Foundation failure of the Vankleek Hill tower silo

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FOUNDATION FAILURE OF THE VANKLEEK HILL TOWER SILO

by

M. Bozozuk

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RUINE DE LA FONDATION DE LA TOUR-SILO DE VANKLEEK HILL

SOMMAIRE

La ruine de la force portante de la fondation d'un silo en béton mesurant 70 pieds (21 m) de hauteur et 20 pieds (6 m) de diamètre a été une excellente occasion d'analyser la résistance du sol au cisaillement et de vérifier les théories actuelles concernant la capacité portante. La résistance du sol d'argile marine, mesurée in situ peu après la ruine au moyen d'un scissomètre, était d'au moins 0.16 kg/cm^2 à une profondeur de 12 pieds (3.7 m) et augmentait graduellement selon la profondeur. Des essais de consolidation sur des échantillons non remaniés de carottier à piston ont montré que les pressions de la fondation avaient excédé de beaucoup la pression de préconsolidation d… e
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M. Bozozuk*

ABSTRACT

The bearing capacity failure of the foundation supporting a 70-ft (21-m) high, 20-ft (6-m) diameter concrete silo provided an excellent opportunity to analyse the shear strength of the soil and to check existing bearing capacity theories. The strength of the marine clay soil measured in situ with a field vane shortly after the failure occurred had a minimum value of 0.16 kg/cm^2 at a depth of 12 ft (3.7 m), then increased gradually with depth. Consolidation tests carried out on undisturbed piston tube samples showed that the foundation pressures had greatly exceeded the preconsolidation pressure of the soil.

Laboratory strength tests included triaxial CAU tests with pore pressure measurements and small vane tests performed at various inclinations from the vertical to investigate strength anisotropy. Preliminary analysis showed a good correlation between the ultimate bearing capacity of the soil and the reduced shear strength due to anisotropy.

On 30 September 1970 a 70-ft (21-m) high, 20-ft (6-m) diameter concrete tower silo overturned suddenly due to a bearing capacity failure of the foundation clay soil, just after it was filled to capacity for the first time with corn silage. The silo was

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destroyed and the estimated 600 tons of feed spilled onto the ground. Although the disaster was costly to the farmer, it did provide an excellent opportunity to check bearing capacity theories. It was also possible to compare (a) the strength of the soil measured in situ with a field vane, (b) the anisotropic strength measured with a laboratory vane on undisturbed soil specimens, and (c) triaxial anisotropically consolidated undrained (CAU) strength tests on undisturbed soil specimens, as the failure provided a full scale field test for the shear strength of the soil.

THE TOWER SILO

The tower silo was constructed in May 1970. The superstructure consisted of a 70-ft (21-m) high, 20-ft (6-m) inside diameter reinforced concrete circular tube with walls $6\frac{1}{2}$ in. (16.5 cm) thick. A 4-in. (10-cm) thick concrete loading chute, cast monolithically with the main walls on the outside, extended for the full height of the silo. The concrete tube was centred on a ring foundation; no floor was provided. Density tests on several samples of the concrete gave an average 141.0 lb/cu ft (2258 kg/m^3) from which the weight of the superstructure was calculated to be 183 tons.

The ring foundation consisted of concrete placed directly in an excavated trench 3 ft (1 m) wide and about 4 ft (1.2 m) deep. Its weight was estimated at 54 tons.

The silo was constructed within one corner of a 70-ft (21-m) wide, 100-ft (30-m) long, 4-in. (10-cm) thick concrete apron placed on 8 in. (20 cm) of fill approximately 25 ft (8 m) away from the main barn. When the silo collapsed, it toppled in the direction of the loading chute onto the paved apron. The soil heaved beyond the apron in the opposite direction of the fall.

During the summer the silo was loaded with about 50 ft (15 m) of hay silage that was used for summer feeding of beef cattle. Approximately 20 ft (6 m) of hay remained when the silo was first filled to capacity with corn silage late in September.

The owner estimated that the total weight of silage at the time of failure was 600 tons. McCalmont (1964) indicated that a silo of this size could contain 582 tons of corn silage provided that the silo was refilled once after the silage had settled and the top had been well tramped. The owner had not had the opportunity to refill the silo due to the sudden failure, nor had the silage been tramped. The actual weight of silage, therefore, must have been less than the above estimates.

To obtain a reasonable estimate of the actual load, a joint research project was undertaken with the Engineering Research Service, Canada Agriculture, in September 1971 to measure the average density of corn silage in an 82-ft (25-m)high, 30-ft (9-m) diameter silo as it was being filled. Over a nine-day period the silo was filled with 1440 tons after which it was topped up several times so that by the end of 30 days it contained 1600 tons. The average density after settlement overnight is plotted against the height of silage in Figure 1. This figure also shows the average density immediately after the silo was filled before the silage settled.

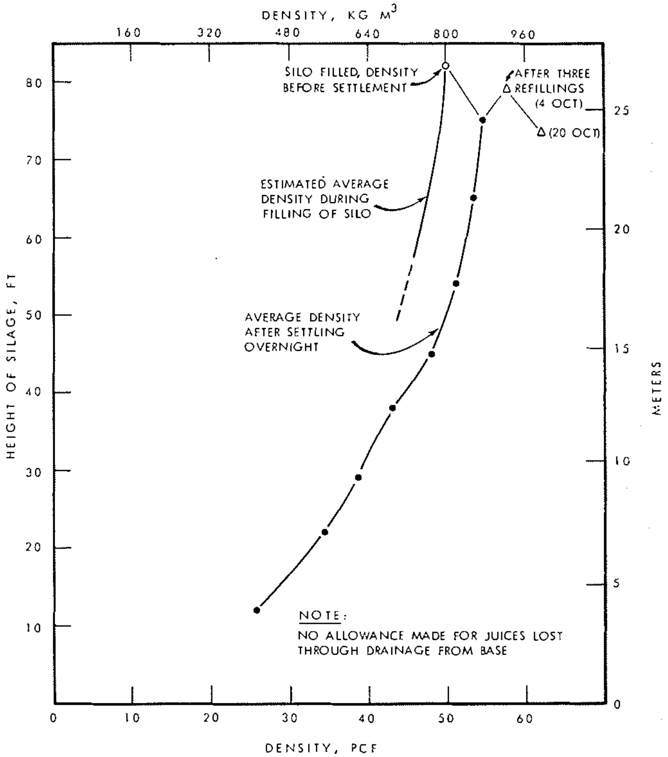

FIGURE 1

AVERAGE WET DENSITY OF CORN SILAGE MEASURED DURING FIRST FILLING OF 30 FT (9 m) DIAMETER BY 82 FT (25 m) HIGH SILO, SEPT, 1971

BR 4888-1

McCalmont (1964) indicated that at the same moisture content hay silage is approximately 5 to 10 per cent heavier than corn silage provided that the silo is refilled once after it settles and the top well tramped. Because the hay was collected during the dry period of the summer its moisture content was probably much less than that of the corn that was collected during the wet period early in the fall; neither was the silo refilled with hay nor tramped. Consequently, for determining the weight of silage placed, it was assumed that the density of the hay and corn silage were the same.

From the information presented on Figure 1, therefore, the estimated weight of silage in the 70-ft (21-m) silo at the time of failure was 533 tons; for 50 ft (15 m) it was 342 tons.

The 533-ton estimate should be corrected further to compensate for the amount of silage juices lost by drainage from ports provided at the base of the tower silo. It is known that during loading a considerable quantity of juice escaped, although the actual amount was not measured. Assuming that 2 lbs per cubic ft (32 kg/m^3) is a realistic average loss, the net weight of silage in the 70-ft (21-m) silo was estimated to be 511 tons at the time of failure.

Due to the configuration of the foundation it was impossible to determine the distribution of stresses imposed on the soil by the above loads. Assuming, therefore, that the loads were distributed uniformly over a circular area immediately below the footings, the net applied vertical pressures due to the total weight of the silo and its contents for the various estimated loads are given in Table 1.

SOIL CONDITIONS

The silo was located on a level clay plain consisting of marine deposits of the Champlain Sea (Gadd, 1963). The clays are generally very weak and highly compressible. Many landslide failures have occurred in gullies and ravines that exist in this region.

Two weeks after the failure occurred continuous undisturbed 2-in. (50-mm) dia. piston tube soil samples were taken with a Norwegian (NGI) soil sampler (Bjerrum, 1954), about 60 ft (18 m) from the silo to a depth of 34 ft (10 m). The in situ shear strength was measured at the same location with a 55- x 110-mm Geonor vane (Anderson and Bjerrum, 1956) to a depth of 64.2 ft (19.6 m), the depth of refusal. A summary of the engineering tests is shown in Figure 2.

The soil profile consists of 1 ft (0.3 m) of organic topsoil over 10 ft (3 m) of desiccated reddish-brown silty clay. From 11 ft

TABLE 1. - NET APPLIED VERTICAL FOUNDATION PRESSURES DUE TO THE TOTAL WEIGHT OF THE SILO AND SILAGE

Height of Silage	Estimated Weight (Tons)	Applied Vertical Pressure (TSF, kg/cm^2)
(a) 70 ft (21 m)	600	1.83
(b) 70 ft (21 m)	533	1.68
(c) 70 ft (21 m)	511	1.63
(d) 50 ft (15 m)	342	1.24

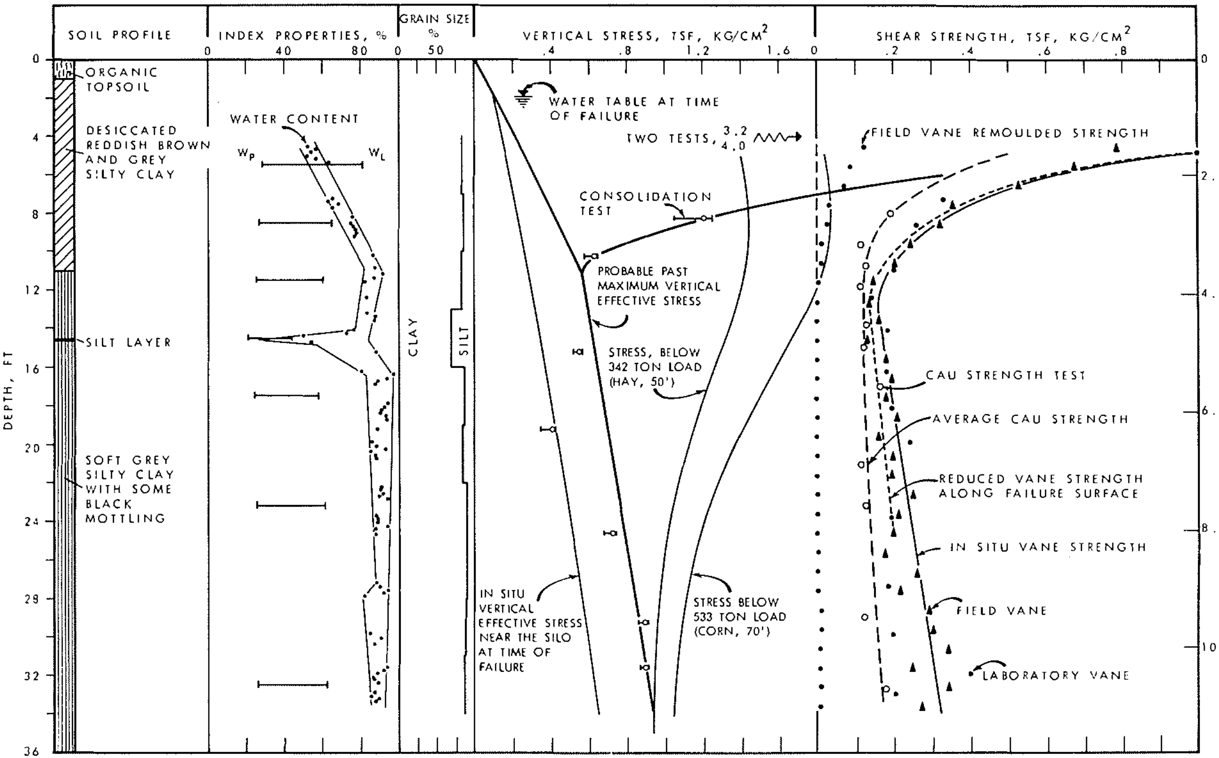

FIGURE 2 SUMMARY OF SOIL TESTS AT VANKLEEK HILL SILO

BR 4888-2

(3.4 m) to 34 ft (10.3 m), the maximum depth of sampling, the soils were mainly soft grey silty clays except for a thin silt layer at 14.6 ft (4.5 m). The grey silty clay contained some black mottling commonly found in the marine clays of this region. Although no samples were obtained from the deeper formations, it appears that the marine clays extended to a depth of 64.2 ft (19.6 m).

Atterberg limit tests were conducted on soil trimmings obtained from the tube samples. Generally the plastic limit was fairly uniform at about 25 per cent. The liquid limit of the soil near the base of the silo footings was approximately 82 per cent. It decreased to about 60 per cent below a depth of 10 ft (3 m), giving an average Plasticity Index of 36 per cent. The natural water content was approximately 55 per cent near the footings and it increased with depth to almost 95 per cent exceeding the liquid limit by nearly 30 per cent. Consequently the deeper soil formations would be very sensitive and would have low remoulded strengths.

The grain size analysis conducted on the soil trimmings showed that 85 to 90 per cent of the soil particles fell within the clay size fraction with the exception of the silt layer at 14.6 ft (4.5 m). There was a complete absence of sand size particles in the soil profile.

Consolidation tests conducted on 20-cm^2 specimens, using a $\Delta p/p$ ratio of $\frac{1}{2}$, showed that the soil profile was normally consolidated (Figure 2). The tests indicated that the maximum depth of the groundwater table was about 11 ft (3.4 m) although it was only 2 ft (0.6 m) deep at the time of the investigation. The average initial void ratio was approximately 1.5 for the desiccated zone and about 2.5 for the soft clay formation below.

The total vertical stresses under the centre line of the silo for 342 tons of hay and 533 tons of corn silage using the Boussinesq stress distribution (Jumikis, 1971) relative to the consolidation tests, are shown on Figure 2. It is evident that these loads would have caused very large settlements had the silo not failed.

DESCRIPTION OF THE FAILURE

The attitude of the ring foundation relative to its original position following the bearing capacity failure is shown on Figure 3. Its final slope was 50 degrees from the horizontal which was identical to that measured on a similar silo that failed at New Liskeard (Eden and Bozozuk, 1962). One end heaved approximately 6 ft (1.8 m) while the opposite end sank about 13 ft (4.0 m). The amount of soil heaved could not be measured as some of it had been

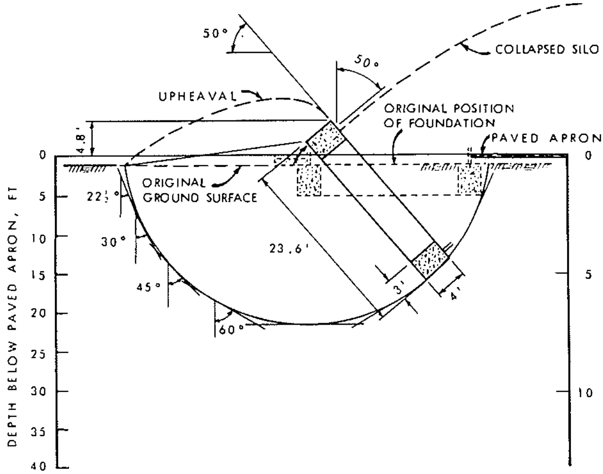

FIGURE 3 ATTITUDE OF SILO FOUNDATION AFTER FAILURE

BR 4888-3

removed prior to the investigation, but it certainly exceeded 6 ft (1.8 m) and could have been as much as 8 ft (2.4 m).

The exact location of the sliding surface was not determined. By studying the rotation of the foundation, however, it was possible to reconstruct the circular failure surface shown on the figure. The failure surface extended to a depth of 23 ft (7.0 m) delineating the soil whose strength governed the bearing capacity for the foundation. This agrees with Skempton's (1951) suggestion that the strength of the soil to a depth below the foundation equal to two-thirds of its diameter, (i.e., 5 ft (1.5 m) to 21 ft (6.4 m)), be used for determining the bearing capacity.

SHEAR STRENGTH OF THE SOIL

The in situ undisturbed and remoulded shear strengths of the soil measured with the field vane to a depth of 34 ft (10.4 m) are plotted on Figure 2, and a summary of all the measurements to a depth of 64 ft (19.6 m) is given in Table 2. The undisturbed strength varies from a high of about 1 TSF (1 kg/cm^2) in the desiccated crust at a depth of 5 ft (1.5 m), to a minimum of 0.16 TSF (0.16 kg/cm^2) in the soft grey silty clay at 12 ft (3.7 m). The strength increases gradually with increasing depth to about 0.8 TSF (0.8 kg/cm^2) at 60 ft (18 m). The average undisturbed shear strength of the soil from 5 ft (1.5 m) to 23 ft (7.0 m) is about 565 psf (0.276 kg/cm^2).

TABLE 2. - IN SITU SHEAR STRENGTH OF SOIL, MEASURED WITH 55- X 110-MM FIELD VANE

Depth (ft)	Shear Strength (psf)		Depth (ft)	Shear Strength (psf)	
	Undisturbed	Remoulded		Undisturbed	Remoulded
4.6	1563	250	26.6	531	9
5.6	1350	170	27.6	438	11
6.6	1058	138	28.6	590	22
7.6	710	65	29.6	603	22
8.6	639	54	30.6	690	16
9.6	486	22	31.6	499	20
10.6	410	22	32.6	694	16
11.6	289	11	33.6	547	13
12.6	272	7	34.6	743	54
13.6	320	0	35.6	636	48
14.6	262	0	36.6	790	45
15.6	360	0	39.6	801	4
16.6	390	0	42.6	1000	0
17.6	359	0	45.6	1025	4
18.6	414	11	48.6	1196	7
19.6	325	0	51.6	970	13
20.6	397	0	53.6	859	17
21.6	392	0	57.6	712	0
22.6	499	4	60.6	1671	35
23.6	420	4	63.6	750	11
24.6	401	7	64.2	Refusal	
25.6	354	17			

The remoulded strength measured in the desiccated crust varied from 22 psf (0.01 kg/cm^2) to 250 psf (0.12 kg/cm^2) indicating a sensitivity of 6 to 22 for this layer. Below this soil formation to a depth of 24 ft (7.3 m), the remoulded strength dropped to practically nothing, indicating an infinite sensitivity. For the soil below 24 ft (7.3 m) the sensitivity varied from 20 to over 100.

Triaxial (CAU) strength tests were conducted on undisturbed test specimens in the laboratory. The specimens were trimmed to 1.4 in. (36 mm) dia. by 3.0 in. (80 mm) high, consolidated anisotropically to the in situ field stresses assuming $K_o = 0.5$, and loaded undrained to failure. The shear strengths defined as $\frac{1}{2}(\Delta\sigma_1 - \Delta\sigma_3)$ are plotted on Figure 2. The average strength of the soil from 5 ft (1.5 m) to 23 ft (7.0 m) was 356 psf (0.174 kg/cm^2), which was 63 per cent of the in situ strength measured with the field vane. The average slope of the failure surface measured on the test specimens was 53.5 degrees.

The field vane and the laboratory triaxial tests are not suitable models for determining the shearing resistance of the soil supporting the silo. The field vane measured the shearing resistance along a vertical plane, whereas the triaxial test gave the shearing resistance along a 53.5-degree slope. The actual failure under the silo probably took place along a curved surface (circle) whose slope varied from 0 to 90 degrees from the vertical. It was necessary, therefore, to determine the shearing resistance of the soil along this surface.

The curved failure surface was replaced with a series of straight lines drawn tangent to it at inclinations varying from 0 to 90 degrees (Figure 3). A total of 67 laboratory vane tests were conducted at various inclinations on test specimens jacked directly from the sample tubes using a small 10-mm dia. by 10-mm high vane. The strengths measured in the normal position (0 degrees) were about the same as those measured in the field as shown on Figure 2. For other inclinations there was a marked reduction in the shearing strength of the soil.

Fifty-one of the vane tests were conducted on the soil at depths from 5 ft (1.5 m) to 24 ft (7.3 m) at inclinations of 0, $22\frac{1}{2}$, 45, $67\frac{1}{2}$ and 90 degrees; 16 were conducted on the soil at depths from 27 ft (8.2 m) to 34 ft (10.4 m) at inclinations of 0, 30, 60 and 90 degrees. For these angles the average per cent reduction in strength was determined relative to the vertical orientation (0 degrees) and the results plotted on Figure 4. From 5 ft (1.5 m) to 24 ft (7.3 m) the strength of the soil decreased up to 20 per cent as the inclination of the vane was increased to 90 degrees. From

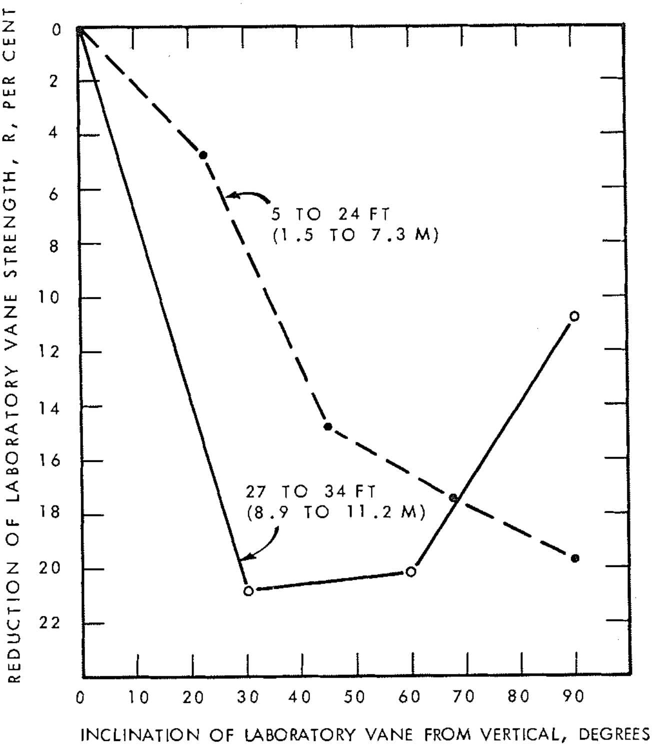

FIGURE 4

EFFECT OF INCLINATION OF LABORATORY VANE ON THE SHEAR STRENGTH OF THE SOIL

BR4888-4

27 ft (8.2 m) to 34 ft (10.4 m), the loss was about 20 per cent at 30 and 60 degrees, but only 11 per cent at 90 degrees. This could be attributed to the greater variation in soil strength at this depth and to the smaller number of tests performed to obtain this curve.

The shear strength of the soil along the failure plane was determined by adjusting the in situ shear strength measured with the field vane by the amounts shown on Figure 4 using the equation:

$$S_a = S_v \, (1 - R) \tag{1}$$

where S_a = anisotropic strength for an angle dictated by the failure surface

S_v = in situ undrained shear strength of the soil measured with the field vane

R = reduction in strength determined from Figure 4 for the appropriate inclination of the failure surface, expressed as a fraction

The resulting strength versus depth curve coincided with the lower limit of the undisturbed field vane strengths shown on Figure 2. The average strength of the soil from 5 ft (1.5 m) to 23 ft (7.0 m) was 500 psf (0.244 kg/cm^2), which was about 12 per cent lower than the in situ vane strengths, and 40 per cent greater than those measured in the laboratory.

The difference in strength of 40 per cent obtained with the laboratory vane compared with the triaxial test cannot be related to the 20 per cent reduction due to anisotropy or to disturbance from sampling (Bozozuk, 1971) but to storage time of the soil samples and possible disturbance from trimming the test specimens. The laboratory vane tests were performed on untrimmed test specimens jacked directly from sample tubes approximately two to three months after the samples were obtained; the strengths correlated with those measured in the field (Figure 2). The triaxial tests were performed on carefully trimmed test specimens that had been extruded from the same sample tubes and stored for 12 to 14 months in a humid room at a constant temperature of 55°F. Although the storage temperature was similar to the ground temperature in this region, the reduction in strength of the soil must have been caused by the long period of storage. Therefore, for accuracy, engineering tests on undisturbed soil samples must be performed as soon as possible after they are obtained (Bozozuk 1971).

ANALYSIS OF BEARING CAPACITY

The bearing capacity of a soil is related to its shear strength and to the size, shape, and depth of the foundations. Skempton (1951) proposed the following equation for the ultimate bearing capacity for rapid loading of clay soil

$$q_u = cN_c + p \quad (2)$$

where q_u = ultimate bearing capacity

c = average shear strength of the soil to a depth below the foundation equal to two-thirds of the diameter

N_c = shape factor = 6.6 for a circular foundation

p = overburden pressure at foundation level.

Earlier, Skempton (1942) had proposed an equation that considered the adhesion between the rough sides of the foundation and the soil. It had the form

$$q_u = cN_c + p + \frac{L}{A}\, c' \tag{3}$$

where L = outside perimeter of the foundation

A = area of the foundation

c' = adhesion between the soil and the foundation.

In this analysis, $c' = c$; q_u, c, N_c and p are the same as for equation (2).

Meyerhof (1951) considered the case of a circular foundation with a rough shaft bearing on purely cohesive soil. He proposed the following formula which takes into account the soil friction acting on the sides of the foundation:

$$q_u = c\,N_c + K_s\,\gamma D \tag{4}$$

where q_u = ultimate bearing capacity

c = average shear strength

N_c = shape factor = 7.5 for circular foundation

K_s = coefficient of earth pressure between the soil and the sides of the foundation = 1

γ = density of the soil above the base of the foundation

D = depth to the base of the foundation.

Using these equations the ultimate bearing capacity was determined for each of the following three estimated average shear strengths of the soil:

(a) In situ undrained strength measured with the field vane	565 psf (0.276 kg/cm^2)
(b) Undrained field vane strength corrected for slope of failure surface (anisotropic strength)	500 psf (0.244 kg/cm^2)
(c) Laboratory triaxial (CAU) strength	356 psf (0.174 kg/cm^2)

The calculated ultimate bearing capacities were compared with the average total foundation pressures for silage loads of 600, 533, 511 and 342 tons, and a factor of safety against failure was determined. A summary of the results is given in Table 3.

Based on the average in situ undrained shear strength of the soil, the equations predicted factors of safety greater than unity for the 600-ton silage load. Because the silo failed, it is apparent that the vane overestimated the shear strength of the soil. Based on the reduced anisotropic strength, however, equations (2) and (3) predicted failure, whereas equation (4) indicated that the foundations were stable.

Considering the average shear strength determined from the CAU tests, equations (2) and (3) indicated that even the 342-ton load (50 ft (15 m) of hay silage) should have caused failure, whereas equation (4) predicted a factor of safety of 1.07. If the bearing capacity is based on the in situ undrained shear strength or on the anisotropic strength, all equations predict a very high factor of safety for this load. As the structure did not fail, it can be concluded that the triaxial tests underestimated the actual shear strength of the soil.

For the 533- and 511-ton silage loads, equation (2) indicated factors of safety of 1.10 and 1.14 respectively based on the average undrained field vane strength of the soil. Based on the anisotropic strength the factors of safety were 0.99 and 1.01 respectively. Because the structure did fail, the real factor of safety had to be of this order. Allowing for soil adhesion (equation (3)) the factors of safety were increased to 1.01 and 1.04 respectively. These values are still so close to unity that the design would have been considered unsafe. On the other hand, equation (4) predicted 1.20 and 1.24 respectively, which would normally have been adequate for design. Thus equations (3) and (4) which allow for soil adhesion to the foundations overestimate the ultimate bearing capacity for the weak marine clay.

TABLE 3. - COMPARISON OF FACTORS OF SAFETY DETERMINED BY THREE METHODS USING DIFFERENT SOIL STRENGTHS FOR VARIOUS SILAGE LOADS

Analysis of Ultimate Bearing Capacity		Silage Loads' Factor of Safety			
Equation	Average Strength of Soil	600 T	533 T	511 T	342 T
(2)	565 psf, (0.276 kg/cm^2)	1.02	1.10	1.14	1.45
	500 psf, (0.244 kg/cm^2)	0.91	0.99	1.01	1.30
	356 psf, (0.174 kg/cm^2)	0.67	0.72	0.74	0.96
(3)	565 psf, (0.276 kg/cm^2)	1.04	1.13	1.16	1.49
	500 psf, (0.244 kg/cm^2)	0.93	1.01	1.04	1.33
	356 psf, (0.174 kg/cm^2)	0.68	0.74	0.76	0.98
(4)	565 psf, (0.276 kg/cm^2)	1.15	1.24	1.28	1.64
	500 psf, (0.244 kg/cm^2)	1.10	1.20	1.24	1.46
	356 psf, (0.174 kg/cm^2)	0.75	0.81	0.84	1.07

$$q_u = cN_c + p \qquad (2)$$

$$q_u = cN_c + p + \left(\frac{L}{A}\right) c' \qquad (3)$$

$$q_u = cN_c + K_s \gamma D \qquad (4)$$

In studying a number of reported failures of fills and excavations in clays from all over the world, Bjerrum* correlated the calculated factors of safety based on the undisturbed field vane strength with the Plasticity Index (I_p) (Figure 5). In this case the calculated factors of safety for the 533- and 511-ton loads based on the field vane strength of 565 psf (0.276 kg/cm^2) using equation (2) was 1.10 and 1.14 respectively, giving an average of 1.12. As shown on Figure 5 this point supported Bjerrum's correlation. It appears that this relationship may be a useful guide for establishing realistic factors of safety in design.

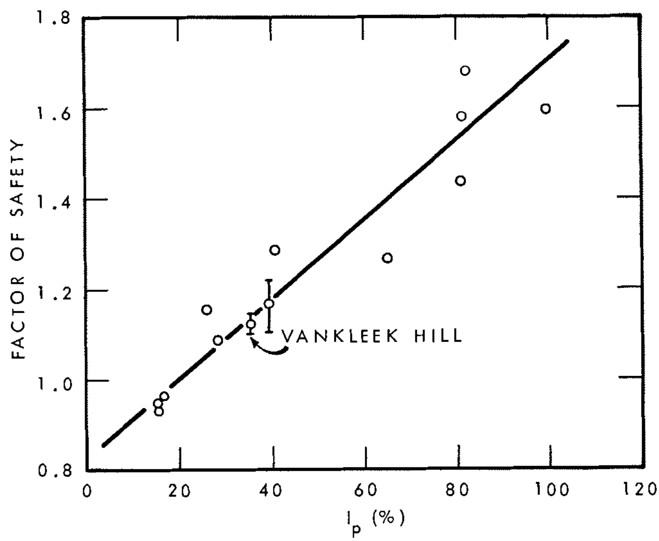

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FIGURE 5

RELATIONSHIP BETWEEN ESTIMATED FACTOR OF SAFETY AT FAILURE AND THE PLASTICITY INDEX

BR 4888-5

CONCLUSIONS

The foundation failure of the tower silo supported on weak marine clay was a full-scale field test of the shear strength of the foundation soil. The dimensions of the structure were known and it

*Personal Communication

was possible to obtain a good estimate of the applied load. The analysis led to the following conclusions:

1. The ultimate bearing capacity calculated from the anisotropic strength of the soil using equation (2) correlated extremely well with the average bearing pressure applied by the structure that contained 511 to 533 tons of silage.

2. Two of the bearing capacity equations that allow for adhesion between the sides of the foundation and the soil, overestimated the ultimate bearing capacity of the soil. It appears that when the soil is loaded rapidly to failure, adhesion does not contribute to the bearing capacity.

3. The maximum depth of the reconstructed failure surface supports Skempton's (1951) rule that the strength of the soil to a depth below the footing equal to two thirds of its diameter be used in design.

4. The field vane overestimates the in situ undrained shear strength of the soil for bearing capacity calculations. The vane measures the shearing resistance along a vertical cylindrical surface whereas the slope of the actual failure surface under the foundations varies with depth.

5. The reduction in strength of the soil along inclined shearing surfaces dictated by the reconstructed failure surface can be measured with a small laboratory vane. The strength reductions were applied to the in situ undrained shear strengths measured with the field vane to obtain the anisotropic strength of the soil.

6. The laboratory triaxial CAU tests underestimated the actual shear strength of the soil. The very low strengths were probably due to the effects of 12 to 14 months storage in a humid room before the specimens were tested.

7. This study supports Bjerrum's correlation between the calculated factor of safety based on undisturbed field vane strengths and the Plasticity Index of the soil.

ACKNOWLEDGEMENTS

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