Report on Foundations for Dynamic Equipment

Reported by ACI Committee 351

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American Concrete Institute
38800 Country Club Drive
Farmington Hills, MI 48331
Phone: +1.248.848.3700
Fax: +1.248.848.3701

www.concrete.org

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Mukti L. Das*, Chair

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Sheng-Chi Wu
Curtis R. Yokoyama

Consulting Members

Navin N. Pandya
Shamsher Prakash
Robert L. Rowan Jr.

The committee would like to thank the following people for their contribution to this report: H. Liu,* C. Coronado,* and X. Wang.*

*Indicates members of the subcommittee who prepared the report.

This report presents to industry practitioners the various design criteria and methods and procedures of analysis, design, and construction applied to foundations for dynamic equipment.

Keywords: amplitude; foundation; reinforcement; vibration.

CONTENTS

ACI 351.3R-18 supersedes ACI 351.3R-04 and was adopted and published January 2018.

CHAPTER 1—INTRODUCTION

1.1—Background

Machinery with rotating, reciprocating, or impacting masses requires a foundation that can resist dynamic forces. Precise machine alignment should be maintained, and foundation vibrations should be controlled to ensure proper functioning of the machinery during its design service life.

Successful design of such foundations for dynamic equipment involves close collaboration and cooperation among machine manufacturers, geotechnical engineers, engineers, owners, and construction personnel. Because different manufacturers may have very different foundation acceptance criteria and their own practices with regards to foundation design requirements, strict adherence to ACI 318 alone may not be necessarily appropriate for certain foundations that support heavy industrial equipment, such as steam turbine generators, combustion turbine generators, or compressors. In addition, different practicing engineering firms may use design approaches based on past successful performance of foundations, even though these may not be the most economical designs. Therefore, this report summarizes current design practices to present a common approach, in principle, for various types of concrete foundations supporting dynamic equipment.

Compared to the previous edition, this document has been reorganized to make the document more systematic and user-friendly. More detailed information on the following subjects has been added on the behavior of foundations subjected to dynamic machine forces:

a) Impedance of the supporting medium (both soil-supported and pile-supported foundations)

b) General overview of vibration analysis (including finite-element modeling) and acceptance criteria, including finite-element analysis

c) Determination of various soil properties required for dynamic analysis of machine foundations

Example problems have been reworked and improved with some additional details to better illustrate the implementation of the calculation procedure in a manual calculation. Latest relevant references have been added to capture the current practice.

1.2—Purpose

The purpose of this report is to present general guidelines and current engineering practices in the analysis and design of reinforced concrete foundations supporting dynamic equipment.

This report presents and summarizes, with reference materials, various design criteria, methods and procedures of analysis, and construction practices currently applied to dynamic equipment foundations by industry practitioners.

1.3—Scope

This document is limited in scope to the engineering, construction, repair, and upgrade of concrete foundations for dynamic equipment. For the purposes of this document, dynamic equipment includes the following:

a) Rotating machinery

b) Reciprocating machinery

c) Impact or impulsive machinery

ACI 351.1R provides an overview of current design practice on grouting. Design practices for foundations supporting static equipment are discussed in ACI 351.2R.

There are many technical areas that are common to both dynamic equipment and static equipment foundations. Various aspects of the analysis design and construction of foundations for static equipment are addressed in ACI 351.2R. To simplify the presentation, this report is limited in scope to primarily address the design and material requirements that are pertinent only to dynamic equipment foundations. Engineers are advised to refer to ACI 351.2R for more information on the foundation design criteria (static loadings, load combinations, design strength, stiffness, and stability) and design methods for static loads. In particular, ACI 351.2R provides detailed coverage on the design of anchorage of equipment to concrete foundations. Note that

ACI 351.2R was published prior to a major revision to ACI 318 and some of the section numbers that it references in ACI 318 may have changed.

CHAPTER 2—NOTATION AND DEFINITIONS

2.1—Notation

A = steady-state vibration amplitude, in. (mm)
A_{head}, A_{crank} = head and crank areas, in.^{2} (mm^2)
A_p = cross-sectional area of the pile, in.^{2} (mm^2)
a, b = plan dimension of a rectangular foundation, ft (m)
a_o = dimensionless frequency
B_c = cylinder bore diameter, in. (mm)
B_i = mass ratio for the i-th direction
B_{mf} = machine footprint width, ft (m)
B_M = width of mat foundation, ft (m)
B_r = ram weight, tons (kN)
b_1, b_2 = constants 0.425 and 0.687, respectively
C = damping coefficient or total damping at center of resistance
$[C]$ = damping matrix
C_{CR} = critical damping coefficient
C_{i1},C_{i2} = dimensionless stiffness and damping parameters, subscription $i = u, v, \psi, \eta$
c = viscous damping constant, lbf-s/ft (N-s/m)
c_i = damping constant for the i-th direction
c_i(adj) = adjusted damping constant for the i-th direction
c_{ij} = equivalent viscous damping of pile j in the i-th direction
CG = center of gravity
CF = center of force
c_{gi} = pile group damping in the i-th direction
D = damping ratio
D_i = damping ratio for the i-th direction
D_{rod} = rod diameter, in. (mm)
d = pile diameter, in (mm)
d_s = displacement of the slide, in. (mm)
d_{mf} = distance from machine shaft centerline to top of foundation, ft (m)
E = static Young's modulus of concrete, psi (MPa)
E_d = dynamic Young's modulus of concrete, psi (MPa)
E_p = Young's modulus of the pile, psi (MPa)
e_m = mass eccentricity, in. (mm)
F = peak value of harmonic dynamic load (force or moment)
F_1 = correction factor
F_{block}= force acting outward on the block from which concrete stresses should be calculated, lbf (N)
$(F_{bolt})_{CHG}$ = force to be restrained by friction at the crosshead guide tie-down bolts, lbf (N)
$(F_{bolt})_{frame}$ = force to be restrained by friction at the frame tie-down bolts, lbf (N)
F_D = damper force, lbf (N)
F_{GMAX} = maximum horizontal gas force on a throw or cylinder, lbf (N)
F_{IMAX}= maximum horizontal inertia force on a throw or cylinder, lbf (N)
F_K = force in vibration isolator spring, lbf (N)
F_o = dynamic force amplitude (zero-to-peak), lbf (N)
F_{pl} = lateral/longitudinal pseudo-dynamic design force, lbf (N)
F_{pv} = vertical pseudo-dynamic design force, lbf (N)
F_r = maximum horizontal dynamic force, lbf (N)
F_{red} = force reduction factor to account for the fraction of individual cylinder load carried by the compressor frame (frame rigidity factor)
F_{rod} = force acting on piston rod, lbf (N)
F_s = dynamic inertia force of slide, lbf (N)
F_{THROW}= horizontal force to be resisted by each throw's anchor bolts, lbf (N)
$F(t)$ = generic representation of time-varying load (force or moment) horizontal
$F_{unbalance}$ = maximum value applied using parameters for a horizontal compressor cylinder, lbf (N)
f_c' = specified concrete compressive strength, psi (MPa)
f_{i1}, f_{i2} = dimensionless pile stiffness and damping functions for the i-th direction
f_o = operating speed, rpm
G, G^*= dynamic shear modulus of the soil, psi (MPa)
G_pJ = torsional stiffness of the pile, lbf-ft^2 (N-m^2)
G_s = dynamic shear modulus of the embedment (side) material, psi (MPa)
H = depth of soil layer, ft (m)
I_g = gross area moment of inertia, in.^{2} (mm^2)
I_p = moment of inertia of the pile cross section in.^{4} (mm^4)
i = $\sqrt{-1}$
i = directional indicator or modal indicator, as a subscript
K = stiffness or total stiffness at center of resistance, lbf/ft (N/m) or lbf-ft/rad (N-m/rad)
$[K]$ = stiffness matrix
K' = total stiffness at center of gravity, lbf/ft (N/m) or lbf-ft/rad (N-m/rad)
K_{ij}^* = impedance in the i-th direction due to a displacement in the j-th direction
K_N = actual negative stiffness, lbf/ft (N/m) or lbf-ft/rad (N-m/rad)
K_P = arbitrary chosen positive stiffness value (typically set equal to the static stiffness), lbf/ft (N/m) or lbf-ft/rad (N-m/rad)
K_{eff} = effective bearing stiffness, lbf/in. (N/mm)
K_s = static soil stiffness, lbf/in^3 (N/m^3)
K_c^G = pile group coupling impedance
K_h^G = pile group horizontal impedance
K_v^G = pile group vertical impedance
K_ψ^G = pile group rocking impedance
k = individual pile stiffness at center of resistance, lbf/ft (N/m) or lbf-ft/rad (N-m/rad)
k_{ei}^* = impedance in the i-th direction due to embedment
k_{gi} = pile group stiffness in the i-th direction, lbf/ft (N/m) or lbf-ft/rad (N-m/rad)
k_i = static stiffness for the i-th direction, lbf/ft (N/m) or lbf-ft/rad (N-m/rad)