A Comparative Study on the Effect of Water Table on Bearing Capacity of Shallow Foundations in Soils

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Abstract - *Shallow foundations are vastly common around the world. It thus becomes very important to analyze the parameters as accurately as possible while designing such footings. Detailed and extensive subsurface exploration is sought and required. One of those parameters is bearing capacity of soil. Bearing capacity is affected by various factors like application of eccentric loads and inclined loads, dimensions of footing, relative density of soil and unit weight of soil. Various theories have been proposed and various studies have been done by scientists time and again to quantitatively analyze the bearing capacity of foundations especially when there are changes in water table depth. This article attempts to present some of those theories/studies and the methodologies adopted and suggested. Results from these theories have been compared in the end using numerical procedures on a rectangular footing. It is hoped that this study shall help civil engineers in their design calculations and also help in possible future studies.*

Key Words: bearing capacity, shallow foundation, water table, submergence

1. INTRODUCTION

Soil is the most important material which is in use for construction of civil engineering structures. During the design of shallow foundations, many considerations are taken into account Amongst all the parameters, the bearing capacity of soil to support the load coming over its unit area occupies prime importance. Principal factors that influence ultimate bearing capacities are type of soil, width of foundation, soil weight in 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. Due to increase in population and industrialization, there is increase in construction activities in the cities and industrial area. Hence, it has become necessary to carry out construction activities on marshy land, low lying area, expansive black cotton soil having swelling and shrinkage characteristics, water logged areas etc. Safe bearing capacity values are assumed depending upon type of soil encountered at proposed depth of foundation. The designers try to ensure sufficient safety factor against bearing capacity failure and also to limit the settlement within a tolerable value. However, the change in moisture content of the soil affects the properties. The natural flow of groundwater is altered by human activities either deliberately by pumping water from wells or by diverting watercourses or inadvertently by land use change. Water table fluctuations due to seasonal changes or due to human activities have considerable effects on both the bearing capacity and the settlement of soil. Many analytical and numerical methods can be used to estimate the vertical bearing capacity of a rigid strip footing. These methods are classified into the following four categories:

1. The Limit Equilibrium method. It is a traditional method used to obtain approximate solutions for stability problems in soil mechanics.
2. The Method of Characteristics, commonly referred to as the slip-line method.
3. The Static and Kinematic Limit Analysis method, which includes upper bound and lower bound theorems.
4. Numerical methods that are based on either the finite-element or the finite-differences approaches.

Many theories have been proposed and many studies done to account for water table fluctuations in bearing capacity calculations. Some of these theories have been discussed below.

2. TERZAGHI'S THEORY

Terzaghi (1943) was the first to propose a bearing capacity equation on the consideration of general shear failure in the soil below a rough strip footing. Using the principle of superposition, he demonstrated the effects of soil cohesion, its angle of internal friction, surcharge (soil lying above the level of footing base), soil unit and foundation width on the ultimate bearing pressure. Based on that theory following equation was put forth:

$$q_u = qN_q + c'\,N_c + 1/2\,B\gamma\,N_\gamma \qquad (1)$$

Where q_u is the ultimate bearing capacity, q is the uniformly distributed surcharge replacing the overburden soil at the footing base, c' is the cohesion intercept of the soil shear strength, B is the foundation width, γ is the soil unit weight, N_q, N_c and N_γ are the bearing capacity factors depending on the soil shearing resistance angle, ϕ. The value of this angle depends on whether it is general shear failure or local failure. Equation (1) is valid for strip footings resting on a homogenous and dry soil that is subjected to a central vertical load and involves a symmetrical failure pattern. To account for the influence of submergence of soil below the footing, Terzaghi proposed that the last term in eq. (1) be reduced suitably according to the water table position. Specifically, if there are no seepage forces and the water table is just at the level of footing base, the submerged unit weight of the saturated soil is used to calculate the bearing capacity with no change in the N_γ value. Moreover, when the water level is at a depth equal to or greater than the foundation width, it is assumed that groundwater does not affect bearing capacity and therefore its presence may be ignored. For an intermediate depth, the N_γ factor is the same as used for dry soil, but the unit weight of the supporting soil is evaluated using the following equation (Vesic 1973):

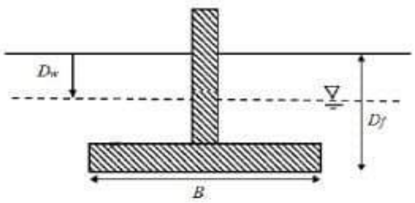
$$\gamma_e = \gamma' + \frac{b}{B}(\gamma - \gamma') \qquad (2)$$

where γ' is the submerged unit weight of the soil, γ is the unit weight of the soil above the water table, b is the depth of water table below the footing base. As for water table located above the base of the footing, the effective surcharge is reduced as the effective weight below the water table is equal to the submerged unit weight. Following equation was proposed for that:

$$q = D_w \gamma + a\gamma' \qquad (3)$$

where D_w is depth of water table below the ground surface, a is the height of water table above the base of footing. Also, we have,

$$a = D_f - D_w \qquad (4)$$



where D_f is the depth of foundation. This gives us

$$q = \gamma' D_f + (\gamma - \gamma') D_w \qquad (5)$$

This value is put in the original equation and value of the ultimate bearing capacity is calculated. Terzaghi's theory has prompted researchers to study this effect in more detail and provide more comprehensive theories and equations.

3. S KRISHNAMURTHY AND KAMESWERA RAO'S STUDY

S Krishnamurthy and Kameswara Rao in 1975 analyzed the effect of submergence of the soil below the foundation on the bearing capacity using the method of characteristics. The analysis was conducted for various depths of submergence of soil and for different values of angle of friction. It was assumed that the parameters c' and ϕ' don't change due to submergence especially in the case of granular soils. Unlike Terzaghi, it was proposed that there is a considerable change in the value of unit weight and that affects the contribution of N_γ factor term in the bearing capacity equation. The analysis was done on a strip footing in soil where the ground water level rises up to depth 'b' below the base of the footing of width 'B'. An exact evaluation of the changes in the bearing capacity of the soil was made for various depths of ground water below the base of the footing using the method of characteristics. For a strip footing it reduced to a two-dimensional problem which could be solved by combining the equilibrium equations and the Mohr-Coulomb failure criterion for the given soil. The solution involved the determination of stresses σ_x, σ_z and τ_{xz} and the location of the slip lines. The different values of unit weight, γ_t (same as γ) and γ'in the respective zones were used while solving for stresses and slip lines, to study the effect of submergence on the bearing capacity. The effect of submergence on the contribution of N_γ term to the bearing capacity was incorporated as a modified value of N_γ factor depending upon angle of internal friction (ϕ), ratio of depth of water table below the base of footing to the width of foundation (b/B) and the value of γ as shown below in graphs.

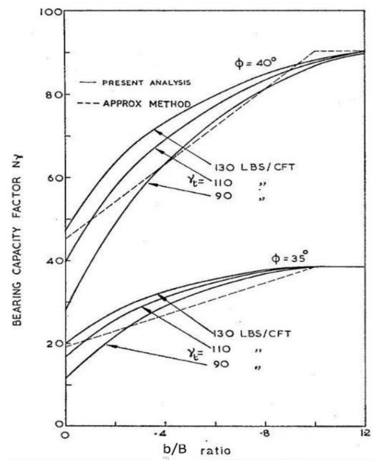


Fig -1: Variation of N_γ with ϕ= 15°, 20°, 25°and 30°

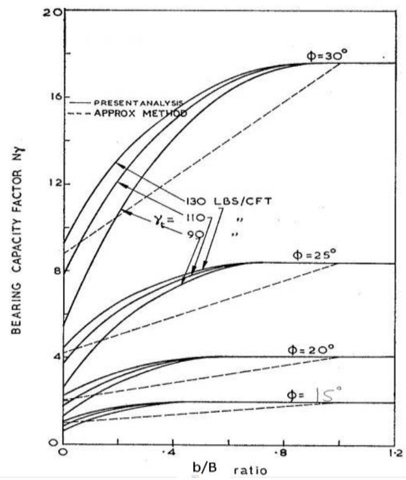


Fig -2: Variation of N_γ with ϕ= 35° and 40°

It was concluded that the approximate method of reducing the contribution of N_γ term by 50% in the case of full submergence and linear interpolation for partial submergence leads to errors depending on the magnitude of unit weight of the soil and b/B ratio. The N_γ term evaluated by approximate method is found to be lower than modified value from exact analysis, especially for higher unit weights of soil, when b/B are nearer to 0.3. The respective deviations can be as high as 35% and 15% for values of ϕ around 35° to 40°. In case of granular soils where the value of ϕ ranges from 30° to 40°, exact analysis gives a more realistic value of bearing capacity. The full value of N_γ is reached beyond b/B=1.2 for ϕ=40° and b/B=0.4 for ϕ=15°. For any level of submergence of the soil below the footing, the modified values of N_γ have to be multiplied by γ.b/2 to obtain the contribution of the soil weight to the bearing capacity. Also, it was concluded that the limiting depth beyond which the ground water table below the base of the foundation has no effect on the bearing capacity, increases as the angle of friction of soil increases.

3. ERNESTO AUSILIO AND ENRICO CONTE'S STUDY

Ausilio and Conte described an approach to account for the influence of groundwater in the kinematic theorem of limit analysis. The limit analysis uses the static and kinematic theorems of plasticity theory to find a range in which the true solution of the problem lies. The range is narrowed by finding the highest possible lower-bound solution and the lowest possible upper-bound solution. It involved analysis of bearing capacity of strip footings resting on a soil where the water table is at some depth below the footing base. Using the kinematic theorem, the work rate done by the buoyancy and seepage forces was calculated and added to that done by external forces. These contributions were determined by using the equilibrium equation of the forces acting on the water mass of the same volume as the submerged soil involved in a failure mechanism. It was shown that the seepage force is the sum of the weight of the water volume considered, and the resultant of the boundary water pressures. In solving this stability problem body forces acting on the soil mass are the total weight of the soil and the resultant of the boundary water forces during seepage force. Equating the rate at which work is done by the external forces to the total energy dissipation rate and after some rearrangements, the following equation was obtained.

$$q_u = qN_q + c' N_c + 1/2\, B\gamma N_\gamma^* \tag{6}$$

The contribution of surcharge applied to the level of the footing base, qN_q, and that owing to the cohesion acting along the failure surfaces, $c' N_c$, are the same as proposed by Terzaghi. Again, as Krishnamurthy and Rao reported, there is a change in the value of N_γ and the modified value, N_γ^* is a function of $\frac{b}{B}$ and γ'/γ as well as α, η and ϕ where α and η are two angles geometrically defining the mechanism of loading in the soil and ϕ is soil shearing resistance angle. Following equation gives that modified value of N_γ.

$$N_\gamma^* = (\gamma'/\gamma)N_\gamma + \frac{b}{B}(1 - \gamma'/\gamma)\, N\gamma w \tag{7}$$

where N_γ is the bearing capacity factor for foundations on dry soils and Nγw is an additional factor. The expression for this additional factor was derived using the kinematic theorem of limit analysis for water table positions varying from the footing base to the depth of the failure zone. As can be noted from eq. (7), when the soil is dry or when the water table rises to the level of the footing base, N_γ^* coincides with N_γ. The upper bound for N_γ^* can be found by minimizing it with respect to the geometric parameters α and η, given ϕ, $\frac{b}{B}$ and γ'/γ. For cohesionless soils, Ausilio proposed the following table.

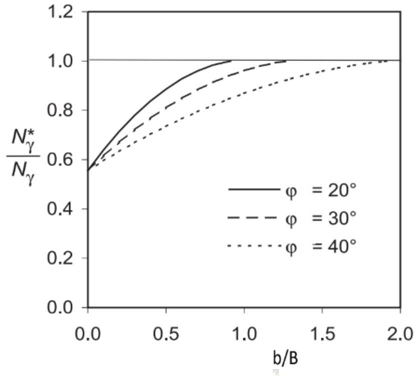


Fig -3: N_γ^*/N_γ against $\frac{b}{B}$ for different values of ϕ

N_γ^*/N_γ represents the ratio of the bearing capacity of the footing resting on a submerged soil where the water table is at depth b, to the bearing capacity of the same foundation when the soil is supposed to be with unit weight,γ. Because of soil submergence, the bearing capacity is significantly reduced and the effect is more pronounced when the value of ϕ is high. The results also showed that the depth beyond which the groundwater has no effect on the bearing capacity is less than the foundation width for ϕ =20° and is about twice the foundation width when ϕ =40°.

4. IS CODE METHOD

IS: 6403-1981 gives the equation for the net ultimate bearing capacity as follows:

$$q_u = c' N_c\, s_c d_c i_c + q(N_q - 1)\, s_q d_q i_q + 0.5\, B\gamma N_\gamma s_\gamma d_\gamma i_\gamma W' \tag{8}$$

where q = effective pressure at base
s_c, s_q and s_γ are shape factors
d_c, d_q and d_γ are depth factors and
i_c, i_q and i_γ are inclination factors.
The effect of water table is considered in the factor W'. If the water table is at or below a depth of $(D_f + B)$, measured from

the ground surface, W' = 1.0. If the water table is likely to rise to the base of the footing or above, the value of W' is taken as 0.5. If the water table is located at a depth D below the ground surface, such that $D_f < D < D_f + B$, the value of W' is obtained by linear interpolation. Also, if the water table is below the ground, say at a distance D_1 and the depth above the footing is D_2, then the effect of surcharge is calculated as follows.

$$q = \gamma D_1 + \gamma' D_2 \quad (9)$$

For depths below the footing, the unit weight of the soil, γ, is used in calculations. Value of unit weight used in the calculation of the last term in equation (8) depends upon the depth of water table. If the water table is above the footing, γ' is used. If the water table is below the footing, the average unit weight is calculated since the soil below the footing is partly above the water table and partly below the water table.

5. NUMERICAL ANALYSIS AND COMPARISON

Numerical studies were performed on a rectangular footing 3m×6m resting on a homogenous cohesionless soil whose unit weight (γ) is 14.13 kN/m³ and submerged unit weight (γ') is 7.77 kN/m³. The angle of internal friction of the soil was taken as 40°. The depth of the foundation (D_f) was taken as 1m and the unit weight of water was taken as 10 kN/m³. Depth of water table was changed and the corresponding values of the bearing capacity were calculated by the four mentioned methods. These values have been calculated by using the modified value of N_γ in the equation (1) depending upon the value of $\frac{b}{B}$. For depths of water table less than 1m, Terzaghi's equations have been followed in Krishnamurthy's and Rao's method and Ausilio and Conte's methods, as no modifications have been suggested by the authors. Ausilio and Conte suggested the use of equation (2) and (5) for the calculation of unit weight when the depth of water table below the ground changes. For IS Code Method, equation (8) and (9) has been used. The results obtained for different depths of water table along with the calculations are given as follows.

Water table at ground level

By Tarzagi's method

$q_u = qN_q + \frac{1}{2}B\gamma' N_\gamma(1 - 0.2\frac{B}{L})$

$q_u = \gamma' D_f N_q + \frac{1}{2}B\gamma' N_\gamma(1 - 0.2\frac{B}{L})$

q_u = 7.77*1*81.3 + 0.5*3*7.77*100.4*(1 – 0.1)

q_u = 7.77*1*81.3 + 0.5*3*7.77*100.4*0.9

q_u = 1684.85 kN/m²

By Krishnamurthy and Rao's method

q_u = 1684.85 kN/m²

By Ausilio and Conte's method

q_u = 1684.85 kN/m²

By IS Code method

$q_u = q(N_q - 1)\, s_q d_q i_q + 0.5\, B\, \gamma' N_\gamma s_\gamma\, d_\gamma i_\gamma W'$

$q_u = (\gamma D_1 + \gamma' D_2)\, D_f\, (N_q - 1)\, s_q d_q i_q + 0.5\, B\, \gamma' N_\gamma s_\gamma\, d_\gamma i_\gamma W'$

q_u =(0 + 7.77*1)(64.1-1)*1.1*1.07*1
+0.5*3*7.77*109.4*0.8*1*1*0.5

q_u = 1087.09 kN/m²

Water table at 0.5m below the ground

By Tarzeghi's method

$q_u = qN_q + \frac{1}{2}B\gamma' N_\gamma(1 - 0.2\frac{B}{L})$

$q_u = \{\gamma' D_f + (\gamma - \gamma') D_w\} N_q + \frac{1}{2}B\gamma' N_\gamma(1 - 0.2\frac{B}{L})$

q_u={7.77*1 + (14.13-7.77)*0.5} * 81.3 + $\frac{1}{2}$*7.77*3*100.4*(1-0.1)

q_u={7.77*1 + (14.13-7.77)*0.5} * 81.3 + $\frac{1}{2}$*7.77*3*100.4*0.9

q_u =1943.38 kN/m²

By Krishnamurthy and Rao's method

q_u =1943.38 kN/m²

By Ausilio and Conte's method

q_u =1943.38 kN/m²

By IS Code method

$q_u = q(N_q - 1)\, s_q d_q i_q + 0.5\, B\, \gamma' N_\gamma s_\gamma\, d_\gamma i_\gamma W'$

$q_u = (\gamma D_1 + \gamma' D_2)\, D_f\, (N_q - 1)\, s_q d_q i_q + 0.5\, B\, \gamma' N_\gamma s_\gamma\, d_\gamma i_\gamma W'$

q_u =(14.13*0.5 + 7.77*0.5)(64.1-1)*1.1*1.07*1
+0.5*3*7.77*109.4*0.8*1*1*0.5

q_u = 1323.27 kN/m²

Water table at 1m below the ground

By Tarzeghi's method

$q_u = qN_q + \frac{1}{2}B\gamma' N_\gamma(1 - 0.2\frac{B}{L})$

$q_u = \{\gamma' D_f + (\gamma - \gamma') D_w\} N_q + \frac{1}{2}B\gamma' N_\gamma(1 - 0.2\frac{B}{L})$

q_u={7.77*1 + (14.13-7.77)*1} * 81.3 + $\frac{1}{2}$*7.77*3*100.4*(1-0.1)

q_u = 2201.92 kN/m²

By Krishnamurthy and Rao's method

q_u = 2201.92 kN/m²

By Ausilio and Conte's method

q_u = 2201.92 kN/m²

By IS Code method

$q_u = q(N_q - 1)\, s_q d_q i_q + 0.5\, B\, \gamma' N_\gamma s_\gamma\, d_\gamma i_\gamma W'$

$q_u = (\gamma D_1 + \gamma' D_2)\, D_f\, (N_q - 1)\, s_q d_q i_q + 0.5\, B\, \gamma' N_\gamma s_\gamma\, d_\gamma i_\gamma W'$

$q_u = (14.13*1 + 0)(64.1-1)*1.1*1.07*1 + 0.5*3*7.77*109.4*0.8*1*1*0.5$

q_u = 1559.44 kN/m²

Water table at 2m below the ground

By Tarzeghi's method

$q_u = qN_q + \frac{1}{2}B\gamma' N_\gamma(1 - 0.2\frac{B}{L})$

$q_u = \gamma D_f\, N_q + \frac{1}{2}B(\gamma' + \frac{b}{B}\,(\gamma - \gamma'))\, N_\gamma(1 - 0.2\frac{B}{L})$

q_u = 14.13*1*81.3 + 0.5*3{ 7.77 + $\frac{1}{3}$(14.13-7.77)}*100.4*0.9

q_u = 2489.26 kN/m²

By Krishnamurthy and Rao's method

$q_u = qN_q + \frac{1}{2}B\gamma' N_\gamma(1 - 0.2\frac{B}{L})$

$q_u = \gamma D_f\, N_q + \frac{1}{2}B(\gamma' + \frac{b}{B}\,(\gamma - \gamma'))\, N_\gamma(1 - 0.2\frac{B}{L})$

q_u = 14.13*1*81.3 + 0.5*3{ 7.77 + $\frac{1}{3}$(14.13-7.77)}*57.57*0.9

q_u = 1917.41 kN/m²

By Ausilio and Conte's method

$q_u = \gamma D_f\, N_q + 1/2\, B\gamma\, N_\gamma^*$

q_u = 14.13*1*81.3 + 0.5*3*14.13*27.61

q_u = 1733.96 kN/m²

By IS Code method

$q_u = q(N_q - 1)\, s_q d_q i_q + 0.5\, B\, \gamma_{avg} N_\gamma s_\gamma\, d_\gamma i_\gamma W'$

$q_u = \gamma D_f\, (N_q - 1)\, s_q d_q i_q + 0.5\, B\, \gamma_{avg} N_\gamma s_\gamma\, d_\gamma i_\gamma W'$

q_u = 14.13*1(64.1-1)*1.1*1.07*1 +0.5*3*10.89*109.4*0.8*1*1*0.67

q_u = 2007.27 kN/m²

Water table at 4m(=D_f + B) below the ground

By Tarzeghi's method

$q_u = qN_q + \frac{1}{2}B\gamma' N_\gamma(1 - 0.2\frac{B}{L})$

$q_u = \gamma D_f\, N_q + \frac{1}{2}B(\gamma' + \frac{b}{B}\,(\gamma - \gamma'))\, N_\gamma(1 - 0.2\frac{B}{L})$

q_u = 14.13*1*81.3 + 0.5*3{ 7.77 + $\frac{3}{3}$(14.13-7.77)}*100.4*0.9

q_u = 3063.95 kN/m²

By Krishnamurthy and Rao's method

$q_u = qN_q + \frac{1}{2}B\gamma' N_\gamma(1 - 0.2\frac{B}{L})$

$q_u = \gamma D_f\, N_q + \frac{1}{2}B(\gamma' + \frac{b}{B}\,(\gamma - \gamma'))\, N_\gamma(1 - 0.2\frac{B}{L})$

q_u = 14.13*1*81.3 + 0.5*3{ 7.77 + $\frac{3}{3}$(14.13-7.77)}*88.11*0.9

q_u = 2829.51 kN/m²

By Ausilio and Conte's method

$q_u = \gamma D_f\, N_q + 1/2\, B\gamma\, N_\gamma^*$

q_u = 14.13*1*81.3 + 0.5*3*14.13*87.85

q_u = 3010.75 kN/m²

By IS Code method

$q_u = q(N_q - 1)\, s_q d_q i_q + 0.5\, B\gamma\, N_\gamma s_\gamma\, d_\gamma i_\gamma W'$

$q_u = \gamma D_f\, (N_q - 1)\, s_q d_q i_q + 0.5\, B\, \gamma N_\gamma s_\gamma\, d_\gamma i_\gamma W'$

q_u = 14.13*1(64.1-1)*1.1*1.07*1 +0.5*3*14.13*109.4*0.8*1*1*1

q_u = 2904.40 kN/m²

Water table at great depth below the footing

In this case, all the values are the same as calculated for depth 4m below the ground.

By Tarzeghi's method

q_u = 3063.95 kN/m²

By Krishnamurthy and Rao's method

q_u = 2829.51 kN/m²

By Ausilio and Conte's method

q_u = 3010.75 kN/m²

By IS Code method

q_u = 2904.40 kN/m²

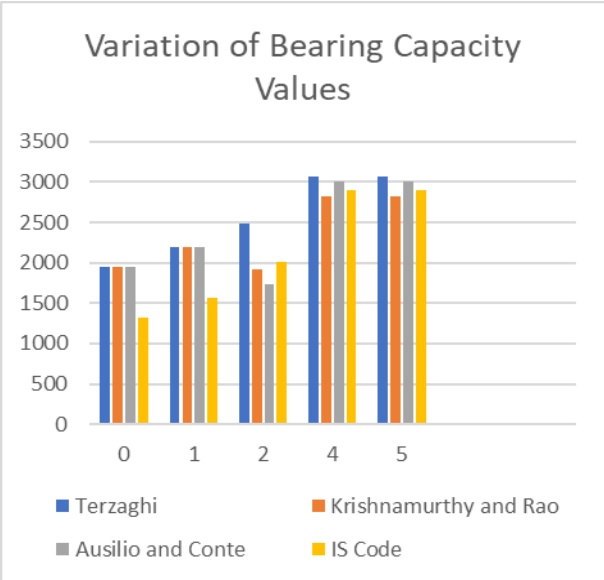


Chart -1: Variation of values of Bearing Capacity

As can be clearly seen, the value of the bearing capacity increases with the increase of the depth of water table below the ground. However, after the depth of water table below the ground surface exceeds (D_f+ B), the values don't change and remain equal to values obtained for depth equal to (D_f+ B). This is agreed upon by all the researchers. All the methods give results that are almost same except for IS Code method which gives less values initially. Later on, the values are almost the same.

6. CONCLUSIONS

Based on the theories presented and studies done by the researchers, following important conclusions can be made.

1. The bearing capacity of foundations decreases with submergence of soil.
2. IS Code method gives the smallest values for lower depths and thus is safest of the 4 methods.
3. As depth of foundation increases, ultimate bearing capacity of soils increases. This is due to increase in surcharge weight.
4. The decrease in the bearing capacity depends on the depth of water table below the ground. If the depth of the water table is equal to or more than the depth of foundation plus the foundation width, the effect is negligible.
5. The limiting depth beyond which the ground water table below the base of the foundation has no effect on the bearing capacity increases as the angle of friction increases.
6. The value of limiting depth coincides with the depth of the failure zone occurring when the soil is dry.
7. All the four methods give values that are in close vicinity of each other.

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