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Publisher’s version / Version de l'éditeur:

Canadian Agricultural Engineering, 25, 1, pp. 81-88, 1983

National Research Council Canada
Conseil national de recherches Canada

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Reprinted from
Canadian Agricultural Engineering
Volume 25, No. 1, Summer 1983
p. 81 - 88

DBR Paper No. 1120
Division of Building Research

Price $1.00

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RÉSUMÉ

On a réalisé une enquête sur le comportement de 108 tours silos en béton, dont les fondations reposent sur des argiles marines peu résistantes et compressibles de l'est de Montréal qui s'étendent sur une zone de 150 km par 60 km. Une classification du comportement a été basée sur les résultats de cette enquête, en considérant le facteur de sécurité vis-à-vis d'un dépassement de la capacité portante, le tassement mesurable et l'inclinaison. Un facteur de sécurité égal ou supérieur à 2.5 à la conception garantit un bon comportement. La présence d'une croûte épaisse, résistante et sèche réduit le tassement et l'inclinaison.

PERFORMANCE OF CONCRETE TOWER SILOS ON CLAYS IN QUEBEC

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Received 28 June 1982, accepted 14 December 1982

Morin, J. P. and **M. Bozozuk**. 1983. Performance of concrete tower silos on clays in Quebec. Can. Agric. Eng. 25: 81–88.

A performance survey has been carried out on 108 concrete tower silos founded on weak, compressible marine clays east of Montreal in an area 150 × 60 km. A performance classification was developed based on the results of the survey, the calculated factor of safety against a bearing capacity failure, measured settlement, and tilt. A factor of safety equal to or greater than 2.5 provided a design that performed well. The presence of a deep, strong, desiccated crust reduces settlement and tilt.

INTRODUCTION

The concrete tower silo has been a popular and efficient structure for storing silage on Canadian farms for about four decades. By the end of 1978 there were 9430 silos in Quebec alone (M. Fortier 1978, pers. commun.). Large concrete tower silos evolved over this time from the original, mainly wooden structures, but most of the development went into the superstructure and mechanical plant for handling silage. The design of the foundations with respect to bearing capacity of the supporting clay soils was largely ignored, with the result that many of the structures settled and tilted various amounts and even overturned on occasion.

As the proportion of large tower silos has grown over the past 10–15 yr, the number of problems has increased alarmingly. Research work conducted in the province of Ontario related many problems such as excessive settling, tilting, and bearing capacity failure to inadequate foundations (Eden and Bozozuk 1962; Bozozuk 1972, 1974, 1976, 1979a,b; Lo and Becker 1979). In Quebec the Ministère de l'agriculture, in 1975, supported a comprehensive study by the University of Sherbrooke to determine the cause of the problem. Gervais (1980) and Morin and Gervais (1980) showed that most foundations were constructed without consideration of the supporting soil. The complete survey covered 138 silos, of which 108 were concrete tower silos constructed on weak marine clays, and 30 were other silos and different soils. This paper reviews the performance of the 108 concrete silos in relation to the bearing capacity of the foundation clays.

GEOLOGY OF STUDY AREA

Most of the silos were located within an area bounded by the St. Lawrence River to the west and north, the towns of Nicolet, Drummondville and Granby to the east, and the U.S. border to the south (Fig. 1). The area is approximately 150 km long by 60 km wide and makes up a large portion of the rich farmland in the Central St. Lawrence Lowland.

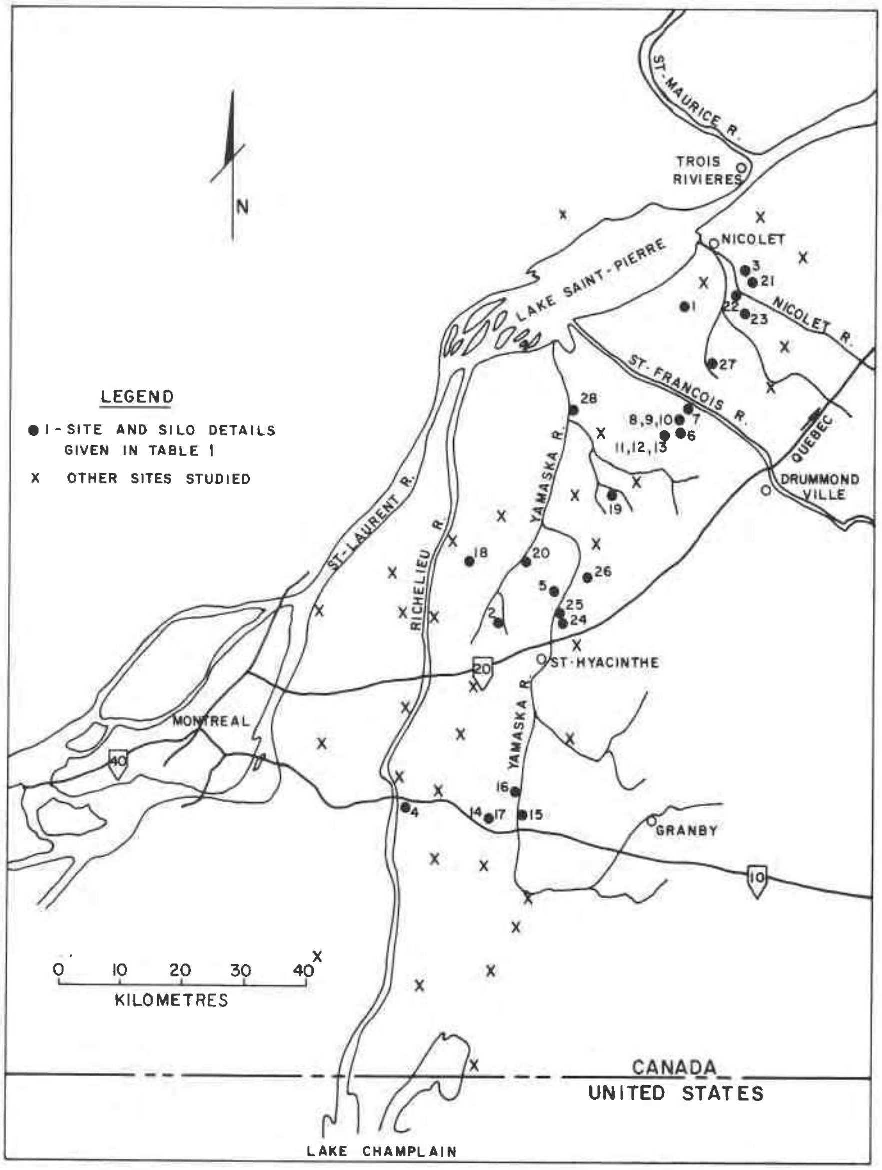

Figure 1. Study area and location of surveyed silos.

The topography is relatively flat and poorly drained, and has a high groundwater table. According to Gadd (1971), La Salle (1963) and La Salle and Elson (1962) the subsoils are mainly marine clays deposited in the Champlain Sea which covered the area 10 000 to 12 000 yr ago. Although these clays are fertile (Lajoie 1975), they are weak structurally and are generally unable to support large surface loads without significant deformation or even failure.

Some areas are better drained than others, and this has caused changes in the physical properties of the soil. Where the hard surface crust is relatively thin, i.e. less than 1 m, the underlying clays are normally very weak. Where the crust is relatively thick (3–4 m) the clays are generally much stronger and are better able to support large tower silos.

In some areas the marine clay deposits are buried by freshwater sediments that now make up high and low sand terraces. The presence of overlying freshwater deposits may present special foundation conditions that must be considered where large tower silos are contemplated.

PERFORMANCE SURVEY

In 1975 and 1976 a comprehensive survey was taken of 95 farmers about the performance of their concrete tower silos (top unloading). Their replies were documented, along with detailed descriptions of the structures: 52% of the silos were cast-in-place and the remaining 48% were made of precast concrete staves. They were supported on concrete ring foundations with the silo wall placed near the inner diameter of the ring. All contained drains for silage juices. The cast-in-place concrete silos also had a thin concrete floor slab independent of the ring foundation.

Footings were generally placed as near the ground surface as possible (i.e. shallow foundations) to benefit from the high strength of the fissured crust. Frost heave did not appear to be much of a problem; only two farmers reported frost action. Frost effects were not cumulative; they disappeared during spring thaw, allowing the structures to settle back into place.

Most farmers were satisfied if their silos remained essentially vertical and experienced little settlement. They accepted those with noticeable tilt or a fair amount of settlement reluctantly, provided there was no problem with the operation of the unloaders. Where settlements and tilt significantly interfered with the operation of the silos the farmers rejected them unanimously. These replies were useful in developing the performance classification for concrete tower silos presented in the paper.

SOILS INVESTIGATIONS

Based upon the results of the questionnaire, 79 sites were selected for subsoil investigation. The Nilcon vane was used to determine the shear strength profile, with measurements made at 0.5-m intervals to a depth of 12 m. Morin and Gervais (1980) observed a wide range of shear strength profiles throughout the area (Fig. 2). Because the ultimate bearing capacity of the soil is directly related to its shear strength, it is apparent that there will also be a wide range in bearing capacity over the same area. It is impossible, therefore, to determine a unique and realistic allowable bearing capacity for the whole region. Visual inspection of the silos and identification of the soil profile were carried out at 64 of the sites on disturbed soil samples obtained with a small-diameter auger to supplement the vane strength tests. Auger depths of 1–3 m were generally sufficient to identify the thickness of the desiccated crust and to establish the depth of the groundwater table.

Detailed undisturbed soil sampling and laboratory testing were carried out at the remaining 15 sites. The tests included measurements of water content, bulk density of the soil, consolidation characteristics, and soil grain size distribution. Figure 3 is a typical set of test results at one location, showing the variations within the soil formations, thickness of the desiccated crust, depth of the groundwater table, shear strength profile, preconsolidation pressure profile, water content, soil grain sizes, and vertical effective stress with depth. This detailed information is required to determine the bearing capacity of the soil and to estimate the settlement behavior of a silo with time. The complete test results are reported elsewhere by Morin and Gervais (1980).

BEARING CAPACITY OF CLAY SOILS

The bearing capacity of a soil is a soil/structure interaction problem. Primarily it is a function of the shear strength of the supporting soil, but it is also related to the number of different formations in the soil profile and to the size, shape, stiffness and depth of the foundation. The analytical methods of Button (1953), Mandel and

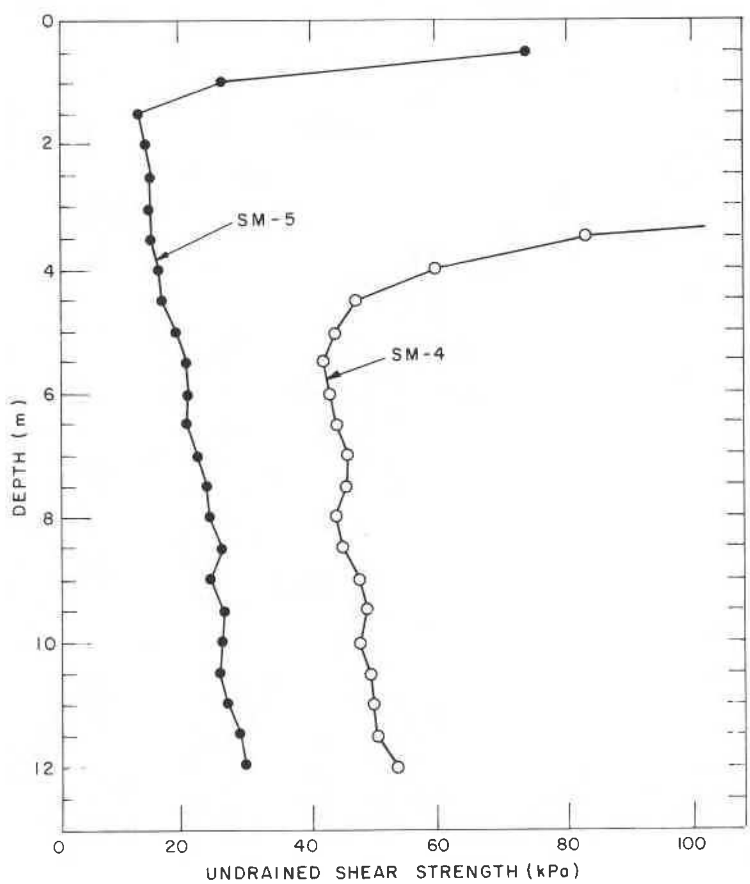

Figure 2. Range of undrained shear strengths measured in situ with a Nilcon vane.

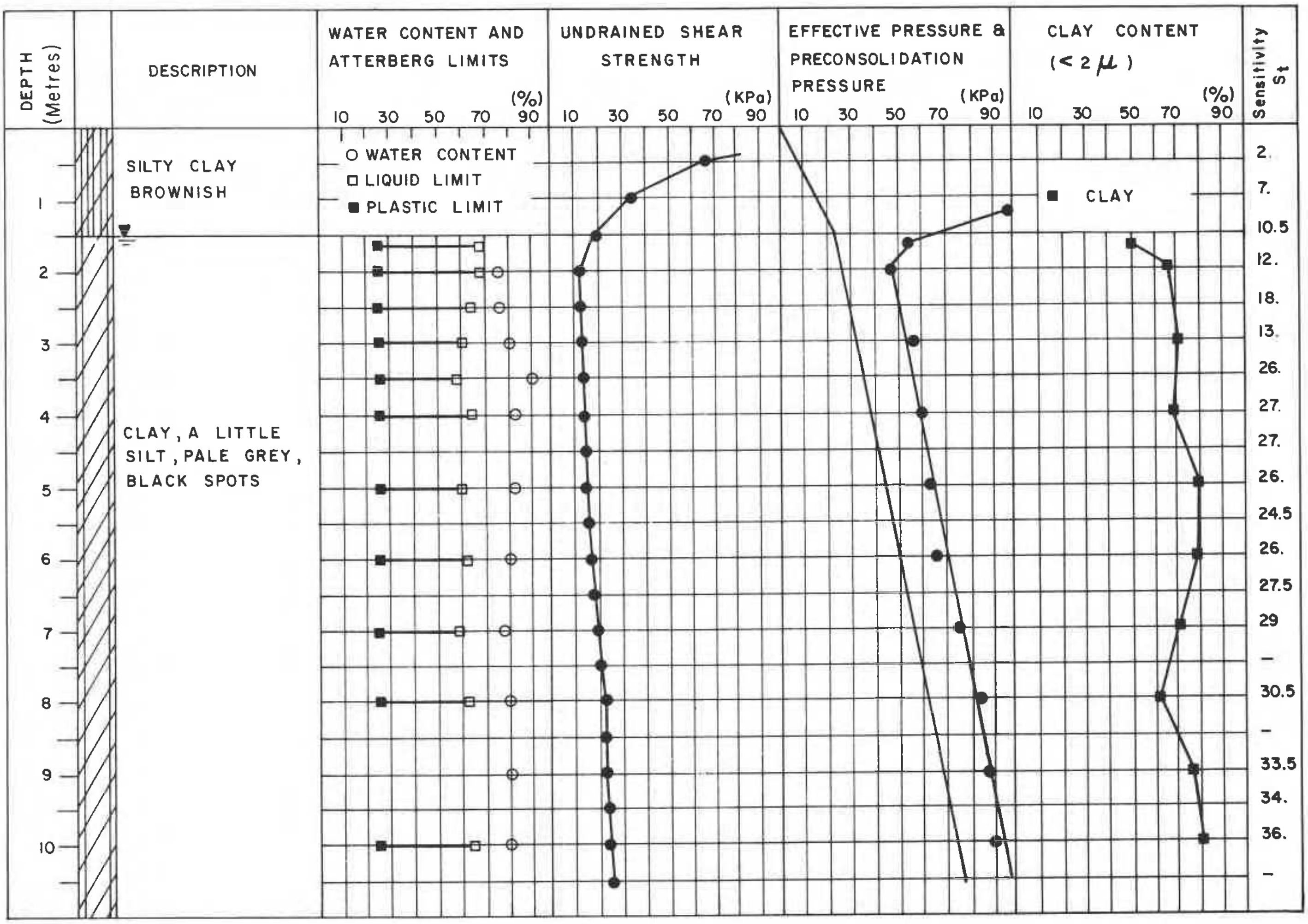

Figure 3. Detailed soil profile and summary of test results.

Salençon (1969), and Skempton (1951) were compared in the study. Of these, the equations proposed by Skempton (1951) were found to give the best estimates of ultimate bearing capacity of the marine clay, supporting the earlier conclusions of Bozozuk (1972).

According to Skempton (1951), the ultimate bearing capacity, q_u, of the clay soil is given by

$$q_u = cN_c + \gamma D \quad (1)$$

where N_c = bearing capacity factor of clay, depending upon shape and depth of footing; c = average shear strength of soil below the foundation to a depth equal to two thirds the outside diameter of the foundation; D = depth of foundation below ground surface; and γ = bulk density of soil to depth D.

The allowable bearing capacity of the soil that is used for the design of a silo foundation on clay is normally given by

$$q_a = \frac{c}{F} N_c + \gamma D \quad (2)$$

where F = the design factor of safety against a bearing capacity failure (usually taken equal to 3.0 for engineering designs). The contribution of γD to the factor of safety is normally very small in shallow foundations and is often omitted in its evaluation for practical purposes.

The adhesion between the side of the foundation and the confining soil may increase the ultimate bearing capacity (Skempton 1942; Meyerhof 1951) provided that it is always fully developed. Because tower silos may settle differentially and therefore tilt, this adhesion is easily destroyed and should not be included in the determination of bearing capacity.

Farmers will accept some tilt and settlement of their silos if there is no safety hazard and no effect on operating procedures. The question is, therefore, what minimum factor of safety, F, can be used in the design of the foundation?

FACTOR OF SAFETY

The factor of safety against a bearing capacity failure is defined by Eq. 2. The applied load consists of the combined weight of the silo superstructure, the silage, and the foundation. In the present study the weight of the silo and its foundation was based on the volume of concrete used, and the weight of silage was determined from the volume of silage stored and the density-height relation introduced by Bozozuk (1972). (The density-height relation was determined for corn silage with 70% moisture). It was assumed that total weight was distributed uniformly over the whole area enclosed by the ring foundation and was applied to the soil at the level of the footing. This assumption was found to be reasonable after several cycles of loading and unloading (Bozozuk 1979b).

The ultimate bearing capacity and the net applied bearing pressure were determined for each of the 28 sites listed in Table I. The resulting factors of safety varied from a minimum of 1.36 to more than 5.0, providing a potentially wide range in behavior from unacceptable to excellent.

TABLE I. DESCRIPTION, STABILITY AND PERFORMANCE OF CONCRETE TOWER SILOS

Location no. (see Fig. 1)†	Silo dimensions (diam. × ht.) (m)	Type‡	Year built	Foundation: Dimensions (thickness × outside diam.) (m)	Foundation: Type§	Average settlement (4 cycles) (mm)	Tilt (% height)	Factor of safety	Perf. (Table II)
1	5.5×18.3	CS	1975	0.6× 8.2	ADN	155	0.27	2.16	C
2[1]	6.1×18.3	CP	1976	0.6× 8.8	BSFDE	27	0.05	2.62	A
3	6.1×18.3	CS	1975	0.6× 9.4	ADN	27	0.38	3.61	B
4	6.1×18.3	CP	1975	0.6× 7.6	BSFDE	67	0.05	2.50	B
5	6.1×18.3	CP	1975	0.6×10.7	BSFDN	408	0.37	1.68	D
6	5.5×14.6	CP	1975	0.9× 9.1	HSFDN	70	0.47	2.36	B
7	4.9×17.1	CP	1975	0.5× 7.9	BSFDN	52	0.35	3.04	B
8	5.5×15.8	CP	1975	0.6× 9.4	BSFDE	259	1.16	1.80	D
9[2]	5.5×18.3	CP	1974	1.1× 7.3	BSFDE	116	0.21	2.31	C
10	5.5×17.1	CP	1975	0.6× 8.5	BSDCE	91	0.26	3.32	C
11	5.5×15.8	CP	1975	0.6× 9.4	BSFDE	143	0.84	3.52	C
12[3]	4.9×17.1	CP	1975	0.6× 8.5	BSFDE	174	1.12	1.80	D
13	6.1×17.1	CP	1975	0.9× 9.4	BSFDN	351	2.42	1.73	E
14	6.1×18.3	CP	1975	0.8× 8.5	BSFDE	195	0.14	2.42	D
15	6.1×21.9	CP	1975	0.6× 9.0	BSFDE	55	0.62	2.29	B
16	6.1×16.8	CS	1975	0.6× 7.9	ADN	3	0	4.03	A
17[4]	6.1×18.3	CP	1974	0.6× 9.1	BSFDE	300	1.20	2.59	D
18[5]	6.1×18.3	CP	1976	0.6×12.2	BSFDN	442	0.43	1.61	E
19	4.9×18.3	CP	1975	0.6× 7.6	BSFDN	219	0.41	1.73	D
20	4.9×19.5	CP	1975	0.8× 6.4	BSFDE	24	0.29	3.28	B
21[6]	6.1×15.2	CS	1975	0.6× 8.2	BDN	402	1.77	1.84	E
22	5.5×16.8	CS	1975	0.6× 8.1	ADN	21	0.05	5.22	A
23	6.1×15.2	CS	1975	0.6× 9.1	ADCN	61	0.20	3.52	B
24	5.5×15.2	CS	1975	0.6× 8.5	ASDN	43	0.27	3.40	B
25	7.3×24.4	CP	1975	0.6×11.0	BSFDN	30	0.08	2.78	B
26[7]	7.3×23.2	CP	1975	0.6× 9.4	BSFDE	168	1.04	1.36	E
27	5.5×18.3	CS	1975	1.2× 8.5	ADCN	168	1.03	1.58	D
28	4.9×15.2	CS	1975	0.9× 6.7	ADN	18	0.24	2.54	B

†[1]Last observed settlement and tilt after first loading. Instrumentation destroyed October 1977.
[2]Structure built in 1974, but full load applied after second year.
[3]According to owner, loads applied were only dead structural load in first year, increasing gradually to maximum nominal load in fourth year. Factor of safety is applied to last load.
[4]Structure straightened after third loading.
[5]Last observed settlement and tilt before third loading; instrumentation destroyed November 1978.
[6]Last observed settlement and tilt before fourth loading; instrumentation destroyed November 1978.
[7]Last observed settlement and tilt on second loading; structure straightened afterwards.
‡CS, precast concrete stave; CP, cast in-place concrete.
§A, annular foundation with small concrete wall at base of tower silo; B, plain annular foundation; H, modification of foundation of previous wooden silo; S, steel reinforcement in footing; F, concrete floor at bottom of silo; D, drainage provided for silage juice; C, cracked foundation (visual observation); N, natural soil, undisturbed; construction may or may not be on a small fill; E, excavation of top part of natural soil; excavation usually less than thickness of annular foundation.

SETTLEMENT AND INCLINATION

Settlement and inclination or tilt were measured at the 28 sites listed in Table I. Four marks were painted at 90-degree intervals around the outside circumference of each silo, just above the foundation, to provide reference marks for the level surveys. A deep benchmark consisting of a long steel pipe with a foot attached at its lower end and protected by a steel casing (Bozozuk et al. 1962) was pushed to refusal through the clay to provide a stable datum for the surveys.

Level surveys were performed on the silos as soon as possible after construction and again just before they were filled. Subsequent surveys were carried out immediately after filling and later in the spring when they were empty. Typical settlement records for two silos are shown on Fig. 4. At site 3, a concrete stave silo that had performed satisfactorily settled an average of 27 mm after 3 yr (three cycles of loading and unloading), and at site 13 a cast-in-place concrete silo that had performed poorly settled an average of 351 mm for comparable loading and time. The observed settlements for the 28 silos after four cycles of loading are reported in Table I.

No attempt was made to estimate vertical settlements. Such a study had been performed by Lo and Becker (1980) on an instrumented cast-in-place concrete silo 9.1 m in diameter and 21.9 m high, founded on compressible soft clays near Wallaceburg, Ontario. They reported that the observed maximum settlement was about 25% of the calculated ultimate, assuming the silo was full all of the time. Furthermore, maximum settlement occurred after about five complete cycles of loading and unloading. Beyond this time, settlements were essentially elastic in nature, in that additional settlement due to loading was about equal to the vertical rebound upon complete unloading. This behavior was assumed to apply to the silos on the marine clays included in this study.

Inclination or tilt is often caused by differential settlement of the foundation. It can be calculated from the product of maximum measured differential settlement and the ratio of silo height to diameter, both of which are known or can be measured. This method was used to determine the tilt of the 28 silos and is expressed as percent of silo height in Table I. It varies from a minimum of 0% for a concrete stave silo that behaved well at site 16 to a maximum of 2.42% for a cast-in-place concrete silo that behaved poorly at site 13. The changes in tilt with time for the silos at sites 3 and 13 are illustrated in Fig. 4.

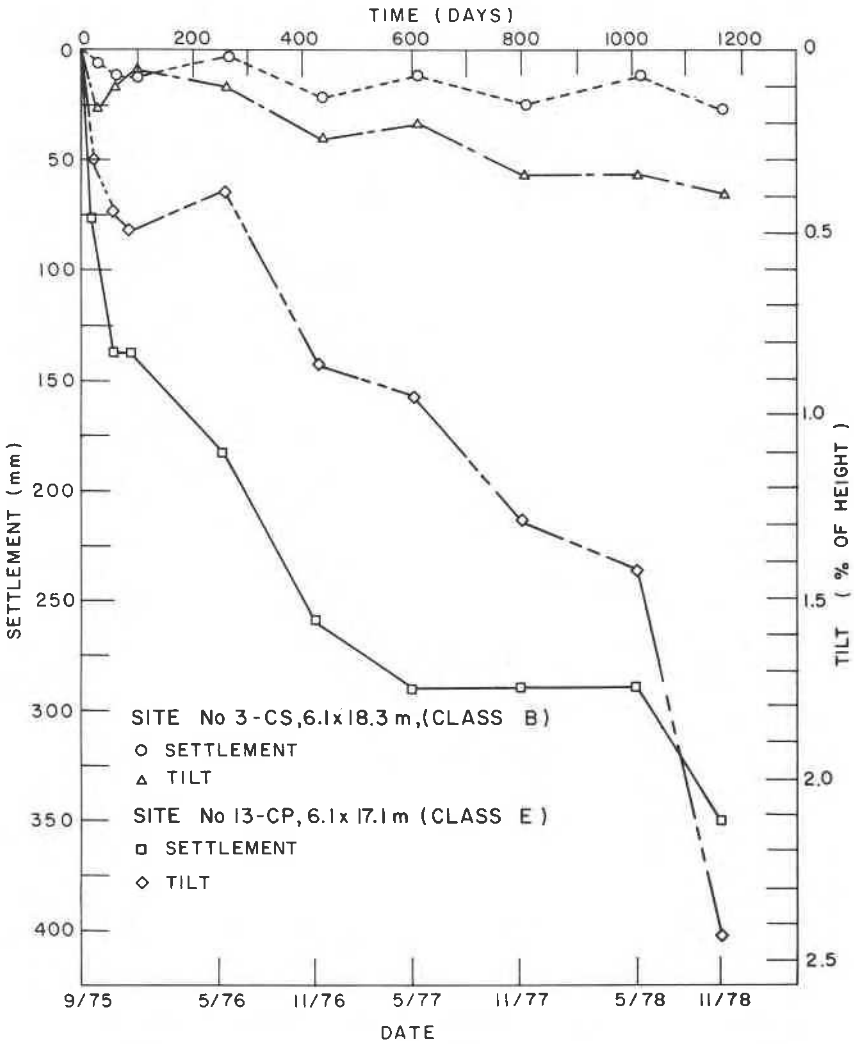

Figure 4. Measured settlement and tilt for two tower silos from 1975 to 1978.

EVALUATION OF PERFORMANCE

A performance classification for concrete tower silos on clay soils was developed primarily from opinions on performance recorded in the questionnaire returned by the farmers. These were correlated with reported or measured settlement and tilt from which five ratings ranging from excellent (A) to unsatisfactory (E) were developed.

A silo with a foundation designed according to good engineering practice, i.e., with a factor of safety ⩾ 3 against a bearing capacity failure, should, in general, settle less than 25 mm. Assuming that the differential settlement would not exceed 75% of this total, a 6-m-diameter silo would not tilt more than 0.3% of its height. Performance of this type was considered excellent by the farmers and was rated A.

Many farmers were willing to accept greater settlement and tilt provided there was no interference with daily operation and use of the silo. The limits for this acceptance coincided with the 75-mm total settlement for structures on clay given in the Canadian Foundation Engineering Manual (1978) and with a maximum inclination or tilt of 0.8% of silo height (out-of-plumb of 25 mm in 3.0 m), originally given by the Ontario Silo Association Standards (1980) and later changed to 25 mm in 4.5 m in 1980. Silos meeting this performance were rated B.

When total settlement and tilt exceeded 150 mm and 1.7%, respectively, serious problems unacceptable to the farmers were frequently reported. These silos were rated D. Very serious problems, including some catastrophic bearing capacity failures, occurred when settlements and tilt exceeded 300 mm and 2.5%, respectively, and dictated an E rating. Settlements between 75 and 150 mm and tilts between 0.8 and 1.7% were often acceptable and these silos were rated C.

A general performance classification for total settlement and tilt for concrete silos on clay soils, based upon the above guidelines, was proposed (Table II). It was applied to the 28 silos in Table I, in which it is possible to compare the factor of safety with performance after four cycles of loading and unloading. Of these, three rated A, ten rated B, four rated C, seven rated D, and four rated E. As expected, silos with good performance ratings had the highest factors of safety. The relation between factor of safety and settlement for the first loading cycle is shown in Fig. 5. Performance classification is also superimposed on the figure. For this loading, silos with high factors of safety had the smallest settlement and gave excellent performance. Tilting in excess of 0.3% occurred in 14% of the structures.

The relation after the fourth cycle is shown in Fig. 6. Compared to the first cycle, the correlation curve is displaced in the direction of increasing settlement, that is, lower down the performance classification. The number of silos that tilted more than 0.3% increased to about 50%.

Based on their laboratory tests and field observations, Lo and Becker (1980) reported that settlements would reach a maximum after about five cycles of loading and unloading. Observations in the present study were, unfortunately, terminated after four cycles (4 yr). Changes in silo performance for the four cycles are illustrated in Fig. 7. It appears that a fifth loading cycle would not provide significantly different correlation among factors

TABLE II. PERFORMANCE CRITERIA FOR TOWER SILOS

Rating	Performance	Vertical settlement (mm)	Tilt: Degrees	Tilt: % height
A	Excellent	Below 25	Below 0.2	0.3
B	Good with light problems	25–75	0.2–0.5	0.3–0.8
C	Important problems	75–150	0.5–1.0	0.8–1.7
D	Serious problems	150–300	1.0–1.5	1.7–2.5
E	Very serious problems	Over 300	Over 1.5	Over 2.5

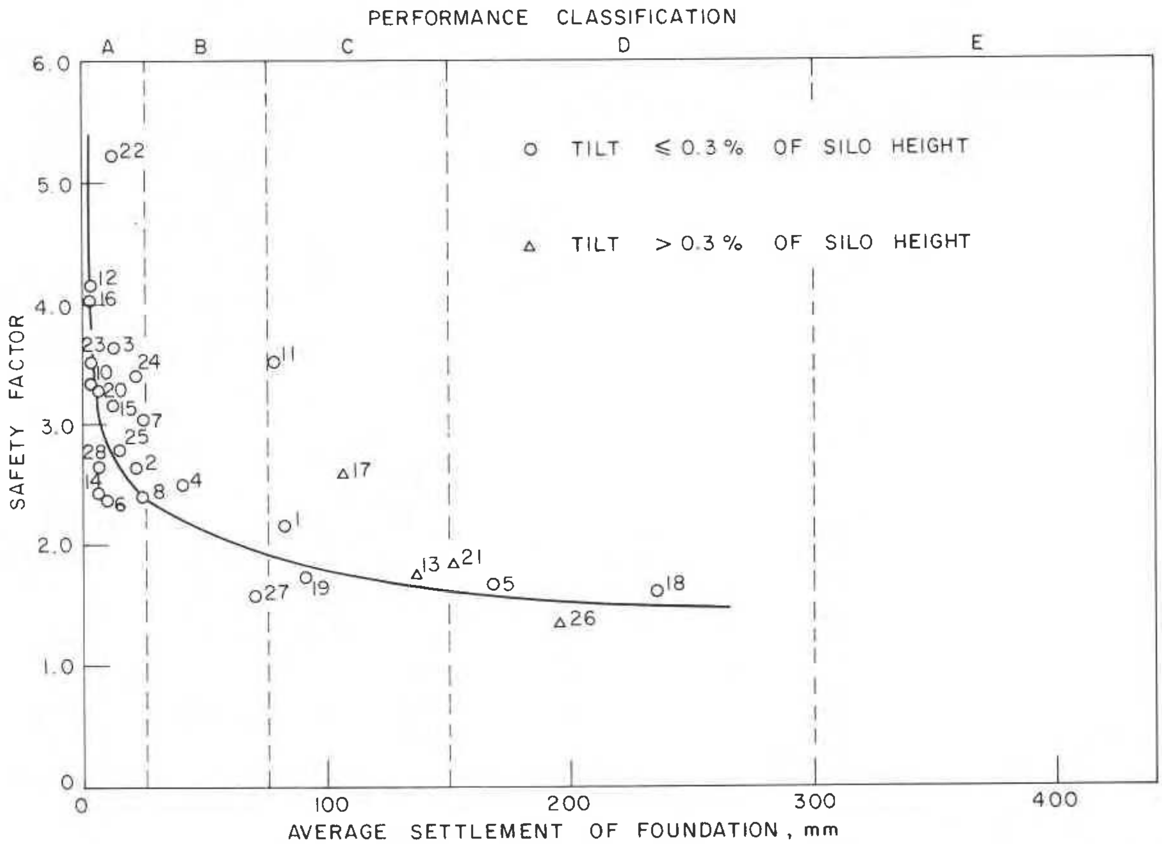

Figure 5. Relation between settlement and safety factor (load cycle no. 1).

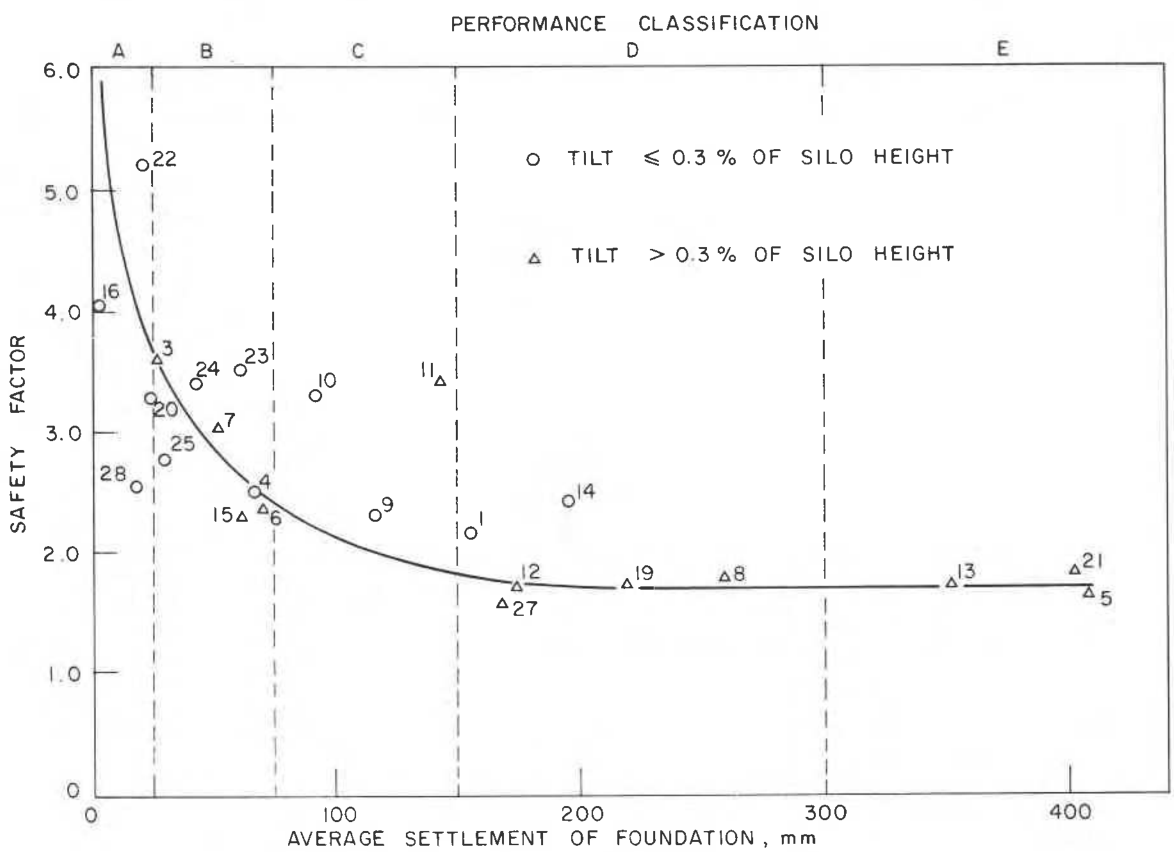

Figure 6. Relation between settlement and safety factor (load cycle no. 4).

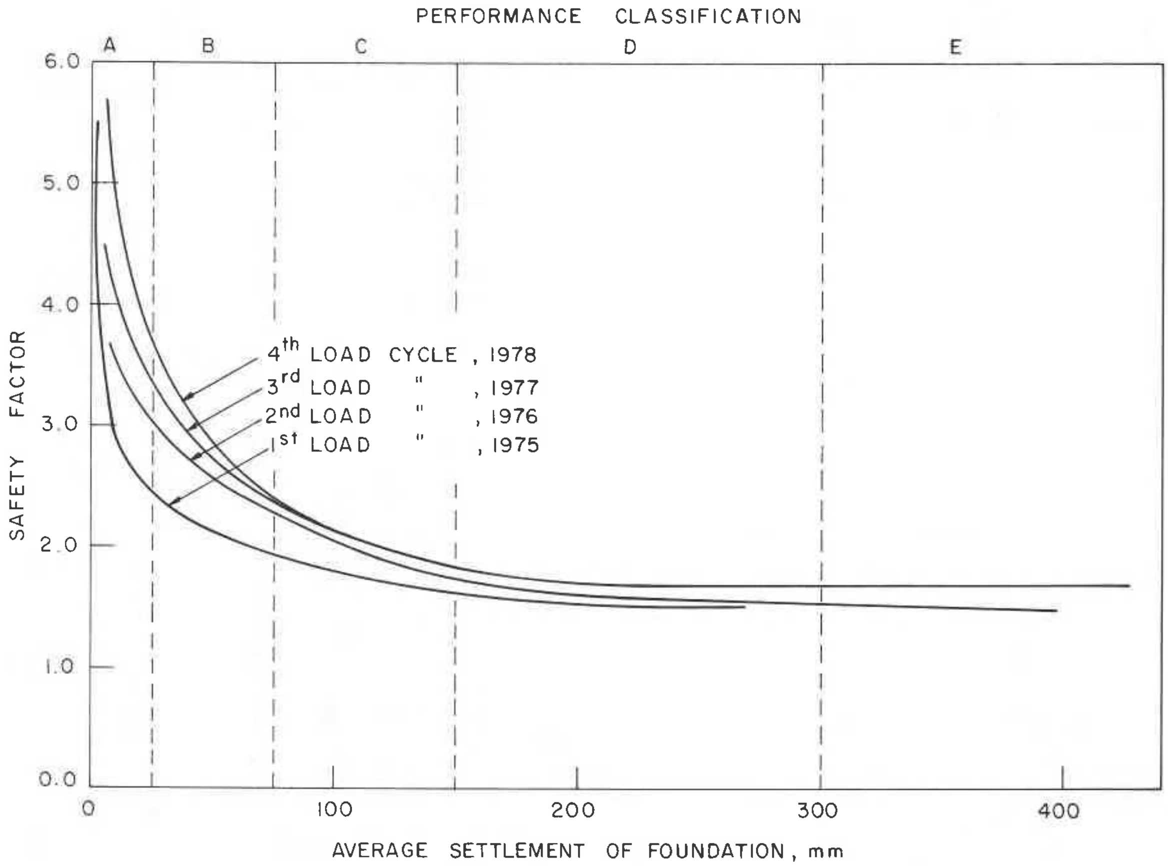

Figure 7. Relation between settlement and safety factor for four loading cycles.

of safety, settlement, and performance from that indicated by the fourth.

Assuming that the correlation from the fourth cycle is reasonable, a foundation on clay constructed with a minimum factor of safety of 2.5 should perform well, and at less than 2.0 the expected performance would be unacceptable. These criteria were applied to 80 silos (other than the 28 where detailed studies were performed). The factor of safety was determined from in situ vane shear tests performed in the vicinity of each silo. The expected performance determined on the basis of factor of safety was as follows:

$F \geqslant 3.0$, excellent

$F \geqslant 2.5$, very good performance, silos were acceptable

$2.5 > F \geqslant 2.0$, performance tolerated, important problems could be expected

$F < 2.0$, performance generally unsatisfactory, serious problems could be expected

According to the replies from the silo survey 55% of the farmers agreed with this over-all performance rating; 30% tolerated less settlement and tilt; and 15% tolerated more settlement and tilt.

The detailed breakdown of support for performance rating based on factor of safety for the 80 silos is shown in Table III. If borderline cases (broken foundations, silos to be straightened, foundations built under the crust) are eliminated, Table 24 of the report by Morin and Gervais (1980) gives the following percentages, which are consistent with the classification: 79% for $F > 2.5$, 71% for F between 2.0 and 2.5 and 56% for $F < 2.0$. Factor of safety is, therefore, an excellent indicator of performance. If a proposed silo is to perform in a manner acceptable to the farmer, it should be designed with a factor of safety against a bearing capacity failure of > 2.5.

DISCUSSION

The support for the performance classification incorporating the factor of safety as presented above was good. Several cases are known, however, where the factor of safety was less than 2 and the performance was acceptable. In these instances the silos remained essentially vertical and there were few operational problems although the vertical settlements were large. Such cases have occurred frequently enough, but other similar silos in neighboring areas do not always perform so well.

When silo foundations are constructed on a deep, strong desiccated crust, as at sites 6, 9, 15 and 28 (Morin and Gervais 1980; Lo and Becker 1980), the crust performs as a raft and spreads the applied load over a large area. The vertical settlement and inclination are therefore reduced, and the silo performs well in spite of the fact that the factor of safety may be low. Factors of safety less than 2.5 can therefore be used for design where a thick

TABLE III. DETAILED BREAKDOWN OF SUPPORT FOR PERFORMANCE RATING BASED ON FACTOR OF SAFETY

Factor of safety	In support of classification (%)	More severe (%)	Less severe (%)
$F \geqslant 2.5$	67	33	0
$2.5 > F \geqslant 2.0$	52	48	0
$F < 2.0$	49	15	36

crust is present, but never without a detailed soils investigation and analysis.

The preceding discussion applies to single, or isolated, silos. When additional silos are to be added adjacent to them, the interaction of the pressure bulbs would increase the differential and total settlements and cause the silos to tilt. This effect becomes more pronounced at the lower factors of safety. Consequently, if a farmer needs more than one silo, each foundation may have to be designed with a factor of safety greater than 2.5.

SUMMARY AND CONCLUSIONS

The performance over a 4-yr period between 1975 and 1979 of 108 concrete cast-in-place and precast stave silos constructed on marine clays in Quebec varied from a rating of A (excellent) to one of E (poor, with very serious problems). Detailed soil testing and analyses at 28 selected sites related performance to settlement, tilt, and factor of safety against a bearing capacity failure. This correlation was applied to 80 silos for which performance was documented by means of a questionnaire and the shear strength of the clays was measured in situ with a field vane. The study produced the following conclusions: (1) The recommended factor of safety for the design of foundations on clay is 3.0 for concrete tower silos. (2) The minimum factor of safety for the design of concrete tower silo foundations on clay with a desiccated crust should be greater than 2.5. (3) Provided they remain vertical, tower silos with low factors of safety and large vertical settlement can perform well. (4) The presence of a deep, strong, desiccated crust spreads the applied load over a large area, reducing settlement and tilt; consequently, factors of safety lower than 2.5 can be used for foundation design in such cases.

ACKNOWLEDGMENTS

This project was carried out with the cooperation of many farmers and silo builders in Quebec. R. Gervais, M.Sc.A., University of Sherbrooke, performed the work for his thesis under the direction of the senior author. Financial support was provided by Ministère de l'agriculture, Gouvernement du Québec. The paper is published with the approval of Prof. G. Lefebvre, Head, Department of Civil Engineering, University of Sherbrooke, and of Mr. C. B. Crawford, Director, Division of Building Research, National Research Council of Canada.

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