Visakhapatnam Chapter

Proceedings of Indian Geotechnical Conference 2020
December 17-19, 2020, Andhra University, Visakhapatnam

Re-evaluation of Failure of Silo Tower Foundations

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Abstract. Silos were constructed in the early 1970s in most parts of Canada on soft deposits by farmers with no or little technical assistance. The majority of these silos constructed on weak compressible deposits have overturned/tilted, and some even collapsed due to inadequate or insufficient bearing capacity and/or differential settlement and tilting. Bozozuk (1972 & 1974) documented some of these failures and analysed the same based on the available theory of bearing capacity of foundations on homogeneous ground. The current study reassess two cases based on current and recent theories of bearing capacity of foundations on normally consolidated ground (strength increasing with depth, Davis and Booker 1972) with desiccated layer over it. A simple theory for bearing capacity of foundations on desiccated layer overlying a normally consolidated soil with undrained strength increasing linearly with depth is developed as an extension of Meyerhof's theory for two-layered soil. The stability of the silos is reassessed based on the proposed approach.

Keywords: Silos; Bearing Capacity; Normally consolidated clays; Desiccation; Two-layered soil.

1 Introduction

Silos are large structures that are commonly used for storing food grains, petrol, fertilizers, etc. for long periods. It is usual practice to design silos with circular or ring footings founded at depth from the ground surface based on requirement of bearing capacity. Skempton [10] proposed a method to estimate ultimate bearing capacity (q_u) of foundations on homogeneous soil as

$$q_u = cN_c + p \tag{1}$$

where c is the average shear strength of the soil to a depth below the foundation equal to two-thirds of the diameter, N_c - bearing capacity factor, p $(=\gamma D_f)$ - overburden pressure at the level of the footing, γ -the unit weight of soil and D_f -depth of footing. Meyerhof [7] considers the average shear strength of soil as cohesion, *'c'* in Eq. (1). Normally consolidated alluvial or marine soils, when exposed to atmosphere, are subjected to seasonal changes [5] and form a crust or desiccated layer because of diurnal heating and cooling, lowering of water table, wetting and drying, etc. Desiccation causes an increase in unit weight and a significant increase in undrained strength of near-surface layers.

Undrained shear strength varies linearly with depth for a young normally consolidated deposit (Fig. 1a). With time, the deposit may gain in shear strength due to aging (Fig. 1b). The strength profile of an aged deposit with a crust/stiff layer on top of NC soil may be represented as in Fig. 1(c). Solutions for bearing capacity of circular footing resting on non-homogeneous aged clays with shear strength profile shown in Fig.1b and 1c are given by Davis and Booker [4], as in Eqs. (2) and (3) respectively.

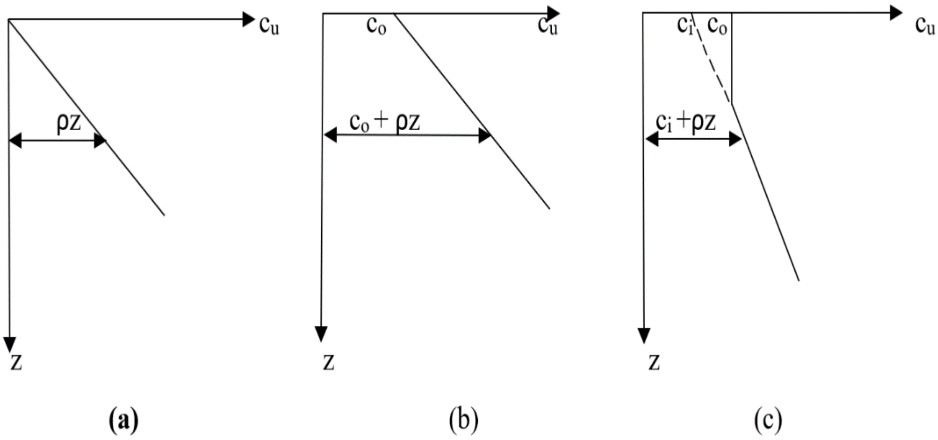

Fig. 1. Shear strength variation with depth of (a) Normally consolidated clay, (b) Aged deposits (c) Normally consolidated clay with crust (after Davis and Booker 1972)

$$q_{uf} = 1.2F_R\left[c_0N_c + \frac{\rho D}{4}\right] \quad (2)$$

$$q_{uf} = 1.2F_{RC}\left[c_0N_c + \frac{\rho D}{4}\right] \quad (3)$$

where $N_c = (2+\pi) = 5.14$; ρ - the rate of increase of shear strength with depth, c_o - undrained shear strength at ground level, D - width of the footing. F_R and $F_{RC} = f(\rho D/c_o)$ - correction factors for roughness of the footing for footing resting on clays without and with crust are given in Fig. 2 and Fig. 3 respectively (Davis and Booker 1973). The intercept, c_i, of the linear profile at the top, shown in Fig. 1c is less than c_0 and can be zero for normally consolidated deposits with no crust.

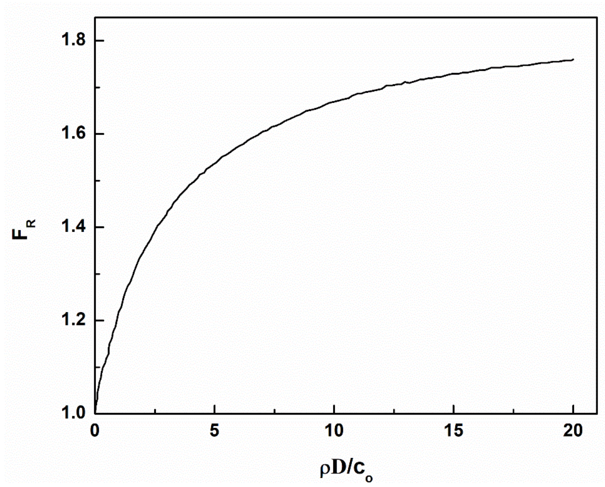

Fig. 2. Correction factor, F_R for rough footing (after Davis and Booker 1972)

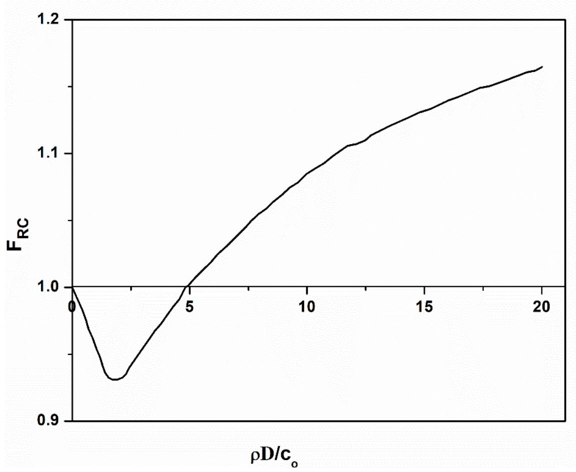

Fig. 3. Correction factor, F_{RC} for rough footing with crust (after Davis and Booker 1972)

2 Case Histories of Collapsed Silos

Failures of several silo structures in Canada in 1970's were presented by Bozozuk [1–3]. The following are the details of the silos with their soil profiles and reported causes of failure

2.1 Vankleek Hill Silo

This silo tower 6 m in dia. and 21 m high, was constructed in May, 1970. The soil profile is shown in Fig. 4. Organic soil 0.3 m thick overlies desiccated silty clay of 3 m thickness. Undrained strength in this layer decreases from 100 kPa at 1.8 m to nearly 12 kPa at 4.0 m illustrating the reducing effect of desiccation with depth. Normally consolidated silty clay with some black mottling, with undrained strength increasing linearly with depth exists from 3.4 m to 10.3 m. The average plasticity index and natural water content were respectively 36 and 55%. The average bearing pressure due to weight of superstructure and foundation was evaluated as 47 kPa. Ring footing 1 m thick and 1.2 m deep was constructed and a concrete apron/raft of diameter 21 m was provided as foundation.The average pressures due to combined load of structure and silage as per owner and calculated from data were 166 kPa and 150 kPa respectively. The non–uniform loading of silage into silos and overlapping of pressure bulbs of adjacent silos resulted in tilting of the structures (Fig. 5). The tilting of silo ultimately caused its failure.

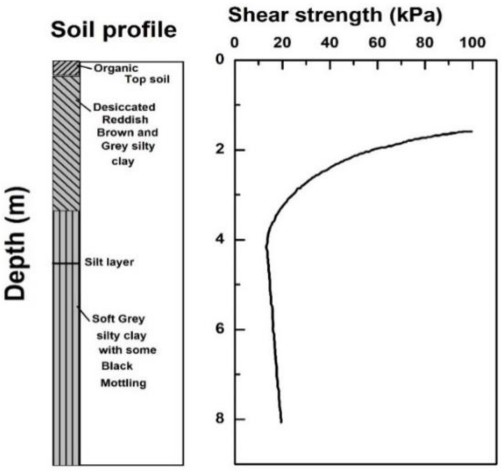

Fig. 4. Shear strength profile at Vankleek Hill tower silo

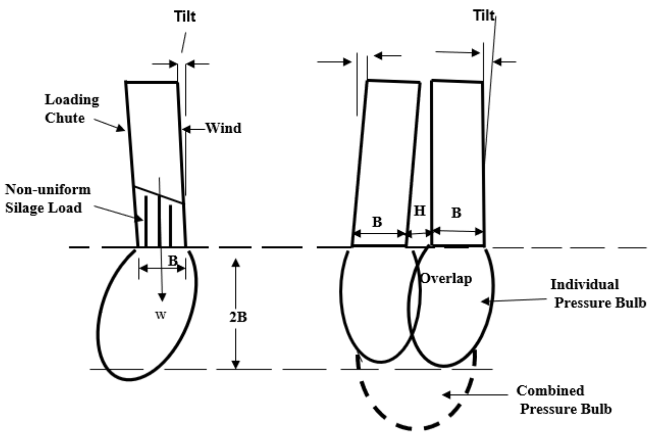

Fig. 5. Non – uniform loading and overlapping pressure bulbs (Redrawn after Bozozuk 1974)

2.2 Richmond silo

A concrete tower silo of 9.14 m diameter and 32.3 m height was constructed on normally consolidated marine deposits of the Champlain Sea in August, 1975. The soil and strength profiles are shown in Fig. 6. Brown desiccated clayey silt exists below the top organic soil, up to 2.4 m at which depth ground water level was met with. Grey clayey silt follows to a depth of 5 m and extends with black mottling up to a depth of 15.5 m. Further down up to 20.0 m, thick brittle grey silty clay was observed.

The liquid limit and plasticity index of soil in the desiccated layer were 40 and 20 respectively. Undrained strength decreases from about 60 kPa at 2.0 m to 25 kPa at 5.0 m and increases linearly with further increase in depth (Fig. 6). Ring footing with inner and outer diameters of 7.62 m and 11.89 m respectively was provided. The thickness of the cast-in-place non-reinforced footing was 0.61 m. The silo with a combined pressure of 203.5 kPa, due to silage and dead load overturned and failed within a month of filling.

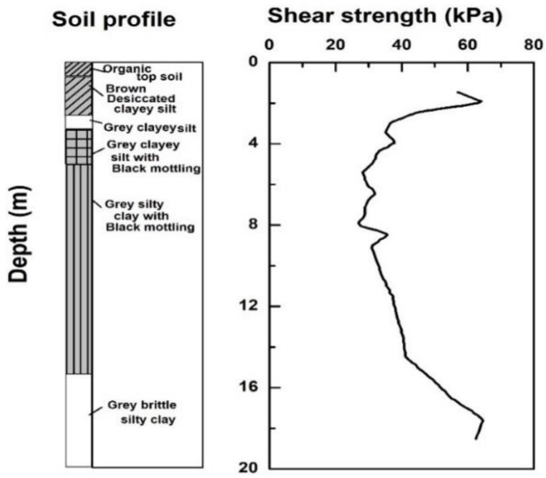

Fig. 6. Shear strength profile at Richmond silo

In both these cases, the actual shear strength variations, i.e., decrease with depth in the zone of desiccation and further a linear increase with depth of clays, have not been considered. Instead, average strength to a depth on 0.67B was used (Bozozuk 1972) to estimate the ultimate bearing capacities of the silo foundations.

3 Problem Definition And Formulation

Foundations for the above silos rest on a desiccated layer overlying normally consolidated soil. However, Bozozuk (1972) used Skempton's (1951) solution (Eq. (1))

to estimate the ultimate bearing capacity of the foundations, which is strictly valid for only homogenous deposits with an average undrained strength corresponding to a depth of 0.67B from the footing level. Based on these case histories of silos, bearing capacity of foundations resting on desiccated layer overlying normally consolidated soil is formulated as follows.

A circular footing of diameter, *D*, at depth, D_f from the ground, rests on soil whose shear strength profile is as shown in Fig. 7. The undrained shear strengths of soil at the base of footing (D_f) and at the interface of desiccated soil and normally consolidated clay (z_o) are c_{uB} and c_{uo} respectively. Desiccation strength ratio, μ_B (= c_{uB}/c_{uo}) is defined as a ratio of strength at the footing level to that at the bottom of the desiccated layer. The footing rests within the desiccated layer of thickness, z_o. Normally consolidated soil whose strength increases linearly with depth lies beneath the desiccated layer. The rate of increase of shear strength with depth in the normally consolidated deposit is denoted by ρ.

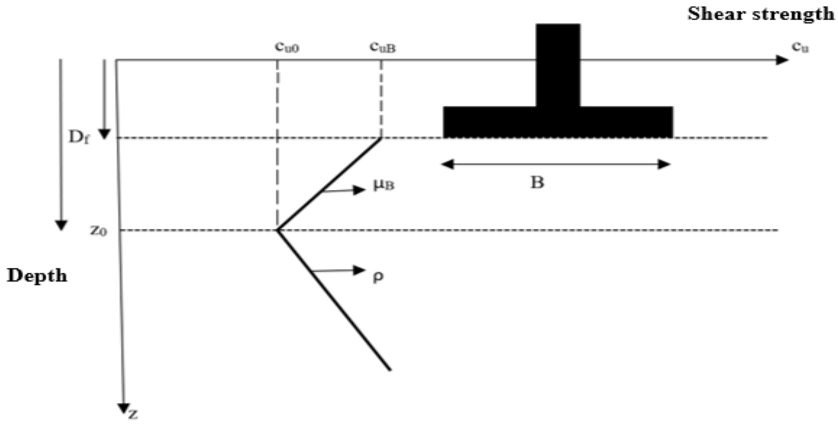

Fig. 7. Undrained Shear Strength Profile

The shear strengths, c_{uz} of soil at a depth, *z*, within desiccated and normally consolidated layers are given in Eqs. (4) and (5) respectively.

$$z < z_0, c_{uz} = \frac{c_{uB}(z_o - z) + c_{u0}(z - D_f)}{(z_o - D_f)} \tag{4}$$

$$z > z_0, c_{uz} = c_{u0} + \rho(z - z_0) \tag{5}$$

Footing resting on strong desiccated soil overlying normally consolidated soil with undrained strength increasing with depth is modelled as a two-layered system similar to Meyerhof [8] and Meyerhof and Hanna [6, 9] but with the proviso that the strength in the desiccated layer is not constant but decreases with depth.

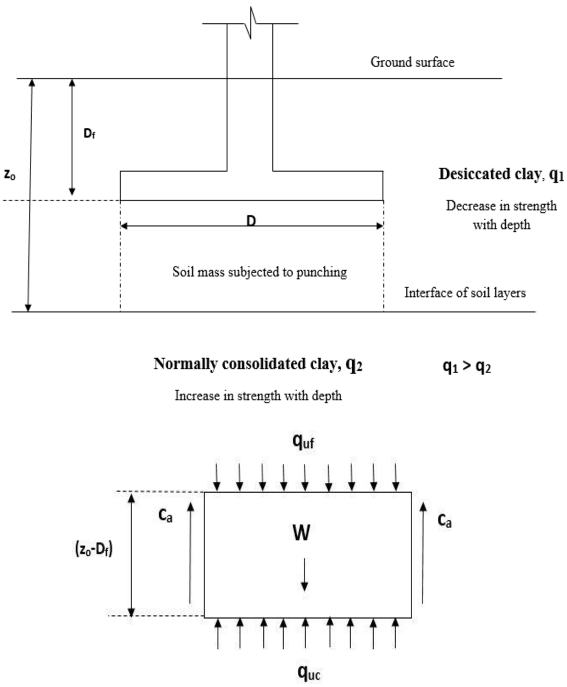

Fig. 8 Free body diagram of soil mass within desiccation layer

The mass of soil below the base of the footing within the desiccated layer (Fig. 8(a)), subjected to punching shear is considered. The various forces acting on the soil element below the footing upto the desiccated layer shown in Fig. 8(b). The forces acting on the elemental mass of thickness (z_o-D_f) are the adhesive force C_a, between the soil mass and the adjacent soil in desiccated clay, ultimate bearing capacities q_{uf} and q_{uc} acting on top and bottom of the soil mass respectively. The self-weight W, of cylindrical soil element acts vertically downwards.

Ultimate bearing capacity, q_{uf}, of circular footing for NC soil with desiccated layer, obtained from equilibrium conditions

$$q_{uf}\left(\frac{\pi D^2}{4}\right) = q_{uc}\left(\frac{\pi D^2}{4}\right) + c_a(z_0 - D_f)(\pi D) - \gamma(z_0 - D_f)\left(\frac{\pi D^2}{4}\right)$$

$$q_{uf} = q_{uc} + \frac{4}{D} c_a(z_0 - D_f) - \gamma(z_0 - D_f) \qquad (6)$$

where, $q_{uc} = 1.2F_R\,[c_{u0}N_c + \frac{\rho B}{4}]$ is the ultimate bearing capacity of a circular footing on non-homogeneous ground with strength increasing with depth (Davis and Booker 1973) with □ the rate of increase of strength with depth as defined earlier. Simplifying Eq (6) and substituting for q_{uc} from Eqs. (2) and (3), ultimate bearing capacities of circular footing q_{uf}, for desiccated NC soil without and with a crust are obtained respectively as

$$q_{uf} = 1.2F_R\left[c_{uo}N_c + \frac{\rho D}{4}\right] + \frac{z_o}{D}\left(1 - \frac{D_f}{z_o}\right)(4c_a - \gamma D) \tag{7}$$

$$q_{uf} = 1.2F_{RC}\left[c_{uo}N_c + \frac{\rho D}{4}\right] + \frac{z_o}{D}\left(1 - \frac{D_f}{z_o}\right)(4c_a - \gamma D) \tag{8}$$

The adhesion c_a, between considered soil mass and adjacent soil is a function of ratio of bearing capacity of bottom and top soils i.e., q_2/q_1, c_1 is cohesion of upper layer. Variation of c_a/c_1 with q_2/q_1 is shown in Fig. 9 (Meyerhof & Hanna 1978). Ultimate bearing capacity of the lower normally consolidated soil, q_2, is c_{uo} N_C^* and that for the top desiccated layer q_1, as c_1 N_C, where c_1 is the average undrained strength of the desiccated layer below the footing, = $0.5(c_{uB}+c_{u0}) = 0.5c_{uo}(\square_B+1)$

The footing is at depth D_f in the desiccated layer of total thickness, z_0. Considering surcharge stress, $q_0 = \gamma D_f$, Eqs. (7) and (8) become

$$q_u = q_{uf} + \gamma D_f$$

$$q_u = 1.2F_R\left[c_{uo}N_c + \frac{\rho D}{4}\right] + \frac{z_o}{D}\left(1 - \frac{D_f}{z_o}\right)(4c_a - \gamma D) + \gamma D_f \tag{9}$$

$$q_u = 1.2F_{RC}\left[c_{uo}N_c + \frac{\rho D}{4}\right] + \frac{z_o}{D}\left(1 - \frac{D_f}{z_o}\right)(4c_a - \gamma D) + \gamma D_f \tag{10}$$

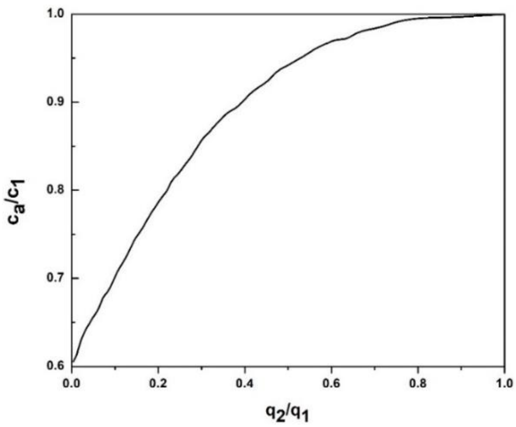

Fig. 9. Variation of $\frac{c_a}{c_1}$ with $\frac{q_2}{q_1}$ (after Meyerhof et al. 1978)

Gross ultimate bearing capacity of the circular footing resting on desiccated layer overlying normally consolidated soil without and with a crust on top of NC clay given in Eq. (9) and Eq. (10) respectively, are derived by incorporating Davis and Booker's (1973) solution into Meyerhof's (1978) punching failure approach for two-layered soil.

Bearing capacity is normalized with undrained strength, c_{u0} and this ratio of gross ultimate bearing capacity to undrained strength is defined as Normalised bearing capacity, NBC and Eq. (10) written as

$$NBC = \frac{q_u}{c_{uo}} = 1.2F_R\left[5.14 + \frac{\rho D}{4c_{uo}}\right] + \frac{z_o}{D}\left(1 - \frac{D_f}{z_o}\right)\left(\frac{4c_a - \gamma D}{c_{uo}}\right) + \frac{\gamma D_f}{c_{uo}} \qquad (11)$$

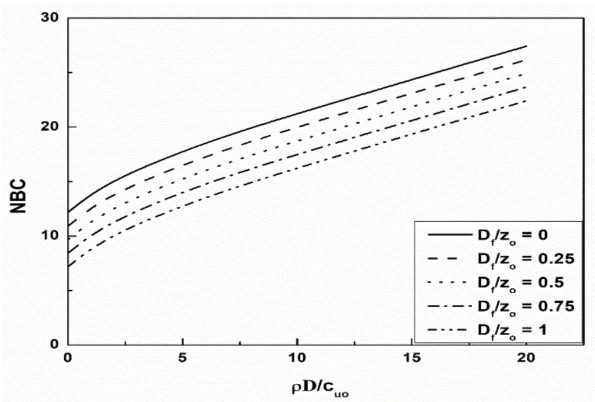

Fig. 10 NBC vs $\rho D/c_{uo}$ – Effect of D_f/z_o for $z_o = 0.5D$

Variations of NBC with $\rho D/c_{uo}$, for different D_f/z_0 and for $z_o = 0.5D$ are shown in Fig. 10. NBC increases with the normalized rate of increase of strength, $\rho D/c_{uo}$ of NC layer but decreases with increase in the depth of the footing as the strength of desiccated layer decreases with depth. For a footing at mid-depth of the desiccated layer, D_f/z_0 equal to 0.5, NBC increases from 9.6 for homogenous deposit ($\rho B/c_{uo}$ =0 strength constant with depth) to 24.9 for NC layer with $\rho D/c_{uo}$ equal to 20. For a moderate rate of increase of strength with depth, i.e., $\rho D/c_{uo}$ equal to 5.0, NBC decreases from 17.8 for a footing at the surface to 12.8 for the footing at the bottom of the desiccated layer, a decrease of about 28%.

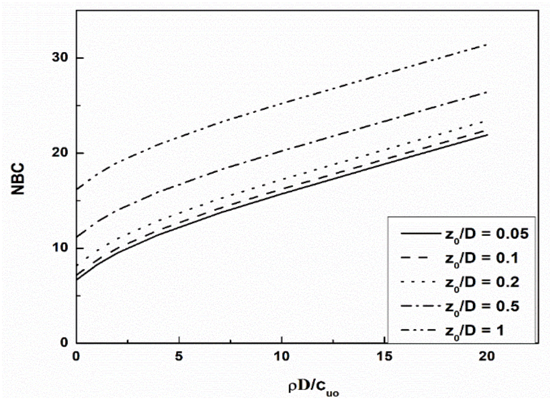

Fig. 11. NBC vs $\rho D/c_{uo}$- Effect of z_0/D for $D_f = 0$.

Variations of NBC with $\rho D/c_{uo}$, for different z_0/D and $D_f = 0$ are shown in Fig. 11. NBC increases with the normalized rate of increase of strength, $\rho D/c_{uo}$ of NC layer and with increase in the thickness of desiccated layer. For a footing at the surface i.e., on top of the desiccated layer, z_0/D equal to 0.5, NBC increases from 11.2 for homogenous deposit ($\rho D/c_{uo}$, strength constant with depth) to 26.5 for NC layer with $\rho D/c_{uo}$ equal to 20. For a moderate rate of increase of strength with depth, i.e., $\rho D/c_{uo}$ equal to 5.0, NBC increases from 12.2 for a thin desiccated layer i.e., z_0 = 5% of size of footing to 21.5 for z_0 = 100% of size of footing, an increase of about 76% is observed.

4 Comparison of Bearing Capacities

Geotechnical parameters of soils and details of the footings for the Vankleek and Richmond silos are given in Table 1. Eqs. (9) and Eq (10) are the utilised for calculating the bearing capacities for these silo foundations considering the given strength profiles. The average shear strength $c_{u\ avg}$, is estimated from Skempton (1951) bearing capacity (Eq (1)), as given in Eq (12). Normalised shear strength, NSS, is defined as the ratio of average undrained strength to undrained strength at the interface of two layers, as in Eq (13).

$$c_{u\ avg} = \frac{q_u}{N_c^*} \tag{12}$$

$$\text{NSS} = \frac{c_{u\ avg}}{c_{uo}} = \frac{q_u}{c_{uo} N_c^*} = \frac{NBC}{N_c^*} \tag{13}$$

where, q_u is the ultimate bearing capacities obtained from Eq. (8) and Eq. (9), N_c^* is Bearing capacity factor (taken as 6.6 as per Skempton 1951) and c_{uo} is undrained cohesion at the interface of desiccated and non-homogeneous layers.

Table 1. Parameters of soils and foundations at silo locations

Parameter	Vankleek Hill silo	Richmond silo
Diameter of footing D, m	8	11.89
Depth of footing D_f, m	1.52	0.61
Unit weight of soil γ, kN/m^3	15	15
Thickness of desiccated layer z_0, m	3.7	2.4
Rate of increase of shear strength, ρ	1.35	1
Strength reduction ratio μ_B	6.25	2
Undrained cohesion at the interface of desiccated and non-homogeneous layers c_{u0}, kPa	16	30
Roughness correction factor F_R	1.06	1.08
Bearing capacity factor N_c^*	6.6	6.6
Undrained cohesion of desiccated soil c_1, kPa	58	45
Ratio of bearing capacities q_2/q_1	0.28	0.67
Ratio of adhesion to cohesion in desiccated clay c_a/c_1	0.84	0.98
Adhesion between footing and soil in desiccation c_a, kPa	48.72	44.1

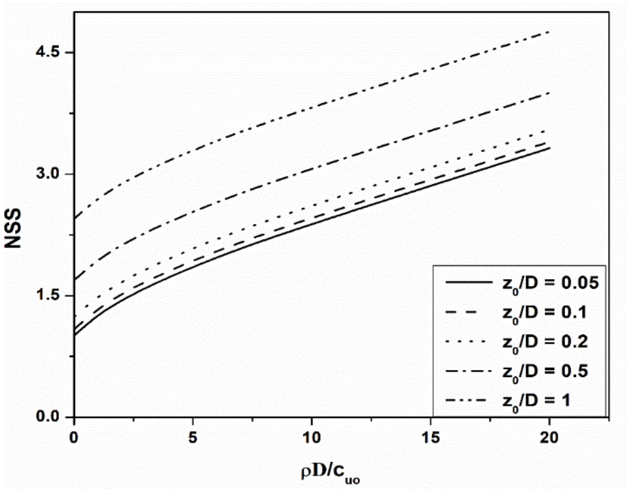

Fig. 12. NSS vs $\rho B/c_{uo}$- Effect of z_0/D

Variation of NSS with $\rho D/c_{uo}$ for different z_0, D_f = 0 and N_c= 6.6 are shown in Fig. 12. NSS increases with the normalized rate of increase of strength, $\rho D/c_{uo}$ of NC layer and increases with increase in thickness of desiccated layer. For a footing at the surface i.e., on top of the desiccated layer, z_0/D equal to 0.5, NSS increases from 1.7 for homogenous deposit ($\rho D/c_{uo}$ = 0, strength constant with depth) to 4 for NC layer with $\rho D/c_{uo}$ equal to 20. For a moderate rate of increase of strength with depth, i.e., $\rho D/c_{uo}$ equal to 5.0, NBC increases from 1.8 for a minimal thickness of desiccated layer i.e., z_0 = 5% of size of footing to 3.3 for z_0 = 100% of size of footing, an increase of about 83% is observed.

Table 2. Comparison of average shear strengths of soils and bearing capacities of foundations of silos

S. No	Name of the silo	Shear strength $c_{u\ avg}$, (kPa)		Ultimate bearing capacity q_u, (kPa)	
		Bozozuk	Proposed	Bozozuk	Proposed
1	Vankleek	24.4	22.9	205	151.3
2	Richmond	36.5	30.5	250	201.2

Bearing capacities of the silo foundations as estimated and reported by Bozozuk (1972, 1974) based on Skempton 1951) equation are compared with those estimated by the present approach. From Table 2, it can be observed that Bozozuk had overestimated the bearing capacities and these high values might have led to the failure of the silos. Bearing capacities estimated by Bozozuk (1972, 1974) are more and on the unconservative side being 205 kPa and 250 kPa compared to the values 151.3 kPa and 201.2 kPa estimated by considering the actual undrained strength profiles i.e., considering both the effect of desiccation and the increase in undrained strength with depth for normally consolidated soil.

The bearing capacities from the proposed equation and by Bozozuk (1972 and 1974) differs by 26% and 20% in cases of Vankleek and Richmond silo respectively. The proposed rigorous theory incorporating the true variation of undrained strength with depth provided a less ultimate bearing capacity of silo foundations.

5 Conclusions

Failure of silos reported by Bozozuk (1972, 1974) are examined in the light of developments in geotechnical engineering, in particular the linear increase in undrained strength with depth of normally consolidated soil and increased strength in the desiccated layer. A new theory based on Meyerhof's approach for bearing capacity of two-layered soils with the above defined strength profile is proposed for the estimation of bearing capacity of foundations. The bearing capacities estimated by the proposed theory are compared with those given Bozozuk (1972, 1974). Bearing capacities from the proposed approach are less by 20 to 26% compared to the values estimated by Bozozuk (1972, 1974).

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