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LIST OF SYMBOLS

a	Maximum cantilever length (inches); measured from the face of block to edge of foundation
d	Maximum deflection (inches), for estimating the fundamental natural frequency of beam or column
e	Rotor eccentricity for centrifugal machines
f_1	First coupled natural frequency
f_2	Second coupled natural frequency
f_0	Machine operating speed (cps or rpm)
f_d	Damped resonant frequency (cps or rpm)
f_n	Undamped natural frequency (cps or rpm)
f_c	Concrete compressive strength
f_y	Yield strength of reinforcement
f_{nx}	Uncoupled natural frequency in translational x direction
f_{ny}	Uncoupled natural frequency in translational y direction
f_{nz}	Uncoupled natural frequency in translational z directions
$f_{n\phi}$	Uncoupled natural frequency , rocking about X
$f_{n\psi}$	Uncoupled natural frequency , rocking about Y
$f_{n\theta}$	Uncoupled natural frequency , rocking about z, Torsional
$f_{x,1}$	Parameters for calculating single pile stiffnesses in horizontal (X),
$f_{z,1}$	Parameters for calculating single pile stiffnesses in vertical (Z),
$f_{\phi,1}$	Parameters for calculating single pile stiffnesses in rocking (ϕ) modes
$f_{x,2}$	Parameters for calculating single pile damping coefficients in horizontal (X),
$f_{z,2}$	Parameters for calculating single pile damping coefficients in vertical (Z)
$f_{\phi,2}$	Parameters for calculating single pile damping coefficients in rocking (ϕ) modes,
g	Acceleration of gravity (32.2 ft/sec ² or 386.4 in/sec ²)

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h	Foundation embedment depth, the distance between the CG of a machine foundation system and the foundation base.
h_i	Thickness of ith soil layer
l	Embedded length of a pile
m	Total mass of a machine foundation system (machine+foundation)
m_e	Rotor mass for centrifugal machines
r	Frequency ratio, defined as f_0/f_d (or f_0/f_n)
r_0	Equivalent radius of foundation; equivalent radius of concrete pile, $\sqrt{\frac{A_p}{\pi}}$
t	Thickness of mat foundation or pile cap
A_0	displacement amplitude
A_i	Stress influence area (spreading below the foundation at a ratio of 2 vertical to 1 horizontal) measured at the centroid of ith soil layer
A_p	Cross sectional area of concrete pile
B	Foundation width, parallel to the y-axis
B_x	Mass ratios for calculating the soil geometrical damping ratios in horizontal X directions
B_y	Mass ratios for calculating the soil geometrical damping ratios in horizontal Y directions
B_z	Mass ratios for calculating the soil geometrical damping ratios in vertical Z directions
B_ϕ	Mass ratios for calculating the soil geometrical damping ratios in rocking about X (ϕ) directions
B_ψ	Mass ratios for calculating the soil geometrical damping ratios in rocking about Y (ψ) directions
B_θ	Mass ratios for calculating the soil geometrical damping ratios in torsional about Z (θ) directions
C_x	Damping coefficients for a single pile in horizontal (X) direction
C_z	Damping coefficients for a single pile in vertical (Z) direction
C_ϕ	Damping coefficients for a single pile in rocking about X (ϕ) directions
D	System damping or equivalent modal damping ratio for a coupled vibrational motion
D_x	Soil or soil-pile damping ratios in horizontal X directions

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D_y	Soil or soil-pile damping ratios in horizontal Y directions
D_z	Soil or soil-pile damping ratios in vertical (Z) directions
D_ϕ	Soil or soil-pile damping ratios in rocking about X(ϕ) directions
D_ψ	Soil or soil-pile damping ratios in rocking about Y (ψ) directions
D_θ	Soil or soil-pile damping ratios in torsional about Z (θ) directions
E_p	Young's modulus of concrete pile
F_0	Machine unbalanced force for centrifugal machines
F_n	Unbalanced force at natural frequency of the foundation system
F_x	Unbalanced force in horizontal x direction
F_y	Unbalanced force in horizontal y direction
F_z	Unbalanced force in vertical z direction
G, G_s	Dynamic soil shear modulus
G_{avg}	Weighted average soil shear modulus
I_o	Mass moment of inertia at the C.G. of a machine foundation
I_p	Area moment of inertia of single pile
I_ϕ	Mass moments of inertia at the foundation base in rocking about X (ϕ) direction
I_ψ	Mass moments of inertia at the foundation base in rocking about Y (ψ) direction
I_θ	Mass moments of inertia at the foundation base in torsional about Z (θ) direction
K_s	Soil dynamic subgrade reaction (lbs/in ³)
K_x	Soil spring constants or single pile spring constants in translational X direction.
K_y	Soil spring constants or single pile spring constants in translational Y direction.
K_z	Soil spring constants or single pile spring constants in translational Z direction.
K_ϕ	Soil spring constants or single pile spring constants in rotational ϕ modes
K_ψ	Soil spring constants or single pile spring constants in rotational ψ modes
K_θ	Soil spring constants or single pile spring constants in rotational θ modes

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$(K_i)_g$	Pile spring constants for a pile group
L	foundation length, parallel to the X-axis .
M_ϕ	Unbalanced moments about X (ϕ),
M_ψ	Unbalanced moments about Y (ψ),
M_θ	Unbalanced moments about Z (θ),
N	Number of soil layers; number of piles
N_i	Dynamic amplification factors at i th vibrational motion
V_0	Maximum velocity amplitude
V_p	Compression wave velocity of pile, $\sqrt{E_p g / \gamma_p}$
V_s	Shear wave velocity of soil $\sqrt{G_s / \rho_s}$
W	Total weight of a machine foundation system (m x g)
W_e	Rotor weight
X	Cartesian coordinates in horizontal X (parallel to L)
Y	Cartesian coordinates in horizontal Y (parallel to B)
Z	Cartesian coordinates in vertical Z
α_x	Coefficients for soil damping calculation due to embedment effect in horizontal (X),
α_z	Coefficients for soil damping calculation due to embedment effect in vertical (Z)
α_ϕ	Coefficients for soil damping calculation due to embedment effect in rocking about X (ϕ) mode
α_ψ	Coefficients for soil damping calculation due to embedment effect in rocking about Y (ψ) mode
β	$\frac{I_0}{I_\psi}$ or $\frac{I_0}{I_\phi}$
β_x	Geometrical coefficients for soil spring calculation for rectangular foundation in translational X direction.
β_y	Geometrical coefficients for soil spring calculation for rectangular foundation in translational Y direction.
β_z	Geometrical coefficients for soil spring calculation for rectangular foundation in translational Z direction.
β_ϕ	Geometrical coefficients for soil spring calculation for rectangular foundation in rotational about X (ϕ) modes.
β_ψ	Geometrical coefficients for soil spring calculation for rectangular foundation in rotational about Y (ψ) modes.
γ	Correction factor for soil damping calculation in rocking mode

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γ_s	Weight density of soil ($D_s \times g$)
γ_p	Weight density of concrete pile
ρ_s	Mass density of soil
μ	Poisson's ratio of soil
ω	Machine operating speed (rad/sec)
η_x	Coefficients for soil spring calculation due to embedment effect in horizontal X direction.
η_y	Coefficients for soil spring calculation due to embedment effect in horizontal Y direction.
η_z	Coefficients for soil spring calculation due to embedment effect in vertical Z direction.
η_ϕ	Coefficients for soil spring calculation due to embedment effect rocking about X (ϕ)
η_ψ	Coefficients for soil spring calculation due to embedment effect rocking about Y (ψ)
θ	rotation about vertical Z-axis (torsion)
ϕ	rotation about horizontal X-axis (rocking)
ψ	rotation about horizontal Y-axis (rocking)

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Table 1

GENERAL MACHINERY - VIBRATION - SEVERITY DATA

Horizontal Peak Velocity (in./sec)	Machine Operation
<0.005	Extremely smooth
0.005-0.010	Very smooth
0.010-0.020	Smooth
0.020-0.040	Very good
0.040-0.080	Good
0.080-0.160	Fair
0.160-0.315	Slightly rough
0.315-0.630	Rough
>0.630	Very rough

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Table 2

ROTOR ECCENTRICITIES

Machine	Operating Speed f (RPM)	Eccentricity e (MILS)
Centrifugal Compressors and Turbines	$f \leq 3000$	$\frac{1.8 \cdot 10^7}{f^2}$ (or $F_o = 0.51 W_e$)
Centrifugal Compressors and Turbines	$f > 3000$	$\sqrt{\frac{12000}{f}}$
Gear Units	$f \leq 8000$	0.8
Gear Units	$f > 8000$	0.5
Motors	$f \leq 1500$	1.5
Motors	$1500 < f < 3000$	1
Motors	$f \geq 3000$	0.5

F_o : Machine unbalanced force

W_e : Rotor weight

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Table 3

SOIL SPRING CONSTANTS FOR RECTANGULAR FOUNDATION

Mode of Vibration	Soil Spring Constants
Horizontal (X)	$K_x = 2(1 + \mu)G \beta_x \sqrt{BL} \eta_x$
Horizontal (Y)	$K_y = 2(1 + \mu)G \beta_y \sqrt{BL} \eta_y$
Vertical (Z)	$K_z = \frac{G}{(1 - \mu)} \beta_z \sqrt{BL} \eta_z$
Rocking (about X)	$K_\phi = \frac{G}{(1 - \mu)} \beta_\phi B^2 L \eta_\phi$
Rocking (about Y)	$K_\psi = \frac{G}{(1 - \mu)} \beta_\psi BL^2 \eta_\psi$
Torsional (about Z)	$K_\theta = \frac{16 G r_o^3}{3}$

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Table 4

SOIL SPRING COEFFICIENTS FOR SOIL SPRING CALCULATION
INCLUDING EMBEDMENT EFFECT

Mode of Vibration	Equivalent Radius (r_o)	Soil Spring Coefficient
Horizontal (X & Y)	$\sqrt{\frac{BL}{\pi}}$	$\eta_x = 1 + 0.55(2 - \mu) \left[\frac{h}{r_o} \right]$ η_y
Vertical (Z)	$\sqrt{\frac{BL}{\pi}}$	$\eta_z = 1 + 0.6(1 - \mu) \left[\frac{h}{r_o} \right]$
Rocking (about X)	$\sqrt[4]{\frac{B^3L}{3\pi}}$	$\eta_\phi = 1 + 1.2(1 - \mu) \left[\frac{h}{r_o} \right] + 0.2(2 - \mu) \left[\frac{h}{r_o} \right]^3$
Rocking (about Y)	$\sqrt[4]{\frac{BL^3}{3\pi}}$	$\eta_\psi = 1 + 1.2(1 - \mu) \left[\frac{h}{r_o} \right] + 0.2(2 - \mu) \left[\frac{h}{r_o} \right]^3$
Torsional (about Z)	$\sqrt[4]{\frac{BL(B^2 + L^2)}{6\pi}}$	N/A

* h = embedment depth

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Table 5

GEOMETRICAL DAMPING RATIOS FOR RECTANGULAR FOUNDATION
(INCLUDING THE EMBEDMENT EFFECT)

Mode of Vibration	Mass Ratio	Damping Ratio (D)
Vertical (Z)	$B_z = \frac{(1 - \mu)}{4} \frac{m}{\rho_s r_o^3}$	$D_z = \frac{0.425}{\sqrt{B_z}} \alpha_z$
Horizontal (X or Y)	$B_x = \frac{(7 - 8\mu)}{32(1 - \mu)} \frac{m}{\rho_s r_o^3}$	$D_x = \frac{0.288}{\sqrt{B_x}} \alpha_x$
Rocking (about X)	$B_\phi = \frac{3(1 - \mu)}{8} \frac{I_\phi}{\rho_s r_o^5}$	$D_\phi = \frac{0.15 \alpha_\phi}{(1 + \gamma B_\phi) \sqrt{\gamma B_\phi}}$
Rocking (about Y)	$B_\psi = \frac{3(1 - \mu)}{8} \frac{I_\psi}{\rho_s r_o^5}$	$D_\psi = \frac{0.15 \alpha_\psi}{(1 + \gamma B_\psi) \sqrt{\gamma B_\psi}}$
Torsional (about Z)	$B_\theta = \frac{I_\theta}{\rho_s r_o^5}$	$D_\theta = \frac{0.5}{1 + 2B_\theta}$

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Table 6

DAMPING COEFFICIENTS FOR SOIL DAMPING CALCULATION
INCLUDING EMBEDMENT EFFECT

Mode of Vibration	Damping Coefficient
Vertical (Z)	$\alpha_z = \frac{I}{\sqrt{\eta_z}} \left[1 + 1.9(1 - \mu) \left(\frac{h}{r_o} \right) \right]$
Horizontal (X or Y)	$\alpha_x = \frac{I}{\sqrt{\eta_x}} \left[1 + 1.9(2 - \mu) \left(\frac{h}{r_o} \right) \right]$
Rocking (about X)	$\alpha_\phi = \frac{I}{\sqrt{\eta_\phi}} \left[1 + 0.7(1 - \mu) \left(\frac{h}{r_o} \right) + 0.6(2 - \mu) \left(\frac{h}{r_o} \right)^3 \right]$
Rocking (about Y)	$\alpha_\psi = \frac{I}{\sqrt{\eta_\psi}} \left[1 + 0.7(1 - \mu) \left(\frac{h}{r_o} \right) + 0.6(2 - \mu) \left(\frac{h}{r_o} \right)^3 \right]$
Torsional (about Z)	N/A

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Table 7

CORRECTION FACTOR FOR SOIL DAMPING CALCULATION IN ROCKING MODE

β_{ψ}	n_{ψ}
5	1.079
3	1.110
2	1.143
1	1.219
0.8	1.251
0.5	1.378
0.2	1.600

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Table 8

PILE STIFFNESSES FOR A SINGLE PILE

Mode of Vibration	Pile Stiffness
Horizontal (X or Y)	$K_x = K_y = E_p I_p f_{x,l} / r_o^3$
Vertical (Z)	$K_z = E_p A_p f_{z,l} / r_o$
Rocking (about X or Y)	$K_\phi = K_\psi = E_p I_p f_{\phi,l} / r_o$
Torsional (about Z)	N/A

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Table 9

DAMPING COEFFICIENTS FOR A SINGLE PILE

Mode of Vibration	Damping Coefficient
Vertical (Z)	$C_z = E_p A_p f_{z,2} \langle V_s \rangle$
Horizontal (X or Y)	$C_x = E_p I_p f_{x,2} \langle r_o^2 \rangle$
Rocking (about X or Y)	$C_\phi = E_p I_p f_{\phi,2} \langle V_s \rangle$
Torsional (about Z)	N/A

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Table 10

PILE STIFFNESS AND DAMPING PARAMETERS $f_{x,1}$, $f_{x,2}$, $f_{\phi,1}$ AND $f_{\phi,2}$

μ	γ_s / γ_p	$\frac{V_s}{V_p}$	<u>Stiffness Parameters</u>		<u>Damping Parameters</u>	
			$f_{x,1}$	$f_{\phi,1}$	$f_{x,2}$	$f_{\phi,2}$
0.4	0.7 (Concrete)	0.01	0.0036	0.202	0.0084	0.139
		0.02	0.0100	0.285	0.0238	0.200
		0.03	0.0185	0.349	0.0438	0.243
		0.04	0.0284	0.403	0.0674	0.281
		0.05	0.0397	0.450	0.0942	0.314
0.25	0.7 (Concrete)	0.01	0.0032	0.195	0.0076	0.135
		0.02	0.0090	0.275	0.0215	0.192
		0.03	0.0166	0.337	0.0395	0.235
		0.04	0.0256	0.389	0.0608	0.272
		0.05	0.0358	0.435	0.0850	0.304

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Table 11

PILE STIFFNESSES FOR A PILE GROUP

Mode of Vibration	Pile Group Stiffness
Vertical (Z)	$(K_z)_g = \sum_{i=1}^n K_{zi}$
Horizontal (X or Y)	$(K_x)_g = (K_y)_g = \sum_{i=1}^n K_{xi}$
Rocking (about X)	$(K_\phi)_g = \sum_{i=1}^n (K_{\phi_i} + K_{zi}y_i^2)$
Rocking (about Y)	$(K_\psi)_g = \sum_{i=1}^n (K_{\phi_i} + K_{zi}x_i^2)$
Torsional (about Z)	$(K_\theta)_g = \sum_{i=1}^n K_{xi}(x_i^2 + y_i^2)$

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Table 12

DAMPING RATIOS FOR A PILE GROUP

Mode of Vibration	Damping Ratios
Vertical (Z)	$D_z = \frac{\sum C_z}{2\sqrt{(K_z)_g} m}$
Horizontal (X or Y)	$D_x = \frac{\sum C_x}{2\sqrt{(K_x)_g} m}$
Rocking (about X)	$D_\phi = \frac{\sum [C_\phi + C_z y_i^2]}{2\sqrt{(K_\phi)_g} I_\phi}$
Rocking (about Y)	$D_\psi = \frac{\sum [C_\psi + C_z x_i^2]}{2\sqrt{(K_\psi)_g} I_\psi}$
Torsional (about Z)	$D_\theta = \frac{\sum C_x (x_i^2 + y_i^2)}{2\sqrt{(K_\theta)_g} I_\theta}$

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Table 13

CALCULATION OF UNCOUPLED NATURAL FREQUENCIES

<u>Mode of Vibration</u>	<u>Uncoupled Frequency (CPS)</u>
Vertical (Z)	$f_{nz} = \frac{1}{2\pi} \sqrt{\frac{K_z}{m}}$
Horizontal (X)	$f_{nx} = \frac{1}{2\pi} \sqrt{\frac{K_x}{m}}$
Horizontal (Y)	$f_{ny} = \frac{1}{2\pi} \sqrt{\frac{K_y}{m}}$
Rocking (about X)	$f_{n\phi} = \frac{1}{2\pi} \sqrt{\frac{K_\phi}{I_\phi}}$
Rocking (about Y)	$f_{n\psi} = \frac{1}{2\pi} \sqrt{\frac{K_\psi}{I_\psi}}$
Torsional (about Z)	$f_{n\theta} = \frac{1}{2\pi} \sqrt{\frac{K_\theta}{I_\theta}}$

* Use pile group stiffness $(K)_g$ for pile-supported foundation

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Table 14

CALCULATION OF DISPLACEMENT AMPLITUDES BASED ON UNCOUPLED MODES OF VIBRATION

Mode of Vibration	Displacement Amplitudes
Vertical (Z)	$d_z = N_z \frac{F_z}{K_z}$
Horizontal (X)	$d_x = N_x \frac{F_x}{K_x}$
Horizontal (Y)	$d_y = N_y \frac{F_y}{K_y}$
Rocking (about X)	$\phi = N_\phi \frac{M_\phi}{K_\phi}$
Rocking (about Y)	$\psi = N_\psi \frac{M_\psi}{K_\psi}$
Torsional (about Z)	$\theta = N_\theta \frac{M_\theta}{K_\theta}$

Dynamic amplification factors: $N_x, N_y, N_z, N_\phi, N_\psi, N_\theta$, are to be calculated as follows:

$$N_i = \frac{1}{\sqrt{(1 - r_i^2)^2 + (2 D_i r_i)^2}}, \text{ where, } r_i = \frac{f_0}{f_{ni}} \text{ and } D_i = \text{Damping ratio at } i\text{th mode.}$$

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Table 15

CALCULATION OF TOTAL DISPLACEMENT AMPLITUDE BASED ON UNCOUPLED MODES OF VIBRATION

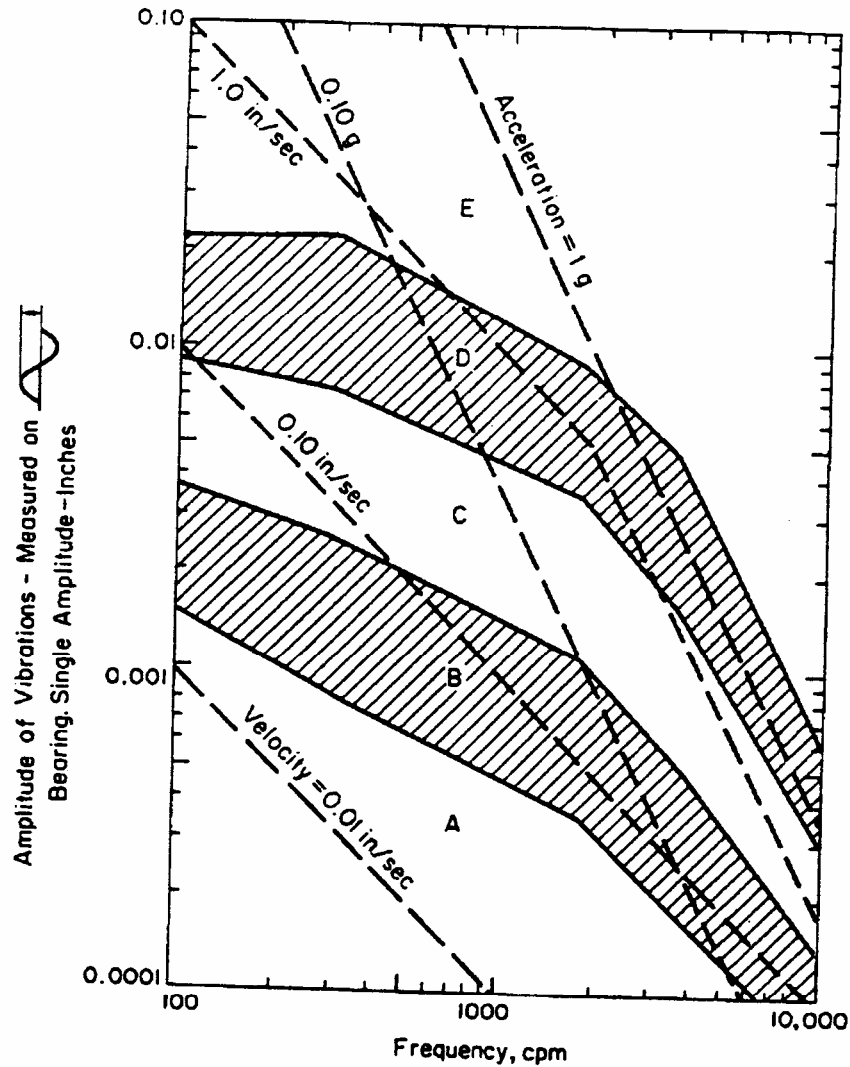
Direction	Displacement Amplitude
Vertical (Z)	$Z = d_z + \phi (\Delta Y) + \psi (\Delta X)$
Horizontal (X)	$X = d_x + \theta (\Delta Y) + \psi (\Delta Z)$
Horizontal (Y)	$Y = d_y + \theta (\Delta X) + \phi (\Delta Z)$

* The total displacement A_o is then obtained as follows:

$$A_o = \sqrt{x^2 + y^2 + z^2}$$

* Δx , Δy and Δz are the distances from the center of foundation base to the point where the amplitude is determined.

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- Explanation of cases:
- E Dangerous. Shut it down now to avoid danger.
 - D Failure is near. Correct to avoid breakdown.
 - C Faulty. Correct to save maintenance dollars.
 - B Minor faults. Correction wastes dollars.
 - A No faults. Typical new equipment.

Figure 1: Criteria for Vibrations of Rotating Machinery

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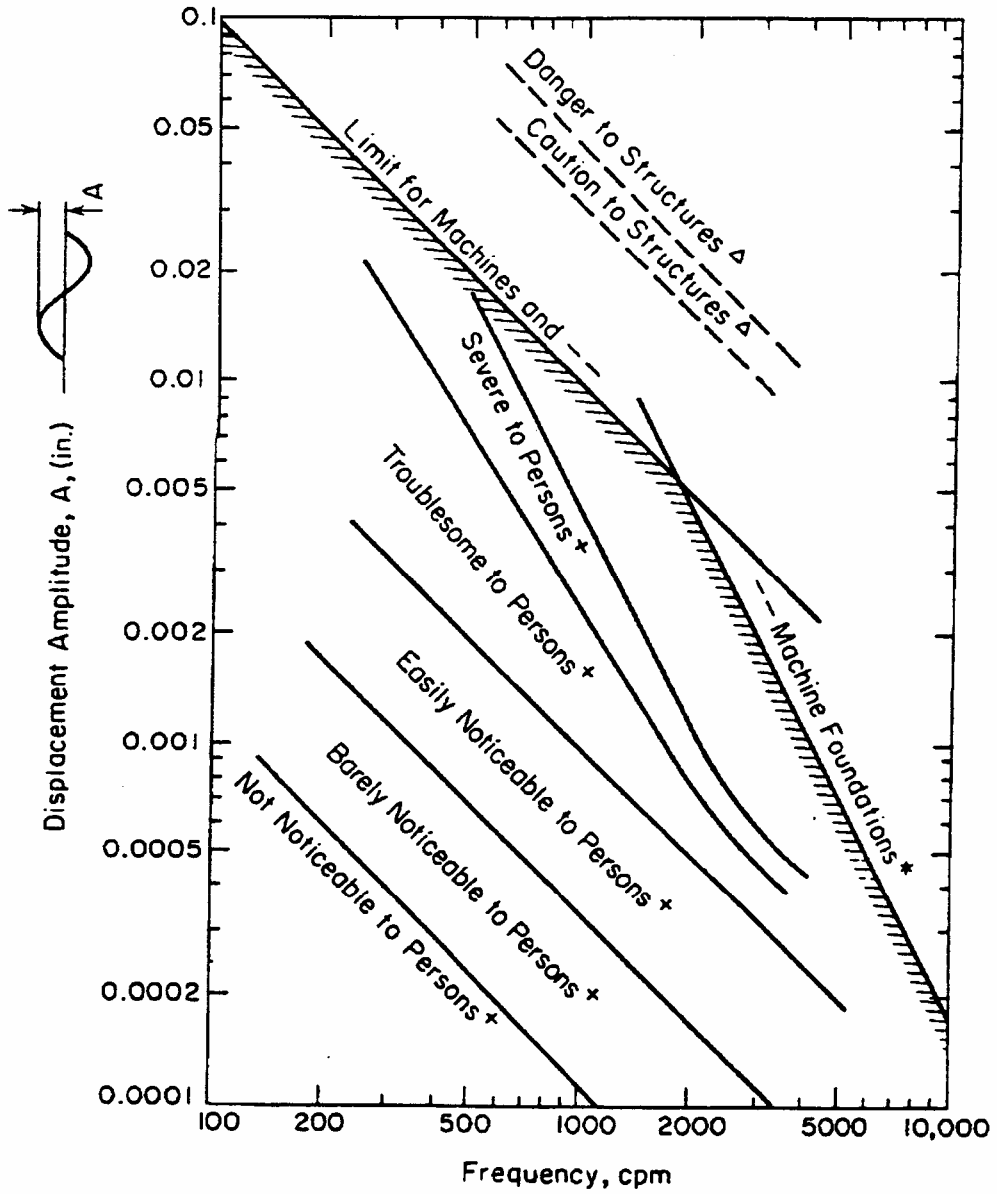
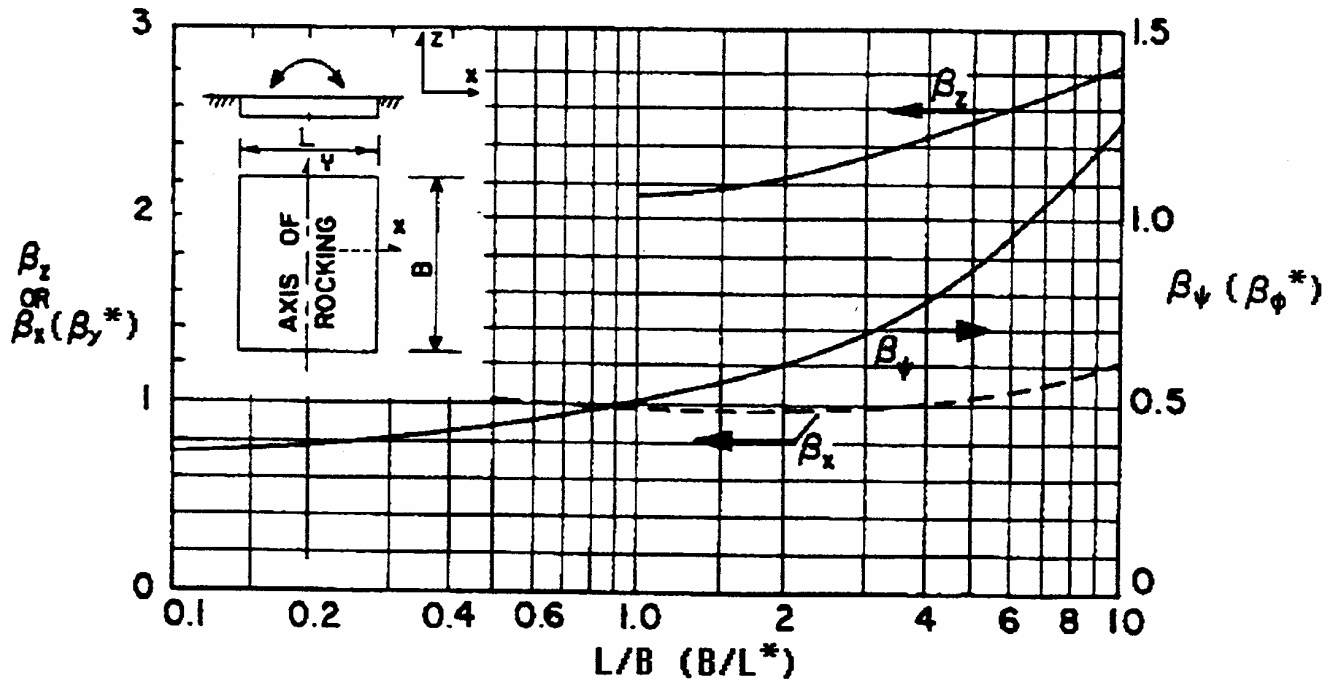


Figure 2 - General Limits of Displacement Amplitude for a Particular Frequency of Vibration

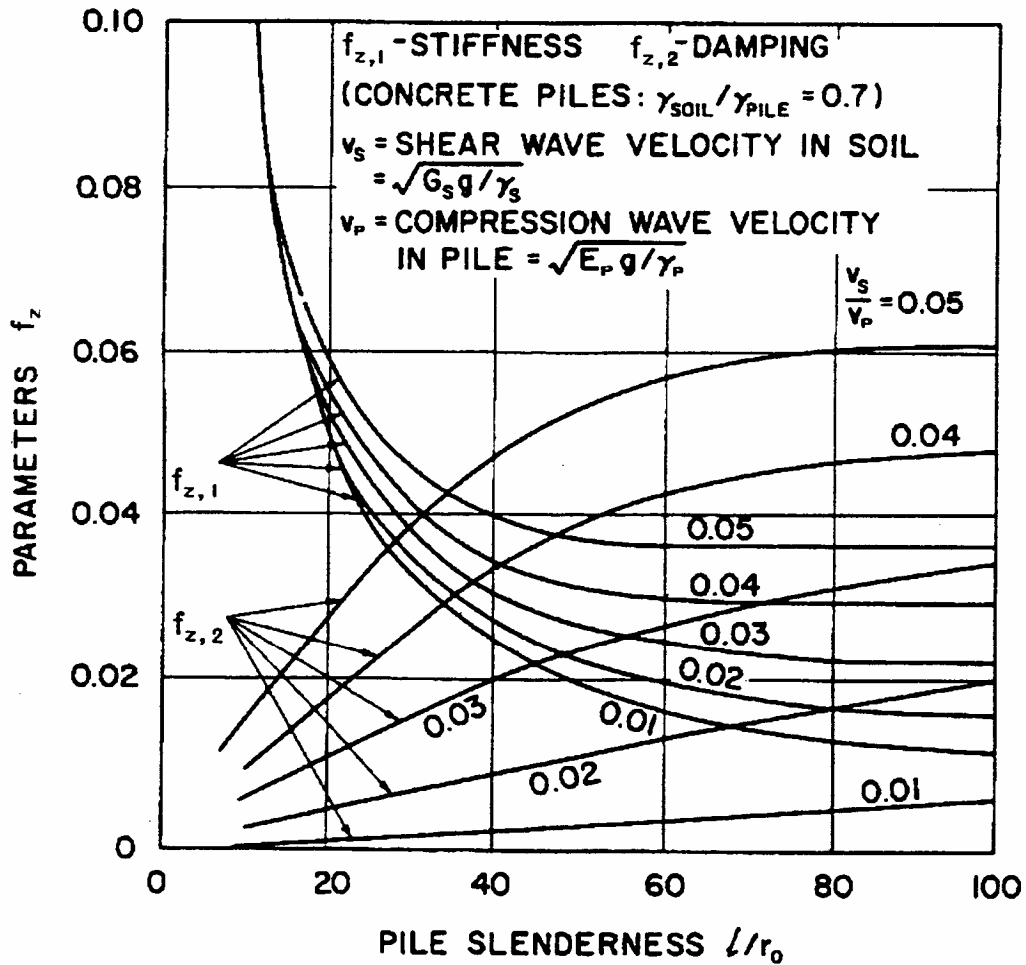
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* The coefficients β_y and β_ϕ are functions of the ratios of B/L , and are derived for dynamic excitation along the horizontal y -axis and rocking about x -axis.

Figure 3 - Geometrical Coefficients for Rectangular Foundation

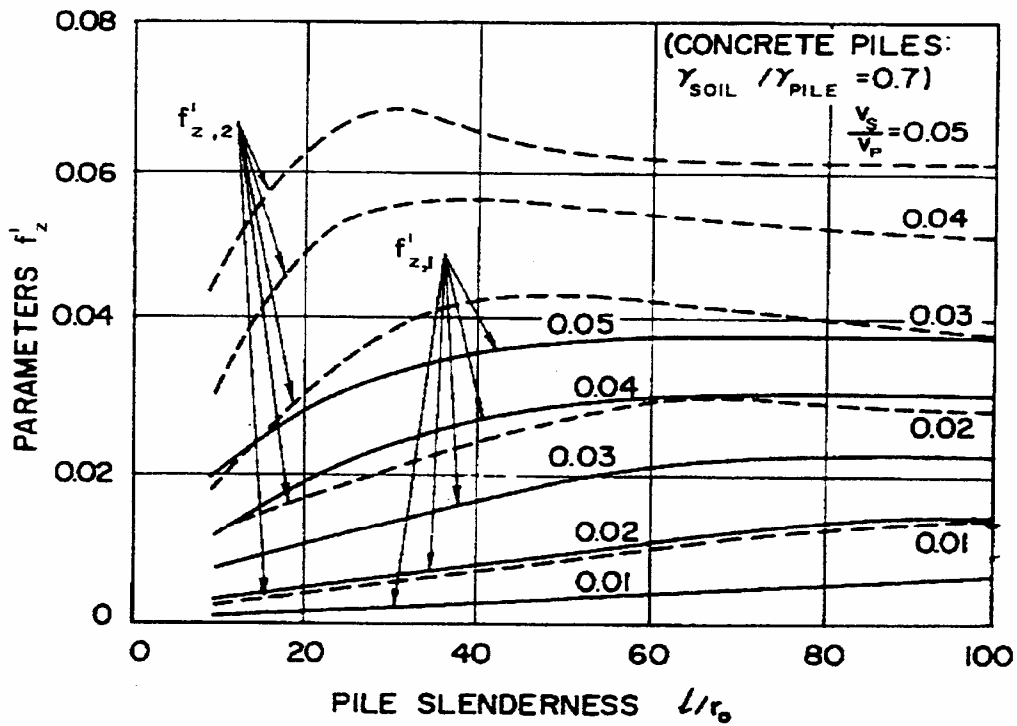
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End Bearing Piles or Combined Friction & End Bearing Piles ($f_{z,1}$ & $f_{z,2}$)

Figure 4: Vertical Pile Stiffness and Damping

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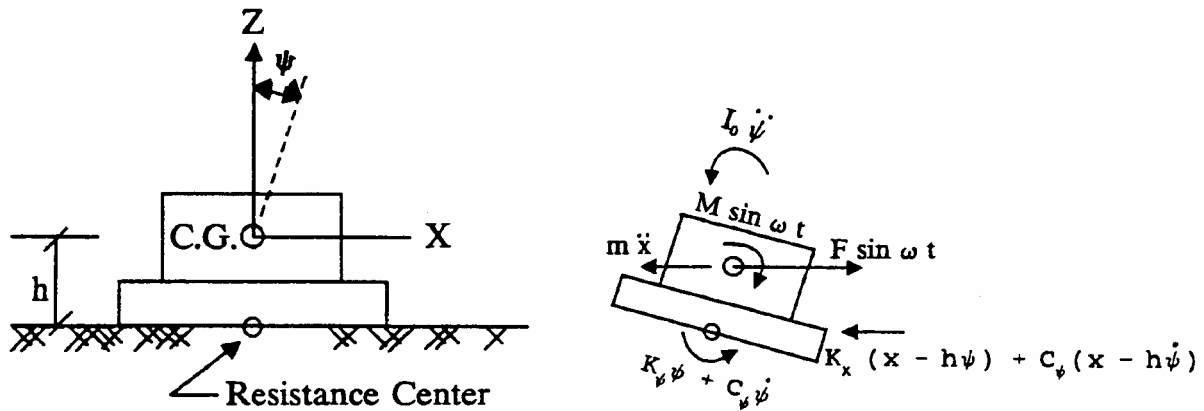


Friction Piles ($f'_{z,1}$ & $f'_{z,2}$)

Figure 5: Vertical Pile Stiffness and Damping Parameters for Friction Piles

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COUPLED HORIZONTAL AND ROCKING MOTIONS



Couple mode frequencies, Sliding along X and rocking about Y

$$f_1^2 = \frac{1}{2\beta} \left[f_{nx}^2 + f_{n\psi}^2 + \sqrt{(f_{nx}^2 + f_{n\psi}^2)^2 - 4\beta f_{nx}^2 f_{n\psi}^2} \right]$$

$$f_2^2 = \frac{1}{2\beta} \left[f_{nx}^2 + f_{n\psi}^2 - \sqrt{(f_{nx}^2 + f_{n\psi}^2)^2 - 4\beta f_{nx}^2 f_{n\psi}^2} \right]$$

Where, $f_{nx} = \frac{1}{2\pi} \sqrt{\frac{K_x}{m}}$; uncoupled sliding frequency along X

$f_{n\psi} = \frac{1}{2\pi} \sqrt{\frac{K_\psi}{I_\psi}}$; uncoupled rocking frequency about Y

K_x : horizontal soil/pile stiffness

K_ψ : rocking soil/pile stiffness

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m: total mass of a machine foundation system

I_{ψ} : $I_0 + mh^2$, the mass moment of inertia at the foundation base

I_0 : the mass moment of inertia at the C.G. of a machine foundation system

h: the distance between combined C.G. and the base of a machine foundation

$$\beta = \frac{I_0}{I_{\psi}}$$

Note that the coupling effect becomes insignificant and can be neglected when the two coupled frequencies are determined to be away from the machine operating speed by at least 40%.