Tishk International University
Civil Engineering Department
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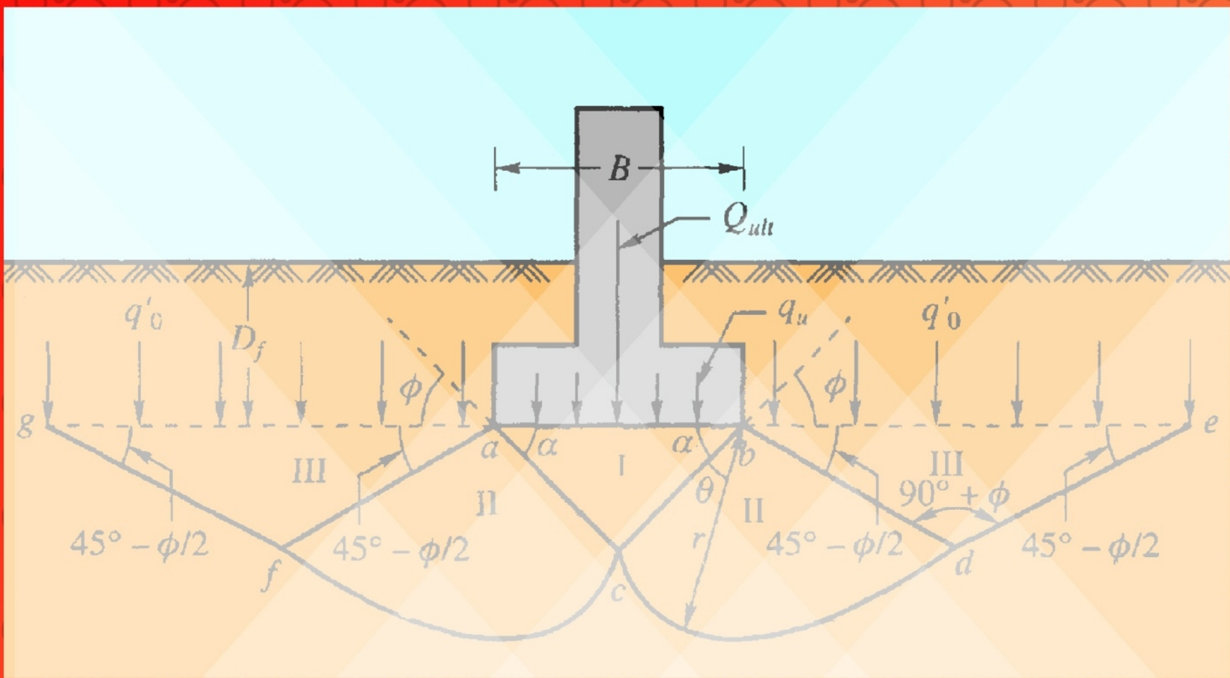
Foundation Engineering



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Course layout

1. Bearing capacity of shallow foundations
    a) Introduction
    b) Terzaghi's method
    c) Meyerhof's method
    d) Hansen's method
    e) Vesic's method
    f) Bearing capacity form SPT
    g) Bearing capacity form CPT
    h) Effect of water table on bearing capacity
    i) Effect of eccentricity of bearing capacity
    j) Bearing capacity of layered soils.
2. Settlement analysis
    a) Stress analysis in soil mass
    b) Immediate settlement computation.
    c) Consolidation settlement
    d) Rotation of footing
3. Structural design of footings
    a) Single footings
    b) Combined footings
    c) Raft foundation.

References

1. "Foundation analysis and design" by Joseph E. Bowles.
2. "Fundamentals of geotechnical engineering" by Braja M. Das.
3. "principles of foundation Engineering" by Braja M. Das.

Chapter 1

Bearing capacity

of shallow foundation

Introduction

- The lowest part of a structure is generally referred to as the foundation. Its function is to transfer the load of the structure to the soil on which it is resting.
- A properly designed foundation is one that transfers the load throughout the soil without overstressing the soil.
- Overstressing the soil can result in either excessive settlement or shear failure of the soil, both of which cause damage to the structure. Thus, geotechnical and structural engineers who design foundations must evaluate the bearing capacity of soils.

Types of foundation

- Spread footing (Shallow foundation).
- Mat foundation (Shallow foundation).
- Pile and drilled shaft foundations (Deep foundation).

In this term, we discuss the soil-bearing capacity for shallow foundations.

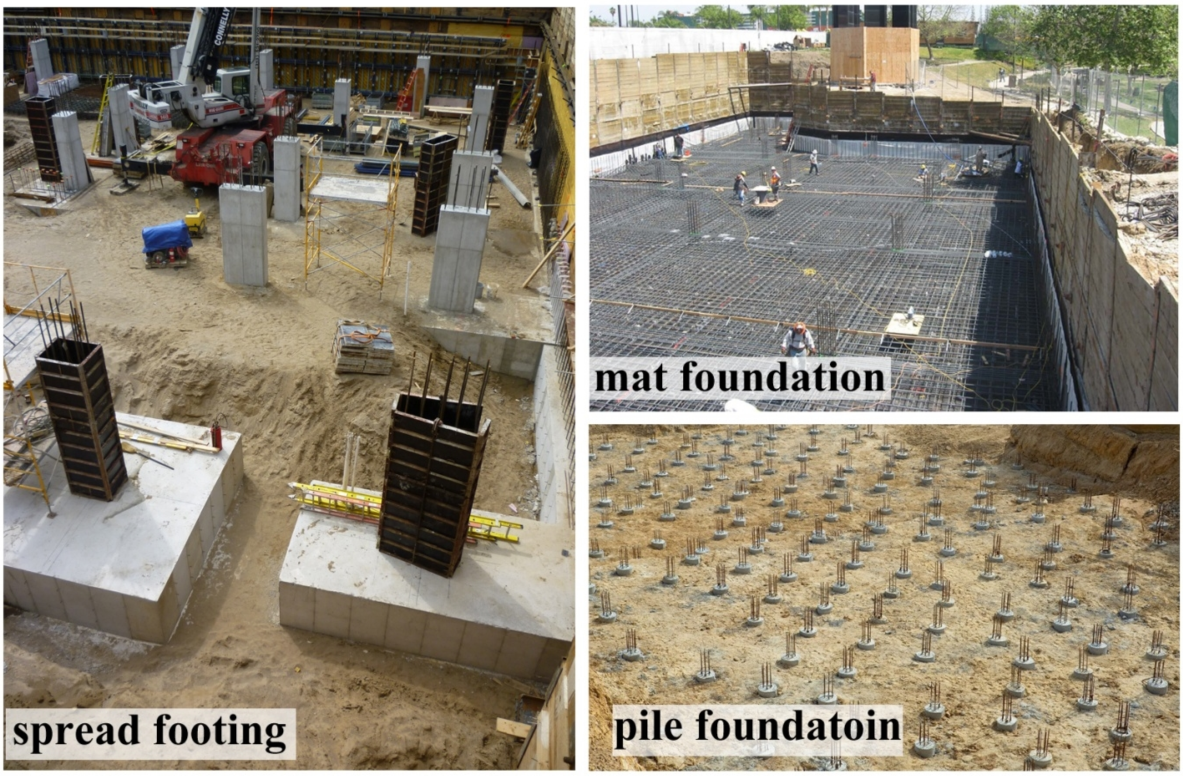


Figure shows different types of foundations

For a foundation to function properly, (1) the settlement of soil caused by the load must be within the tolerable limit, and (2) shear failure of the soil supporting the foundation must not occur.

ULTIMATE BEARING CAPACITY OF SHALLOW FOUNDATIONS

General Concepts

Consider a strip foundation with a width of B is resting on the surface of soil and a load is gradually applied to the foundation, settlement will increase in three different forms depending on the soil density or stiffness.

1. **If the soil is dense sand or stiff cohesive soil:** The variation of the load per unit area on the foundation, q, with the foundation settlement is shown in Figure 1.1a. At a certain point when the load per unit area equals q_u(ultimate bearing capacity), a sudden failure in the soil supporting the foundation will take place, and the failure surface in the soil will extend to the ground surface. When this type of sudden failure in soil takes place, it is called "*general shear failure*".
2. **If the foundation rests on sand or clayey soil of medium compaction** (Figure 1.1b), an increase of load on the foundation will also be accompanied by an increase of settlement. However, in this case the failure surface in the soil will gradually extend outward from the foundation, as shown by the solid lines in Figure 1.1b. When the load per unit area on the foundation equals q_{u1}, the foundation movement will be accompanied by sudden jerks. A considerable movement of the foundation is then required for the failure surface in soil to extend to the ground surface (as shown by the broken lines in Figure 1.1b). The load per unit area at which this happens is the ultimate bearing capacity, qu. Beyond this point, an increase of load will be accompanied by a large increase of foundation settlement. The load per unit area of the foundation, qu(1), is referred to as the first failure load (Vesic, 1963). Note that a peak value of q is not realized in this type of failure, which is called "*local shear failure in soil*".

3. **If the foundation is supported by a fairly loose soil**, the load–settlement plot will be like the one in Figure 1.1c. In this case, the failure surface in soil will not extend to the ground surface. Beyond the ultimate failure load, qu, the load-settlement plot will be steep and practically linear. This type of failure in soil is called "*punching shear failure*".

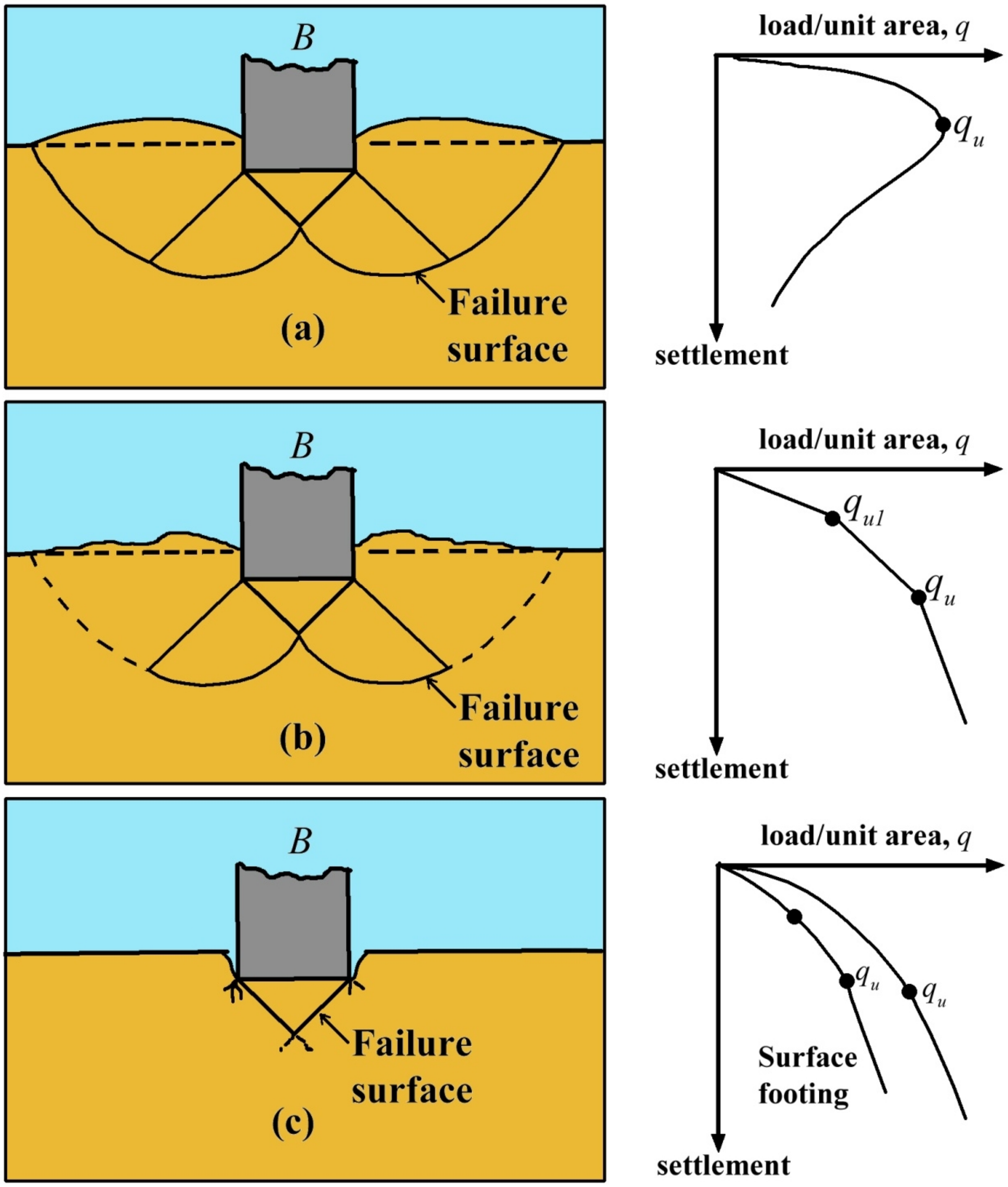


Figure 1.1 Nature of bearing capacity failure in soil: (a) general shear failure; (b) local shear failure; (c) punching shear failure

Based on experimental results, Vesic proposed a relationship for the mode of bearing capacity failure of foundations resting on sands. Figure 1.2 shows this relationship, which involves the following notation:

D_r= relative density of sand

D_f=depth of foundation measured from the ground surface

B= width of foundation

L= length of foundation

From Figure 1.2 it can be seen that

Nature of failure = $f\left(D_r, \frac{D_f}{B}, \frac{B}{L}\right)$

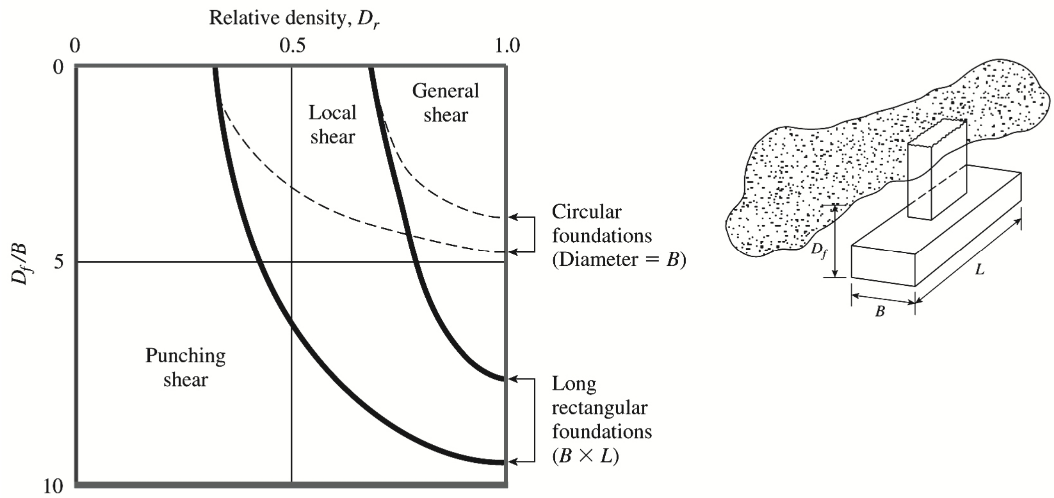


Figure 1.2 Vesic's test results for modes of foundation failure in sand

Ultimate Bearing Capacity Theory

Terzaghi's Bearing-Capacity Equation

- Terzaghi was the first to present a comprehensive theory for evaluating the ultimate bearing capacity of shallow foundations.
- A foundation is *shallow* if the D_f<B.
- The foundation is continuous, or strip, (that is, B/L approaches 0).
- The failure surface may be assumed to be similar to that shown in Figure 1.3. (Note that this is the case of *general shear failure* as defined in (Figure 1.1a.)
- The effect of soil above the bottom of the foundation may also be assumed to be replaced by an equivalent surcharge, $q = \gamma D_f$ (where γ unit weight of soil).
- The failure zone under the foundation can be separated into three parts (see Figure 1.3):
    1) *The triangular zone ACD* immediately under the foundation
    2) The *radial shear zones ADF* and *CDE*, with the curves *DE* and *DF* being arcs of a logarithmic spiral
    3) Two *triangular Rankine passive zones AFH* and *CEG*
- The angles *CAD* and *ACD* are assumed to be equal to the soil friction angle (that is, $\alpha = \phi$).
- The shear resistance of the soil along the failure surfaces *GI* and *HJ* was neglected (due to the replacement of the soil above the bottom of the foundation by an equivalent surcharge q)

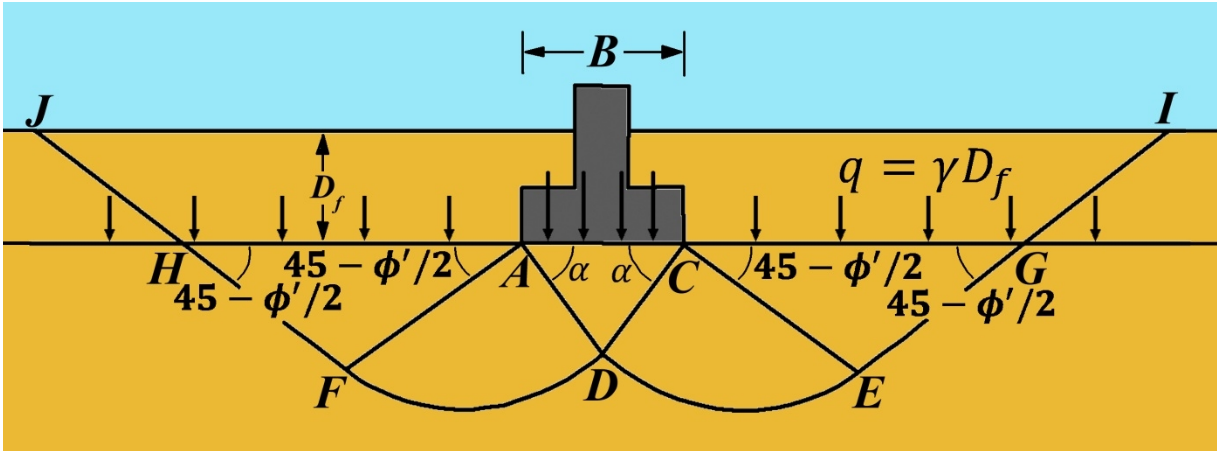


Figure 1.3 Bearing capacity failure in soil under a rough rigid continuous foundation

Using the equilibrium analysis, Terzaghi expressed the ultimate bearing capacity in the form:

$$q_u = cN_c s_c + qN_q + \frac{1}{2}\gamma B N_\gamma s_\gamma$$

where

c cohesion of soil
γ= unit weight of soil
$q = \gamma D_f$
N_c, N_q, N_γ= bearing capacity factors that are non-dimensional and are only functions of the soil friction angle, ϕ
B= width of the footing (or diameter of circular footings)

The values of N_c, N_q, and N_γ can be computed as

$$N_q = \frac{a^2}{a\, cos^2(45 + \phi/2)}$$

$$a = e^{\left(0.75\pi - \frac{\phi}{2}\right)\tan\phi}$$

$$N_c = (N_q - 1)\cot\phi$$

$$N_\gamma = \frac{\tan\phi}{2}\left(\frac{K_{p\gamma}}{cos^2\phi} - 1\right)$$

The variation of N_c, N_q, and N_γ with ϕ' is given in Table 1.1

The values of the shape factors

Strip footing	$s_c = 1.0$ $s_\gamma = 1.0$
Round footing	$s_c = 1.3$ $s_\gamma = 0.6$
Square footing	$s_c = 1.3$ $s_\gamma = 0.8$

Table 1.1 Terzaghi's Bearing Capacity Factors (N_c, N_q, and N_γ)

ϕ'	N_c	N_q	N_γ
0	5.7	1	0
1	6	1.1	0.01
2	6.3	1.22	0.04
3	6.62	1.35	0.06
4	6.97	1.49	0.1
5	7.34	1.64	0.14
6	7.73	1.81	0.2
7	8.15	2	0.27
8	8.6	2.21	0.35
9	9.09	2.44	0.44
10	9.61	2.69	0.56
11	10.16	2.98	0.69
12	10.76	3.29	0.85
13	11.41	3.63	1.04
14	12.11	4.02	1.26
15	12.86	4.45	1.52
16	13.68	4.92	1.82
17	14.6	5.45	2.18
18	15.12	6.04	2.59
19	16.56	6.7	3.07
20	17.69	7.44	3.64
21	18.92	8.26	4.31
22	20.27	9.19	5.09
23	21.75	10.23	6
24	23.36	11.4	7.08
25	25.13	12.72	8.34

ϕ'	N_c	N_q	N_γ
26	27.09	14.21	9.84
27	29.24	15.9	11.6
28	31.61	17.81	13.7
29	34.24	19.98	16.18
30	37.16	22.46	19.13
31	40.41	25.28	22.65
32	44.04	28.52	26.87
33	48.09	32.23	31.94
34	52.64	36.5	38.04
35	57.75	41.44	45.41
36	63.53	47.16	54.36
37	70.01	53.8	65.27
38	77.5	61.55	78.61
39	85.97	70.61	95.03
40	95.66	81.27	115.31
41	106.81	93.85	140.51
42	119.67	108.75	171.99
43	134.58	126.5	211.56
44	151.95	147.74	261.6
45	172.28	173.28	325.34
46	196.22	204.19	407.11
47	224.55	241.8	512.84
48	258.28	287.85	650.67
49	298.71	344.63	831.99
50	347.5	415.14	1072.8

The Factor of Safety

Calculating the gross allowable load-bearing capacity of shallow foundations requires the application of a factor of safety (*FS*) to the gross ultimate bearing capacity, or

$$q_{all} = \frac{q_u}{FS}$$

Example 1-1.

Compute the allowable bearing pressure using the Terzaghi equation for the footing and soil parameters shown in Figure 1-4. Use a safety factor of 3 to obtain q_a.

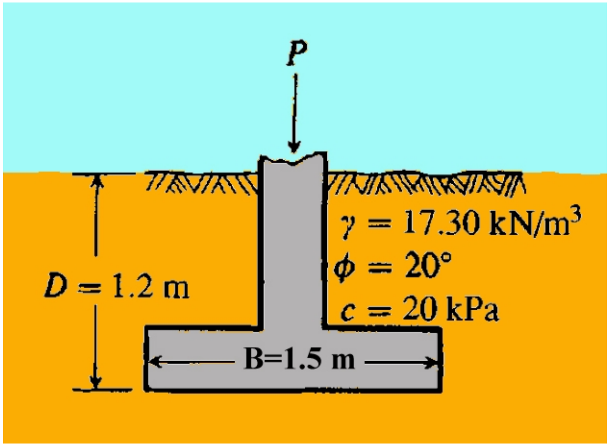


Figure 1-4 Soil properties and footing dimensions of Example 1-1

Solution

$$q_{ult} = cN_cS_c + qN_q + 0.5\gamma BN_\gamma S_\gamma$$

From Table 1-1, for $\phi = 20^\circ$

$$N_c = 17.69 \quad N_q = 7.44 \quad N_\gamma = 3.64$$

For square footing

$$s_c = 1.3 \quad s_\gamma = 0.8$$

So,

$$q_{ult} = 20(17.69)(1.3) + 1.2(17.3)(7.44) + 0.5(17.3)(1.5)(3.64)(0.8)$$

$$q_{ult} = 652.2$$

For factor of safety, $SF = 3$

$$q_a = \frac{q_{ult}}{SF}$$

$$q_a = \frac{652.2}{3} \approx 217\ kPa$$

Example 1-2.

Resolve Example 1-1 if the footing is circular and its diameter equals to 1.5m.

Solution

$$q_{ult} = cN_cS_c + qN_q + 0.5\gamma BN_\gamma S_\gamma$$

From Table 1-1, for $\phi = 20^\circ$

$$N_c = 17.69 \quad N_q = 7.44 \quad N_\gamma = 3.64$$

For ciruclar footing

$$s_c = 1.3 \quad s_\gamma = 0.6$$

So,

$$q_{ult} = 20(17.69)(1.3) + 1.2(17.3)(7.44) + 0.5(17.3)(1.5)(3.64)(0.6)$$

$$q_{ult} = 642.7$$

$q_a = \frac{652.2}{3} \approx 214\ kPa$, it doesn't differ significantly from value obtained for square footing.

Example 1-3.

Resolve Example 1-1 if the depth of the footing is increased to 1.5m.

Solution

$$q_{ult} = cN_cS_c + qN_q + 0.5\gamma BN_\gamma S_\gamma$$

From Table 1-1, for $\phi = 20^\circ$

$$N_c = 17.69 \quad N_q = 7.44 \quad N_\gamma = 3.64$$

For circular footing

$$s_c = 1.3 \quad s_\gamma = 0.8$$

So,

$$q_{ult} = 20(17.69)(1.3) + 1.5(17.3)(7.44) + 0.5(17.3)(1.5)(3.64)(0.8)$$

$$q_{ult} = 690.8$$

$q_a = \frac{690.8}{3} \approx 230\ kPa$, there is some increment compare to that obtained for depth=1.2 m

Meyerhof 's Bearing-Capacity Equation

Meyerhof proposed a bearing-capacity equation similar to that of Terzaghi but included a shape factor s_q with the depth term N_q. He also included depth factors d_i and inclination factors i_i.

The bearing capacity equation of Meyerhof is:

For vertical load: $q_{ult} = cN_cS_cd_c + qN_qS_qd_q + 0.5\gamma B'N_\gamma S_\gamma d_\gamma$

For inclined load: $q_{ult} = cN_cS_ci_c + qN_qS_qi_q + 0.5\gamma B'N_\gamma S_\gamma i_\gamma$

The bearing capacity factors are:

$N_q = e^{\pi \tan\phi} \tan^2\left(45 + \frac{\phi}{2}\right)$

$N_c = \left(N_q - 1\right)\cot\phi$

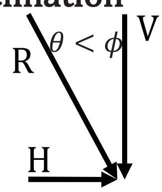
$N_\gamma = \left(N_q - 1\right)\tan(1.4\phi)$

And they can be obtained from Table 1-2

Table 1-2 Bearing-capacity factors for Meyerhof bearing-capacity equation

ϕ	N_c	N_q	N_γ
0	5.14	1.00	0.00
1	5.38	1.09	0.00
2	5.63	1.20	0.01
3	5.90	1.31	0.02
4	6.19	1.43	0.04
5	6.49	1.57	0.07
6	6.81	1.72	0.11
7	7.16	1.88	0.15
8	7.53	2.06	0.21
9	7.92	2.25	0.28
10	8.34	2.47	0.37
11	8.80	2.71	0.47
12	9.28	2.97	0.60
13	9.81	3.26	0.74
14	10.37	3.59	0.92
15	10.98	3.94	1.13
16	11.63	4.34	1.37
17	12.34	4.77	1.66
18	13.10	5.26	2.00
19	13.93	5.80	2.40
20	14.83	6.40	2.87
21	15.81	7.07	3.42
22	16.88	7.82	4.07
23	18.05	8.66	4.82
24	19.32	9.60	5.72
25	20.72	10.66	6.77
26	22.25	11.85	8.00
27	23.94	13.20	9.46
28	25.80	14.72	11.19
29	27.86	16.44	13.24
30	30.14	18.40	15.67
31	32.67	20.63	18.56
32	35.49	23.18	22.02
33	38.64	26.09	26.17
34	42.16	29.44	31.15
35	46.12	33.30	37.15
36	50.59	37.75	44.43
37	55.63	42.92	53.27
38	61.35	48.93	64.07
39	67.87	55.96	77.33
40	75.31	64.20	93.69
41	83.86	73.90	113.99
42	93.71	85.37	139.32
43	105.11	99.01	171.14
44	118.37	115.31	211.41
45	133.87	134.87	262.74
46	152.10	158.50	328.73
47	173.64	187.21	414.33
48	199.26	222.30	526.45
49	229.92	265.50	674.92
50	266.88	319.06	873.86

TABLE 1-3 Shape, depth, and inclination factors for the Meyerhof bearing-capacity equations of Table 4-1

Factors	Value	For
Shape	$s_c = 1 + 0.2K_p \frac{B}{L}$	Any ϕ
	$s_q = s_\gamma = 1 + 0.1K_p \frac{B}{L}$	$\phi > 0$
	$s_q = s_\gamma = 1$	$\phi = 0$
Depth	$d_c = 1 + \sqrt{K_p} \frac{D}{B}$	Any ϕ
	$d_q = d_\gamma = 1 + 0.1\sqrt{K_p} \frac{D}{B}$	$\phi > 0$
	$d_q = d_\gamma = 1$	$\phi = 0$
Inclination 	$i_c = i_q = \left(1 - \frac{\theta^\circ}{90^\circ}\right)^2$	Any ϕ
	$i_\gamma = \left(1 - \frac{\theta^\circ}{90^\circ}\right)^2$	$\phi > 0$
	$i_\gamma = 0 \quad for \quad \theta > 0$	$\phi = 0$

Where : $K_p = \tan^2(45 + \phi/2)$

θ = angle of resultant R measured from vertical without a sign: if $\theta = 0$ all $i_i = 1.0$

NOTES

- The shape factors do not greatly differ from those given by Terzaghi except for the addition of s_q.
- Observing that the shear effect along line cd of Figure 1-3 was still being somewhat ignored.
- Meyerhof proposed depth factors d_i. and he also proposed using the inclination factors of Table 1-3 to reduce the bearing capacity when the load resultant was inclined from the vertical by the angle θ.
- When the i_γ factor is used, it should be self-evident that it does not apply when $\phi = 0°$, since a base slip would occur with this term—even if there is base cohesion for the i_c term.
- The i_i factors all = 1.0 if the angle $\theta = 0$.

Example 1-4

Compute the allowable bearing pressure (of Example 1-1) using the Meyerhof equation. Use a safety factor of 3 to obtain q_a.

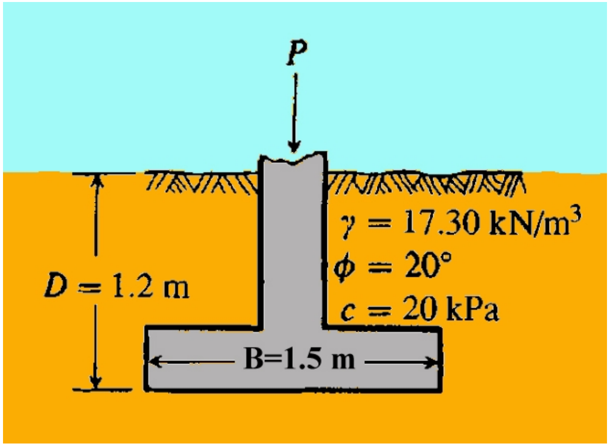


Figure 1-5 Soil properties and footing dimensions of Example 1-4

Solution

Meyerhof's bearing capacity equation for vertical load is

$$q_{ult} = cN_cS_cd_c + qN_qS_qd_q + 0.5\gamma B'N_\gamma S_\gamma d_\gamma$$

From Table 1-2, for $\phi = 20^\circ$, $N_c = 14.83$ $\quad N_q = 6.40$ $\quad N_\gamma = 2.87$

From Table 1-3, shape and depth factors are computed as:

First, compute the value of K_p,

$$K_p = \tan^2(45 + \phi/2) = \tan^2(45 + 20/2) = 2.04$$

$s_c = 1 + 0.2K_p\frac{B}{L}$	→	$s_c = 1 + (0.2)(2.04)\frac{1.5}{1.5}$	→	$s_c = 1.41$
$s_q = s_\gamma = 1 + 0.1K_p\frac{B}{L}$	→	$s_q = s_\gamma = 1 + (0.1)(2.04)\frac{1.5}{1.5}$	→	$s_q = s_\gamma = 1.20$
$d_c = 1 + \sqrt{K_p}\frac{D}{B}$	→	$d_c = 1 + \sqrt{2.04}\frac{1.2}{1.5}$	→	$d_c = 2.14$
$d_q = d_\gamma = 1 + 0.1\sqrt{K_p}\frac{D}{B}$	→	$d_q = d_\gamma = 1 + 0.1\sqrt{2.04}\frac{1.2}{1.5}$	→	$d_q = d_\gamma = 1.11$

$$q_{ult} = (20)(14.83)(1.41)(2.14) + (1.2)(17.3)(6.40)(1.20)(1.11) + (0.5)(17.3)(1.5)(2.87)(1.20)(1.11)$$

$$q_{ult} = 1121.5\ kPa$$

For factor of safety, $SF = 3$

$$q_a = \frac{q_{ult}}{SF}$$

$$q_a = \frac{1121.5}{3} \approx 374\ kPa$$