

Suggested Analysis and Design Procedures for Combined Footings and Mats

Reported by ACI Committee 336

Edward J. Ulrich
Chair

Shyam N. Shukla
Secretary

Clyde N. Baker, Jr.
Steven C. Ball
Joseph E. Bowles
Joseph P. Colaco
M. T. Davisson

John A. Focht, Jr.
M. Gaynor
John P. Gnaedinger
Fritz Kramrisch

Hugh S. Lacy
Jim Lewis
James S. Notch
Ingvar Schousboe

John F. Seidensticker
Bruce A. Suprenant
Jagdish S. Syal
John J. Zils

This report deals with the design of foundations carrying more than a single column of wall load. These foundations are called combined footings and mats. Although it is primarily concerned with the structural aspects of the design, considerations of soil mechanics cannot be eliminated and the designer should focus on the important interrelation of the two fields in connection with the design of such structural elements. This report is limited to vertical effects of all loading conditions. The report excludes slabs-on-grade.

Keywords: concretes; earth pressure; footings; foundations; loads (forces); mat foundations; reinforced concrete; soil mechanics; stresses; structural analysis; structural design.

CONTENTS

Chapter 1—General, p. 336.2R-2

- 1.1—Notation
- 1.2—Scope
- 1.3—Definitions and loadings
- 1.4—Loading combinations
- 1.5—Allowable pressure
- 1.6—Time-dependent considerations
- 1.7—Design overview

ACI Committee Reports, Guides, Manuals, Standard Practices, 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.

Chapter 2—Soil structure interaction, p. 336.2R-5

- 2.1—General
- 2.2—Factors to be considered
- 2.3—Investigation required to evaluate variable factors

Chapter 3—Distribution of soil reactions, p. 336.2R-6

- 3.1—General
- 3.2—Straight-line distribution of soil pressure
- 3.3—Distribution of soil pressure governed by modulus of subgrade reaction

Chapter 4—Combined footings, p. 336.2R-7

- 4.1—Rectangular-shaped footings
- 4.2—Trapezoidal or irregularly shaped footings
- 4.3—Overturning calculations

Chapter 5—Grid foundations and strip footings supporting more than two columns, p. 336.2R-8

- 5.1—General
- 5.2—Footings supporting rigid structures
- 5.3—Column spacing
- 5.4—Design procedure for flexible footings
- 5.5—Simplified procedure for flexible footings

Chapter 6—Mat foundations, p. 336.2R-9

- 6.1—General
- 6.2—Finite difference method
- 6.3—Finite grid method

ACI 336.2R-88 supersedes ACI 336.2R-66 (Reapproved 1980).
Copyright © 1988, 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 proprietor.

- 6.4—Finite element method
- 6.5—Column loads
- 6.6—Symmetry
- 6.7—Node coupling of soil effects
- 6.8—Consolidation settlement
- 6.9—Edge springs for mats
- 6.10—Computer output
- 6.11—Two-dimensional or three-dimensional analysis
- 6.12—Mat thickness
- 6.13—Parametric studies
- 6.14—Mat foundation detailing/construction

Chapter 7—Summary, p. 336.2R-19

Chapter 8—References, p. 336.2R-20

- 8.1—Specified and/or recommended references
- 8.2—Cited references

CHAPTER 1—GENERAL

1.1—Notation

The following dimensioning notation is used: F = force; ℓ = length; and Q = dimensionless.

- | | |
|---|--|
| A = base area of footing, ℓ^2 | I = plan moment of inertia of footing (or mat) about any axis $x(I_x)$ or $y(I_y)$, ℓ^4 |
| b = width of pressed edge, ℓ | I_B = moment of inertia of one unit width of the superstructure, ℓ^4 |
| B = foundation width, or width of beam column element, ℓ | I_F = moment of inertia per one unit width of the foundation, ℓ^4 |
| B_m = mat width, ℓ | I_w = base shape factor depending on foundation shape and flexibility, ℓ^4 |
| B_p = plate width, ℓ | i = vertical displacement of a node, ℓ |
| c = distance from resultant of vertical forces to overturning edge of the base, ℓ | J = torsion constant for finite grid elements, ℓ^4 |
| D = dead load or related internal moments and forces, F | k_p = coefficient of subgrade reaction from a plate load test, F/ℓ^3 |
| D_f = the depth D_f should be the depth of soil measured adjacent to the pressed edge of the combined footing or mat at the time the loads being considered are applied | k_s = q/δ = coefficient (or modulus) of vertical subgrade reaction; generic term dependent on dimensions of loaded area, F/ℓ^3 |
| D_o = dead load for overturning calculations, F | k_{si} = coefficient of subgrade reaction contribution to node i , F/ℓ^3 |
| D_{st} = stage dead load consisting of the unfactored dead load of the structure and foundation at a particular time or stage of construction, F | k'_{si} = revised coefficient of subgrade reaction contribution to node i , F/ℓ^3 , see Section 6.8 |
| e = eccentricity of resultant of all vertical forces, ℓ | k_{v1} = basic value of coefficient of vertical subgrade reaction for a square area with width $B = 1$ ft, F/ℓ^3 |
| e_i = eccentricity of resultant of all vertical forces with respect to the x - and y -axes (e_x and e_y , respectively), ℓ | K = spring constant computed as contributory node area xk_s , F/ℓ |
| E = vertical effects of earthquake simulating forces or related internal moment or force, F | K_r = relative stiffness factor for foundation, Q |
| E' = modulus of elasticity of the materials used in the superstructure, F/ℓ^2 | L = live load or related internal moments and forces produced by the load, F |
| E_e = modulus of elasticity of concrete, F/ℓ^2 | L_s = sustained live loads used to estimate settlement, F . A typical value would be 50% of all live loads. |
| E_s = soil modulus of elasticity, F/ℓ^2 | L_{st} = stage service live load consisting of the sum of all unfactored live loads at a particular stage of construction, F |
| F_{vh} = vertical effects of lateral loads such as earth pressure, water pressure, fill pressure, surcharge pressure, or similar lateral loads, F | M' = bending moment per unit length, $F\ell$ |
| G = shear modulus of concrete, F/ℓ^2 | M_E = overturning moment about base of foundation caused by an earthquake simulating force, $F\ell$ |
| h_w = height of any shearwalls in structure, ℓ | M_F = overturning moment about base of foundation, caused by F_{vh} loads, $F\ell$ |
| H = settlement of foundation or point, ℓ | M_o = largest overturning moment about the pressed edge or centroid of the base, $F\ell$ |
| H_{ci} = consolidation (or recompression) settlement of point i , ℓ | M_R = resultant resisting moment, $F\ell$ |
| ΔH = magnitude of computed foundation settlement, ℓ | M_W = overturning moment about base of foundation, caused by wind loads, blast, or similar lateral loads, $F\ell$ |
| | n = exponent used to relate plate k_p to mat k_s , Q |
| | P = any force acting perpendicular to base area, F |
| | q = soil contact pressure computed or actual, F/ℓ^2 |
| | q_a = allowable soil contact pressure, F/ℓ^2 |
| | q_i = actual or computed soil contact pressure at a node point as furnished by the mat analysis. The contact pressures are evaluated by the geotechnical analysis for compatibility with q_a and foundation movement, F/ℓ^2 |
| | q_u = unconfined (undrained) compression strength of a cohesive soil, F/ℓ^2 |
| | q_{ult} = ultimate soil bearing capacity; a computed value to allow computation of ultimate strength design moments and shears for the foundation design, also used in overturning calculations, F/ℓ^2 |

R_v	= resultant of all given design loads acting perpendicular to base area, F
$R_{v\ min}$	= least resultant of all forces acting perpendicular to base area under any condition of loading simultaneous with the overturning moment, F
S	= section modulus of mat plan area about a specified axis; S_x about x-axis; S_y about y-axis, ℓ^3
SR	= stability ratio (formerly safety factor), Q
t_w	= thickness of shearwalls, ℓ
v	= distance from the pressed edge to $R_{v\ min}$ (see Fig. 4.1 and 4.2), ℓ
W	= vertical effects of wind loads, blast, or similar lateral loads, F
X_i	= the maximum deflection of the spring at node i as a linear model, ℓ
Z	= foundation base length or length of beam column element, ℓ
Z'	= footing effective length measured from the pressed edge to the position at which the contact pressure is zero, ℓ
δ	= vertical soil displacement, ℓ
Δ_q	= average increase in soil pressure due to unit surface contact pressure, F/ℓ^2
λ	= footing stiffness evaluation factor defined by Eq. (5-3), $1/\ell$
μ	= Poisson's ratio, Q
Σ	= summation symbol, Q
γ	= unit weight of soil, F/ℓ^3
α	= torsion constant adjustment factor, Q

1.2—Scope

This report addresses the design of shallow foundations carrying more than a single column or wall load. Although the report focuses on the structural aspects of the design, soil mechanics considerations are vital and the designer should include the soil-structure interaction phenomenon in connection with the design of combined footings and mats. The report excludes slabs-on-grade.

1.3—Definitions and loadings

Soil contact pressures acting on a combined footing or mat and the internal stresses produced by them should be determined from one of the load combinations given in Section 1.3.2, whichever produces the maximum value for the element under investigation. Critical maximum moment and shear may not necessarily occur with the largest simultaneously applied load at each column.

1.3.1 Definitions

coefficient of vertical subgrade reaction k_s —ratio between the vertical pressure against the footing or mat and the deflection at a point of the surface of contact

$$k_s = q/\delta$$

combined footing—a structural unit or assembly of units supporting more than one column load.

contact pressure q —pressure acting at and perpendicular to the contact area between footing and soil, produced by the weight of the footing and all forces acting on it.

continuous footing—a combined footing of prismatic or truncated shape, supporting two or more columns in a row.

grid foundation—a combined footing, formed by intersecting continuous footings, loaded at the intersection points and covering much of the total area within the outer limits of assembly.

mat foundation—a continuous footing supporting an array of columns in several rows in each direction, having a slab-like shape with or without depressions or openings, covering an area of at least 75% of the total area within the outer limits of the assembly.

mat area—contact area between mat foundation and supporting soil.

mat weight—weight of mat foundation.

modulus of subgrade reaction—see **coefficient of vertical subgrade reaction**.

overburden—weight of soil or backfill from base of foundation to ground surface. Overburden should be determined by the geotechnical engineer.

overturning—the horizontal resultant of any combination of forces acting on the structure tending to rotate the structure as a whole about a horizontal axis.

pressed edge—edge of footing or mat along which the greatest soil pressure occurs under the condition of overturning.

soil stress-strain modulus—modulus of elasticity of soil and may be approximately related (Bowles 1982) to the coefficient of subgrade reaction by the equation

$$E_s = k_s B(1 - \mu^2)I_w$$

soil pressure—see **contact pressure**.

spring constant—soil resistance in load per unit deflection obtained as the product of the contributory area and k_s . See also **coefficient of vertical subgrade reaction**.

stability ratio (SR)—formally known as safety factor, it is the ratio of the resisting moment M_R to the overturning moment M_o .

strip footing—see **continuous footing**.

subgrade reaction—see **contact pressure** and Chapter 3.

surcharge—load applied to ground surface above the foundation.

1.3.2 Loadings—Loadings used for design should conform to the considerations and factors in Chapter 9 of ACI 318 unless more severe loading conditions are required by the governing code, agency, structure, or conditions.

1.3.2.1 Dead loads—Dead load D consisting of the sum of:

- Weight of superstructure.
- Weight of foundation.
- Weight of surcharge.
- Weight of fill occupying a known volume.

1.3.2.2 Live loads—Live load L consisting of the sum of:

- Stationary or moving loads, taking into account allowable reductions for multistory buildings or large floor areas, as stated by the applicable building code.

b. Static equivalents of occasional impacts.

Repetitive impacts at regular intervals, such as those caused by drop hammers or similar machines, and vibratory excitations, are not covered by these design recommendations and require special treatment.

1.3.2.3 Effects of lateral loads—Vertical effects of lateral loads F_{vh} , such as:

- a. Earth pressure.
- b. Water pressure.
- c. Fill pressure, surcharge pressure, or similar.
- d. Differential temperature, differential creep and shrinkage in concrete structures, and differential settlement.

Vertical effects of wind loads, blast, or similar lateral loads W .

Vertical effects of earthquake simulating forces E .

Overturning moment about base of foundation, caused by earthquake simulating forces M_E .

Overturning moment about base of foundation, caused by F_{vh} loads M_F .

Overturning moment about foundation base, caused by wind loads, blast, or similar lateral loads M_W .

Dead load for overturning calculations D_o , consisting of the dead load of the structure and foundation but including any buoyancy effects caused by parts presently submerged or parts that may become submerged in the future. The influence of unsymmetrical fill loads on the overturning moments M_o , as well as the resultant of all vertical forces R_{vmin} , shall be investigated and used if found to have a reducing effect on the stability ratio SR .

Service live load L_s , consisting of the sum of all unfactored live loads, reasonably reduced and averaged over area and time to provide a useful magnitude for the evaluation of service settlements. Also called *sustained live load*.

Stage dead load D_{st} , consisting of the unfactored dead load of the structure and foundation at a particular time or stage of construction.

Stage service live load L_{st} , consisting of the sum of all unfactored live loads up to a particular time or stage of construction, reasonably reduced and averaged over area and time, to provide a useful magnitude for the evaluation of settlements at a certain stage.

1.4—Loading combinations

In the absence of conflicting code requirements, the following conditions should be analyzed in the design of combined footings and mats.

1.4.1 Evaluation of soil pressure—Select the combinations of unfactored (service) loads that will produce the greatest contact pressure on a base area of given shape and size. The allowable soil pressure should be determined by a geotechnical engineer based on a geotechnical investigation.

Loads should be of Types D , L , F_{vh} , W , and E as described in Section 1.3.2, and should include the vertical effects of moments caused by horizontal components of these forces and by eccentrically (eccentric with regard to the centroid of the area) applied vertical loads.

a. Consider buoyancy of submerged parts where this reduces the stability ratio or increases the contact pressures, as in flood conditions.

b. Obtain earthquake forces using the applicable building code, and rational analysis.

1.4.2 Foundation strength design—Although the allowable stress design according to the Alternate Design Method (ADM) is considered acceptable, it is best to design footings or mat foundations based on the Strength Design Method of ACI 318. Loading conditions applicable to the design of mat foundations are given in more detail in Chapter 6.

After the evaluation of soil pressures and settlement, apply the load factors in accordance with Section 9.2 of ACI 318.

1.4.3 Overturning—Select from the several applicable loading combinations the largest overturning moment M_o as the sum of all simultaneously applicable unfactored (service) load moments (M_F , M_W , and M_E) and the least unfactored resistance moment M_R resulting from D_o and F_{vh} to determine the stability ratio SR against overturning in accordance with the provisions of Chapter 4.

1.4.4 Settlement—Select from the combinations of unfactored (service) loads, the combination that will produce the greatest settlement or deformation of the foundation, occurring either during and immediately after the load application or at a later date, depending on the type of subsoil. Loadings at various stages of construction such as D , D_{st} , and L_{st} should be evaluated to determine the initial settlement, long-term settlement due to consolidation, and differential settlement of the foundation.

1.5—Allowable pressure

The maximum unfactored design contact pressures should not exceed the allowable soil pressure, q_a . The value of q_a should be determined by a geotechnical engineer.

Where wind or earthquake forces form a part of the load combination, the allowable soil pressure may be increased as allowed by the local code and in consultation with the geotechnical engineer.

1.6—Time-dependent considerations

Combined footings and mats are sensitive to time-dependent subsurface response. Time-dependent considerations include: 1) stage loading where the initial load consists principally of dead load; 2) foundation settlement with small time dependency such as mats on sand and soft carbonate rock; 3) foundation settlement, which is time-dependent (usually termed consolidation settlements), where the foundation is sited over fine-grained soils of low permeability such as silt and clay or silt-clay mixtures; 4) variations in live loading; and 5) soil shear displacements. These five factors may produce time-dependent changes in the shears and moments.

1.7—Design overview

Many structural engineers analyze and design mat foundations by computer using the finite element method. Soil response can be estimated by modeling with coupled or uncoupled “soil springs.” The spring properties are usually

calculated using a modulus of subgrade reaction, adjusted for footing size, tributary area to the node, effective depth, and change of modulus with depth. The use of uncoupled springs in the model is a simplified approximation. Section 6.7 considers a simple procedure to couple springs within the accuracy of the determination of subgrade response. The time-dependent characteristics of the soil response, consolidation settlement or partial-consolidation settlement, often can significantly influence the subgrade reaction values. Thus, the use of a single constant modulus of subgrade reaction can lead to misleading results.

Ball and Notch (1984), Focht et al. (1978), and Banavalkar and Ulrich (1984) address the design of mat foundations using the finite element method and time-dependent subgrade response. A simplified method, using tables and diagrams to calculate moments, shears, and deflections in a mat may be found in Bowles (1982), Hetenyi (1946), and Shukla (1984).

Caution should be exercised when using finite element analysis for soils. Without good empirical results, soil springs derived from values of subgrade reaction may only be a rough approximation of the actual response of soils. Some designers perform several finite element analyses with soil springs calculated from a range of subgrade moduli to obtain an adequate design.

CHAPTER 2—SOIL STRUCTURE INTERACTION

2.1—General

Foundations receive loads from the superstructure through columns, walls, or both and act to transmit these loads into the soil. The response of a footing is a complex interaction of the footing itself, the superstructure above, and the soil. That interaction may continue for a long time until final equilibrium is established between the superimposed loads and the supporting soil reactions. Moments, shears, and deflections can only be computed if these soil reactions can be determined.

2.2—Factors to be considered

No analytical method has been devised that can evaluate all of the various factors involved in the problem of soil-structure interaction and allow the accurate determination of the contact pressures and associated subgrade response. Simplifying assumptions must be made for the design of combined footings or mats. The validity of such simplifying assumptions and the accuracy of any resulting computations must be evaluated on the basis of the following variables.

2.2.1 Soil type below the footing—Any method of analyzing a combined footing should be based on a determination of the physical characteristics of the soil located below the footing. If such information is not available at the time the design is prepared, assumptions must be made and checked before construction to determine their validity. Consideration must be given to the increased unit pressures developed along the edges of rigid footings on nongranular soils and the opposite effect for footings on granular soils. The effect of embedment of the footing on pressure variation must also be considered.

2.2.2 Soil type at greater depths—Consideration of long-term consolidation of deep soil layers should be included in

the analysis of combined footings and mats. Since soil consolidation may not be complete for a number of years, it is necessary to evaluate the behavior of the foundations immediately after the structure is built, and then calculate and superimpose stresses caused by consolidation.

2.2.3 Size of footing—The effect of the size of the footing on the magnitude and distribution of the contact pressure will vary with the type of soil. This factor is important where the ratio of perimeter to area of a footing affects the magnitude of contact pressures, such as in the case of the increased edge pressure (Section 2.2.1) and the long-term deformation under load (Section 2.2.2). The size of the footing must also be considered in the determination of the subgrade modulus. Refer to Section 3.3.

2.2.4 Shape of footing—This factor also affects the perimeter-to-area ratio. Generally, simple geometric forms of squares and rectangles are used. Other shapes such as trapezoids, octagons, and circles are employed to respond to constraints dictated by the superstructure and property lines.

2.2.5 Eccentricity of loading—Analysis should include consideration of the variation of contact pressures from eccentric loading conditions.

2.2.6 Footing stiffness—The stiffness of the footing may influence the deformations that can occur at the contact surface and this will affect the variation of contact pressures (as will be seen in Fig. 3.1). If a flexible footing is founded on sand and the imposed load is uniformly distributed on top of the footing, then the soil pressure is also uniformly distributed. Since the resistance to pressure will be smallest at the edge of the footing, the settlement of the footing will be larger at the edges and smaller at the center. If, however, the footing stiffness is large enough that the footing can be considered to act as a rigid body, a uniform settlement of the footing occurs and the pressure distribution must change to higher values at the center where the resistance to settlement is greater and lower values at the perimeter of the footing where the resistance to settlement is lower.

For nongranular soils, the stiffness of the footing will affect the problem in a different manner. The settlement of a relatively flexible footing supported on a clay soil will be greatest at the center of the footing although the contact soil pressure is uniform. This occurs because the distribution of soil pressure at greater depths has a higher intensity under the center of the footing. If the footing may be considered to act as a rigid body, the settlement must be uniform and the unit soil pressures are greater at the edge of the footing.

2.2.7 Superstructure stiffness—This factor tends to restrict the free response of the footing to the soil deformation. Redistribution of reactions occur within the superstructure frame as a result of its stiffness, which reduces the effects of differential settlements. This factor must be considered together with Section 2.2.6 to evaluate the validity of stresses computed on the basis of foundation modulus theories. Also, such redistribution may increase the stresses in elements of the superstructure.

2.2.8 Modulus of subgrade reaction—For small foundations [B less than 5 ft (1.5 m)], this soil property may be estimated on the basis of field experiments that yield load-deflection

relationships, or on the basis of known soil characteristics. Soil behavior is generally more complicated than that which is assumed in the calculation of stresses by subgrade reaction theories. However, provided certain requirements and limitations are fulfilled, sufficiently accurate results can be obtained by the use of these theories. For mat foundations, this soil property cannot be reliably estimated on the basis of field plate load tests because the scale effects are too severe.

Sufficiently accurate results can be obtained using subgrade reaction theory, but modified to individually consider dead loading, live loading, size effects, and the associated subgrade response. Zones of different constant subgrade moduli can be considered to provide a more accurate estimate of the subgrade response as compared to that predicted by a single modulus of subgrade reaction. A method is described in Ball and Notch (1984) and Bowles (1982), and case histories are given in Banavalkar and Ulrich (1984) and Focht et al. (1978). Digital computers allow the designer to use mat models having discrete elements and soil behavior having variable moduli of subgrade reaction. The modulus of subgrade reaction is addressed in more detail in Section 3.3 and Chapter 6.

2.3—Investigation required to evaluate variable factors

Methods are available to estimate the influence of each of the soil structure interaction factors listed in Section 2.2. Desired properties of the structure and the combined footing can be chosen by the design engineer. The designer, however, must usually accept the soil as it exists at the building site, and can only rely on careful subsurface exploration and testing, and geotechnical analyses to evaluate the soil properties affecting the design of combined footings and mats. In some instances it may be practical to improve soil properties. Some soil improvement methods include: dynamic consolidation, vibroflotation, vibroreplacement, surcharging, removal and replacement, and grouting.

CHAPTER 3—DISTRIBUTION OF SOIL REACTIONS

3.1—General

Except for unusual conditions, the contact pressures at the base of a combined footing may be assumed to follow either a distribution governed by elastic subgrade reaction or a straight-line distribution. At no place should the calculated contact pressure exceed the maximum allowable value q_a .

3.2—Straight-line distribution of soil pressure

A linear soil pressure distribution may be assumed for footings which can be considered to be a rigid body to the extent that only very small relative deformations result from the loading. This rigid body assumption may result from the spacing of the columns on the footing, from the stiffness of the footing itself, or the rigidity of the superstructure. Criteria that must be fulfilled to make this assumption valid are discussed in the following sections.

3.2.1 Contact pressure over total base area—If the resultant of all forces is such that all portions of the foundation contact area are in compression, the maximum and minimum soil pressure may then be calculated from the following

formula, which applies only to rectangular base areas and only when e is located along one of the principal axes

$$q_{min}^{max} = \frac{\Sigma P}{BZ} \left(1 \pm \frac{6e}{Z} \right) \quad (3-1)$$

3.2.2 Contact pressure over part of area—The soil pressure distribution should be assumed to be triangular. The resultant of this distribution has the same magnitude and colinear, but acts in the opposite direction of the resultant of the acting forces.

The maximum and minimum soil pressure under this condition can be calculated from the following expressions:

At the footing edge

$$q_{ult} = \frac{2P}{3B} \left(\frac{Z}{2} - e \right) \quad (3-2)$$

At distance Z' from the prestressed edge

$$q_{min} = 0 \quad (3-3)$$

$$Z' = 3 \left(\frac{Z}{2} - e \right) \quad (3-4)$$

Equations (3-1) to (3-4) are based on the assumption that no tensile (—) stresses exist between footing and soil. The equations may be applied with the details to be shown in the stability ratio calculation in Chapter 4, Fig. 4.2. Equations (3-2) through (3-4) apply for cases where the resultant force falls out of the middle third of the base.

3.3—Distribution of soil pressure governed by the modulus of subgrade reaction

The assumption of a linear pressure distribution is commonly used and is satisfactory in most cases because of conservative load estimates and ample safety factors in materials and soil. The actual contact pressure distribution in cohesionless soils is concave; in cohesive soils, the pressure distribution is convex (Fig. 3.1). Refer to Chapter 2 for more discussion of foundation stiff and pressure distributions.

The suggested initial design approach is to size the thickness for shear without using reinforcement. The flexural steel is then obtained by assuming a linear soil pressure distribution and using simplified procedures in which the foundation satisfies statics. The flexural steel may also be obtained by assuming that the foundation is an elastic member interacting with an elastic soil. Simplified methods are found in some textbooks and references: Bowles (1974, 1982); Hetenyi (1946); Kramrisch (1984); and Teng (1962).

3.3.1 Beams on elastic foundations—If a combined footing is assumed to be a flexible slab, it may be analyzed as a beam on elastic foundation using the methods found in Bowles (1974, 1982), Hetenyi (1946), Kramrisch and Rogers (1961), or Kramrisch (1984). The discrete element method has distinct advantages of allowing better modeling of