CHAPTER 1

INTRODUCTION

1-1. **Purpose and Scope.** This manual presents guidelines for calculation of the bearing capacity of soil under shallow and deep foundations supporting various types of structures and embankments. This information is generally applicable to foundation investigation and design conducted by Corps of Engineer agencies.

a. **Applicability.** Principles for evaluating bearing capacity presented in this manual are applicable to numerous types of structures such as buildings and houses, towers and storage tanks, fills, embankments and dams. These guidelines may be helpful in determining soils that will lead to bearing capacity failure or excessive settlements for given foundations and loads.

b. **Evaluation.** Bearing capacity evaluation is presented in Table 1-1. Consideration should be given to obtaining the services and advice of specialists and consultants in foundation design where foundation conditions are unusual or critical or structures are economically significant.

(1) Definitions, failure modes and factors that influence bearing capacity are given in Chapter 1.

(2) Evaluation of bearing capacity can be complicated by environmental and soil conditions. Some of these non-load related design considerations are given in Chapter 2.

(3) Laboratory and in situ methods of determining soil parameters required for analysis of bearing capacity are given in Chapter 3.

(4) Analysis of the bearing capacity of shallow foundations is given in Chapter 4 and of deep foundations is given in Chapter 5.

c. **Limitations.** This manual presents estimates of obtaining the bearing capacity of shallow and deep foundations for certain soil and foundation conditions using well-established, approximate solutions of bearing capacity.

(1) This manual excludes analysis of the bearing capacity of foundations in rock.

(2) This manual excludes analysis of bearing capacity influenced by seismic forces.

(3) Refer to EM 1110-2-1902, Stability of Earth and Rockfill Dams, for solution of the slope stability of embankments.

d. **References.** Standard references pertaining to this manual are listed in Appendix A, References. Each reference is identified in the text by the designated Government publication number or performing agency. Additional reading materials are listed in Appendix B, Bibliography.

TABLE 1-1

Bearing Capacity Evaluation

Step	Procedure
1	Evaluate the ultimate bearing capacity pressure q_u or bearing force Q_u using guidelines in this manual and Equation 1-1.
2	Determine a reasonable factor of safety FS based on available subsurface surface information, variability of the soil, soil layering and strengths, type and importance of the structure and past experience. FS will typically be between 2 and 4. Typical FS are given in Table 1-2.
3	Evaluate allowable bearing capacity q_a by dividing q_u by FS; i.e., $q_a = q_u/FS$, Equation 1-2a or $Q_a = Q_u/FS$, Equation 1-2b.
4	Perform settlement analysis when possible and adjust the bearing pressure until settlements are within tolerable limits. The resulting design bearing pressure q_d may be less than q_a. Settlement analysis is particularly needed when compressible layers are present beneath the depth of the zone of a potential bearing failure. Settlement analysis must be performed on important structures and those sensitive to settlement. Refer to EM 1110-1-1904 for settlement analysis of shallow foundations and embankments and EM 1110-2-2906, Reese and O'Neill (1988) and Vanikar (1986) for settlement of deep foundations.

1-2. **Definitions.**

a. **Bearing Capacity.** Bearing capacity is the ability of soil to safely carry the pressure placed on the soil from any engineered structure without undergoing a shear failure with accompanying large settlements. Applying a bearing pressure which is safe with respect to failure does not ensure that settlement of the foundation will be within acceptable limits. Therefore, settlement analysis should generally be performed since most structures are sensitive to excessive settlement.

(1) **Ultimate Bearing Capacity.** The generally accepted method of bearing capacity analysis is to assume that the soil below the foundation along a critical plane of failure (slip path) is on the verge of failure and to calculate the bearing pressure applied by the foundation required to cause this failure condition. This is the ultimate bearing capacity q_u. The general equation is

$$q_u = cN_c\zeta_c + \frac{1}{2}B\gamma'_H N_\gamma \zeta_\gamma + \sigma'_D N_q \zeta_q \quad (1\text{-}1a)$$

$$Q_u = q_u BW \quad (1\text{-}1b)$$

where

q_u = ultimate bearing capacity pressure, kips per square foot (ksf)
Q_u = ultimate bearing capacity force, kips

- c = soil cohesion (or undrained shear strength C_u), ksf
- B = foundation width, ft
- W = foundation lateral length, ft
- γ'_H = effective unit weight beneath foundation base within failure zone, kips/ft^3
- σ'_D = effective soil or surcharge pressure at the foundation depth D, $\gamma'_D \cdot D$, ksf
- γ'_D = effective unit weight of surcharge soil within depth D, kips/ft^3
- N_c, N_γ, N_q = dimensionless bearing capacity factors for cohesion c, soil weight in the failure wedge, and surcharge q terms
- $\zeta_c, \zeta_\gamma, \zeta_q$ = dimensionless correction factors for cohesion, soil weight in the failure wedge, and surcharge q terms accounting for foundation geometry and soil type

A description of factors that influence bearing capacity and calculation of γ'_H and γ'_D is given in section 1-4. Details for calculation of the dimensionless bearing capacity "N" and correction "ζ" factors are given in Chapter 4 for shallow foundations and in Chapter 5 for deep foundations.

(a) Bearing pressures exceeding the limiting shear resistance of the soil cause collapse of the structure which is usually accompanied by tilting. A bearing capacity failure results in very large downward movements of the structure, typically 0.5 ft to over 10 ft in magnitude. A bearing capacity failure of this type usually occurs within 1 day after the first full load is applied to the soil.

(b) Ultimate shear failure is seldom a controlling factor in design because few structures are able to tolerate the rather large deformations that occur in soil prior to failure. Excessive settlement and differential movement can cause distortion and cracking in structures, loss of freeboard and water retaining capacity of embankments and dams, misalignment of operating equipment, discomfort to occupants, and eventually structural failure. Therefore, settlement analyses must frequently be performed to establish the expected foundation settlement. Both total and differential settlement between critical parts of the structure must be compared with allowable values. Refer to EM 1110-1-1904 for further details.

(c) Calculation of the bearing pressure required for ultimate shear failure is useful where sufficient data are not available to perform a settlement analysis. A suitable safety factor can be applied to the calculated ultimate bearing pressure where sufficient experience and practice have established appropriate safety factors. Structures such as embankments and uniformly loaded tanks, silos, and mats founded on soft soils and designed to tolerate large settlements all may be susceptible to a base shear failure.

(2) **Allowable Bearing Capacity.** The allowable bearing capacity q_a is the ultimate bearing capacity q_u divided by an appropriate factor of safety FS,

$$q_a = \frac{q_u}{FS} \qquad (1\text{-}2a)$$

$$Q_a = \frac{Q_u}{FS} \qquad (1\text{-}2b)$$

FS is often determined to limit settlements to less than 1 inch and it is often in the range of 2 to 4.

(a) Settlement analysis should be performed to determine the maximum vertical foundation pressures which will keep settlements within the predetermined safe value for the given structure. The recommended design bearing pressure q_d or design bearing force Q_d could be less than q_a or Q_a due to settlement limitations.

(b) When practical, vertical pressures applied to supporting foundation soils which are preconsolidated should be kept less than the maximum past pressure (preconsolidation load) applied to the soil. This avoids the higher rate of settlement per unit pressure that occurs on the virgin consolidation settlement portion of the e-log p curve past the preconsolidation pressure. The e-log p curve and preconsolidation pressure are determined by performing laboratory consolidation tests, EM 1110-2-1906.

(3) **Factors of Safety.** Table 1-2 illustrates some factors of safety. These FS's are conservative and will generally limit settlement to acceptable values, but economy may be sacrificed in some cases.

(a) FS selected for design depends on the extent of information available on subsoil characteristics and their variability. A thorough and extensive subsoil investigation may permit use of smaller FS.

(b) FS should generally be $\geq$ 2.5 and never less than 2.

(c) FS in Table 1-2 for deep foundations are consistent with usual compression loads. Refer to EM 1110-2-2906 for FS to be used with other loads.

b. **Soil.** Soil is a mixture of irregularly shaped mineral particles of various sizes containing voids between particles. These voids may contain water if the soil is saturated, water and air if partly saturated, and air if dry. Under unusual conditions, such as sanitary landfills, gases other than air may be in the voids. The particles are a by-product of mechanical and chemical weathering of rock and described as gravels, sands, silts, and clays. Bearing capacity analysis requires a distinction between cohesive and cohesionless soils.

(1) **Cohesive Soil.** Cohesive soils are fine-grained materials consisting of silts, clays, and/or organic material. These soils exhibit low to high strength when unconfined and when air-dried depending on specific characteristics. Most cohesive soils are relatively impermeable compared with cohesionless soils. Some silts may have bonding agents between particles such as soluble salts or clay aggregates. Wetting of soluble agents bonding silt particles may cause settlement.

(2) **Cohesionless Soil.** Cohesionless soil is composed of granular or coarse-grained materials with visually detectable particle sizes and with little cohesion or adhesion between particles. These soils have little or no strength, particularly when dry, when unconfined and little or no cohesion when submerged. Strength occurs from internal friction when the material is confined. Apparent adhesion between particles in cohesionless soil may occur from capillary tension in the pore water. Cohesionless soils are usually relatively free-draining compared with cohesive soils.

TABLE 1-2

Typical Factors of Safety

Structure	FS
Retaining	
Walls	3
Temporary braced excavations	> 2
Bridges	
Railway	4
Highway	3.5
Buildings	
Silos	2.5
Warehouses	2.5*
Apartments, offices	3
Light industrial, public	3.5
Footings	3
Mats	> 3
Deep Foundations	
With load tests	2
Driven piles with wave equation analysis calibrated to results of dynamic pile tests	2.5
Without load tests	3
Multilayer soils	4
Groups	3

*Modern warehouses often require superflat floors to accommodate modern transport equipment; these floors require extreme limitations to total and differential movements with FS > 3

c. **Foundations.** Foundations may be classified in terms of shallow and deep elements and retaining structures that distribute loads from structures to the underlying soil. Foundations must be designed to maintain soil pressures at all depths within the allowable bearing capacity of the soil and also must limit total and differential movements to within levels that can be tolerated by the structure.

(1) **Shallow Foundations.** Shallow foundations are usually placed within a depth D beneath the ground surface less than the minimum width B of the foundation. Shallow foundations consist of spread and continuous footings, wall footings and mats, Figure 1-1.

(a) A spread footing distributes column or other loads from the structure to the soil, Figure 1-1a, where $B \le W \le 10B$. A continuous footing is a spread footing where $W > 10B$.

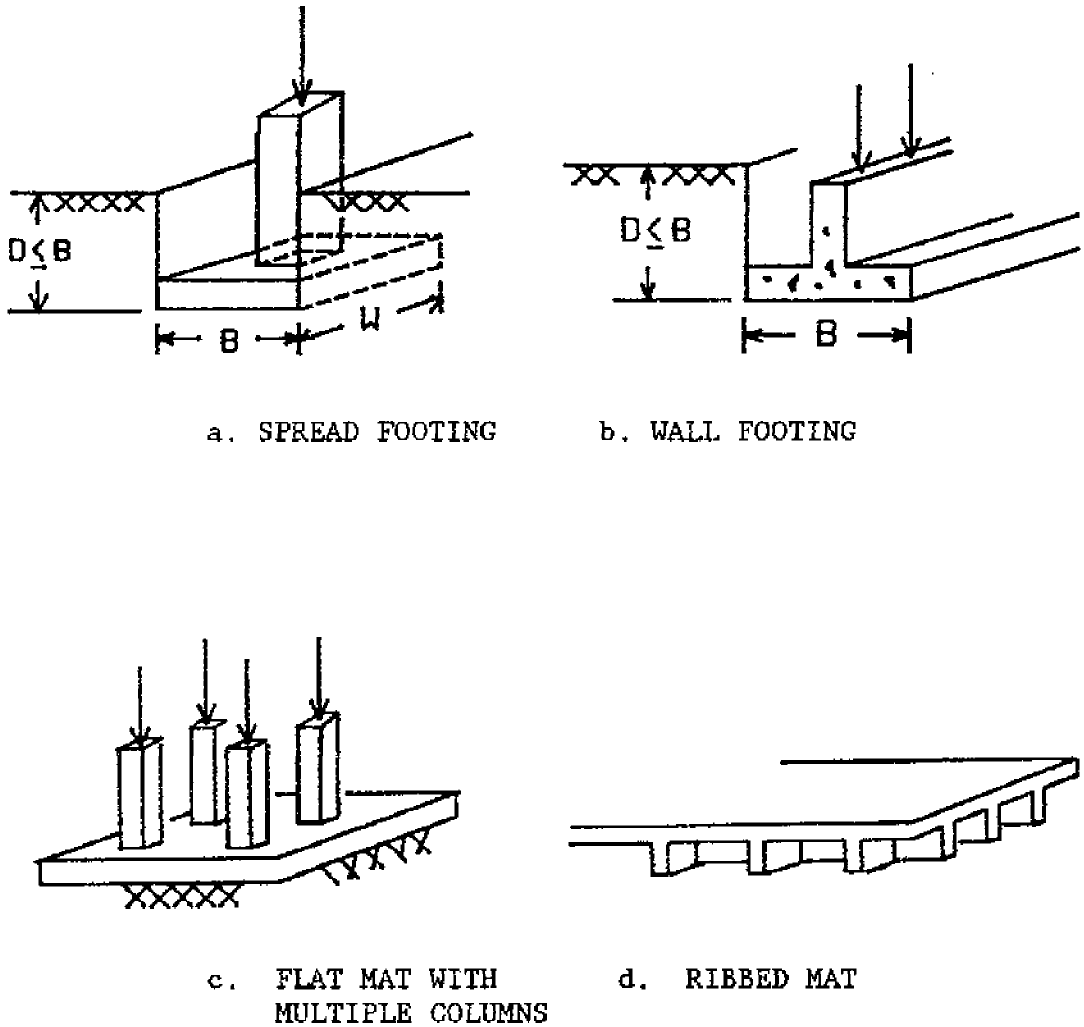

Figure 1-1. Shallow Foundations

(b) A wall footing is a long load bearing footing, Figure 1-1b.

(c) A mat is continuous in two directions capable of supporting multiple columns, wall or floor loads. It has dimensions from 20 to 80 ft or more for houses and hundreds of feet for large structures such as multi-story hospitals and some warehouses, Figure 1-1c. Ribbed mats, Figure 1-1d, consisting of stiffening beams placed below a flat slab are useful in unstable soils such as expansive, collapsible or soft materials where differential movements can be significant (exceeding 0.5 inch).

(2) **Deep Foundations.** Deep foundations can be as short as 15 to 20 ft or as long as 200 ft or more and may consist of driven piles, drilled shafts or stone columns, Figure 1-2. A single drilled shaft often has greater load bearing capacity than a single pile. Deep foundations may be designed to carry superstructure loads

through poor soil (loose sands, soft clays, and collapsible materials) into competent bearing materials. Even when piles or drilled shafts are carried into competent materials, significant settlement can still occur if compressible soils are located below the tip of these deep foundations. Deep foundation support is usually more economical for depths less than 100 ft than mat foundations.

(a) A pile may consist of a timber pole, steel pipe section, H-beam, solid or hollow precast concrete section or other slender element driven into the ground using pile driving equipment, Figure 1-2a. Pile foundations are usually placed in groups often with spacings S of 3 to 3.5B where B is the pile diameter. Smaller spacings are often not desirable because of the potential for pile intersection and a reduction in load carrying capacity . A pile cap is necessary to spread vertical and horizontal loads and any overturning moments to all of the piles in the group. The cap of onshore structures usually consists of reinforced concrete cast on the ground, unless the soil is expansive. Offshore caps are often fabricated from steel.

(b) A drilled shaft is a bored hole carried down to a good bearing stratum and filled with concrete, Figure 1-2b. A drilled shaft often contains a cage of reinforcement steel to provide bending, tension, and compression resistance. Reinforcing steel is always needed if the shaft is subject to lateral or tensile loading. Drilled shaft foundations are often placed as single elements beneath a column with spacings greater than 8 times the width or diameter of the shaft. Other names for drilled shafts include bored and underreamed pile, pier and caisson. Auger-cast or auger-grout piles are included in this category because these are not driven, but installed by advancing a continous-flight hollow-stem auger to the required depth and filling the hole created by the auger with grout under pressure as the auger is withdrawn. Diameters may vary from 0.5 to 10 ft or more. Spacings > 8B lead to minimal interaction between adjacent drilled shafts so that bearing capacity of these foundations may be analyzed using equations for single shafts. Shafts bearing in rock (rock drilled piers) are often placed closer than 8 diameters.

(c) A stone column, Figure 1-2c, consists of granular (cohesionless) material of stone or sand often placed by vibroflotation in weak or soft subsurface soils with shear strengths from 0.2 to 1 ksf. The base of the column should rest on a dense stratum with adequate bearing capacity. The column is made by sinking the vibroflot or probe into the soil to the required depth using a water jet. While adding additional stone to backfill the cavity, the probe is raised and lowered to form a dense column. Stone columns usually are constructed to strengthen an area rather than to provide support for a limited size such as a single footing. Care is required when sensitive or peaty, organic soils are encountered. Construction should occur rapidly to limit vibration in sensitive soils. Peaty, organic soils may cause construction problems or poor performance. Stone columns are usually not as economical as piles or piers for supporting conventional type structures but are competitive when used to support embankments on soft soils, slopes, and remedial or new work for preventing liquefaction.

(d) The length L of a deep foundation may be placed at depths below ground surface such as for supporting basements where the pile length $L \le D$, Figure 1-2a.

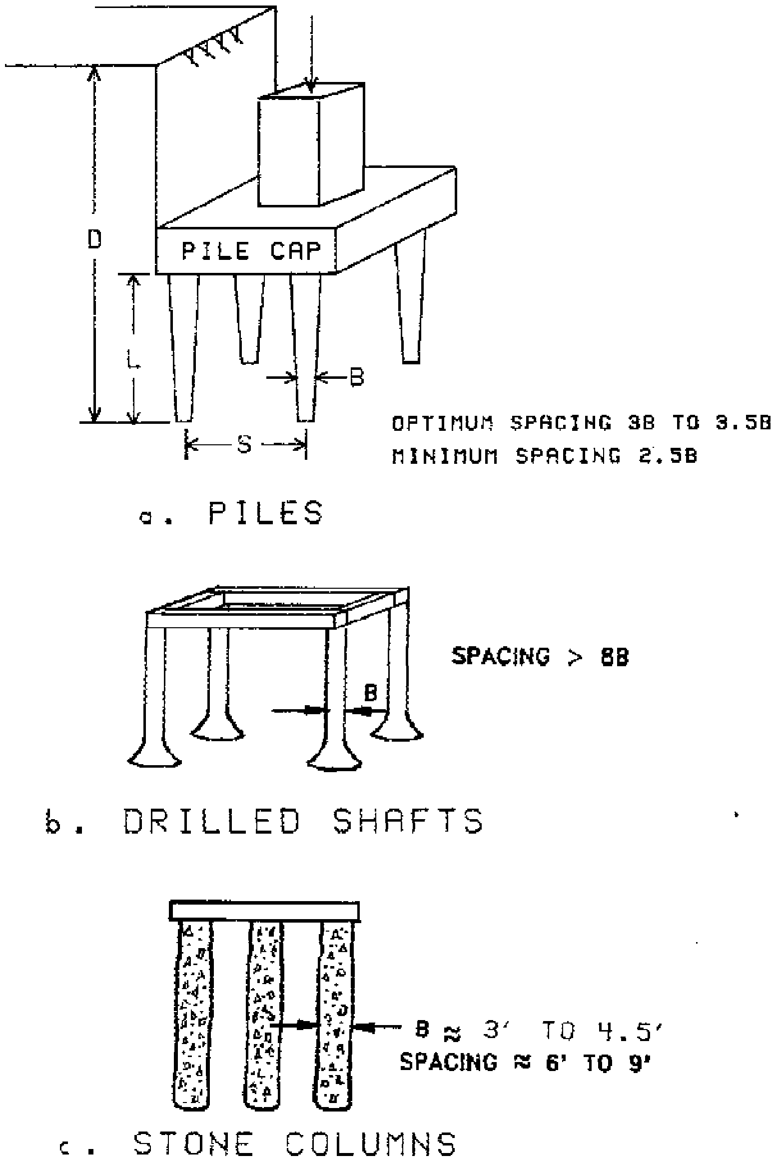

Figure 1-2. Deep foundations

(3) **Retaining Structures.** Any structure used to retain soil or other material in a shape or distribution different from that under the influence of gravity is a retaining structure. These structures may be permanent or temporary and consist of a variety of materials such as plain or reinforced concrete, reinforced soil, closely spaced piles or drilled shafts, and interlocking elments of wood, metal or concrete.

1-3. **Failure Modes.** The modes of potential failure caused by a footing of width B subject to a uniform pressure q develop the limiting soil shear strength τ_s at a given point along a slip path such as in Figure 1-3a

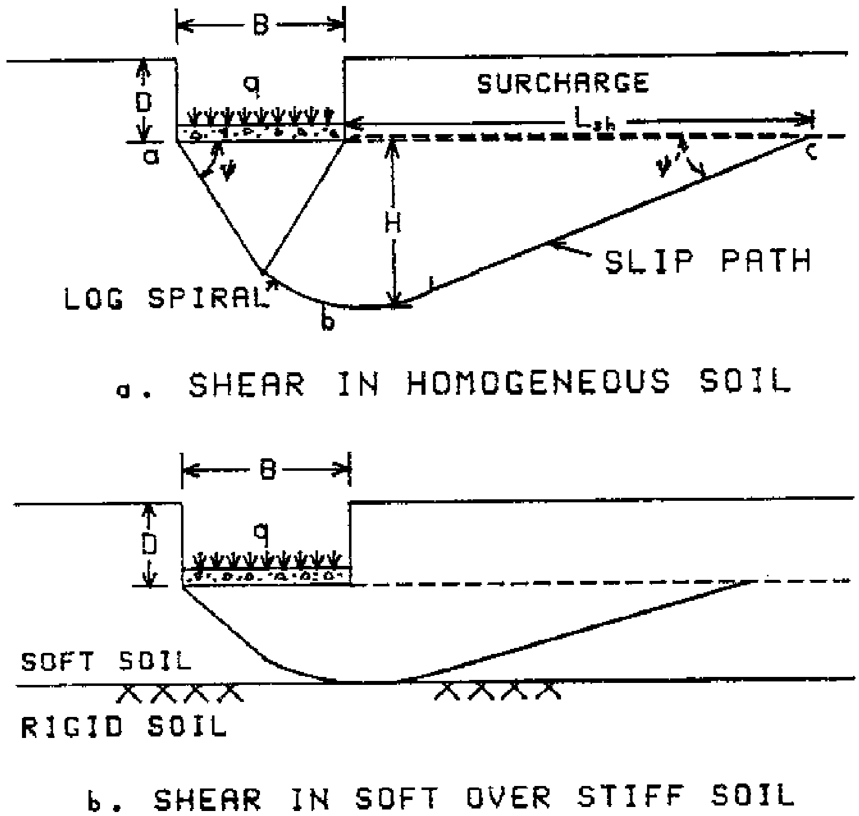

Figure 1-3. General shear failure

$$\tau_s = c + \sigma_n \tan\phi \qquad (1\text{-}3)$$

where

τ_s = soil shear strength, ksf
c = unit soil cohesion (undrained shear strength C_u), ksf
σ_n = normal stress on slip path, ksf
ϕ = friction angle of soil, deg

From Figure 1-3a, the force on a unit width of footing causing shear is q_u times B, $q_u \cdot B$. The force resisting shear is τ_s times the length of the slip path 'abc' or $\tau_s \cdot$ 'abc'. The force resisting shear in a purely cohesive soil is $c \cdot$ 'abc' and in a purely friction soil $\sigma_n \tan\phi \cdot$ 'abc'. The length of the slip path 'abc' resisting failure increases in proportion to the width of footing B.

a. **General Shear.** Figure 1-3a illustrates right side rotation shear failure along a well defined and continuous slip path 'abc' which will result in bulging of the soil adjacent to the foundation. The wedge under the footing goes down and the soil is pushed to the side laterally and up. Surcharge above and outside the footing helps hold the block of soil down.

(1) **Description of Failure.** Most bearing capacity failures occur in general shear under stress controlled conditions and lead to tilting and sudden catastrophic type movement. For example, dense sands and saturated clays loaded rapidly are practically incompressible and may fail in general shear. After failure, a small increase in stress causes large additional settlement of the footing. The bulging of surface soil may be evident on the side of the foundation undergoing a shear failure. In relatively rare cases, some radial tension cracks may be present.

(a) Shear failure has been found to occur more frequently under shallow foundations supporting silos, tanks, and towers than under conventional buildings. Shear failure usually occurs on only one side because soils are not homogeneous and the load is often not concentric.

(b) Figure 1-3b illustrates shear failure in soft over rigid soil. The failure surface is squeezed by the rigid soil.

(2) **Depth of Failure.** Depth of shear zone H may be approximated by assuming that the maximum depth of shear failure occurs beneath the edge of the foundation, Figure 1-3a. If $\psi = 45 + \phi'/2$ (Vesic 1973), then

$$H = B \cdot \tan\psi \tag{1-4a}$$

$$H = B \cdot \tan\left(45 + \frac{\phi'}{2}\right) \tag{1-4b}$$

where

H = depth of shear failure beneath foundation base, ft
B = footing width, ft
ψ = 45 + ϕ'/2, deg
ϕ' = effective angle of internal friction, deg

The depth H for a shear failure will be 1.73B if ϕ' = 30°, a reasonable assumption for soils. H therefore should not usually be greater than 2B. If rigid material lies within 2B, then H will be < 2B and will not extend deeper than the depth of rigid material, Figure 1-3b. Refer to Leonards (1962) for an alternative method of determining the depth of failure.

(3) **Horizontal Length of Failure.** The length that the failure zone extends from the foundation perimeter at the foundation depth L_{sh}, Figure 1-3a, may be approximated by

$$L_{sh} = (H+D)\ \cot\psi' = (H+D)\tan\psi \tag{1-5a}$$

$$L_{sh} = (H+D)\tan\left(45 + \frac{\phi'}{2}\right) \tag{1-5b}$$

where D is the depth of the foundation base beneath the ground surface and ψ' = 45 - ϕ'/2. $L_{sh} \approx 1.73(H + D)$ if ϕ' = 30 deg. The shear zone may extend horizontally about 3B from the foundation base. Refer to Leonards (1962) for an alternative method of determining the length of failure.

b. **Punching Shear.** Figure 1-4 illustrates punching shear failure along a wedge slip path 'abc'. Slip lines do not develop and little or no bulging occurs at the ground surface. Vertical movement associated with increased loads causes compression of the soil immediately beneath the foundation. Figure 1-4 also illustrates punching shear of stiff over soft soil.

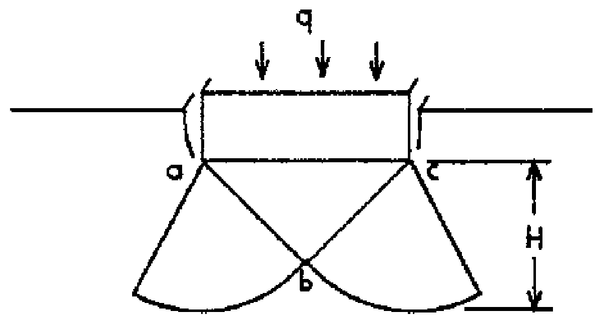

Figure 1-4. Punching failure

(1) Vertical settlement may occur suddenly as a series of small movements without visible collapse or significant tilting. Punching failure is often associated with deep foundation elements, particularly in loose sands.

(2) Local shear is a punching-type failure and it is more likely to occur in loose sands, silty sands, and weak clays. Local shear failure is characterized by a slip path that is not well defined except immediately beneath the foundation. Failure is not catastrophic and tilting may be insignificant. Applied loads can continue to increase on the foundation soil following local shear failure.

c. **Failure in Sand.** The approximate limits of types of failure to be expected at relative depths D/B and relative density of sand D_R vary as shown in Figure 1-5. There is a critical relative depth below which only punching shear failure occurs. For circular foundations, this critical relative depth is about D/B = 4 and for long ($L \approx 5B$) rectangular foundations around D/B = 8. The limits of the types of failure depend upon the compressibility of the sand. More compressible materials will have lower critical depths (Vesic 1963).

1-4. **Factors Influencing Ultimate Bearing Capacity.** Principal factors that influence ultimate bearing capacities are type and strength of soil, foundation width and depth, soil weight in the shear zone, and surcharge. Structural rigidity and the contact stress distribution do not greatly influence bearing capacity. Bearing capacity analysis assumes a uniform contact pressure between the foundation and underlying soil.

a. **Soil Strength.** Many sedimentary soil deposits have an inherent anisotropic structure due to their common natural deposition in horizontal layers. Other soil deposits such as saprolites may also exhibit anisotropic properties. The undrained strength of cohesive soil and friction angle of cohesionless soil will be influenced by the direction of the major principal stress relative to the direction of deposition. This manual calculates bearing capacity using strength parameters determined when the major principal stress is applied in the direction of deposition.

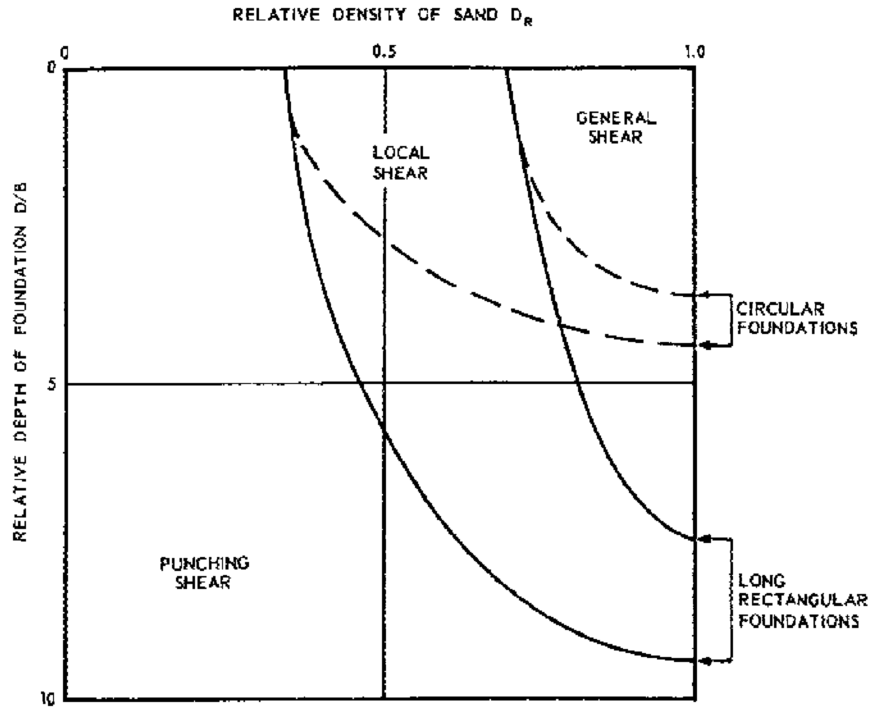

Figure 1-5. Variation of the nature of bearing capacity failure in sand with relative density D_R and relative depth D/B (Vesic 1963). Reprinted by permission of the Transportation Research Board, Highway Research Record 39, "Bearing Capacity of Deep Foundations in Sands" by A. B. Vesic, p. 136

(1) **Cohesive Soil.** Bearing capacity of cohesive soil is proportional to soil cohesion c if the effective friction angle ϕ' is zero.

(2) **Cohesionless Soil.** Bearing capacity of cohesionless soil and mixed "c-ϕ" soils increases nonlinearly with increases in the effective friction angle.

b. **Foundation Width.** Foundation width influences ultimate bearing capacity in cohesionless soil. Foundation width also influences settlement, which is important in determining design loads. The theory of elasticity shows that, for an ideal soil whose properties do not change with stress level, settlement is proportional to foundation width.

(1) **Cohesive Soil.** The ultimate bearing capacity of cohesive soil of infinite depth and constant shear strength is independent of foundation width because c·'abc'/B, Figure 1-3a, is constant.

(2) **Cohesionless Soil.** The ultimate bearing capacity of a footing placed at the surface of a cohesionless soil where soil shear strength largely depends on internal friction is directly proportional to the width of the bearing area.

c. **Foundation Depth.** Bearing capacity, particularly that of cohesionless soil, increases with foundation depth if the soil is uniform. Bearing capacity is reduced if the foundation is carried down to a weak stratum.

(1) The bearing capacity of larger footings with a slip path that intersects a rigid stratum will be greater than that of a smaller footing with a slip path that does not intersect a deeper rigid stratum, Figure 1-3.

(2) Foundations placed at depths where the structural weight equals the weight of displaced soil usually assures adequate bearing capacity and only recompression settlement. Exceptions include structures supported by underconsolidated soil and collapsible soil subject to wetting.

d. **Soil Weight and Surcharge.** Subsurface and surcharge soil weights contribute to bearing capacity as given in Equation 1-1. The depth to the water table influences the subsurface and surcharge soil weights, Figure 1-6. Water table depth can vary significantly with time.

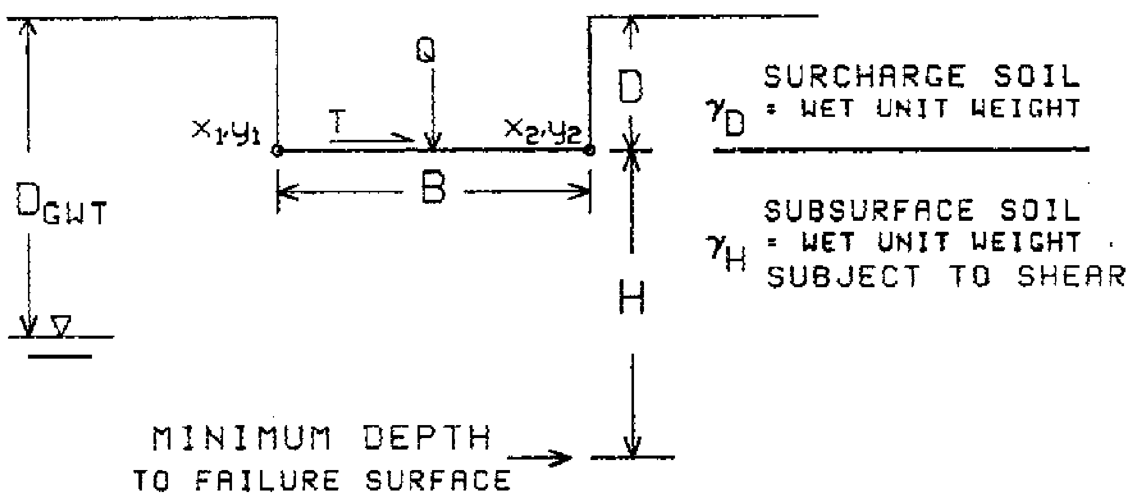

Figure 1-6. Schematic of foundation system

(1) If the water table is below the depth of the failure surface, then the water table has no influence on the bearing capacity and effective unit weights γ'_D and γ'_H in Equation 1-1 are equal to the wet unit weight of the soils γ_D and γ_H.

(2) If the water table is above the failure surface and beneath the foundation base, then the effective unit weight γ'_H can be estimated as

$$\gamma'_H = \gamma_{HSUB} + \frac{D_{GWT} - D}{H} \cdot \gamma_w \qquad (1\text{-}6)$$

where

γ_{HSUB} = submerged unit weight of subsurface soil, $\gamma_H - \gamma_w$, kips/ft^3
D_{GWT} = depth below ground surface to groundwater, ft
H = minimum depth below base of foundation to failure surface, ft
γ_w = unit weight of water, 0.0625 kip/ft^3

(3) The water table should not be above the base of the foundation to avoid construction, seepage, and uplift problems. If the water table is above the base of the foundation, then the effective surcharge term σ'_D may be estimated by

$$\sigma'_D = \gamma'_D \cdot D \tag{1-7a}$$

$$\gamma'_D = \gamma_D - \frac{D - D_{GWT}}{D} \cdot \gamma_w \tag{1-7b}$$

where

σ'_D = effective surcharge soil pressure at foundation depth D, ksf
γ_D = unit wet weight of surcharge soil within depth D, $kips/ft^3$
D = depth of base below ground surface, ft

(4) Refer to Figure 2, Chapter 4 in Department of the Navy (1982), for an alternative procedure of estimating depth of failure zone H and influence of groundwater on bearing capacity in cohesionless soil. The wet or saturated weight of soil above or below the water table is used in cohesive soil.

e. **Spacing Between Foundations.** Foundations on footings spaced sufficiently close together to intersect adjacent shear zones may decrease bearing capacity of each foundation. Spacings between footings should be at least 1.5B, to minimize any reduction in bearing capacity. Increases in settlement of existing facilities should be checked when placing new construction near existing facilities.