SHALLOW FOUNDATIONS

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INTRODUCTION

To perform satisfactorily:

- The foundation has to be safe against overall shear failure in the soil that supports it. (bearing capacity)
- The foundation cannot undergo excessive displacement → settlement.

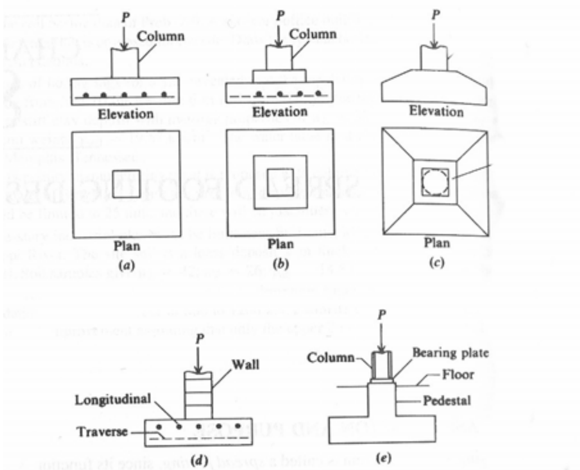
Design considerations

- Foundations must be designed both structurally and geotechnically
- Able to safely carry compression, tension and shear loads, and possible moments
- Structurally efficient
- Geotechnically efficient
- Take tolerance of structure to movement into account

FOUNDATION TYPES

SHALLOW
Soil layer is suitable for supporting a structure at a relatively shallow depth

DEEP
Upper layer of soil is not suitable to carry/support a structure. The weight of the structure is transferred to stable layers at greater depths (piles, piers, caissons)



Typical Footings. a)Single or spread footings, b) stepped footing, c) sloped footing, d) wall footing, e) footing with pedestal (Bowles, 1997)

Single Footings

Types;

- Masonry footings (very light loads)
- Timber grillage footings (temporary buildings)
- Steel grillage footings (large shear stresses, heavy loads)
- Plain concrete footings (light column load)
- Reinforced concrete footings (high bearing capacity)

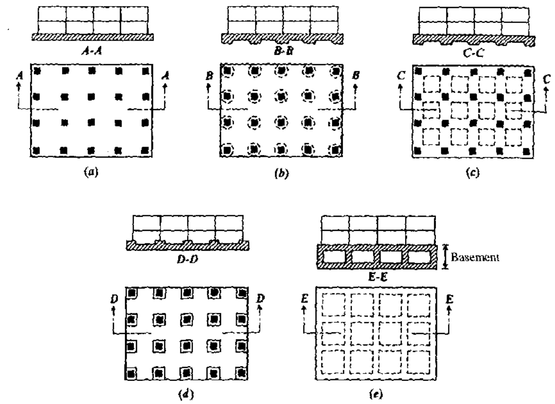
A strip footing (continuous footing) supports a load bearing wall or group of columns.

Combined Footing supports a number of columns.

Mat (Raft) foundations

is a relatively large slab supporting the structure as a whole.

•Low bearing capacity, but high structural loads
•Area required for individual/combined footings > 50% of area
•Heterogeneous soil profile : minimizes differential settlements



Bowles, 1997

a) Flat plate
b) Flat plate thickened under columns
c) Waffle and slab
d) Plate with pedestals
e) Basement wall as part of mat

SHALLOW FOUNDATION DESIGN

i) All loads that may act on foundations should be studied and determined.

ii) Site investigation should be carried out.

iii) Depth of foundation must be determined.

iv) Foundations must be analyzed with respect to two failure types:
   1) Settlement failure
   2) Bearing capacity failure

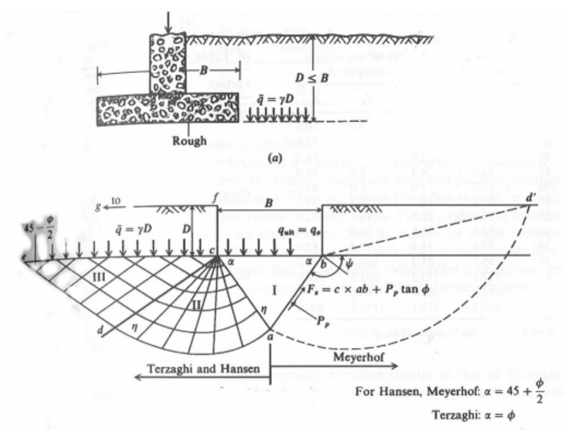
BEARING CAPACITY

Safe Bearing Capacity is the value of gross pressure that can be applied without danger of shear failure.
Allowable Bearing Capacity (q_a) is the maximum (net) pressure which may be applied to the soil such that:
1. F.S. against shear failure of supporting soil is adequate (F_s=2 or 3)
2. The total and differential settlements are within permissible limits.

Ultimate Bearing Capacity (q_{ult}) is the least (gross) pressure that will cause shear failure in the vicinity of the foundation.

Terzaghi's Bearing Capacity Theory for Shallow Foundations

- According to this theory, a foundation is shallow if the depth, D_f of the foundation is less than or equal to the width of the foundation. D_f=3 to 4B considered shallow.
- Terzaghi suggested that for a continuous or strip foundation, the failure surface in soil at ultimate load may be assumed to be similar to that shown in the figure.
- The effect of soil above the bottom of the foundation may also be assumed to be replaced by an equivalent surcharge, $q=\gamma D_f$.
- The failure zone under the foundation can be separated into three parts.

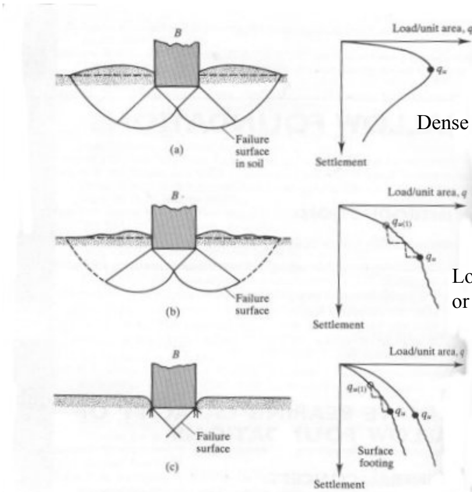


Bearing Capacity (Bowles, 1997)

I Active Rankine zone

II Zones of Radial Shear

III Passive Rankine Zone



Dense sand or stiff clay

Loose sand or soft clay

FIGURE 3.1 Nature of bearing capacity failure in soil: (a) general shear failure; (b) local shear failure; (c) punching shear failure (redrawn after Vesic, 1973)

(Das, 1995)

For a strip footing: $$q_{ult} = \frac{1}{2}\gamma B N_\gamma + c N_c + \gamma D_f N_q$$

Where ;

q_u : Ultimate bearing capacity

N_γ : Bearing capacity factor due to weight of soil with zero surcharge

N_c : Bearing capacity factor due to cohesion of soil, assuming soil to be weightless and surcharge as zero

N_q : Bearing capacity factor due to surcharge pressure, $q_0=\gamma D$ an horizontal plane at foundation base level, assuming soil below foundation as weightless

For a square footing with side B

$$q_{ult} = 0.4\gamma B N_\gamma + 1.3 c N_c + \gamma D_f N_q$$

For a circular footing with diameter D:

$$q_{ult} = 0.3\gamma D N_\gamma + 1.3 c N_c + \gamma D_f N_q$$

Note: For a rectangular footing (L*B) use linear interpolation between strip footing (B/L=0) and square footing (B/L=1.0)

$$N_{c_{rect}} = N_{c_{strip}}\left(1 + 0.2\frac{B}{L}\right)$$

$$N_{\gamma_{rect}} = N_{\gamma_{strip}}\left(1 - 0.2\frac{B}{L}\right)$$

$$N_{q_{rect}} = N_{q_{strip}}$$

*For the same soil conditions, for different foundation shapes, q_{ult} values are different.

ϕ	N_c	N_q	N_γ*	ϕ	N_c	N_q	N_γ*
0	5.70	1.00	0.00	26	27.09	14.21	9.84
1	6.00	1.1	0.01	27	29.24	15.90	11.60
2	6.30	1.22	0.04	28	31.61	17.81	13.70
3	6.62	1.35	0.06	29	34.24	19.98	16.18
4	6.97	1.49	0.10	30	37.16	22.46	19.13
5	7.34	1.64	0.14	31	40.41	25.28	22.65
6	7.73	1.81	0.20	32	44.04	28.52	26.87
7	8.15	2.00	0.27	33	48.09	32.23	31.94
8	8.60	2.21	0.35	34	52.64	36.50	38.04
9	9.09	2.44	0.44	35	57.75	41.44	45.41
10	9.61	2.69	0.56	36	63.53	47.16	54.36
11	10.16	2.98	0.69	37	70.01	53.80	65.27
12	10.76	3.29	0.85	38	77.50	61.55	78.61
13	11.41	3.63	1.04	39	85.97	70.61	95.03
14	12.11	4.02	1.26	40	95.66	81.27	115.31
15	12.86	4.45	1.52	41	106.81	93.85	140.51
16	13.68	4.92	1.82	42	119.67	108.75	171.99
17	14.60	5.45	2.18	43	134.58	126.50	211.56
18	15.12	6.04	2.59	44	151.95	147.74	261.60
19	16.56	6.70	3.07	45	172.28	173.28	325.34
20	17.69	7.44	3.64	46	196.22	204.19	407.11
21	18.92	8.26	4.31	47	224.55	241.80	512.84
22	20.27	9.19	5.09	48	258.28	287.85	650.67
23	21.75	10.23	6.00	49	298.71	344.63	831.99
24	23.36	11.40	7.08	50	347.50	415.14	1072.80
25	25.13	12.72	8.34				

* From Kumbhojkar (1993)

Terzaghi's Bearing Capacity Factors (Das,1995)

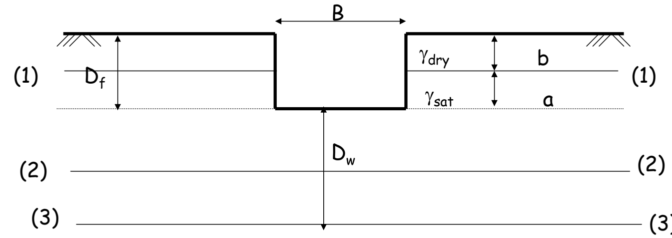
Table 4.2 Approximate allowable bearing values, after BS 8004: 1986

Group	Types of rocks and soils	Approximate bearing value (kPa)	Remarks
1 Rocks	Hard igneous and gneissic rocks in sound condition	10 000	These values are based on the assumption that the foundations are carried down to unweathered rock
	Hard limestones and hard sandstones	4000	
	Schists and slates	3000	
	Hard shales, hard mudstones and soft sandstones	2000	
	Soft shales and soft mudstones	600 to 1000	
	Hard sound chalk, soft limestone	600	
	Thinly bedded limestones, sand-stones, shales	To be assessed after inspection	
	Heavily shattered rocks		
2 Non-cohesive soils	Compact gravel, or compact sand and gravel	>600	Width of foundation (B) not less than 1 m. Ground water level assumed to be a depth not less than B below the base of the foundation
	Medium dense gravel, or medium dense sand and gravel	200 to 600	
	Loose gravel, or loose sand and gravel	<200	
	Compact sand	>300	
	Medium dense sand	100 to 300	
	Loose sand	<100	
3 Cohesive soils	Very stiff boulder clays and hard clays	300 to 600	Group 3 is susceptible to long-term consolidation settlement
	Stiff clays	150 to 300	
	Firm clays	75 to 150	
	Soft clays and silts	<75	
	Very soft clays and silts	Not applicable	

Simons and Menzies, 1999

Water Table Effects

On the bearing capacity of a strip footing on *sand*



$$q_{ult} = \frac{1}{2}\gamma B N_\gamma + cN_c + \gamma D_f N_q$$

(3-3) If depth D_w of water table below base of footing not less than B, then net ultimate bearing capacity $q_{u(net)}=q_u-D_f$

$$q_u = \cancel{cN_c}^{\,0} + \gamma D_f(N_q-1) + \tfrac{1}{2}\gamma B N_\gamma$$

(2-2) If $0<D_w<B$

$$q_u = \cancel{cN_c}^{\,0} + \gamma D_f(N_q-1) + \tfrac{1}{2}\gamma_{sub} B N\gamma$$

(1-1) Water tabel between foundation level and ground surface (i.e., 0>Dw>Df)

$$q_u = \cancel{cN_c}^{\,0} + \sigma'_o(N_q-1) + \tfrac{1}{2}\gamma_{sub} B N_\gamma$$

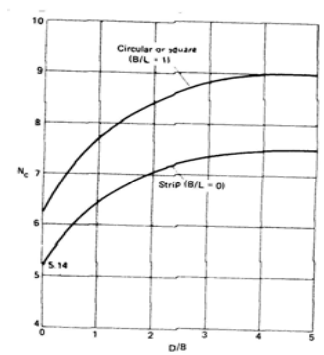
σ'_0: Initial effective overburden pressure at foundation level.

$$\sigma'_0=\gamma_{dry}b+(\gamma_{sat}-\gamma_w)a$$

Skempton's Method for Determining N_c

For saturated, undrained clays (ϕ_u=0); the ultimate bearing capacity of a foundation footing is:

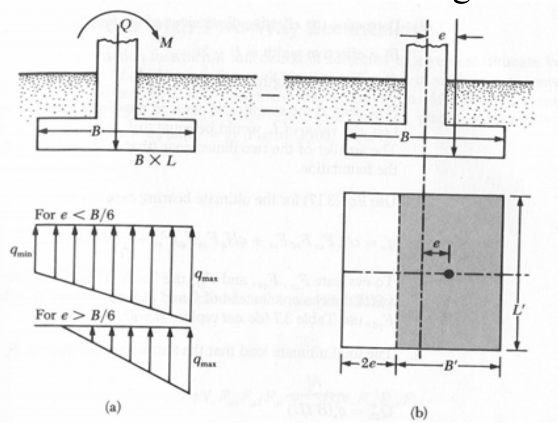
$$q_{ult} = c_u N_c + \gamma D_f$$



Where;

N_c : Dependent on shape of footing and B/L , D/B

Eccentric Loading



▼ FIGURE 3.8 Eccentrically loaded foundations

Eccentricity tends to decrease the load-bearing capacity of a foundation.

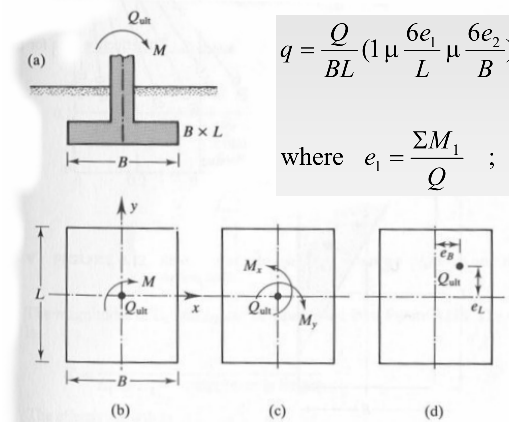
(Das, 1995)

$$q_{ult} = \frac{1}{2}\gamma B' N_{\gamma} + cN_c + \gamma DN_q$$

$$B' = B - 2e_x$$

$$L' = L - 2e_y$$

Two way eccentricity



▼ FIGURE 3.10 Anaysis of foundation with two-way eccentricity

$$q = \frac{Q}{BL}(1 \mu \frac{6e_1}{L} \mu \frac{6e_2}{B})$$

where $e_1 = \frac{\Sigma M_1}{Q}$; $e_2 = \frac{\Sigma M_2}{Q}$

Das. 1995

Inclined Loading

If angle of inclination of resultant load is 'α' to the vertical, then bearing capacity factors (N_γ,N_c & N_q) need to be multiplied by:

$$i_{\gamma} = \left[1 - \frac{\alpha}{\phi}\right]^2$$

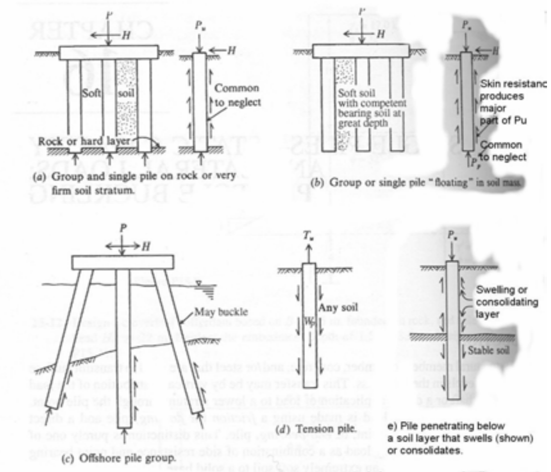
$$i_c = i_q = \left[1 - \frac{\alpha}{90^{\circ}}\right]^2$$

PILE (DEEP) FOUNDATIONS

Introduction

Pile foundations are used when:

- The soil near the surface does not have sufficient bearing capacity to support the structural loads.
- The estimated settlement of the soil exceeds tolerable limits (i.e. Settlement greater than the serviceability limit state)
- Differential settlement due to soil variability or nonuniform structural loads is excessive.
- The structural loads consist of lateral loads and/or uplift forces
- Excavations to construct a shallow foundation on a firm soil layer are difficult or expensive.



Typical Pile Configurations , Bowles, 1997.

Pile Foundation Types

- Pile types in terms of material

-Timber piles; They are tree trunks that have had their branches and barks carefully trimmed off. The maximum length of most timber piles is 10-20m. Splicing of timber piles should be avoided.

-Concrete piles;

a) Precast and b) cast-in-situ piles.

Pile Foundation Types

- Pile types in terms of material (cont.)

- Precast piles can be prepared by using ordinary reinforcement and they can be square or octagonal in cross section. Reinforcement is provided to enable the pile to resist the bending moment develop during pickup and transportation, the vertical load and the bending moment caused by lateral load.
- The piles are cast to desired lengths before being transported to the work sites. Cast-in-place piles are built by making a hole in the ground and then filling with concrete.
- Cased and uncased.

Pile Foundation Types

• Pile types in terms of material (cont.)

-Steel piles (H-section & pipe piles); Pipe piles can be driven into the ground with their ends open or closed. Steel piles are merged together by welding or riveting (rivets or bolts). Epoxy coatings or concrete encasement of steel piles are done to protect against corrosion.

-Composite piles; The upper and lower portions of composite piles are made of different materials.

- Steel and concrete
- Timber and concrete

Comparison of Piles Made of Different Materials

Steel: 15-60m

Advantages:

- easy to handle wrt cut-off and extension to the desired length,
- can stand high driving stresses,
- can penetrate hard layers such as dense gravel, soft rock,
- high load-carrying capacity.

Disadvantages:

- Relatively costly material,
- high level of noise during pile driving,
- subject to corrosion,
- H-piles may be damaged or deflected from the vertical during driving through hard layers or past major obstructions.

Comparison of Piles Made of Different Materials

Precast Concrete: 10-15m (precast) and 10-35m (prestressed)

Advantages:

- can be subjected to hard driving,
- corrosion resistant,
- can be easily combined with concrete superstructure.

Disadvantages:

- difficult to achieve proper cut-off,
- difficult to transport.

Comparison of Piles Made of Different Materials

Cased cast-in place concrete: 5-15m

Advantages:

- relatively cheap,
- possibility of inspection before pouring concrete,
- easy to extend.

Disadvantages:

- difficult to splice after concreting,
- thin casing may be damaged during driving.

Comparison of Piles Made of Different Materials

Uncased cast-in place concrete: 5-15m

Advantages:

- initially economical,
- can be finished at any elevation.

Disadvantages:

- voids may be created if concrete is placed rapidly,
- difficult to splice after concreting,
- in soft soils the sides of the hole may cave in, thus squeezing the concrete.

Comparison of Piles Made of Different Materials

Wood: 10-15m

Advantages:

- economical,
- easy to handle,
- permanently submerged piles are fairly resistant to decay.

Disadvantages:

- decay above water table,
- can be damaged in hard driving,
- low load-bearing capacity,
- low resistance to tensile load when spliced.

Pile types in terms of load transfer to the soil

a) Point Bearing Piles:

If the presence of bedrock or rocklike material at a site within a reasonable depth, piles can be extended to the rock surface, then the ultimate bearing capacity of the piles depends entirely on the load-bearing capacity of the underlying material.

Pile types in terms of load transfer to the soil

b) Friction Piles:

- When no layer of rock or rocklike material is present at a reasonable depth at a site, point bearing piles become very long and uneconomical.
- piles are driven through the softer material to specified depths.
- most of the resistance is derived from skin friction.

c) Compaction piles:

Piles are driven in granular soils to achieve proper compaction of soil close to ground surface. generally short.

Floating Pile is a friction pile in which the end bearing resistance is neglected.

Pile types in terms of building style

- Driven piles,
- Bored piles,

Hammer types

- Drop hammers,
  - Steam,
  - Pneumatic,
  - Hydraulic,
- Diesel hammers,
- Vibratory hammers,

Determination of Bearing Capacity of Piles

1) Static pile capacity:

$$Q_u = Q_b + Q_s$$
$$Q_u = \sigma'_o N_q A_b + \sum \sigma'_{ort} K_s \tan\delta A_s$$

For silts & clays; (saturated clays and undrained conditions)

$$Q_u = Q_b + Q_s$$
$$Q_u = 9c_u A_b + \sum \alpha c_u A_s$$

PS: α is 0.45-0.50 for hard clays and 0.8-1.0 for soft clays as a factor of adhesion.

Q_u: ultimate pile capacity
Q_b: load-carrying capacity of pile point
Q_s: frictional resistance
A_b: area of pile tip
σ'_0: effective vertical stress at the level of the pile tip
c_u: undrained cohesion of the soil below the pile tip
K_s: earth pressure coefficient
δ: soil-pile friction angle

Empirical values for ϕ, K_s and δ based on pile material types;

		K_s	δ	$\beta_s = K_s . \tan\delta$	
				Φ'=25°	Φ'=40°
Concrete piles	Loose sand	1	3/4Φ'	0.34	0.58
	Dense sand	2	3/4Φ'	0.68	1.15
Steel piles	Loose sand	0.5	20°		0.18
	Dense sand	1	20°		0.36

2) Dynamic Analysis: (Pile-driving formulas)

The ultimate bearing capacity formulas of a pile are found by accepting that the energy for driving the pile is equal to the work done by penetration of a pile.

Engineering News Record formula

$$Q_u = \frac{W_T H}{6(s+c)}$$

Q_u : Ultimate load (Maximum F_s=6)
W_T: Weight of hammer (ton)
H : Height of blow (cm)
s : Amount of penetration of pile per hammer blow (cm)
c : Coefficient (2.5- Drop hammers)
(0.25- Steam hammers)

Pile Load Test

Reasons:

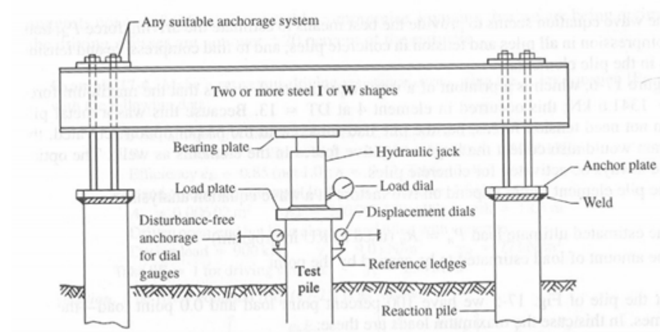
1. To determine the settlement under working load
2. To determine the ultimate bearing capacity
3. As proof of acceptibility

❑Vertical and lateral load-bearing capacity of a pile can be tested in the field.
❑The load is applied to the pile by a hydraulic jack.

Pile Load Test

❑Step loads are applied to the pile and sufficient time is allowed to elapse after each load so that a small amount of settlement occurs.
❑The settlement of the pile is measured by dial gauges.
❑Total load of twice the proposed working load.

- Conventional static load test,
- Instrumented static load test,
- Osterberg load test.



(c) Typical pile load test setup using adjacent piles in group for reaction.

Figure 17-7(c) Typical pile load test setup using adjacent piles in group for reaction.

Bowles, 1997