Report on Foundations for Dynamic Equipment

Reported by ACI Committee 351

ACI 351.3R-18

American Concrete Institute
Always advancing

First Printing
January 2018
ISBN: 978-1-945487-98-9

Report on Foundations for Dynamic Equipment

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-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 Committee Reports, Guides, and Commentaries are intended for 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.

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)

k_i^* = frequency-dependent impedance in the i-th direction
$k_i(adj)$ = adjusted static stiffness for the i-th direction, lbf/ft (N/m) or lbf-ft/rad (N-m/rad)
$k_i^*(adj)$ = adjusted frequency-dependent impedance in the i-th direction
k_{ij} = stiffness of pile j in the i-th direction, lbf/ft (N/m) or lbf-ft/rad (N-m/rad)
k_{ij}^{st} = static stiffness of an individual pile j in the i-th direction, lbf/ft (N/m) or lbf-ft/rad (N-m/rad)
k_s = soil modulus of subgrade reaction, lbf/in.^{3} (N/m^3)
k_{st} = static stiffness constant
k_u^* = horizontal impedance of supporting medium
k_v^* = vertical impedance of supporting medium
k_ψ^* = rocking impedance of supporting medium
k_η^* = torsional impedance of supporting medium
$k(\omega)$ = frequency (ω)-dependent dynamic impedance
L = length of connecting rod, in. (mm)
L_M = greater plan dimension of the mat foundation, ft (m)
L_{mf} = machine footprint length, ft (m)
L_P = lateral distance from center of resistance to individual piles, ft (m)
l = depth of embedment, ft (m)
l_p = pile length, ft (m)
M = mass, lbm (kg)
$[M]$ = mass matrix
M_h = hammer mass, including any auxiliary foundation, lbm (kg)
M_o = overturning moment on foundation, lbf-ft (N-m)
MR = mass ratio of concrete foundation to machine
M_r = ram mass, including dies and ancillary parts, lbm (kg)
M_{res} = foundation overturning resistance, lbf-ft (N-m)
M_Δ = added mass, lbm (kg)
m = mass of the machine-foundation system; lbm (kg)
m_d = slide mass including the effects of any balance mechanism, lbm (kg)
m_r = rotating mass, lbm (kg)
m_{rec} = reciprocating mass in a reciprocating machine, lbm (kg)
m_{rot} = rotating mass in a reciprocating machine, lbm (kg)
m_s = added mass (inertial), lbm (kg)
N = number of piles
$(N_{bolt})_{CHG}$ = number of bolts holding down one crosshead guide
$(N_{bolt})_{frame}$ = number of bolts holding down the frame, per cylinder
NT = normal torque, lbf-ft (N-m)
P_{ALL} = allowable bearing pressure, ksf (kPa)
P_{head}, P_{crank} = instantaneous head and crank pressures, psi (MPa)
P_{max} = maximum bearing pressure, ksf (kPa)
P_s = power being transmitted by the shaft at the connection, horsepower (kilowatts)
R = circular foundation radius, equivalent translation radius of rectangular foundation, ft (m)
R_i = equivalent radius of rectangular foundation, ft (m)
$R_{\psi a}$, $R_{\psi b}$ = equivalent rocking radius of foundation about a- and b-axis, respectively, ft (m)
R_η = equivalent torsional radius of foundation, ft (m)
r = length of crank, in. (mm)
r_i = radius of the crank mechanism of the i-th cylinder, in. (mm)
r_o = pile radius or equivalent radius, in. (mm)
S = press stroke, in. (mm)
S_{all} = allowable foundation settlement, in. (mm)
S_f = service factor, used to account for increasing unbalance during the design service life of the machine
S_{i1}, S_{i2} = dimensionless stiffness and damping parameters for side layer, subscription $i = u, v, \psi, \eta$
S_{max} = maximum foundation settlement, in. (mm)
SV_R = seismic shear force due to the rigid foundation and other rigid components, lbf (N)
SVs = seismic shear force due to the superstructure, machine and other flexible components, lbf (N)
$SV_{seismic}$ = total seismic shear force machine-foundation system, lbf (N)
s = pile center-to-center spacing, ft (m)
$[T]$ = transfer matrix
T_M = mat foundation thickness, ft (m)
T_{min} = minimum required anchor bolt tension, lbf (N)
t = time, s
u = displacement amplitude, in. (mm)
u_0 = peak displacement amplitude, in. (mm)
V_c = compressive velocity of a pile, ft/s (m/s)
V_F = transmissibility factor
V_{La} = Lysmer's analog wave velocity, ft/second (m/s)
V_{max} = maximum allowable bearing vibration, in. (mm)
V_{peak} = peak velocity, in./s (mm/s)
V_{RMS} = root mean square velocity, in./s (mm/s)
V_s = shear wave velocity of the soil, ft/s (m/s)
v_h = post-impact hammer velocity, in./s (mm/s)
v_o = reference velocity = 18.4 ft/s (5.6 m/s) from a free fall of 5.25 ft (1.6 m)
v_r = ram impact velocity, ft/s (m/s)
W_a = equipment weight at anchorage location, lbf (N)
W_f = weight of the foundation, tons (kN)
W_m = machine weight, tons (kN)
W_r = rotating weight, lbf (N)
y = generic representation of displacement (translational or rotational), in. (mm) or rad
y' ($\ddot{y}$) = generic representation of velocity (translational or rotational), in./s (mm/s) or rad/s
y'' ($\ddot{y}$) = generic representation of acceleration (translational or rotational), in./s^2 (mm/s^2) or rad/s^2
y_c = crank pin displacement in local y-axis, or distance from the center of gravity to the base support, in. (mm)
y_e = distance from the center of gravity to the level of embedment resistance, ft (m)
z_c = crank pin displacement in local z-axis, in. (mm)
z_p = piston displacement, in. (mm)
α = angle between battered piles and vertical piles, rad
α_h = ram rebound velocity to impact velocity ratio

α_i = pile dynamic interaction factor in the i-th direction, subscription $i = z$ (axial), HH (horizontal), MM (in phase rocking), MH (sway rocking)
α_j = coefficients, $j = 1$
β_i = rectangular footing coefficient for the i-th direction
β_j, γ_j= coefficients, $j = 1$ to 4
β_m = material damping ratio
γ_c = concrete density, lbf/ft^3 (kN/m^3)
ϕ = phase angle
$\{\phi\}$ = mode shape vector
ϕ_i = mode shape factor
η = tuning ratio
θ = phase angle, or angle between the direction of load action and the plane in which piles lie, rad
ρ = soil mass density, lbm/ft^3 (kg/m^3)
ρ_p = pile mass density, lbm/ft^3 (kg/m^3)
Δ = peak amplitude (translational or rotational), in. or rad
μ = coefficient of friction
ν = Poisson's ratio of the soil
ω = circular frequency of motion, rad/s
ω_d = damped circular natural frequency, rad/s
ω_i = undamped circular natural frequency for the i-th mode, rad/s
ω_n = undamped circular natural frequency, rad/s
ω_o = circular operating frequency of a machine or other driving force, rad/s
$\omega_{su,}$ ω_{sv} = circular natural frequencies of a soil layer in horizontal (u) and vertical (v) directions, rad/s
u, v,
ψ, η = subscriptions used for notating horizontal, vertical, rocking, and torsional direction, respectively

2.2—Definitions

Please refer to the latest version of ACI Concrete Terminology for a comprehensive list of definitions. Definitions provided herein complement that resource.

root cause analysis—collective term that describes a wide range of approaches, tools, and techniques used to uncover causes of problems.

CHAPTER 3—FOUNDATION AND MACHINE TYPES

3.1—General considerations

The type, configuration, and installation of a foundation or support structure for dynamic machinery may depend on the following factors:

a) Site conditions such as soil characteristics, topography, seismicity, climate, and other effects

b) Machine base configuration such as frame size, cylinder supports, pulsation bottles, drive mechanisms, and exhaust ducts

c) Process requirements such as elevation requirements with respect to connected process equipment and support requirements for piping

d) Anticipated loads such as the equipment static weight, along with loads developed during construction, startup, operation, shutdown, and maintenance

e) Allowable amplitudes of vibration associated with each dynamic load case

f) Construction requirements such as limitations or constraints imposed by construction equipment, procedures, techniques, or the sequence of construction

g) Operational requirements such as accessibility, settlement limitations, temperature effects, and drainage

h) Maintenance requirements such as temporary access, laydown space, in-plant crane capabilities, and machine removal considerations

i) Regulatory factors, owner requirements, or building code provisions such as tied pile caps in seismic zones

j) Economic factors such as capital cost, useful or design service life, and replacement or repair cost

k) Environmental requirements such as secondary containment or special concrete coating requirements

l) Recognition that certain machines, particularly large reciprocating compressors, rely on the foundation to add strength and stiffness that is not inherent in the structure of the machine

3.2—Machine types

3.2.1 *Rotating machinery*—This category includes gas turbines, steam turbines, and other expanders; turbopumps and compressors; fans; motors; and centrifuges. These machines are characterized by the motion of rotating components.

Unbalanced forces in rotating machines are created when the mass centroid of the rotating component does not coincide with the center of rotation (Fig. 3.2.1). This dynamic force is a function of the mass of the rotating component, speed of rotation, and the magnitude of the eccentricity of offset. The offset or eccentricity should be minor under manufactured conditions when the machine is well balanced, clean, and without wear or erosion. Changes in alignment, operation near resonance, turbine blade loss, and other malfunctions or undesirable conditions can greatly increase the force applied to its bearings by the rotor.

3.2.2 *Reciprocating machinery*—For reciprocating machinery, such as compressors or diesel engines, a piston moving in a cylinder interacts with a gas through the kinematics of a slider crank mechanism driven by, or driving, a rotating crankshaft. Individual inertia forces from each cylinder are inherently unbalanced with dominant frequencies at one and two times the rotational frequency (Fig. 3.2.2).

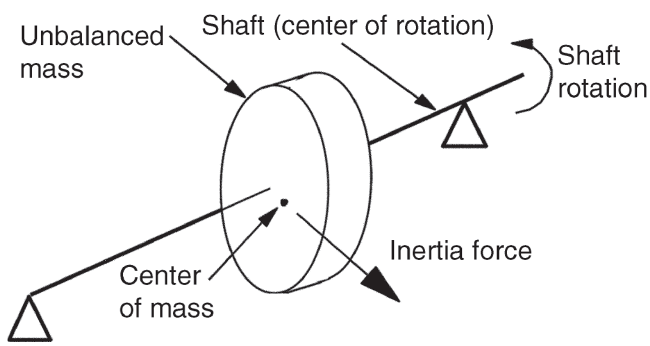

Fig. 3.2.1—Rotating machine diagram.

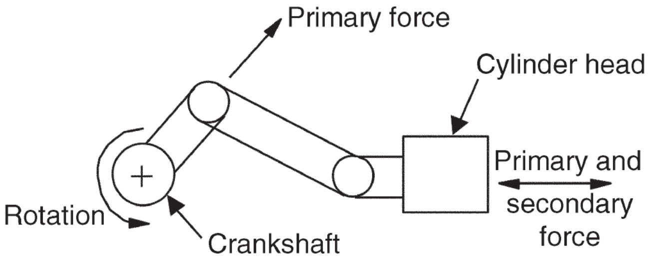

Fig. 3.2.2—Reciprocating machine diagram.

The unbalanced forces and moments generated by reciprocating machines with more than one piston are dependent on the crank arrangement. The optimum crank arrangement that minimizes loading is generally not possible because the mechanical design will be optimized to satisfy the operating requirements. This leads to piston/cylinder assemblies and crank arrangements that do not completely counter-oppose; therefore, unbalanced loads occur, which should be resisted by the foundation.

Individual cylinder fluid forces act outward on the cylinder head and inward on the crankshaft (Fig. 3.2.2). For a rigid cylinder and frame, these forces are internally balanced in the machine, but deformations of large machines can cause a significant portion of the forces to be transmitted to the mounts and into the foundation. Particularly on large reciprocating compressors with horizontal cylinders, it is inappropriate and unconservative to assume the compressor frame and cylinder are sufficiently stiff to internally balance all forces. Such an assumption has led to many inadequate mounts for reciprocating machines.

3.2.3 *Impulsive machinery*—Equipment, such as forging hammers and some metal-forming presses, operate with regulated impacts or shocks between different parts of the equipment. This shock loading is often transmitted to the foundation system of the equipment and can propagate into the surroundings and is a factor in the design of the foundation.

Closed die forging hammers typically operate by dropping a weight (ram) onto hot metal, forcing it into a predefined shape. While the intent is to use this impact energy to form and shape the material, there is significant energy transmission, particularly late in the forming process. During these final blows, the material being forged is cooling and less shaping takes place. Thus, pre-impact kinetic energy of the ram converts to post-impact kinetic energy of the entire forging hammer. As the entire hammer moves downward, it becomes a simple dynamic mass oscillating on its supporting medium. This system should be well damped so that the oscillations decay sufficiently before the next blow. Timing of the blows commonly range from 40 to 100 blows per minute. The ram weights vary from a few hundred pounds to 35,000 pounds (16 tons). Impact velocities in the range of 25 ft/s (7.6 m/s) are common. Open die hammers operate in a similar fashion but are often of two-piece construction with a separate hammer frame and anvil.

Forging presses perform a similar manufacturing function as forging hammers but are commonly mechanically or hydraulically driven. These presses form the material at

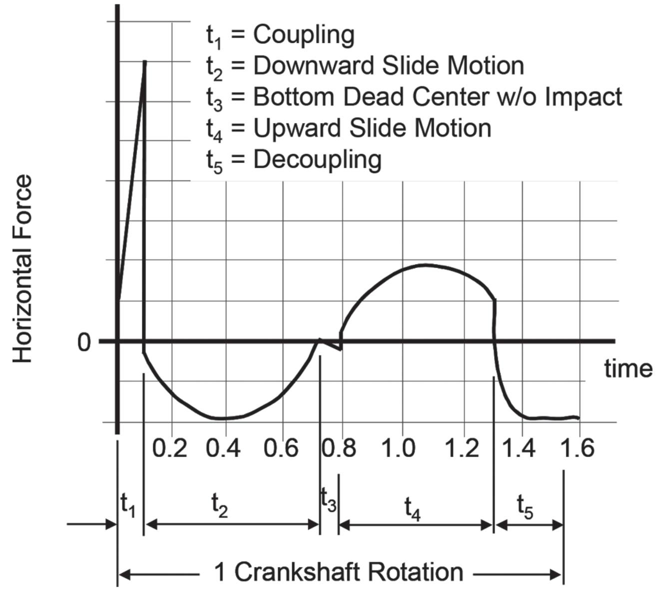

Fig. 3.2.3—Example of a forcing function for a forging press.

low velocities but with greater forces. The mechanical drive system generates horizontal dynamic forces that the engineer should consider in the design of the support system. Rocking stability of this construction is important. Figure 3.2.3 shows a typical example of a horizontal forcing function through one full stroke of a forging press.

Mechanical metal forming presses operate by squeezing and shearing metal between two dies. Because this equipment can vary greatly in size, weight, speed, and operation, forces and design criteria used for the foundation design can vary greatly. Speeds can vary from 30 to 1800 strokes per minute. Dynamic forces from the press develop from two sources: the mechanical imbalance of the moving parts in the equipment and the response of the press frame as the material is sheared (snap-through forces). Imbalances in the mechanics of the equipment can occur both horizontally and vertically. Generally, high-speed equipment is well balanced. Low-speed equipment is often not balanced because the inertia forces at low speeds are small. The dynamic forces generated by all of these presses can be significant as they are transmitted into the foundation and propagate into the subgrade.

3.2.4 *Other machine types*—Other machinery generating dynamic loads include rock crushers and metal shredders. While part of the dynamic load from these types of equipment tend to be based on rotating imbalances, there are also random characteristics to the dynamic forces that vary with the particular operation and design.

3.3—Foundation types

3.3.1 *Block-type foundation*—Dynamic machines are preferably located close to grade to minimize the elevation difference between the machine dynamic forces and the center of gravity of the machine-foundation system (Fig. 3.3.1). The low location also reduces the moments due to horizontal forces. The ability to use such a founda-