Report on Foundations for Dynamic Equipment

Reported by ACI Committee 351

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ACI 351.3R-18

Report on Foundations for Dynamic Equipment

Reported by ACI Committee 351

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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.

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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

ω_{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).

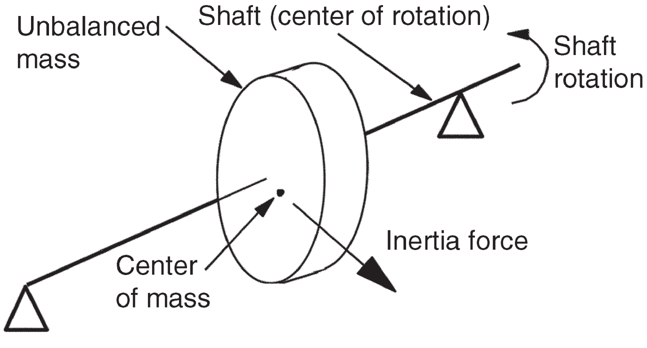

Fig. 3.2.1—Rotating machine diagram.

constrained and transmitted smoothly from the machine down through the foundation and into the soil below. When the symptoms are high vibration of the equipment, cracked concrete and grout, anchorage failure, or foundation rocking, the causes could be one or more of the following:

a) Incorrect original calculation of the projected magnitude of the dynamic forces, or a change in magnitude after a mechanical repair. Note that sometimes a very small change in a rotating part's weight can cause large increases in vibratory forces.

b) A change in operating speed can increase dynamic forces

c) A tall narrow foundation, made only as wide as the footprint of the machine

Often the minimum width and length supplied by the original equipment manufacturer (OEM) will have more rocking around the horizontal axis than a shorter, wider foundation. An OEM suggested concrete outline should only be a guide to minimum size. The OEM is not the foundation designer, and it is the engineer of record's responsibility to provide the best width-to-height ratio to help control rocking. Excessive rocking can be reduced in an existing foundation by adding vertical post-tension bolts (9.2.3(a)) and by adding foundation mass (9.2.3(e)). However, a revised vibration analysis with new parameters needs to be conducted to verify vibration levels and design allowable. When applicable, soil-structure interaction effects need to be included in the revised vibration analysis, as discussed in Chapter 5. Moreover, a parametric study would be beneficial to determine optimum values for bolt tension or additional foundation mass.

For any repair options, concrete foundation problems caused by equipment vibration can worsen over time as the equipment foundation deteriorates and causes an increase in equipment vibratory forces. These increased equipment forces may further deteriorate the dynamic equipment foundation with potential for further cracking of the concrete foundation and loosening of anchor bolts. This results in even further increases in vibratory forces. This cycle of degradation phenomenon continues as time progresses, demonstrating that an early and timely repair is always warranted for a dynamic machine foundation.

9.2.3 *Tools and techniques for machine foundation repair*—A variety of tools and techniques exist that may be applicable to the repair of a foundation that has deteriorated due to the problems described previously. The tools and techniques are described in the following:

a) Drill and install vertical post-tension bolts completely through the cracked sections and often down to an underlying concrete mat foundation or pile cap.

b) After partial or complete removal of the concrete and grout in the upper one-third of the foundation, replace it with a dense reinforcing bar grid of 1 percent (No. 6s [No. 19] on 6 in. [150 mm] centers in 6 in. [150 mm] vertical layers), and replace with a stronger concrete such as a steel fiber-reinforced polymer-modified concrete (PMC).

PMC (ACI 548.3R) is considered because the repair is being made, in most cases, from a degraded foundation or an inadequate original foundation design. A stronger concrete is beneficial in such situations. PMC is stronger in tensile and flexural strength, develops a better bond and adhesion to the original concrete, and develops less heat of hydration than ready mixed concrete.

Material selection for concrete repair is an important step. ACI 546R and ACI 546.3R provide guidelines for material selection of concrete repairs.

c) Upgrade the anchor bolts from typical 36,000 psi (248 MPa) lower-strength steel to higher-strength alloy steel, such as ASTM A193/A193M, Grade B7, with rolled threads. This material has minimum tensile strength of 125,000 psi (860 MPa) and minimum yield strength of 105,000 psi (720 MPa) for rods of various diameters (ACI 355.3R-11 Appendix A). The increased clamping force transfers the vibratory forces more efficiently into the foundation.

d) Add horizontal post-tensioning both ways in the upper one-third of the foundation. Earlier repair techniques used steel bolts to accomplish this, but newer techniques have been developed using closely spaced post-tensioned cables because of lower cost and ease of installation in a dense reinforcing bar grid. This technique is beneficial when severe vertical cracks exist.

e) Make changes to the concrete mass by increasing the horizontal width, length, or both, of the concrete where possible without equipment interference.

f) The connection between the equipment and the foundation is a critical point in providing a smooth path of the equipment vibratory forces down into the concrete foundation and into the soil or bedrock below. The improved anchorage suggested in 9.2.3(c) can help with increased clamping forces. Further, transmission of vibratory forces can be improved by changes such as using a poured polymer chock at each anchorage point in place of a full bed of grout, or one of the several adjustable steel or composite machinery supports that additionally correct for angularity and vertical alignment.

The aforementioned tools and techniques are generic suggestions; details depend on specific repair conditions, budget availability, significance of machine, desired design service life extension of the machine foundation, and feasible design details. It is advisable to verify design modifications for the repair job against applicable codes, standards, and specifications, and it should depend on the discretion of the engineer. Consider different options and costs associated with each of them and come to an optimum solution for the repair job.

CHAPTER 10—REFERENCES

Committee documents are listed first by document number and year of publication followed by authored documents listed alphabetically.

Acoustical Society of America

ASA/ANSI S2.19:1999—Mechanical Vibration—Balance Quality Requirements of Rigid Rotors, Part 1: Determination of Permissible Residual Unbalance

American Concrete Institute

ACI 207.2R-07—Report on Thermal and Volume Change Effects on Cracking of Mass Concrete

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APPENDIX A—DYNAMIC SOIL PROPERTIES

Soil properties should be provided by a geotechnical engineer. Appendix A, however, provides engineers with a general overview of methods used to determine the various soil properties required for the dynamic analysis of machine foundations. Many references are available that provide a greater level of detail on the theory, standard practice, and factors that affect dynamic soil properties (Mitchell and Soga 2005; Seed and Idriss 1970; Stokoe et al. 1999; Andrus et al. 2003).

Many factors affect the ability of a given soil to support a dynamic machine foundation. These include excessive settlement caused by dynamic or static loads, liquefaction, expansive soils, and frost heave. All these should be addressed by a geotechnical engineer familiar with the local conditions.

The soil properties that are most important for the dynamic analysis of machine foundations are stiffness, density (ρ) and material damping (D_m). Stiffness properties are typically provided in the form of small strain Poisson's ratio (ν), and shear modulus (G), or alternatively in the form of shear (V_s) and compressional (V_p) wave velocities, as discussed in the following.

A.1—Poisson's ratio

Poisson's ratio (ν) is the ratio of transverse strain to longitudinal strain in the direction of applied force. In general, most soils have Poisson's ratio values in the range from 0.2 to 0.5. Laboratory determination of Poisson's ratio is difficult; therefore, it is sometimes estimated. Alternatively, for soils above the water table, ν is often determined, per Eq. (A.1), based on in-place measurements of the shear (V_s) and compressional (V_p) wave velocities.

$$\nu = \frac{1}{2}\left(\frac{(V_p/V_s)^2-2}{(V_p/V_s)^2-1}\right) \qquad \text{(A.1)}$$

The dynamic response of a foundation system is generally insensitive to variations of Poisson's ratio in the range of values common for dry or partial saturated soils (that is, 0.25

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