CHAPTER-II-BEARING CAPACITY OF SOILS

INTRODUCTION

- The subject of bearing capacity is perhaps the most important of all the aspects of geotechnical engineering.
- Loads from buildings are transmitted to the foundation by columns, by load bearing walls or by such other load-bearing components of the structures.
- Sometimes the material on which the foundation rests is ledge, very hard soil or bed-rock, which is known to be much stronger than is necessary to transmit the loads from the structure.
- Such a ledge, or rock, or other stiff material may not be available at reasonable depth and it becomes invariably necessary to allow the structure to bear directly on soil, which will furnish a satisfactory foundation, if the bearing members are properly designed.

Definitions of bearing capacity

Bearing capacity: The load-carrying capacity of foundation soil or rock which enables it to bear and transmit loads from a structure.

Ultimate bearing capacity: Maximum pressure which a foundation can withstand without the occurrence of shear failure of the foundation.

Gross bearing capacity: The bearing capacity inclusive of the pressure exerted by the weight of the soil standing on the foundation, or the ‘surcharge’ pressure, as it is sometimes called.

Net bearing capacity: Gross bearing capacity minus the original overburden pressure or surcharge pressure at the foundation level; obviously, this will be the same as the gross capacity when the depth of foundation is zero, i.e., the structure is founded at ground level.

Safe bearing capacity: Ultimate bearing capacity divided by the factor of safety. The factor of safety in foundation may range from 2 to 5, depending upon the importance of the structure, and the soil profile at the site.

It is defined as the maximum intensity of loading which can be transmitted to the soil without the risk of shear failure, irrespective of the settlement that may occur.

Allowable bearing pressure: The maximum allowable net loading intensity on the soil at which the soil neither fails in shear nor undergoes excessive or intolerable settlement, detrimental to the structure.

Factors Affecting Bearing Capacity

The following are some of the factors which affect bearing capacity are,

(i) Nature of soil and its physical and engineering properties;

(ii) Nature of the foundation and other details such as the size, shape, depth below the ground surface and rigidity of the structure;

(iii) Total and differential settlements that the structure can withstand without functional failure;

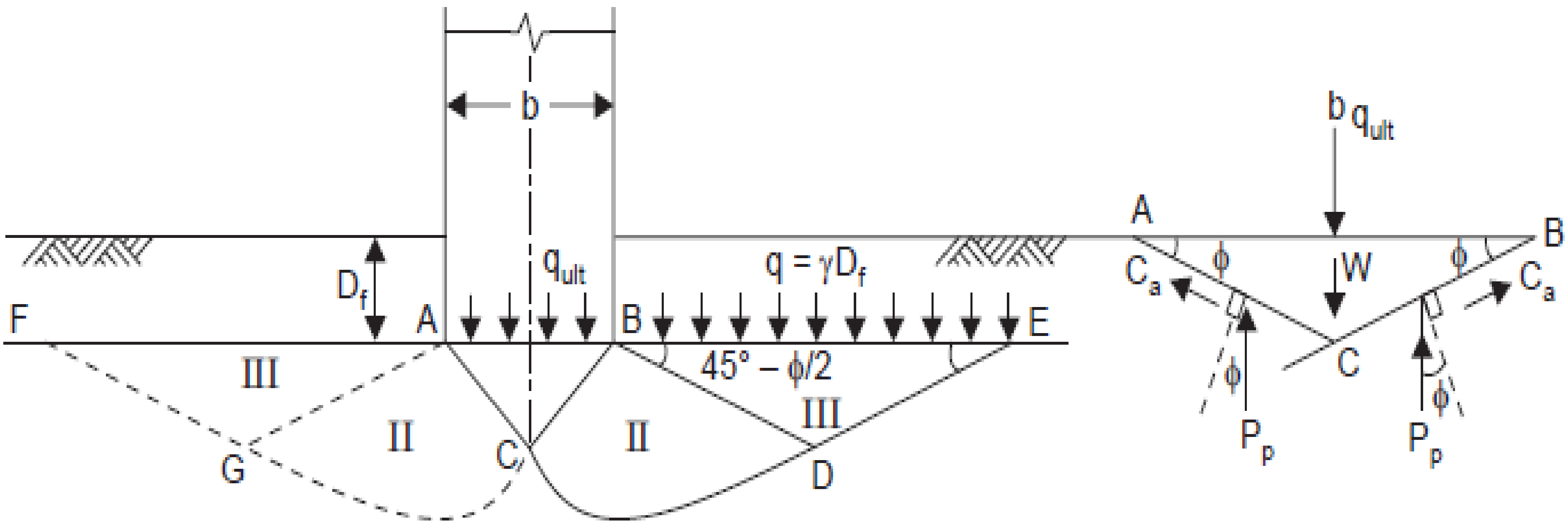
(iv) Location of the ground water table relative to the level of the foundation; and

(v) Initial stresses, if any.

General determination of bearing capacity of soils using different methods.

1)Terzaghi's Method

Terzaghi considered the base of the footing to be rough, which is nearer facts, and that it is located at a depth **D_f** below the ground surface (**$D_f \le b$**, where **b** is the width of the footing).



(a) Terzaghi system for ideal soil, rough base and surcharge (b) Forces on the elastic wedge

Fig. Terzaghi's method for bearing capacity of strip footing

- The soil above the base of the footing is replaced by an equilvalent surcharge, $\boldsymbol{q(= \gamma D_f)}$.This substitution simplifies the computations very considerably, the error being unimportant and on the safe side. This, in effect, means that the shearing resistance of the soil located above the base is neglected. (For deep foundations, where $\boldsymbol{D_f > b}$, this aspect becomes important and cannot be ignored).
- The zone of plastic equilibrium, **CDEFG**, can be subdivided into **I** a wedge-shaped zone located beneath the loaded strip, in which the major principal stresses are vertical, **II** two zones of radial shear, **BCD** and **ACG**, emanating from the outer edges of the loaded strip, with their boundaries making angles **(45° – φ/2)** and **φ** with the horizontal, and **III** two passive Rankine zones, **AGF** and **BDE**, with their boundaries making angles **(45° – φ/2)** with the horizontal.

Bearing capacity of shallow circular and square footings

The bearing capacity of circular footings has been proposed by Terzaghi as follows,

$$q_{ult_c} = 1.3\, cN_c + \gamma D_f N_q + 0.3\, \gamma\, d\, N_\gamma$$

where d = diameter of the circular footing.

The critical load for the footing is given by

$$Q_{ult_c} = \left(\frac{\pi d^2}{4}\right) \cdot q_{ult_c}$$

Similarly, the bearing capacity of a square footing of side b is:

$$q_{ult_s} = 1.3\, cN_c + \gamma D_f N_q + 0.4\, \gamma b\, N_\gamma$$

The critical load for the footing is given by

$$Q_{ult_s} = (b^2) \cdot q_{ult_s}$$

For a continuous footing of width b, it is already seen that,

$$q_{ult} = cN_c + \gamma D_f N_q + 0.5\, \gamma\, b\, N_\gamma$$

The bearing capacity factors of Terzaghi are tabulated in Table for certain values of φ:

Table Terzaghi's bearing capacity factors

Angle of shearing resistance ϕ°	*Terzaghi's bearing capacity factors*		
	N_c	N_q	N_γ
0	5.7	1.0	0.0
5	7.3	1.6	1.5
10	9.6	2.7	1.2
15	12.9	4.4	2.5
20	17.7	7.4	5.0
25	25.1	12.7	9.7
30	37.2	22.5	19.7
35	57.8	41.4	42.4
40	95.7	81.3	100.4
45	172.3	173.3	297.5
50	347.5	415.1	1153.0

2)Meyerhof’s Method

- The important difference between Terzaghi’s and Meyerhof’s approaches is that the latter considers the shearing resistance of the soil above the base of the foundation, while the former ignores it. Thus, Meyerhof allows the failure zones to extend up to the ground surface (Meyerhof, 1951). Meyerhof ’s equation for the bearing capacity of a strip footing is of the same general form as that of Terzaghi:

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

wherein **Nc, Nq** and **Nγ** are “Meyerhof’s bearing capacity factors”, which depend not only on **φ,** but also on the depth and shape of the foundation and roughness of the base.

The typical failure surface assumed by Meyerhof is shown in Fig.

The significant zones are:

Zone	*I*	*ABC*	... elastic
Zone	*II*	*BCD*	... radial shear
Zone	*III*	*BDEF*	... mixed shear

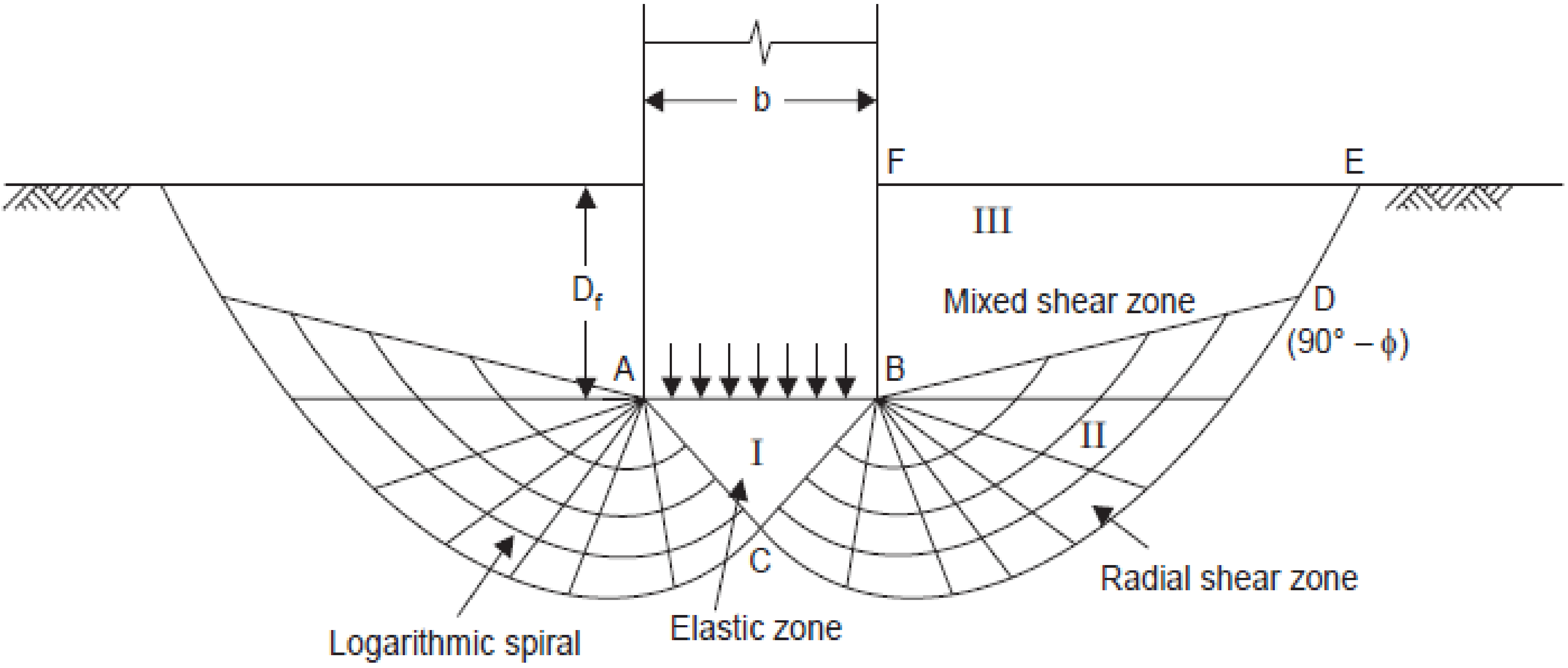


Fig. Meyerhof's method for the bearing capacity of shallow foundation

- The nature of the failure surface assumed by Meyerhof implies the occurrence of a substantial downward movement of the footing before the full value of the shearing resistance is mobilised.
- This may be more probable in the case of purely cohesive soils as indicated by the available experimental evidence. Hence, the values of **Nc** from Meyerhof's theory for cohesive soils are given as follows:

For strip footings: ***Nc = 5.5(1 + 0.25 Df/b)***

with a limiting value of 8.25 ***for Nc for Df /b > 2.5.***

For square or circular footings: ***Nc = 6.2 (1 + 0.32 Df /b)***

with a limiting value of 9.0 for ***Nc for Df /b > 2.5.***

(b is the side of a square or diameter of circular footing).

3) Skempton's Method

- Skempton proposed equations for bearing capacity of footings founded in purely cohesive soils based on extensive investigations (Skempton, 1951). He found that the factor Nc is a function of the depth of foundation and also of its shape. His equations may be summarised as follows:
- The net ultimate bearing capacity is given by:

$$q_{net\ ult} = c \cdot N_c$$

wherein ***Nc** is given as follows:*

Strip footings: ***Nc = 5 (1 + 0.2 Df /b)***

with a limiting value of ***Nc of 7.5 for Df /b > 2.5.***

Square or circular footings: $N_c = 6(1 + 0.2 D_f / b)$

with a limiting value of Nc of 9.0 for **Df /b >2.5.**

(**b** is the side of square or diameter of circular footing).

Rectangular footings:

$$N_c = 5\left(1 + 0.2\frac{b}{L}\right)\left(1 + 0.2\frac{D_f}{b}\right)$$

for $D_f/b \le 2.5$, and $\quad N_c = 7.5\,(1 + 0.2\,b/L)$

for $D_f/b > 2.5$,

wherein b = width of the rectangular footing, and

L = length of the rectangular footing.

4) Brinch Hansen's Method

Brinch Hansen (1961) has proposed the following semi-empirical equation for the bearing capacity of a footing, as a generalisation of the Terzaghi equation:

$$q_{ult} = \frac{Q_{ult}}{A} = cN_c s_c d_c i_c + qN_q s_q d_q i_q + \frac{1}{2}\gamma b N_\gamma s_\gamma i_\gamma$$

where **Q_{ult}** = vertical component of the total load **(= V),**

A = effective area of the footing (this will arise for inclined and eccentric loads, when the area **A** is transformed to an estimated equivalent rectangle with sides **b** and **L**, such that the load is central to the area),

q = overburden pressure at the foundation level (= γ . Df),

Nc, Nq and Nγ = bearing capacity factors of Hansen, given as follows:

Nq = Nφ . eπ tan φ

Nc = (Nq – 1) cot φ

Nγ = 1.8 (Nq – 1) tan φ

(Nφ = tan2 (45° + φ/2), with the usual notation.)

s′s = shape factors

d′s = depth factors, and

i′s = inclination factors.

The bearing capacity factors of Hansen, shape factors, depth factors, and inclination factors are given in Table

Table Brinch Hansen's bearing capacity factors

Angle of shearing Resistance $\phi°$	*Hansen's Bearing Capacity Factors*		
	N_c	N_q	N_γ
0	5.14	1.00	0
5	6.49	1.57	0.09
10	8.34	2.47	0.47
15	10.98	3.94	1.42
20	14.83	6.40	3.54
25	20.72	10.66	8.11
30	30.14	18.40	18.08
35	46.13	33.29	40.69
40	95.41	75.32	64.18
45	133.89	134.85	240.85
50	266.89	318.96	681.84

Table Brinch Hansen's shape factors

Type of footing	*Hansen's shape factors*		
	s_c	s_q	s_γ
Continuous (Width b)	1.0	1.0	1.0
Rectangular ($b \times L$)	$1 + 0.2\,\dfrac{b}{L}$	$1 + 0.2\,\dfrac{b}{L}$	$1 - 0.4\,\dfrac{b}{L}$
Square (Size b)	1.3	1.2	0.8
Circular (Diameter b)	1.3	1.2	0.6

Table Brinch Hansen's depth factors

d_c	d_q	d_γ
$1 + 0.35\, D_f/b$	$1 + 0.35\, D_f/b$	1.0

$d_q = d_c$ for $\phi > 25°$

$d_q = 1.0$ for $\phi = 0°$

Table Brinch Hansen's inclination factors

i_c	i_q	i
$1 - \dfrac{H}{2c_a bL}$	$1 - 0.5\dfrac{H}{V}$	$(i_q)^2$

Limitation: $H \leq V \tan\delta + c_a bL$.

where H and V = horizontal and vertical components of total load

δ = angle of friction between base of footing and soil

c_a = adhesion between footing and soil

L = length of footing parallel to H

Revised values of inclination factors:

$$i_c = i_q = \left(1 - \frac{H}{V + A\,.\,c\cot\phi}\right)^2$$

$$i_\gamma = i_q^{\,2}$$

But, for $\phi = 0°$, $\quad i_c = i_q = 0.5 + 0.5\sqrt{1 - \dfrac{H}{Ac}}$

Example-1: A continuous footing of width 2.5m rests 1.5m below the ground surface in clay. The unconfined compressive strength of the clay is 150kN/m2. Calculate the ultimate bearing capacity of the footing. Assume unit weight of soil is 16 kN/m3.

<u>Solution</u>

Continuous footing $b = 2.5$ m $D_f = 1.5$ m

Pure clay.

$\phi = 0°$ $\quad q_u = 150\ \text{kN/m}^2$ $\quad \gamma = 16\ \text{kN/m}^3$

$$c = \frac{q_u}{2} = 75\ \text{kN/m}^2$$

For $\phi = 0°$, Terzaghi's factors are: $N_\gamma = 0$, $N_q = 1$, and $N_c = 5.7$.

$$q_{\text{ult}} = cN_c + \frac{1}{2}\gamma b\, N_\gamma + \gamma D_f N_q = cN_c + \gamma D_f N_q, \text{ in this case.}$$

$$\therefore \quad q_{\text{ult}} = 5.7 \times 75 + 16 + 1.5 \times 1 = 451.5\ \text{kN/m}^2 \approx 450\ \text{kN/m}^2.$$

Example-2 Compute the safe bearing capacity of a continuous footing 1.8m wide, and located at a depth of 1.2m below ground level in a soil with unit weight γ=20kN/m3,c=20kN/m2, and φ = 20°. Assume a factor of safety of 2.5. Terzaghi's bearing capacity factors for φ = 20° are Nc = 17.7, Nq = 7.4, and Nγ = 5.0, what is the permissible load per metre run of the footing ?

Solution

$b = 1.8$ m continuous footing $D_f = 1.2$ m

$\gamma = 20$ kN/m^3 $c = 20$ kN/m^2

$\phi = 20°$ $N_c = 17.7$

$N_q = 7.4$ $N_\gamma = 5.0$ $\eta = 2.5$

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

$$= 20 \times 17.7 + \frac{1}{2} \times 20 \times 1.8 \times 5.0 + 20 \times 1.2 \times 7.4$$

$$= 621.6 \text{ kN/m}^2$$

$$q_{net\ ult} = q_{ult} - \gamma D_f = 621.6 - 20 \times 1.2 = 597.6 \text{ kN/m}^2$$

$$q_{net\ safe} = \frac{q_{net\ ult}}{\eta} = \frac{597.6}{2.5} = 239 \text{ kN/m}^2$$

$$q_{safe} = q_{net\ safe} + \gamma D_f = 239 + 20 \times 1.2 = \mathbf{263\ kN/m^2}$$

Permissible load per metre run of the wall = 263 × 1.8 kN = **473.5 kN**.

Example-3: What is the ultimate bearing capacity of a square footing resting on the surface of a saturated clay of unconfined compressive strength of 100kN/m2.

Solution

Square footing. Saturated clay, φ = 0° Df = 0.

Terzaghi's factors for $\phi = 0°$ are : $N_c = 5.7$, $N_q = 1$, and $N_\gamma = 0$.

$$q_u = 100 \text{ kN/m}^2$$

$$\therefore \quad c = \frac{1}{2} q_u = 50 \text{ kN/m}^2$$

$$q_{ult} = 1.3\, cN_c = 1.3 \times 50 \times 5.7 = 370 \text{ kN/m}^2$$

$$\therefore \quad q_{ult} = 370 \text{ kN/m}^2.$$

Example-4: A steam turbine with base 6m × 3.6m weighs 10,000kN. It is to be placed on a clay soil with C =135 kN/m2. Find the size of the foundation required if the factor of safety is to be 3. The foundation is to be 60cm below ground surface.

Solution

Skempton's equation:

$$q_{\text{net ult}} = 5c\left(1+0.2\frac{b}{L}\right)\left(1+0.2\frac{D_f}{b}\right) \text{ for } D_f/b \le 2.5.$$

$$D_f = 0.6 \text{ m}$$

For $\phi = 0°$, $N_\gamma = 0$ and $N_q = 1$ Assume $\gamma = 18$ kN/m^3.

Adopt $b/L = 0.6$, same as that for the turbine base.

$$D_f/b = 0.6/b$$

Area, $$A = bL = \frac{b^2}{0.6} = \left(\frac{5b^2}{3}\right) \text{ m}^2$$

$$\therefore \quad q_{\text{net ult}} = 5 \times 135\,(1 + 0.2 \times 0.6)\left(1+\frac{0.2\times 0.6}{b}\right) = 756\left(1+\frac{0.12}{b}\right) \text{ kN/m}^2$$

$$q_{safe} = \frac{q_{net\ ult}}{\eta} + \gamma D_f = \left[\frac{756\left(1+\frac{0.12}{b}\right)}{3} + 18 \times 0.6 \right] \text{kN/m}^2$$

$$Q_{safe} = q_{safe} \times A = \frac{5b^2}{3}\left[756\frac{\left(1+\frac{0.12}{b}\right)}{3} + 10.8 \right] \text{kN}$$

Equating Q_{safe} to 10,000, we have

$$420\, b^2 \left(1+\frac{0.12}{b}\right) + 18\, b^2 = 10{,}000$$

Solving for b,

b = 4.72 m, say 4.80 m. ($D_f/b < 2.5$ is satisfied)

L = 4.8/0.6 = 8.0 m

Hence, the size of the foundation required is 4.8 m × 8.0 m.

Example-5: What is the safe bearing capacity of a rectangular footing, 1m × 2m, placed at a depth of 2m in a saturated clay having unit weight of 20kN/m3 and unconfined compression strength of 100kN/m2 ? Assume a factor of safety of 2.5.

Solution

Rectangular footing:

$b = 1 \text{ m} \qquad L = 2 \text{ m} \qquad D_f = 2 \text{ m} \qquad q_u = 100 \text{ kN/m}^2 \qquad \gamma = 20 \text{ kN/m}^3$

$D_f/b = \frac{2}{1} = 2 \quad b/L = \frac{1}{2} \qquad c = \frac{1}{2} \qquad q_u = 50 \text{ kN/m}^3$

Skempton's equation:

$$q_{\text{net ult}} = c \,.\, N_c, \text{ where } N_c = 5\left(1+0.2\frac{b}{L}\right)\left(1+0.2\frac{D_f}{b}\right) \text{ for } D_f/b \le 2.5$$

Since $D_f/b = 2 < 2.5$,

$$N_c = 5\left(1+0.2\times\frac{1}{2}\right)(1 + 0.2 \times 2/1) = 7.7$$

$$\therefore \qquad q_{\text{net ult}} = 7.7 \times 50 = 385 \text{ kN/m}^2$$

$$q_{\text{net safe}} = \frac{q_{\text{net ult}}}{\eta} = \frac{385}{2.5} = 154 \text{ kN/m}^2$$

$$q_{\text{safe}} = q_{\text{net safe}} + \gamma D_f = 154 + 20 \times 2 = \mathbf{194\ kN/m^2}.$$