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INFLUENCE OF STATIC WATER TABLE ON THE BEARING CAPACITY OF SHALLOW FOUNDATIONS

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ABSTRACT

The presence of a static water table reduces the bearing capacity of a shallow foundation by reducing effective stresses in the soil. Rational solutions exist for the quantification of the reduction in bearing capacity for the case of a static water table below foundation level in a cohesionless soil. For c - ϕ soils and static water tables above foundation level, empirical procedures that utilize the submerged unit weight for the soil below the water table are used. This paper presents rational limit equilibrium solutions that can be used to quantify the reduction in bearing capacity due to static water tables at any depth in a c - ϕ soil.

Keywords: *bearing capacity, shallow foundations, water table, limit equilibrium, uniform pore-water pressure, hydrostatic pore-water pressure*

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INTRODUCTION

The general equation for the bearing capacity of a shallow foundation as proposed by Terzaghi (1943) is given by:

[1] $$q_f = cN_c + P_o N_q + \frac{1}{2} B\gamma N_\gamma$$

where:

q_f = bearing capacity

c = cohesion of the soil

γ = unit weight of the soil

B = width of the foundation

P_o = surcharge pressure due to soil above foundation level

N_c = bearing capacity factor with respect to cohesion

N_q = bearing capacity factor with respect to surcharge

N_γ = bearing capacity factor with respect to self weight of the soil

Eq. 1 applies to a dry soil in which the water table is at a depth below the depth of influence of the foundation. In practice the water table can occur within the zone of influence of the foundation resulting in a reduction in bearing capacity. Terzaghi (1925) proposed the following equation for the bearing capacity of a footing resting on the surface of a cohesionless soil with a static water table at the ground surface:

[2] $$q_f = (\gamma - \gamma_w) \frac{B}{2} N_\gamma$$

Meyerhof (1955) extended Eq. 2 for static water tables above and below foundation level. For a footing on the surface of a cohesionless soil with a static water table at a depth, *d*, below the foundation he proposed the following equation:

[3] $$q_f = \left[\gamma' + F(\gamma - \gamma')\frac{B}{2}N_\gamma\right]$$

where γ' is the submerged unit weight and *F* is a weighting factor which varies between zero for $d = 0$ and one for a water table at the theoretical depth of the failure surface.

For the case of a water table above foundation level, Meyerhof (1955) proposed the following equation:

[4] $$q_f = \frac{1}{2}B(\gamma - \gamma_w)N_\gamma + [\gamma D - \gamma_w(D-d)]N_q + \gamma_w(D-d)$$

where *D* and *d* are the depths of the foundation and water table, respectively.

Other empirical solutions have been proposed that recommend the use of the submerged unit weight for a fully submerged footing and unit weights which increase in proportion to the depth of the water table from the submerged unit weight to the saturated unit weight at a depth of twice the width of the footing.

This paper presents rational limit equilibrium solutions that can be used to quantify the influence of the water table at any depth in a c - ϕ soil.

RATIONALE OF SOLUTION

The solution is based on the limit equilibrium approach used by Terzaghi (1943). Terzaghi assumed a general shear failure mechanism consisting of an active, passive and radial shear zones as shown in Fig. 1. The shear strength of the soil above the foundation level was ignored and its effect replaced by a surcharge. The bearing capacity was determined by considering the equilibrium of the passive and active soil wedges. The forces acting on these soil wedges are shown in Fig. 2.

The passive pressure on the side of the passive wedge can be determined from lateral earth pressure theory as follows:

[5] $$p_p = \gamma z K_p + 2c\sqrt{K_p}$$

where:

- p_p = passive pressure at depth, z
- γ = unit weight of the soil
- K_p = Rankine's passive pressure coefficient given by $\tan^2(45^\circ+\phi/2)$
- c = cohesion of the soil
- ϕ = friction angle of the soil

The weights of the passive and radial shear zone were determined from the geometry of the wedges and the unit weight of the soil. The moment, M_c, due to cohesion along the log spiral was calculated from the length of the log spiral and the cohesion of the soil. The resultant force, *P*, was calculated by taking moments about the center of the log spiral. The resultant normal force at the base of the log spiral is inclined at an angle equal to the angle of internal friction of the soil and therefore acts through the center. Since the resultant force has no moment, its value need not be determined. To solve for the resultant force, *P*, assumptions were made with regard to the points of action of the weight and passive forces. These assumptions are discussed in detail in the derivations.

Once the resultant force, *P*, was determined, the bearing capacity of the footing was calculated by considering the equilibrium of the active wedge in Fig. 2(b). The cohesive force, *C*, and the weight of the active wedge, W_2, were calculated from the geometry of the wedge, unit weight and cohesion of the soil.

Separate determinations were made for the components of bearing capacity due to cohesion, surcharge and self weight. Superposition was assumed to be applicable so that the total bearing capacity could be determined by the summation of the cohesion, surcharge and self weight components of bearing capacity.

The component of bearing capacity due to cohesion was determined by considering the equilibrium of a weightless soil without surcharge but having both cohesion and friction. This eliminated the components due to surcharge and self weight and allowed the bearing capacity factor due to cohesion, N_c, to be determined. The component due to surcharge was determined by considering a cohesionless and weightless soil with surcharge while the component due to self weight was determined by considering a cohesionless soil without surcharge.

The passive force on the side of the passive wedge is the main determinant of bearing capacity. For a saturated soil with a static water table, the passive pressure can be expressed as follows (Pufahl *et al*,1993):

[6] $$p_p = 2c'\sqrt{K_p} + P_o K_p + \gamma z K_p + u_w(1 - K_p)$$

where:

c' = effective cohesion

γ = unit weight of the soil

z = depth of interest

P_o = surcharge pressure

u_w = pore water pressure

The term $2c'\sqrt{K_p}$ accounts for the component of bearing capacity due to cohesion, $P_o K_p$ for the component due to surcharge and $\gamma z K_p$ for the component due to self weight. The term $u_w(1-K_p)$ accounts for the presence of pore water pressures in the soil. Since the components of bearing capacity due to cohesion, surcharge and self weight can be determined separately then superimposed, it stands to reason that the same can be done with the component due to pore water pressures. The component of bearing capacity due to pore water pressures was therefore determined by considering the equilibrium of the passive and active soil wedges for a cohesionless, weightless soil without surcharge but subjected to water pressures arising from a static water table.

The following derivations are based on the general approach outlined above. Separate derivations are made for soils with static water tables below and above the foundation level.

Water Table Below Foundation Level

The forces on the radial shear zone and the passive wedge due to a static water table at a depth, h_w, are shown in Fig. 3. The effects of negative pore-water pressures above the water table are neglected in this analysis. The following lengths and angles are applicable to the geometry of the active, passive and radial shear zones:

$$\alpha = 45^\circ + \frac{\phi}{2} \qquad \beta = 45 - \frac{\phi}{2} \qquad \theta = 180 - \alpha - \beta$$

$$r_o = \frac{B}{2\cos\alpha} \qquad r_1 = r_o e^{\theta \tan\phi} \qquad H = r_o \sin\alpha \qquad H_d = r_1 \sin\alpha$$

$$K_p = \tan^2(45^\circ + \frac{\phi}{2})$$

Water Forces on the Passive Wedge

The water force on the passive wedge arising from the position of the static water table can be determined from the following equation:

[7] $$P_{pu} = \frac{1}{2}\gamma_w (H_d - h_w)^2 (1 - K_p)$$

Since the variation of pore-water pressure is hydrostatic, the force associated with this pressure distribution is assumed to act at the two-third point from the water table level. Its moment arm is therefore given by:

[8] $$l_{pu} = \frac{2}{3}(H_d - h_w) + h_w$$

This force vanishes when h_w is greater than H_d.

Water Forces on the Active Wedge

The force due to water pressures on the side of the active wedge is given by:

[9] $$P_{u1} = \frac{1}{2\sin\alpha}\gamma_w (H - h_w)^2$$

P_{u1} is equal to zero when h_w is greater than H. It is assumed to act at the two-third point below the level of the water table. The moment arm about the center of the log spiral is given by the following expression:

[10] $$l_{u1} = \frac{1}{\sin\alpha}(\frac{2}{3}(H - h_w) + h_w)$$

Water Force along the Log Spiral

The force due to pore-water pressures acting along the length of the log spiral and the position of the moment arm will depend on the depth of the water table relative to the depths of the active and passive wedges. Three possible pore-water pressure distribution patterns are shown in Fig. 4. The distribution of pore-water pressure along the length of the log spiral varies in proportion to the depth. Water force along the length of the log spiral vanishes when h_w exceeds the maximum depth of the failure surface, h_{max} given by the following expression:

[11] $$h_{max} = r_0 \cos\phi \exp[(90^\circ - \alpha - \phi)\tan\phi]$$

The water force on the log spiral at any depth can be determined by considering an elemental sector of the log spiral as shown in Fig. 5. The water force on the elemental sector is given by:

[12] $$dP_{u2} = \gamma_w (r\sin(\alpha + \theta) - h_w) r d\theta$$

The lever arm of this force about the center of the log spiral is given by:

[13] $$l_{u2} = r\sin\phi$$

The moment about the center of the log spiral is obtained by integration over the entire length to result in the following expression:

[14] $$M_{u2} = \int_0^{\alpha_2} \gamma_w \left(r\sin(\alpha + \theta) - h_w\right) r^2 \sin\phi d\theta$$

By making the substitutions $u = \sin(\alpha + \theta)$ and $dv = e^{\theta \tan\phi} d\theta$ and integrating twice by parts, the following expression is obtained for the moment about the center of the log spiral.

[15]
$$M_{u2} = \frac{\gamma_w \sin\phi}{(9\tan^2\phi + 1)}[r_f^3(3\tan\phi\sin(\alpha_1 + \alpha_2) - \cos(\alpha_1 + \alpha_2)) - r_i^3(3\tan\phi\sin\alpha_1 - \cos\alpha_1)] - h_w\gamma_w\frac{\cos\phi}{2}(r_f^2 - r_i)$$

The variables in eg. 5 take on values depending on the form of the pore-water pressure distribution as illustrated in Fig. 4.

Resultant Water Force

The resultant force, P_u, is assumed to be inclined at an angle equal to the friction angle of the soil and is calculated by summing moments about the center of the log spiral. The moment arm due to P_u is given by the following equation:

[16] $l_u = l_{u1}\cos\phi$

The following equation for the resultant water force is obtained by summing moments about the center of the log spiral:

[17]
$$P_u = \frac{1}{l_u}[P_{pu}l_{pu} + P_{u1}l_{u1} + M_{u2}]$$

Equilibrium of the Active Wedge

The forces acting on the active wedge due to a water table at depth, h_w, are shown in Fig. 6. The component of bearing capacity due to the static water table is determined by considering the vertical equilibrium of the active wedge. The following expression is obtained by summing forces in the vertical direction:

[18] $$q_f = \frac{2}{B}(P_u \cos(\alpha - \phi) + P_{u1} \cos\alpha)$$

A bearing capacity factor with respect to the position of the water table can then be defined as follows:

[19] $$q_f = \frac{B}{2}\gamma_w N_w$$

The form of definition of the bearing capacity factor, N_w, is similar to that of the bearing capacity factor with respect to self weight, N_γ. The similarity of definition was maintained to form a basis for comparison between the two factors.

Results of the Bearing Capacity Factor, N_w

The value of the bearing capacity factor corresponding to a given geometry and angle of shearing resistance of the soil was obtained by varying the position of the centre of the log spiral along the line AB in Fig. 3 to obtain the minimum bearing capacity. Alteration of the centre of the log spiral resulted in changes in the magnitudes of the moment arms for the various components of force. The changes can be easily calculated from the geometry of the radial shear zone.

The variation of N_w with the angle of shearing resistance of the soil is depicted in Fig. 7, for a range of water table depths. The component of bearing capacity due to pore-water pressures increases as the angle of shearing resistance of the soil increases.

Eq. 3 proposed by Meyerhof (1955) can be expressed in the following form:

[20] $$q_f = \frac{B}{2}\gamma N_\gamma + \gamma_w (F - 1)\frac{B}{2} N_\gamma$$

Comparison between eg. 19 and eq. 20 indicates the term $(F - 1)N_\gamma$ in Meyerhof's equation is equivalent to N_w in the proposed solution. The factor, N_w, was calculated using values of F given by Meyerhof (1955) and compared with the proposed solution in Fig. 8. There appears to be reasonable agreement between the two solutions at shallow depths of the water table. However, the proposed solution gives higher values of the bearing capacity factor for a deeper water table.

The variation of the bearing capacity factor, N_w, with the depth of the water table is illustrated in Fig. 9 for a soil with an angle of shearing resistance of 20°. The decreasing influence of water pressures on bearing capacity with increasing water table depth is apparent. Also apparent is the smooth transition from the fully submerged to the dry case.

The bearing capacity of a shallow foundation in a c - ϕ soil with a static water table below foundation level is then given by:

$$[21] \quad q_f = c'N_c + P_o N_q + \frac{1}{2}B(\gamma N_\gamma - \gamma_w N_w)$$

A special case of the solution for water table at depth occurs when the water table is at foundation level. Terzaghi (1925) proposed Eq. 2 for a fully submerged foundation in a cohesionless soil. Comparison between [2] and [19] indicates that the proposed bearing capacity factor, N_w, for the case of a fully submerged foundation is equal to the bearing capacity factor N_γ. A comparison has been made between the factor, N_w, for a water table at foundation level with the Caquot and Kerisel (1953) solution for N_γ in Fig. 10. There is close agreement between the two factors, especially at angles of shearing resistance less than 30°.

Water Table Above Foundation Level

The distribution of pore-water pressures arising from a static water table above the level of the foundation can be considered as a combination of the following three components (Fig. 11):

1. A surcharge pressure due to the weight of water above foundation level.
2. A uniform pore-water pressure distribution below foundation level due to the weight of water above foundation level.
3. A hydrostatic pore-water pressure distribution due to water pressures below foundation level.

The bearing capacity arising from the weight of water above foundation level can be determined using conventional bearing capacity theory for surcharge pressures. A solution has been presented for the case of hydrostatic pressure due to a water table at foundation level. By assuming the applicability of the principle of superposition, the bearing capacity due to a water table above foundation level can be determined by the summation of the three components. Referring to Fig. 11, the expressions for each component are given by:

[22] $$q_1 = \gamma_w (D-d) N_q$$

[23] $$q_2 = -\gamma_w (D-d) N_u$$

[24] $$q_3 = -\frac{1}{2}\gamma_w N_w$$

where:

q_1 = component due to surcharge weight of water above foundation level

q_2 = component due to uniform pore-water pressure below foundation level

q_3 = component due to hydrostatic pore-water pressure below foundation level

N_q = bearing capacity factor with respect to surcharge

N_u = bearing capacity factor due to uniform pore water pressure

N_w = bearing capacity factor due to hydrostatic pore water pressures variation. $N_w = N_\gamma$ for fully submerged case

The only unknown in the above equations is the bearing capacity factor due to uniform pore water pressure, N_u. Its determination is outlined below.

Uniform Pore-Water Pressures

The forces acting on the soil wedges and the corresponding moment arms about the center of the log spiral for the case of uniform pore water pressures under a footing are shown in Fig.

12. The solution for the forces proceeds in the same way as for the case of a water table below foundation level.

Water Forces on the Passive Wedge

The water force on the passive wedge (Fig. 12(a)) is given by the following equation:

[25] $$P_{pu} = u_w(1 - K_p)H_d$$

where u_w is the uniform pore-water pressure in the soil.

The force is assumed to act through the center point of the passive wedge. Its moment arm about the center of the log spiral is given by:

[26] $$l_{pu} = \frac{H_d}{2}$$

Water Forces on the Failure Surfaces

The water force along the side of the active wedge and its moment arm about the center of the log spiral are given by:

[27] $$P_{u1} = u_w r_o$$

[28] $$l_{u1} = \frac{r_o}{2}$$

The force and moment arm due to pore-water pressures acting along the length of the log spiral can be calculated by considering an elemental sector and integrating over its entire length.

[29] $$P_{u2} = \int_0^{\theta_1} u_w r d\theta$$

[30] $$l_{u2} = r \sin\phi$$

[31] $$M_{u2} = \int_0^{\theta_1} u_w r^2 \sin(\phi) d\theta$$

[32] $$M_{u2} = u_w \frac{\cos\phi}{2}(r_1^2 - r_o^2)$$

Resultant Water Force

The resultant force, P_u, is determined by taking moments about the center of the log spiral. It is assumed to be inclined at an angle equal to the angle of shearing resistance of the soil and to act through the center of the active wedge. The moment arm of the resultant force about the center of the log spiral is given by:

[33] $$l_u = \frac{r_o}{2}\cos\phi$$

Summing moments about the center of the log spiral,

[34] $$P_u = \frac{1}{l_u}[P_{pu} l_{pu} + P_{u1} l_{u1} + M_{u2}]$$

Equilibrium of the Active Wedge

The forces acting on the active wedge are shown in Fig. 12(b). The bearing capacity is determined by summing forces on the active wedge in the vertical direction to obtain the following expression for bearing capacity:

[35] $$q_{fu} = \frac{2}{B}[P_u \cos(\alpha - \phi) + P_{u1} \cos\alpha]$$

The bearing capacity due to the uniform pore-water pressures below the footing can be expressed in the form of a bearing capacity factor, N_u, defined as follows:

[36] $$N_u = \frac{q_{fu}}{u_w}$$

The value of the bearing capacity factor, N_u, depends on the assumption made with respect to the active wedge angle, α. The angle, α, is varied to obtain the minimum value of N_u.

Results of the Bearing Capacity Factor, N_u

The results of the bearing capacity factor, N_u, are presented in Table 1. Also presented in the table are the values of the wedge angle, α, corresponding to the minimum bearing capacity factor. The minimum value of N_u occurs at wedge angles equal to $(45^o + \phi / 2)$. By assigning this value to α, a closed form solution for the bearing capacity factor is given by:

[37] $$N_u = \left[\tan(45^o + \phi / 2)[1 - \frac{1}{\cos\phi} - (1 + \tan\phi)\exp(\pi \tan\phi)] + 1 \right]$$

A comparison was made between the bearing capacity factor, N_u, and the bearing capacity factor with respect to surcharge, (N_q -1), in Fig. 13. It is apparent from the figure that for angles of internal friction less than 30°, N_u is approximately equal to *(N_q-1)*.

The component of bearing capacity due to a static water table above the level of the foundation is determined by combining equations 22, 23 and 24 and substituting *(N_q-1)* for N_u and N_γ for N_w to obtain the following expressions:

[38] $$q_{fw} = \gamma_w(D-d)N_q - \gamma_w(D-d)(N_q-1) - \frac{1}{2}B\gamma_w N_\gamma$$

[39] $$q_{fw} = \gamma_w(D-d) - \frac{1}{2}B\gamma_w N_\gamma$$

The component of bearing capacity due to the soil can be determined from conventional bearing capacity theory. For a c-ϕ soil, the following expression is applicable to the bearing capacity component due to soil:

[40] $$q_{fs} = c'N_c + [\gamma d + (\gamma - \gamma_w)(D-d)]N_q + \frac{1}{2}B\gamma N_\gamma$$

The total bearing capacity can be determined by combining the components due to soil and pore-water pressure.

[41] $$q_f = q_{fs} + q_{fw}$$

[42] $$q_f = c'N_c + [\gamma d + (\gamma - \gamma_w)(D-d)]N_q + \frac{1}{2}B(\gamma - \gamma_w)N_\gamma + \gamma_w(D-d)$$

Empirical methods to account for static water tables above foundation level recommend the use of the submerged unit weight for both the surcharge and self weight components of bearing capacity. It is apparent from eq. 42 that this neglects the term $\gamma_w(D-d)$ and therefore underestimates the bearing capacity.

For the special case of a cohesionless soil, eq. 42 can re-written as follows:

$$[43] \quad q_f = \frac{1}{2}B(\gamma - \gamma_w)N_\gamma + [\gamma D - \gamma_w(D-d)]N_q + \gamma_w(D-d)$$

Eq. 43 is similar to eq. 4 proposed by Meyerhof (1955) for the bearing capacity of a cohesionless soil with a static water table above foundation level.

CONCLUSIONS

A bearing capacity factor, N_w, has been proposed for the evaluation of bearing capacity arising from changes in the position of the static water table below foundation level. The value of N_w depends on the ratio of the depth of the water table to the width of the footing and on the angle of shearing resistance of the soil. For the case of a static water table above foundation level, a solutions is proposed which combines the effects of uniform and hydrostatic pore water pressures on bearing capacity. The solutions can be used to quantify the reduction in bearing capacity arising from a static water table at any depth in any kind of soil.

ACKNOWLEDGMENTS

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APPENDIX I. REFERENCES

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APPENDIX II. NOTATION

The following symbols are used in this paper:

c = cohesion of the soil;

c' = effective cohesion of the soil;

p_p = passive pressure at depth, z;

q_f = bearing capacity;

q_1 = bearing capacity component due to surcharge weight of water above foundation level;

q_2 = bearing capacity component due to uniform pore-water pressure below foundation level;

q_3 = bearing capacity component due to hydrostatic pore-water pressure below foundation level;

u_w = pore water pressure;

B = width of the foundation;

F = weighting factor which varies between zero and one;

K_p = Rankine passive pressure coefficient;

P_o = surcharge pressure due to soil above foundation level;

N_c = bearing capacity factor with respect to cohesion;

N_q = bearing capacity factor with respect to surcharge;

N_u = bearing capacity factor due to uniform pore-water pressure;

N_w = bearing capacity factor due to hydrostatic pre-water pressure;

N_γ = bearing capacity factor with respect to self weight of the soil;

P_o = surcharge pressure;

γ = unit weight of the soil;

γ' = submerged unit weight;

ϕ = friction angle of the soil;

Table 1. Variation of the bearing capacity factor, N_u, with the angle of shearing resistance of the soil.

Angle of friction ϕ (deg.)	Angle, α (deg.) for minimum N_u	Bearing capacity factor N_u
5	47.4	0.57
10	49.9	1.46
15	52.5	2.88
20	55.0	5.20
25	57.5	9.11
30	60.1	15.99
35	62.55	28.82

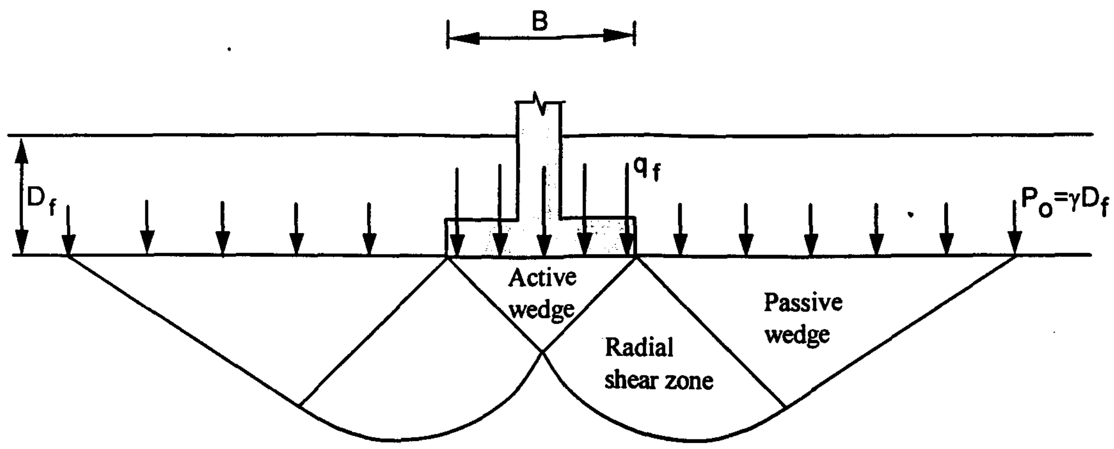


Fig. 1. Terzaghi's general shear failure mechanism.

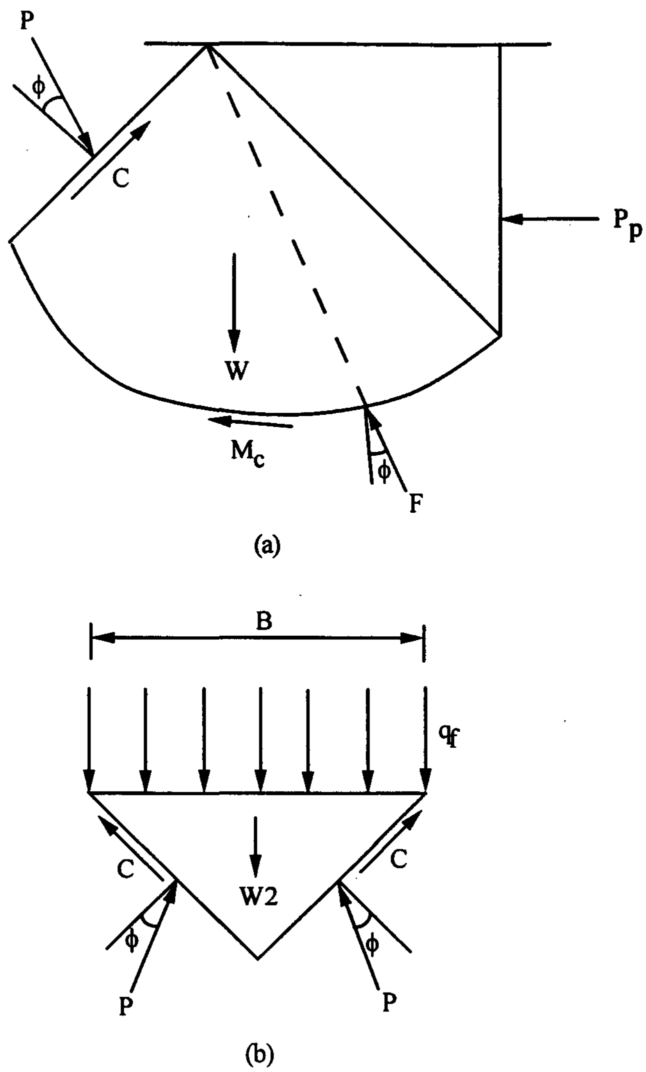


Fig. 2. Forces acting on the (a) passive wedge and radial shear zone (b) active wedge

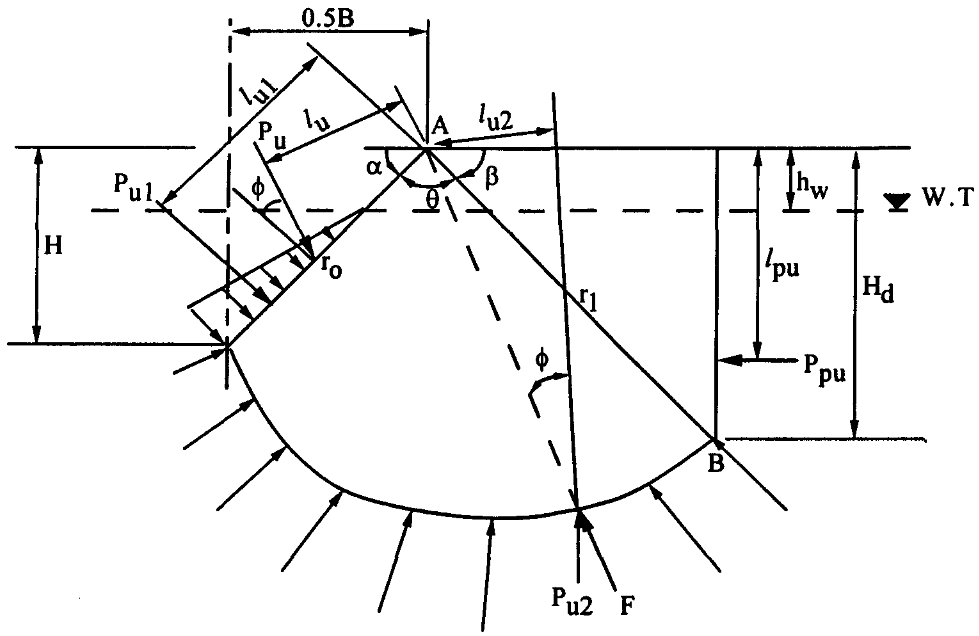
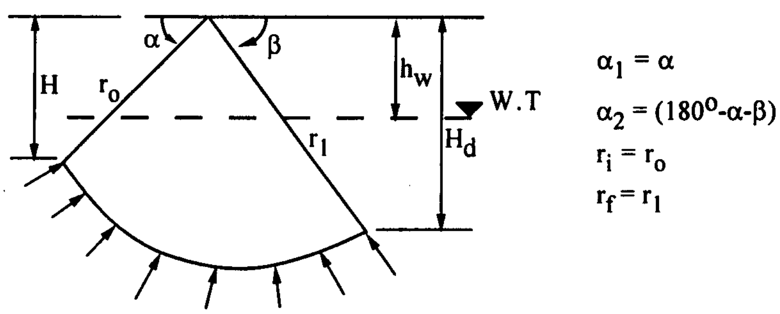
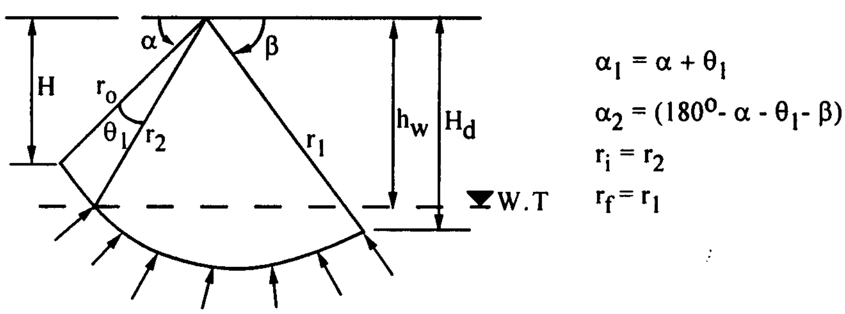


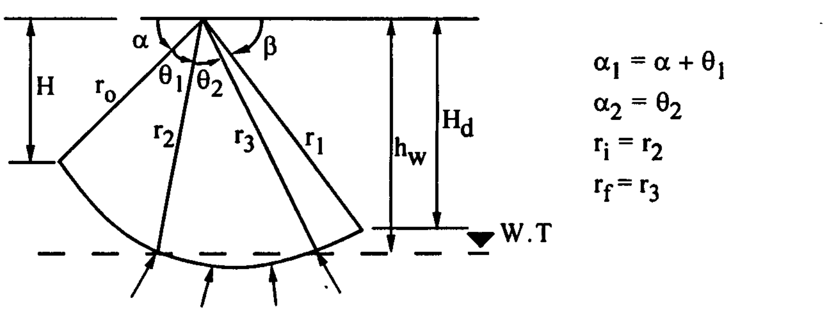
Fig. 3. Forces on the passive wedge and radial shear zone and their lever arms about the centre of the log spiral



(a) $h_w < H$



(b) $h_w > H$ and $h_w < H_d$



(c) $h_w > H$ and $h_w > H_d$

Fig. 4. Possible distribution patterns of pore water pressure along the length of the log spiral

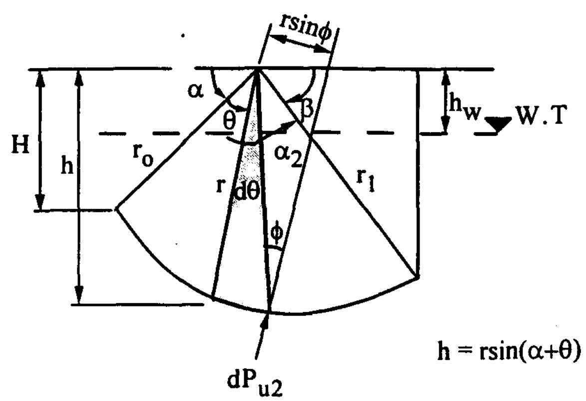


Fig. 5. Calculation of moment due to water forces along the length of the log spiral

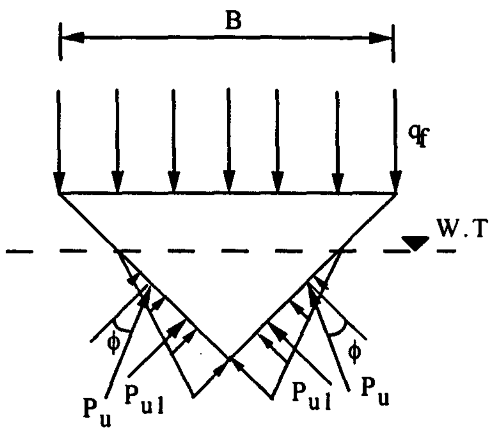


Fig. 6. Forces acting on the active wedge.

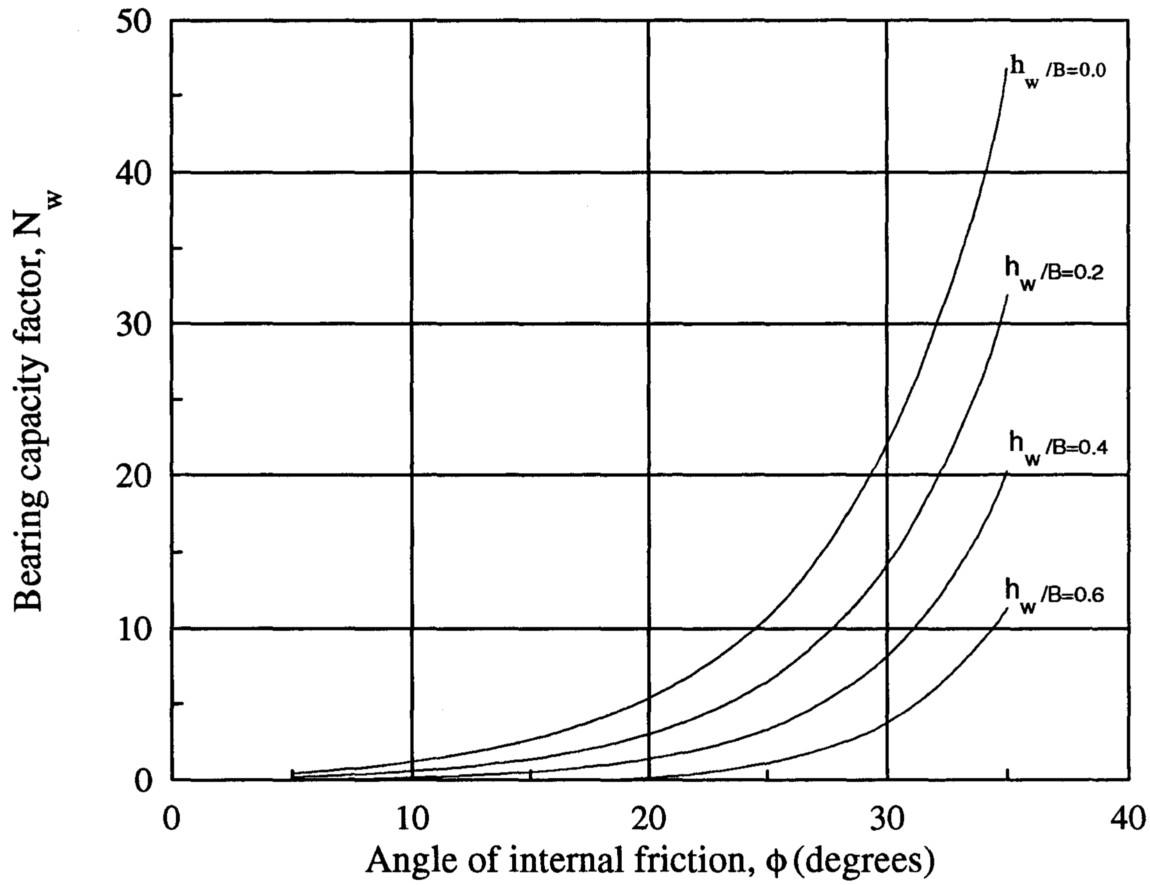


Fig. 7. Variation of the bearing capacity factor, N_w, with angle of friction and depth of the water table.

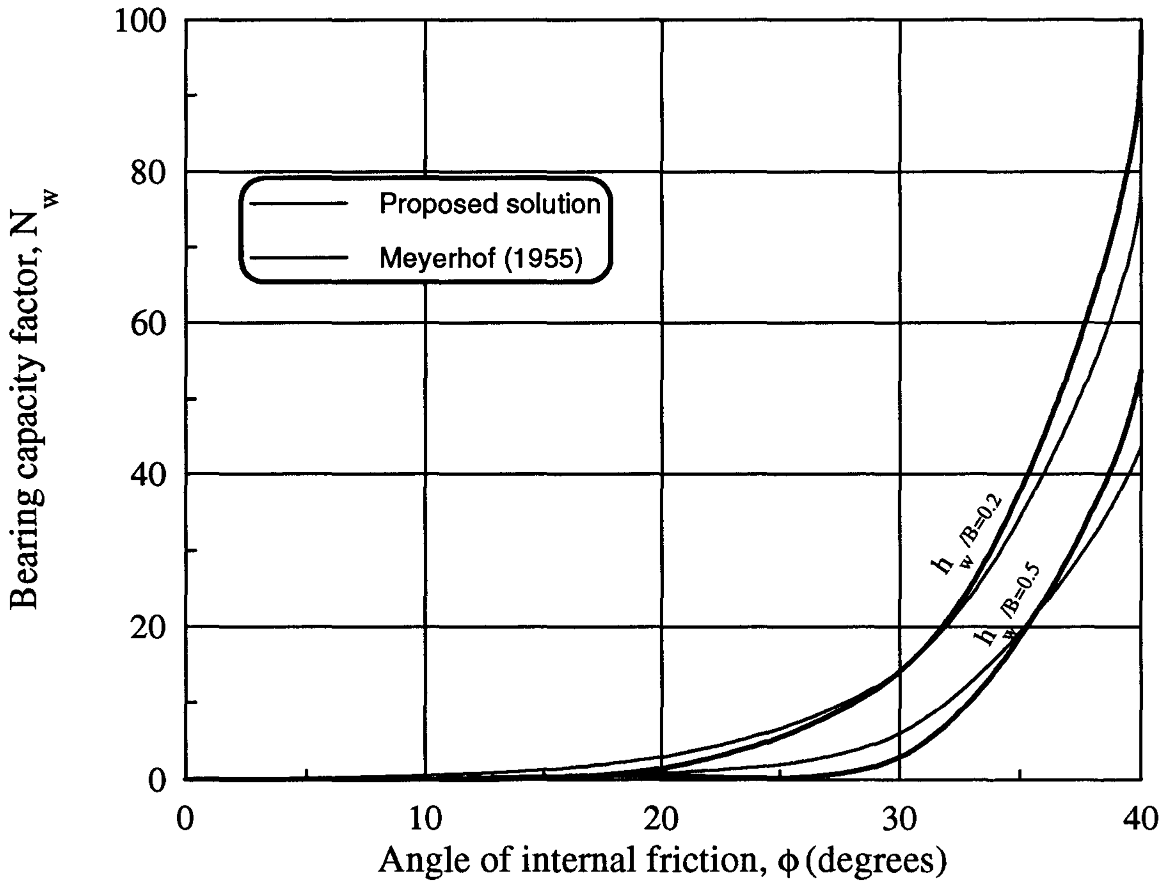


Fig. 8. Comparison between proposed solution for N_w and the solution by Meyerhof (1955).

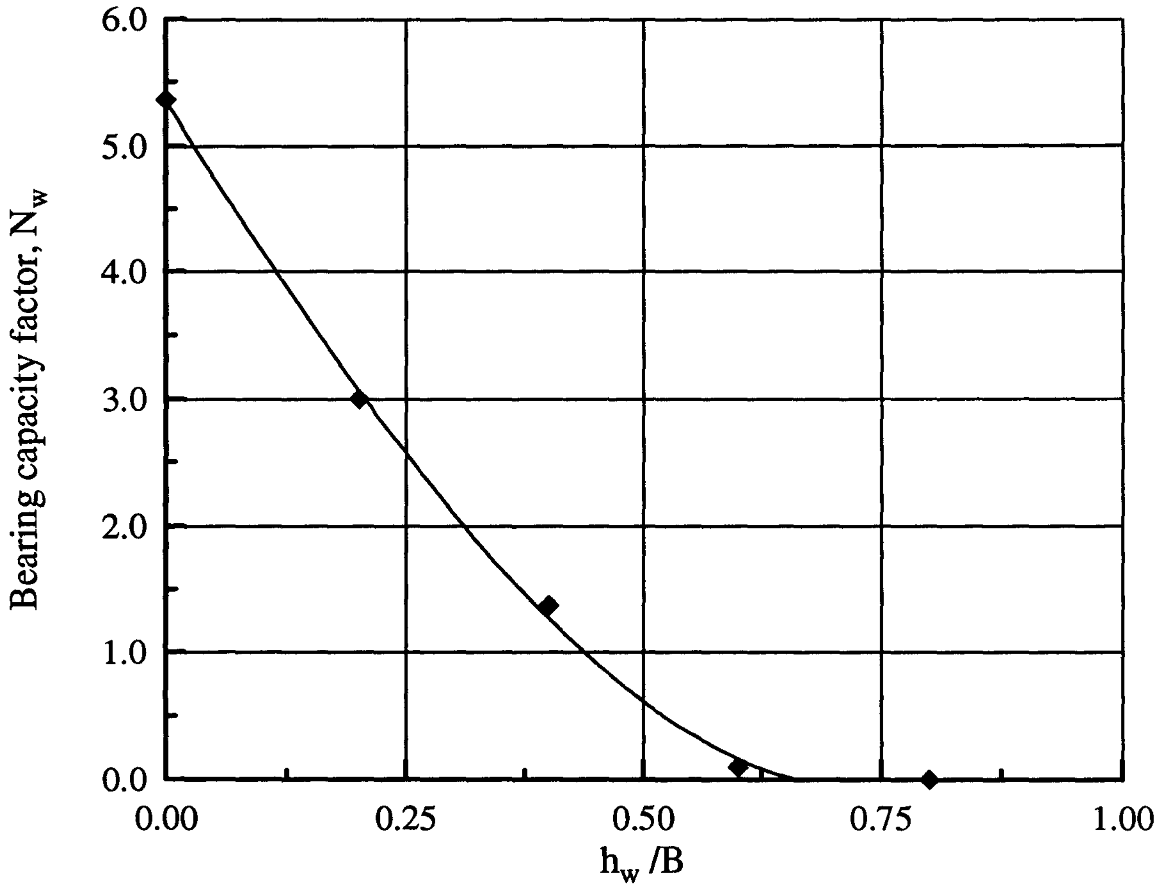


Fig. 9. Variation of the bearing capacity factor, N_w with depth of the water table for a soil with $\phi = 20°$.

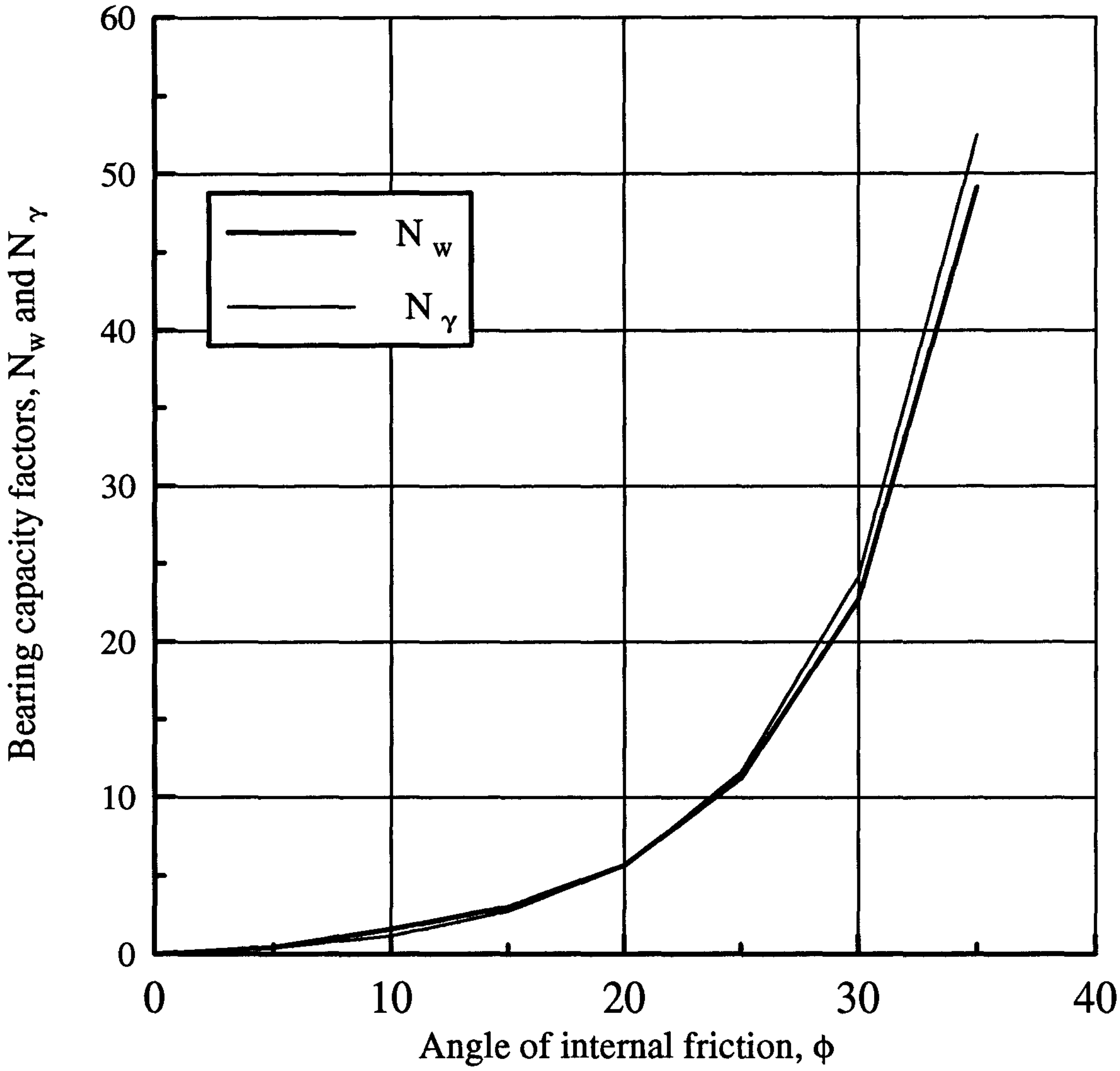


Fig. 10. Comparison between the bearing capacity factors N_γ and N_w.

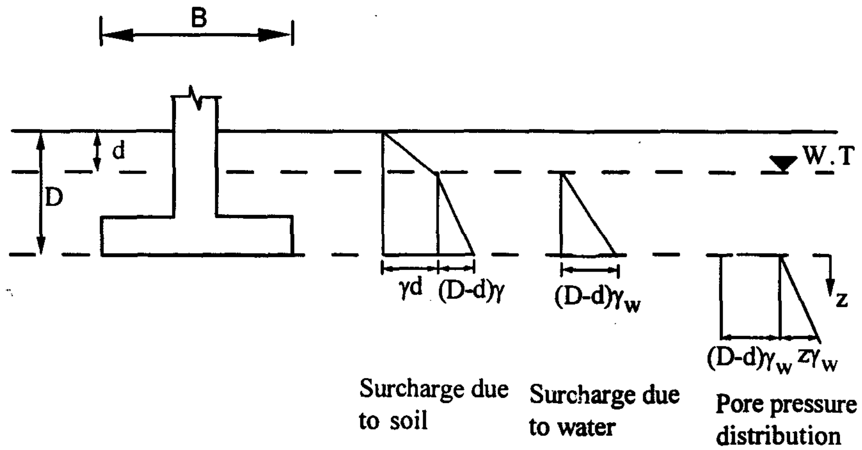


Fig. 11. Consideration of water table above foundation level

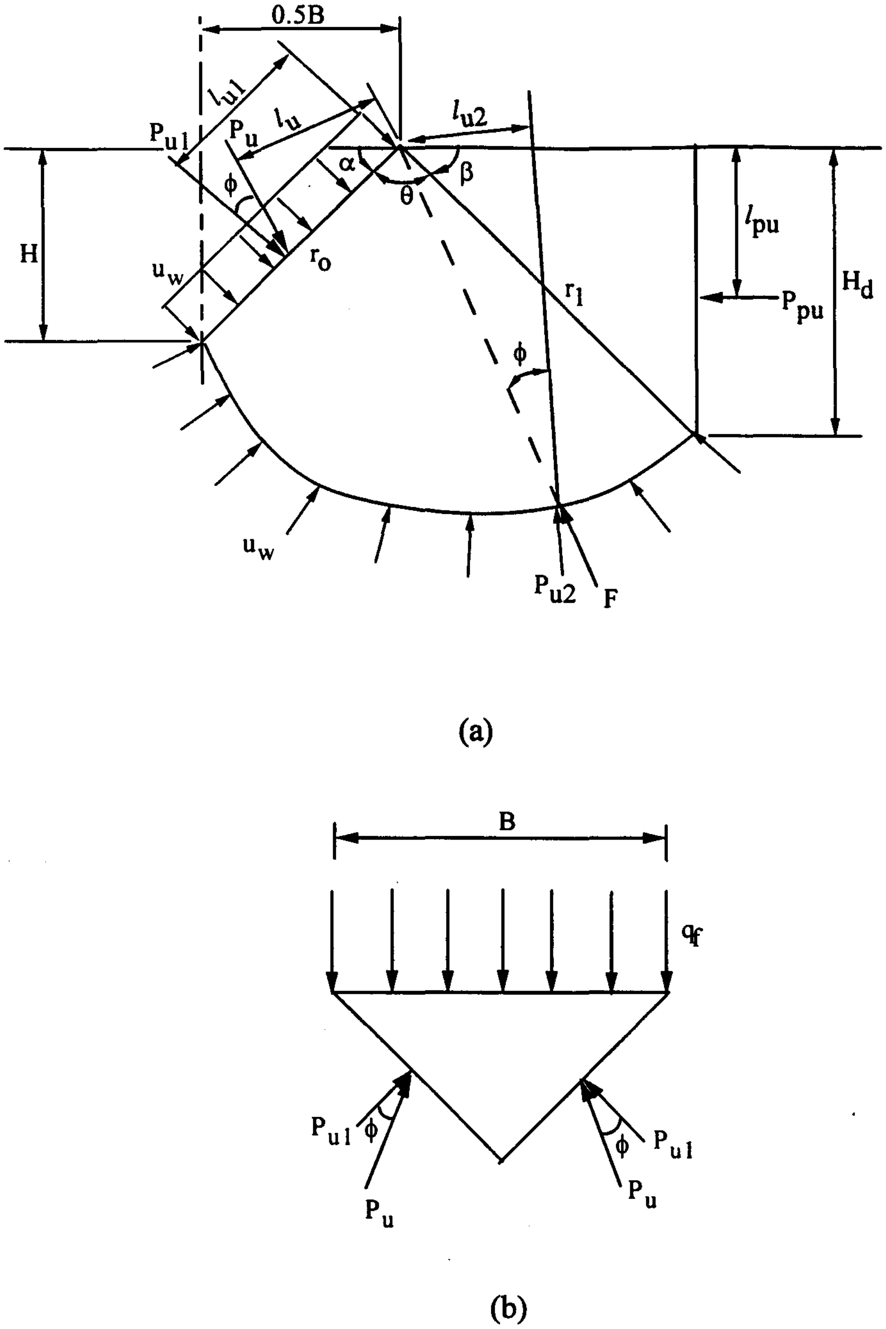


Fig. 12. Forces acting on the (a) passive wedge and radial shear zone (b) active wedge.

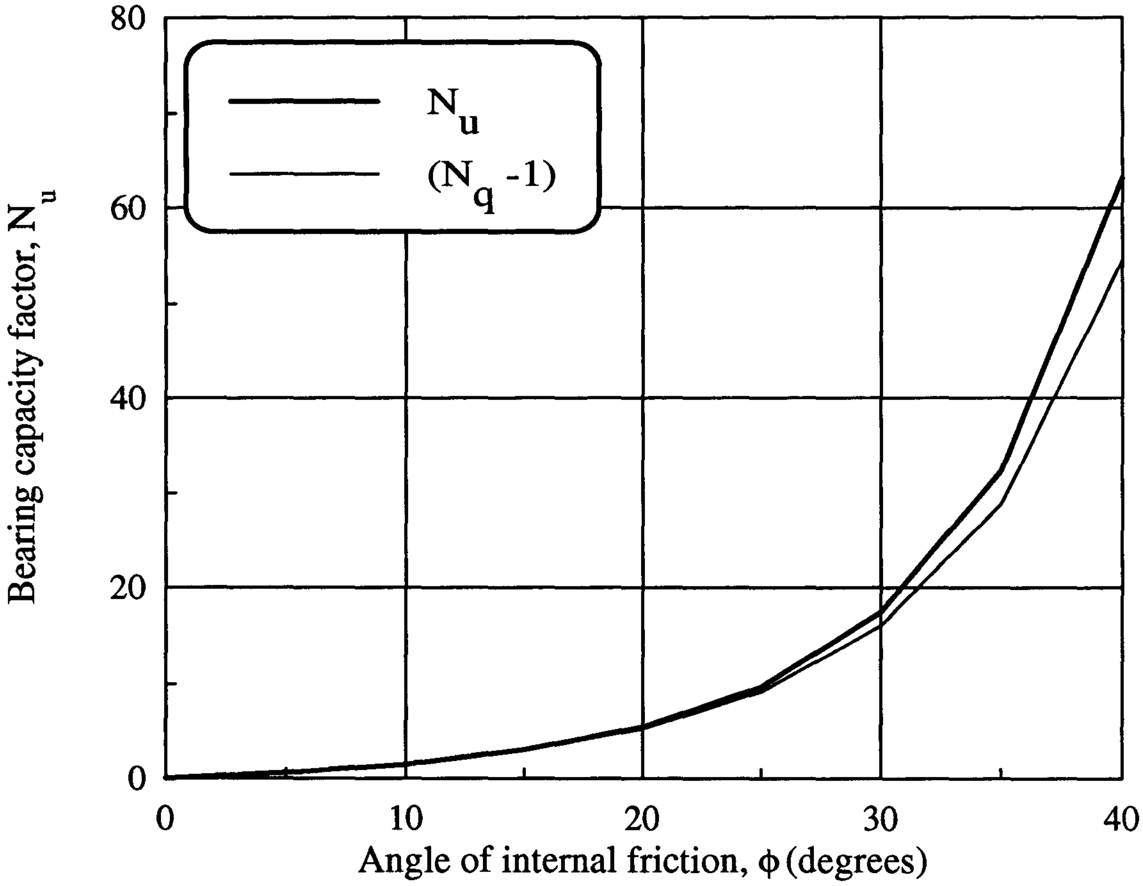


Fig. 13. Comparison between the bearing capacity factors, N_u and (N_q-1).