Standard. It is characterized by verbs of a nonmandatory nature. It is indicated by the expression: **[Recommended Practice]**.

Copies of the registered "non-conformities" to this Standard that may contribute to the improvement thereof shall be submitted to the CONTEC - Authoring Subcommittee.

Proposed revisions to this Standard shall be submitted to the CONTEC - Authoring Subcommittee, indicating the alphanumeric identification and revision of the Standard, the section, subsection and enumerate to be revised, the proposed text, and technical/economic justification for revision. The proposals are evaluated during the work for alteration of this Standard.

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Introduction

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Foreword

This Standard is the English version (issued in 07/2013) of PETROBRAS N-1848 REV. C 12/2011. In case of doubt, the Portuguese version, which is the valid document for all intents and purposes, shall be used.

1 Scope

1.1 This Standard sets out the geotechnical, dimensional and performance checking parameters for preparation of design of foundations for stationary machinery (rotary and reciprocating) subject to vibrating loads.

1.2 This Standard applies to procedures beginning from its issue date.

1.3 This Standard contains Technical Requirements and Recommended Practices.

2 Normative References

The documents listed below are essential to the application of this Standard. For determined references, only the mentioned editions shall be applied. For non-determined references, the newest editions of the mentioned documents are applied (including amendments).

PETROBRAS [N-1644](#) - Construction of Reinforced Concrete Foundations and Structures;

PETROBRAS [N-1784](#) - Presentation of Designs in Concrete Structures;

ABNT [NBR 6118](#) - Projeto de Estruturas de Concreto;

ABNT [NBR 6122](#) - Projeto e Execução de Fundações;

ABNT [NBR 6489](#) - Prova de Carga Direta sobre Terreno de Fundação;

ABNT [NBR 8681](#) - Ações e Segurança nas Estruturas;

ABNT [NBR 12131](#) - Estacas - Prova de Carga Estática;

ABNT [NBR 13208](#) - Estacas - Ensaio de Carregamento Dinâmico;

ABNT [NBR 15928](#) - Ensaio Não Destrutivo - Análises de Vibrações - Terminologia;

API-[686](#) - Recommended Practice for Machinery Installation and Installation Design;

DIN [4024](#) - Machine Foundations;

ISO [2631](#) - Mechanical Vibration and Shock - Evaluation of Human Exposure to Whole-Body Vibration.

3 Terms and Definitions

For purposes of this Standard, the terms and definitions indicated in items 3.1 to 3.29 are adopted.

3.1**coupling**

a physical phenomenon in which energy is transferred between different modes of vibration in an elastic system. This changes the original modes of vibration (also called uncoupled modes of vibration) and their respective natural vibration frequencies.

3.2**damping**

a phenomenon associated with the dissipation of energy and that opposes the vibration of an elastic system.

NOTE For the purposes of this Standard, damping means the "geometric damping" of the foundation.

3.3**amplitude**

maximum deviation of a point or part of a vibrating system from its "at rest" position.

3.4**dynamic analysis (for vibration)**

a study of the movement of a physical system over a particular period of time.

3.5**static analysis**

investigation of a physical system in equilibrium under the action of a stationary system of forces.

3.6**modal analysis**

dynamic analysis of a system with multiple degrees of freedom, where the responses obtained for each mode of vibration (each of which is treated independently as a system with a single degree of freedom) are determined separately and then superimposed (or "coupled") to obtain the final response resulting from the system.

3.7**balancing**

adjustment of the mass distribution of a rotating body in such a manner as to control or prevent vibration.

3.8**cycle**

the full range of states or values through which a periodic function or phenomenon goes through before being repeated identically. The cycle of a particle is associated with an angular displacement of 360° , where the particle begins the movement at an angular position $\theta = 0^\circ$ and completes the cycle at $\theta = 360^\circ$.

3.9**harmonic excitation**

effort (force or moment) described through a trigonometric (sinusoidal) function, which repeats itself at identical time intervals.

3.10**dynamic amplification factor**

the ratio of the deformation produced at a given point of a structure by dynamic application of force or moment to the deformation produced at that same point by static application of that force or moment.

3.11**dynamic force (dynamic load)**

force which duration and amplitude is a function of time.

3.12**frequency (f)**

the reciprocal of a period: It is the number of cycles completed by a particle in periodic movement in a unit of time. The following ratio is applied:

$$f = 1/T$$

NOTE The units most used are Hertz (Hz) or cycles/second and Revolutions Per Minute (RPM) or cycles/minute

3.13**angular frequency (ω)**

the product of the frequency of a sinusoidal quantity by the factor 2π . The unit of angular frequency is the radian per unit of time.

NOTE The following may be used: 1 Hz = 6.28 rad/s = 60 rpm

3.14**natural frequency**

a dynamic property of elastic systems by which they oscillate harmonically in relation to a fixed point when the excitation frequency is removed.

NOTE An elastic system has as many natural frequencies as degrees of freedom. In the case of rigid compressor bases, the number of natural frequencies of the foundation is 6.

3.15**over-tuned foundations**

machinery foundations in which the fundamental frequency of the foundation is higher than the operating frequency or exciting frequency of the machine. In this type of foundation, the frequency ratio is less than one.

3.16**low-tuned foundations**

machinery foundations in which the fundamental frequency of the foundation is lower than the operating frequency or exciting frequency of the machine. In this type of foundation, the frequency ratio is greater than one.

3.17**mode of vibration**

orderly motion of an elastic system where each point of the system vibrates at the same frequency, which is one of the natural frequencies of the system.

NOTE An elastic system has as many principal modes of vibration as natural frequencies.

3.18**fundamental mode**

also called 1st mode of vibration, it is the mode of vibration associated with the lowest natural frequency of an elastic system. This frequency is called fundamental frequency.

3.19**simple harmonic motion**

the motion of a body or part of a system, described through a trigonometric (sinusoidal) function, which repeats itself at identical time intervals.

NOTE All harmonic motion is necessarily periodic.

3.20**periodic movement**

movement that is repeated identically at regular intervals of time.

3.21**oscillation**

variation of a quantity, often as a function of time, in relation to its specified reference value, when that quantity varies around a particular mean value.

3.22**period (T)**

the smallest independent variable increment of a periodic quantity, before it is repeated identically.

3.23**frequency ratio**

the ratio of the frequency of the exciting force to the natural frequency of the system.

NOTE In resonance, the frequency ratio becomes one.

3.24**dynamic response**

a set of time-dependent displacements and/or stresses that emerge in an elastic system when a dynamic load is applied to it.

3.25**resonance**

a phenomenon that occurs when the excitation frequency matches one of the natural frequencies of an elastic system. The vibration amplitudes of a system in resonance may reach very high values, for which reason this condition shall be prevented.

3.26**vibration severity**

in this Standard, vibration severity is defined as a simple and understandable unit to describe the state of vibration of a machine. Based on theoretic considerations and practical experience, root mean square velocity has been chosen as the unit of measure for vibration severity.

3.27**root mean square velocity (v_{ef})**

the maximum root mean square velocity of vibration measured at significant points of a machine, such as bearings, a point of the foundation etc.

3.28**vibration**

variation over time of the value of a quantity describing the movement or position of a mechanical system, when the value is alternately greater or less than a given mean or reference value, usually the position of equilibrium.

3.29**forced vibration**

vibration induced by exciting forces applied externally. Forced vibration occurs at the frequency of the exciting force applied.

NOTE The excitation frequency does not depend on the natural frequency of the system.

4 Basic Data for Machine Foundation Design

When designing foundations for machinery, the information listed in 4.1 to 4.3 shall be obtained.

4.1 Soil Parameters

- a) position and nature of the soil layers/profile;
- b) maximum elevation of groundwater table;
- c) penetration resistance, as determined through an SPT test;
- d) specific weight of the soil (ρ);
- e) shear modulus of the soil (G);
- f) Poisson's ratio (ν);
- g) elastic modulus of the soil (E).

4.2 Equipment Parameters

The documentation of the equipment manufacturing shall contain the following information:

- a) dimensional drawing of the equipment, containing:
 - frame dimensions;
 - the main dimensions of the equipment;
 - position of the center of gravity of the assembly or its parts and components;
 - means of securing the equipment to the base/foundation (anchors, inserts);
- b) the weight of the assembly or the components of the assembly;
- c) operating frequencies of the elements of the assembly;
- d) dynamic loads (centrifugal forces, inertia forces of the moving masses and moments);
- e) critical operating frequencies of the machine (f_c);
- f) maximum permissible vibration amplitudes;
- g) short-circuit moment (for motors or generators).

4.3 Geometric Parameters of the Foundation

- a) centroid of the base area;
- b) combined center of gravity of foundation + machine;
- c) moment of inertia of the base area;
- d) mass moment of the foundation + machine.

5 General Design Requirements

5.1 Direct or Pile Foundations

The design of the foundation shall meet the requirements set out in standard PETROBRAS [N-1644](#), [N-1784](#), ABNT [NBR 6118](#), [NBR 6122](#), [NBR 6489](#), [NBR 8681](#), [NBR 12131](#), [NBR 13208](#), [NBR 15928](#), API [686](#), DIN [4024](#), and ISO [2631](#).

5.1.1 Machine foundations shall be detached from neighboring structures and foundations. If this is not possible, special precautions shall be taken to prevent the transmission of vibration to these structures.

5.1.2 Vibration analysis shall be conducted considering the soil as an elastic body with the characteristics of transverse elastic modulus (G), Poisson's coefficient (ν) and specific weight of the soil (ρ).

5.1.3 If a dynamic analysis detects a resonance condition for a frequency within the operation velocity of the machine, the mass of the foundation or its spring constants shall be changed. The operating frequency shall be kept at a distance of, at least, 20 % from the natural frequency of the foundation.

5.1.4 The settling of the foundation shall be less than permitted by the piping connected to the machine.

5.1.5 It is recommended the use of pile foundations for cases where: **[Recommended Practice]**

- a) the bearing capacity of the soil is low;
- b) settlement is expected to be high;
- c) the groundwater table is high;
- d) nearby foundations do not comply with item 5.1.2.

5.2 Direct Foundations

5.2.1 The combined center of gravity of foundation + machine shall be in the same vertical line as the centroid of the base area in contact with the soil. The plan distance between the 2 points, plotted along one of the (plan) dimensions of the base, shall not exceed 5 % of this dimension.

5.2.2 The stress on the ground due to static loads shall equal no more than 50 % of its allowable bearing pressure. The sum of stresses due to static and dynamic effects shall not exceed 75 % of the allowable bearing pressure of the soil.

5.2.3 Base thickness shall be at least 0.6 m, in order to provide a "rigid" foundation in accordance with the design theory developed for this type of foundation.

5.2.4 The height of the foundation block shall be no less than 1/5 of its smallest dimension or 1/10 of its largest dimension.

5.2.5 The ratio of foundation mass / machine mass shall be greater than 3 for rotary machinery, and from 5 to 10 for reciprocating machines.

5.2.6 The mass ratio shown in item 5.2.5 shall be adopted, unless the dynamic analysis proves that a value lower than the one specified may be used in a proper manner.

5.2.7 A clearance of at least 0.30 m shall be maintained around the machine for maintenance and other activities.

5.2.8 The base shall not be laid in terrain with high groundwater table, since the vibrations are amplified in saturated soils. Special attention shall be given to the effect of vibrations in saturated sandy soils.

5.2.9 The foundation shall not be laid on landfill soil.

5.2.10 The dimension of the base in the direction of rotation shall be at least 1.5 times larger than the vertical distance between the centerline of the machine and the base.

5.2.11 For neighboring foundations of the same characteristic, the settlement elevation of vibrating foundation shall be away and under the non-vibrating, complying, at least, with the 1:3 ratio (V:H).

5.3 Pile Foundations

5.3.1 The following ratio is recommended. **[Recommended Practice]**
 $s/d \geq 5$

Where:

s is pile spacing (axis to axis);
d is pile diameter.

5.3.2 The static load on each pile shall be limited to 50 % of its allowable load.

5.3.3 For rotating machine, the crowning block must have a mass of about 1.5 times the 2.5 times the mass of the machine. For alternatives, this relationship shall be 2.5 times the 4 times.

5.3.4 The mass ratio shown in item 5.3.3 shall be adopted, unless the dynamic analysis proves that a value lower than the one specified may be used in a proper manner.

5.3.5 The centroid of the piling and the combined center of gravity of foundation + machine shall be on the same vertical line. The plan distance between the 2 points, plotted along one of the (plan) dimensions of the pile cap, shall not exceed 5 % of this dimension.

5.3.6 Proper anchoring shall be provided between the piles and the pile cap. As a minimum requirement, the steel elements of the pile shall penetrate 60 cm into the pile cap, and steel piles shall have at least 30 cm embedded.

5.4 Foundations for Elevated Machinery

5.4.1 The thickness of the foundation slab shall be no less than $0.11 L^{4/3}$, where L (in meters) is the average of 2 adjacent spans between columns.

5.4.2 The static load on the columns shall be no greater than 1/6 of their maximum allowable load, and the mean compressive stress shall be approximately the same for all columns.

5.4.3 Maximum spacing between columns shall be 3.5 m.

5.4.4 The height of the beams shall be greater than 1/5 of the span. The sag due to static loading shall not exceed 0.5 mm.

5.4.5 The bending stiffness of the beams shall be at least twice that of the columns.

5.4.6 For rotary machines, the total mass of the structure shall be at least 3 times that of the supported machine. This ratio shall be 5 for reciprocating machinery.

5.4.7 The mass ratio shown in item 5.4.6 shall be adopted, unless the dynamic analysis proves that a value lower than the one specified may be used in a proper manner.

5.4.8 The mass of the top slab shall not be less than that of the machine.

5.4.9 The centroid of the columns shall coincide with the (plan) center of gravity of machine plus the upper half of the structure. The plan distance between the 2 points, plotted along one of the (plan) dimensions of the foundation slab, shall not exceed 5 % of this dimension.

5.4.10 The horizontal deflection of the columns due to dynamic loading shall not exceed 0.5 mm in any case.

5.4.11 The columns and beams of the gantry shall be examined to prevent the isolated resonance of the members of the structure.

5.4.11.1 The lowest-order natural frequency f_n , in revolutions per minute, of a column is given approximately by:

$$f_n = \frac{44\,800 \cdot \sqrt[4]{f_{ck}}}{\sqrt{\sigma_c \cdot H}}$$

Where:

f_{ck} is the strength of the concrete in psi (1 psi = 6 895 KPa);
 σ_c is the mean compressive stress acting on the column, in psi;
 H is the height of the column in inches (1 inch = 2.54 cm).

5.4.11.2 The natural frequency of beam spans between columns may be estimated using Table 1.

Table 1 - Natural Frequencies

Beam	f_n
simply supported on both ends	$\frac{9,87}{2\pi} \sqrt{\frac{EI}{ql^4}}$
clamped-simply supported	$\frac{15,4}{2\pi} \sqrt{\frac{EI}{ql^4}}$
clamped-clamped	$\frac{22,4}{2\pi} \sqrt{\frac{EI}{ql^4}}$
clamped-free	$\frac{3,52}{2\pi} \sqrt{\frac{EI}{ql^4}}$

Where:

- q is the total load per unit length of the beam (usually t/m);
- l is the length of the span (in m);
- E is the elastic modulus of the material (in t/m²);
- I is the area moment of inertia of the beam (usually in m⁴)

6 Calculation Criteria

6.1 Soil Parameters

The soil parameters required for analysis of compressor foundations, regardless of the type of base and the theory employed, are described in 6.3.1 to 6.3.4

6.1.1 Specific Weight of the Soil (ρ)

If no geotechnical tests are conducted, $\rho = 1.8 \text{ t/m}^3$ is recommended. **[Recommended Practice]**

6.1.2 Dynamic Shear Modulus of the Soil (G)

Obtained through a cross-hole test. In the absence of the said test, the following is recommended: **[Recommended Practice]**

$$G = 12\,000 N^{0.8}$$

Where:

- G is obtained in KPa;
- N is the number of STP blows (obtained from probing).

6.1.3 Poisson's ratio (ν)

In the absence of geotechnical or cross-hole tests, the values listed in Table 2 shall be adopted.

Table 2 - Poisson's Ratio

Type of soil	Poisson's ratio (ν)
Saturated clay	0.45 - 0.50
Partially saturated clay	0.35 - 0.45
Dense sand or gravel	0.40 - 0.50
Moderately dense sand or gravel	0.30 - 0.40
Silt	0.30 - 0.40

6.1.4 Elastic Modulus of the Soil (E)

Obtained through a cross-hole test, using formula (1). In the absence of said test, formula (2) shall be adopted:

$$E = 2\rho \cdot V_s^2 (1 + \nu) \quad (1)$$

$$E = 2 \cdot G (1 + \nu) \quad (2)$$

Where:

V_s is shear wave velocity, as obtained in the test.

6.2 Geometric Parameters of the System (Foundation + Machine)

6.2.1 Centroid

6.2.1.1 Direct Foundation

The (x_c , y_c) coordinates of the base area centroid are given by:

$$x_c = \frac{\sum_i A_i x_i}{\sum_i A_i}; \quad y_c = \frac{\sum_i A_i y_i}{\sum_i A_i}$$

Where:

x_i , y_i are the coordinates of the center of each area.

NOTE Once the centroid of the base area has been located, the origin of the rectangular coordinate system (x , y , z) shall be located at this point, such that all subsequent calculations are made in relation to this system of axes.

6.2.1.2 Pile (Deep) Foundation

The centroid of the pile cluster is given by:

$$X_c = \frac{\sum_i X_i}{n}; \quad Y_c = \frac{\sum_i y_i}{n}$$

Where:

x_i , y_i are the coordinates of each pile;
 n is the number of piles.