

Report on Foundations for Dynamic Equipment

Reported by ACI Committee 351

ACI 351.3R-18



American Concrete Institute
Always advancing



Report on Foundations for Dynamic Equipment

Copyright by the American Concrete Institute, Farmington Hills, MI. All rights reserved. This material may not be reproduced or copied, in whole or part, in any printed, mechanical, electronic, film, or other distribution and storage media, without the written consent of ACI.

The technical committees responsible for ACI committee reports and standards strive to avoid ambiguities, omissions, and errors in these documents. In spite of these efforts, the users of ACI documents occasionally find information or requirements that may be subject to more than one interpretation or may be incomplete or incorrect. Users who have suggestions for the improvement of ACI documents are requested to contact ACI via the errata website at <http://concrete.org/Publications/DocumentErrata.aspx>. Proper use of this document includes periodically checking for errata for the most up-to-date revisions.

ACI committee documents are intended for the use of individuals who are competent to evaluate the significance and limitations of its content and recommendations and who will accept responsibility for the application of the material it contains. Individuals who use this publication in any way assume all risk and accept total responsibility for the application and use of this information.

All information in this publication is provided "as is" without warranty of any kind, either express or implied, including but not limited to, the implied warranties of merchantability, fitness for a particular purpose or non-infringement.

ACI and its members disclaim liability for damages of any kind, including any special, indirect, incidental, or consequential damages, including without limitation, lost revenues or lost profits, which may result from the use of this publication.

It is the responsibility of the user of this document to establish health and safety practices appropriate to the specific circumstances involved with its use. ACI does not make any representations with regard to health and safety issues and the use of this document. The user must determine the applicability of all regulatory limitations before applying the document and must comply with all applicable laws and regulations, including but not limited to, United States Occupational Safety and Health Administration (OSHA) health and safety standards.

Participation by governmental representatives in the work of the American Concrete Institute and in the development of Institute standards does not constitute governmental endorsement of ACI or the standards that it develops.

Order information: ACI documents are available in print, by download, through electronic subscription, or reprint and may be obtained by contacting ACI.

Most ACI standards and committee reports are gathered together in the annually revised the ACI Collection of Concrete Codes, Specifications, and Practices.

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

www.concrete.org

Report on Foundations for Dynamic Equipment

Reported by ACI Committee 351

Mukti L. Das*, Chair

Susan Isble*, Secretary

Omesh B. Abhat*
William L. Bounds*
William D. Brant*
Michael M. Chehab
Shu-Jin Fang*
Fred R. Goodwin

Ping Jiang
David Kerins*
Hoan-Kee Kim
Robert R. McGlohn
Abbas Mokhtar-Zadeh
Carl A. Nelson*

Richard O'Malley
Michael A. Paipal
Ira W. Pearce
William E. Rushing Jr.
Larry W. Schulze*
Widianto*

F. Alan Wiley
Sheng-Cri. 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. Zhang.*

*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

CHAPTER 1—INTRODUCTION, p. 2

- 1.1—Background, p. 2
- 1.2—Purpose, p. 2
- 1.3—Scope, p. 2

CHAPTER 2—NOTATION AND DEFINITIONS, p. 3

- 2.1—Notation, p. 3
- 2.2—Definitions, p. 5

CHAPTER 3—FOUNDATION AND MACHINE TYPES, p. 5

- 3.1—General considerations, p. 5

3.2—Machine types, p. 5

3.3—Foundation types, p. 6

CHAPTER 4—DESIGN LOADS, p. 8

- 4.1—Overview of design loads and criteria, p. 8
- 4.2—Static machine loads, p. 9
- 4.3—Dynamic machine loads, p. 11
- 4.4—Environmental loads, p. 17
- 4.5—Load conditions, p. 17
- 4.6—Load combinations, p. 18

CHAPTER 5—IMPEDANCE OF THE SUPPORTING MEDIUM, p. 18

- 5.1—Overview and use of soil impedance, p. 18
- 5.2—Basic dynamic concepts, p. 19
- 5.3—Calculation of dynamic foundation impedances, p. 21
- 5.4—Dynamic impedance of soil-supported foundations, p. 22
- 5.5—Dynamic impedance of pile foundations, p. 28
- 5.6—Transformed impedance relative to center of gravity, p. 35
- 5.7—Added mass concept, p. 35
- 5.8—Sample impedance calculations, p. 36

ACI Committee Reports, Guides, and Commentaries are intended to provide guidance in planning, designing, executing, and inspecting construction. This document is intended for the use of individuals who are competent to evaluate the significance and limitations of its content and recommendations and who will accept responsibility for the application of the material it contains. The American Concrete Institute disclaims any and all responsibility for the stated principles. The Institute shall not be liable for any loss or damage arising therefrom.

Reference to this document shall not be made in contract documents. If items found in this document are desired by the Architect/Engineer to be a part of the contract documents, they shall be restated in mandatory language for incorporation by the Architect/Engineer.

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

Copyright © 2018, American Concrete Institute.

All rights reserved including rights of reproduction and use in any form or by any means, including the making of copies by any photo process, or by electronic or mechanical device, printed, written, or oral, or recording for sound or visual reproduction or for use in any knowledge or retrieval system or device, unless permission in writing is obtained from the copyright proprietors.

CHAPTER 6—VIBRATION ANALYSIS AND ACCEPTANCE CRITERIA, p. 40

- 6.1—Overview, p. 40
- 6.2—Modeling for rigid foundations, p. 41
- 6.3—Modeling for flexible foundations, p. 42
- 6.4—Solution methods, p. 46
- 6.5—Frequency analysis, p. 49
- 6.6—Forced response analysis, p. 50
- 6.7—Sample calculations, p. 52

CHAPTER 7—DESIGN AND MATERIALS, p. 56

- 7.1—Overview of design methods, p. 56
- 7.2—Concrete, p. 59
- 7.3—Reinforcement, p. 61
- 7.4—Machine anchorage, p. 62
- 7.5—Elastic support systems, p. 63
- 7.6—Grout, p. 63
- 7.7—Seismic design considerations, p. 64
- 7.8—Fatigue considerations, p. 64
- 7.9—Special considerations for compressor block post-tensioning, p. 64
- 7.10—Sample calculations, p. 64

CHAPTER 8—CONSTRUCTION CONSIDERATIONS, p. 67

- 8.1—Subsurface preparation and improvement, p. 67

CHAPTER 9—REPAIR AND UPGRADE, p. 67

- 9.1—Overview of need for repair, p. 67
- 9.2—Discussion of repair options, p. 68

CHAPTER 10—REFERENCES, p. 69

- Authored documents, p. 71

APPENDIX A—DYNAMIC SOIL PROPERTIES, p. 71

- A.1—Poisson's ratio, p. 73
- A.2—Dynamic shear modulus, p. 74
- A.3—Soil damping, p. 75
- A.4—Radiation damping, p. 76

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