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SOMMAIRE

Chaque année, plusieurs milliers de tours d'ensilage sont construites au Canada et la plupart d'entre elles fonctionnent très bien. Récemment, des problèmes sont survenus dans les constructions plus grandes concernant la capacité portante des sols, les fondations inadéquates ou mal conçues, les jus d'ensilage, la détérioration du béton avec le temps, le relâchement des cerclages d'acier, la répartition non uniforme à l'ensilage et les surchages entraînant des déformations et des contraintes excessives aux parois. L'auteur décrit ces problèmes dans le cadre de 6 cas concrets.

PROBLEMS WITH CONCRETE TOWER SILOS

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Several thousand tower silos are erected on Canadian farms each year, and for the most part perform very well. Recently some problems with larger structures have appeared in connection with bearing capacity of the soils, inadequate and underdesigned foundations, silage juices, deterioration of concrete with time, relaxation of steel hoops, non-uniform placement of silage, and overloading resulting in deformation and overstressing of silo walls. These problems are discussed in the six selected case histories presented in this paper.

INTRODUCTION

Over the past 10 yr, an average of nearly 1500 concrete stave and cast-in-place concrete tower silos were constructed annually for the agricultural industry in Ontario. In Quebec the number constructed was about three-quarters of that in Ontario. The number of steel silos built is unknown, but it is reasonable to assume that over 3000 tower silos of all types have been constructed annually for the past 10 yr in this country.

If surveyed carefully, many of these silos will show some differential settlement or tilting which goes unnoticed as there is no interference with the farmers' operations and use of the structures. Considering the large numbers constructed, it is a tribute to the silo construction industry that so many structures behave so well.

In a small percentage of cases, however, serious problems have occurred. In weak compressible clay areas, tall silos have overturned when the applied loads exceeded the bearing capacity of the foundation soils (Bozozuk 1972, 1977; Eden and Bozozuk 1962). Others have tilted or deformed to such an extent that they cannot be used, and sometimes become a hazard to neighboring structures and to livestock. This paper presents a number of selected case histories to identify many of the serious problems encountered recently with tower silos. During the investigations, the farmers' descriptions were used to describe the condition of the silage, as measurements of moisture content were not made when the silos were filled or when the studies were made. All silos were filled using distributors.

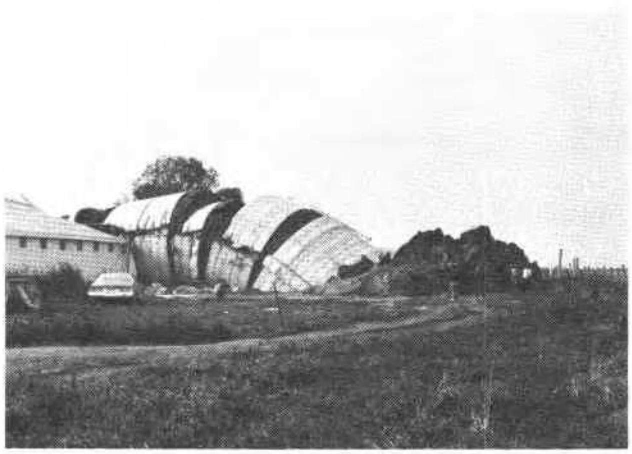

Figure 1. Bearing capacity failure of soil for 9.14-m diameter, 32.3-m high concrete silo at Richmond, 30 Sept. 1975.

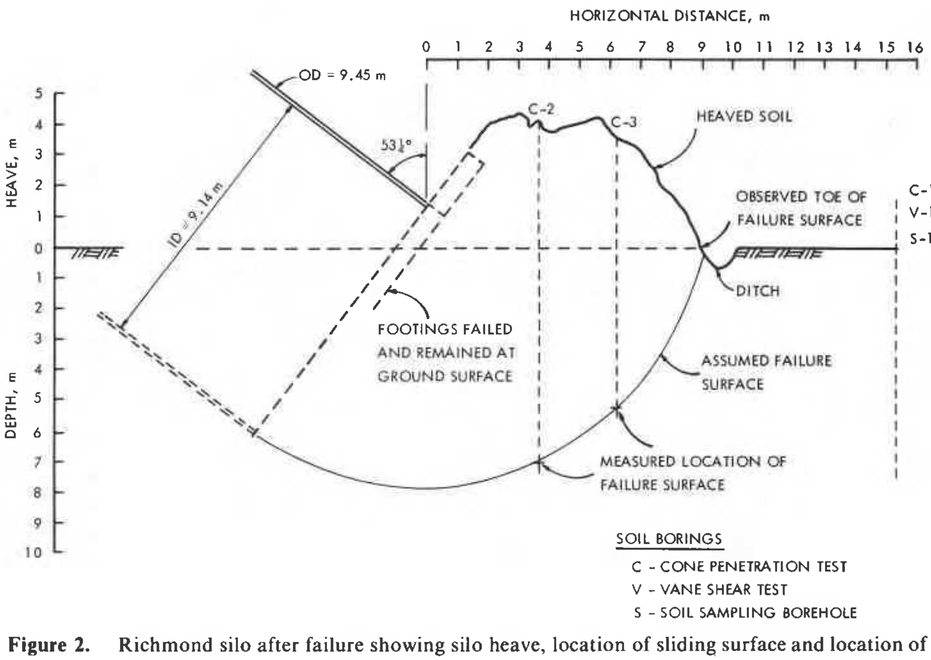

Figure 2. Richmond silo after failure showing silo heave, location of sliding surface and location of soil borings.

RICHMOND

In August 1975, a concrete tower silo 9.14 m in diameter, 32.3 m high, was constructed on overconsolidated marine deposits of the Champlain Sea. The cylindrical concrete wall was 152 mm thick and was reinforced circumferentially with steel bars embedded in the concrete during construction. The foundation was cast-in-place non-reinforced concrete in the form of a ring 610 mm thick, with inside and outside diameters of 7.62 m and 11.89 m, respectively. Drains were provided in the base of the silo wall to control the silage juices.

The Failure

On 30 Sept. when the silo was being filled, it overturned at a load of 1800 tonnes (Fig. 1). The combined mass of the structure and its contents at the time was 2260 tonnes. In falling, it destroyed a large part of a new barn, and damaged part of an old one; the explosive force on impact blew the roof off the silo and overturned a truck parked on the other side of the new barn. Neighbours 0.5 km away felt the ground vibrations at the time of impact. Fortunately the livestock were evacuated from the barn just prior to the failure.

When the silo was being filled, it was observed that the concrete footing had cracked. As filling continued, the cracks widened, the toes of the cracked sections heaved, and the silo started tilting, at which time filling was suspended. Unfortunately the contact area under the foundation was reduced, and the silo overturned.

The position of the silo foundation after failure is shown in Fig. 2. The intact part of the silo was inclined 53° from the vertical. As the base rotated, part of the silo tube sank 6 m, whereas the opposite edge heaved 1.5 m. The soil heaved for a distance of 9 m and formed a mound about 4.5 m high.

Soil Investigation

The soils investigation consisted of sampling for laboratory analysis, in situ vane shear strength tests for determining the bearing capacity of the soil, and in situ cone penetration tests to locate the failure surface. The locations of these borings are shown in Fig. 2.

The soil profile is shown in Fig. 3a. Below the topsoil, a hard desiccated brown clayey silt formation extended to a depth of 2.4 m, the depth where the groundwater table was encountered. The underlying material was a softer gray clayey silt with traces of black mottling at 3.1 m. At 5.0 m the soil changed to gray silty clay with black mottling. This formation extended to a depth of 15.5 m. The last 4.5 m of the borehole contained brittle gray silty clay with no mottling.

The classification tests (Fig. 3b) indicated a plasticity index of 20% and a liquid limit of 40% for the soil profile. (The classification test results are indicators of the engineering behavior of the soils (Lambe 1951)). At 2 m the water content of the soil was about equal to the liquid limits, but it gradually increased with depth to 60% at 9 m indicating that the clays were extremely sensitive. Grain size analysis showed 37% clay and 63% silt size particles at 2 m, changing almost linearly with depth to 58% clay and 42% silt at 16 m.

The in situ shear strength of the soil measured with the NGI vane (Andresen and Bjerrum 1956) is shown in Fig. 3c. The strength was quite high in the desiccated crust, reaching 65 kPa. It reduced rapidly to 45 kPa at the base of this formation and continued to decrease to a minimum of 31 kPa at 5 m. The strength was about constant for the next 3 m, then increased with depth to the bottom of the boring. The average shear strength below the footing to a depth of two-thirds the outside diameter of the ring foundation was 36.5 kPa.

The cone penetration tests were conducted through the heaved soil to locate the failure surface. As shown in Fig. 2, the soundings and the profile of the heaved soil delineated a failure surface which compared well with the theoretical circle of failure.

Bearing Capacity

The ultimate bearing capacity for the soil was 241 kPa, calculated from $q_u = c\,Nc + P$ (Skempton 1951) and the average in situ

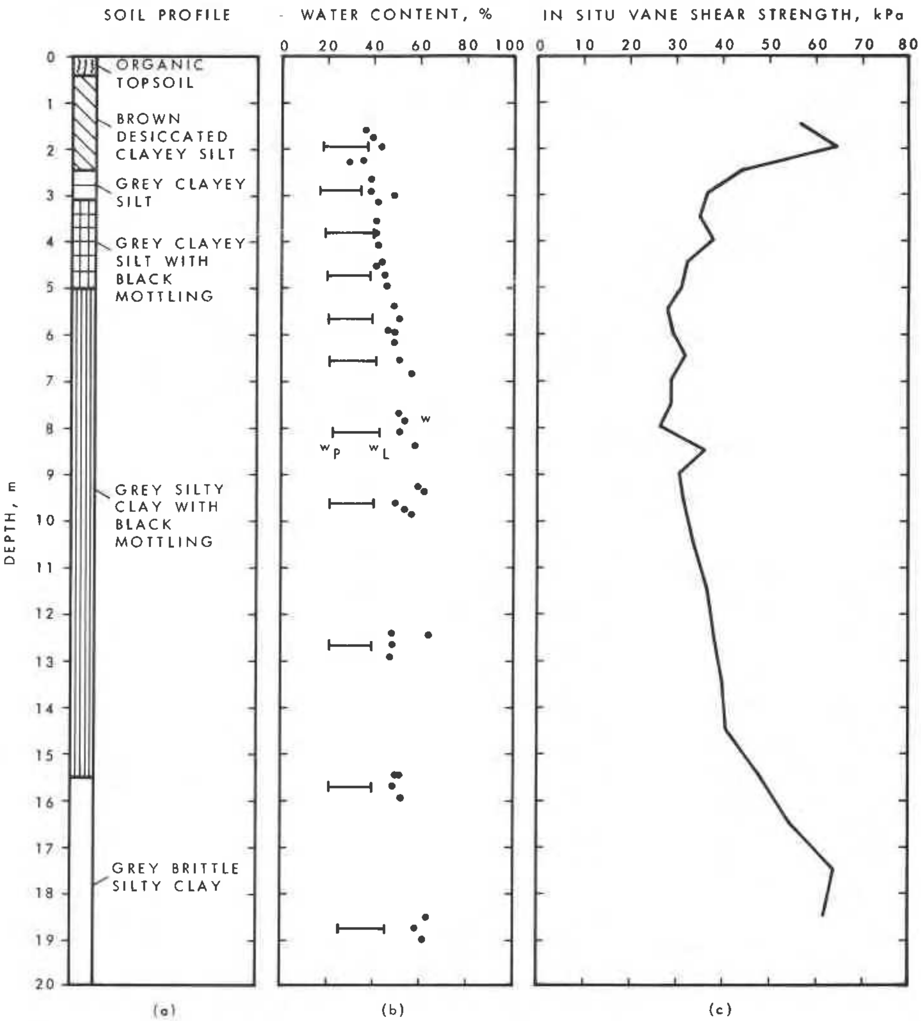

Figure 3. Engineering properties of soil at Richmond.

vane shear strength. Assuming a full contact area of 111.0 m² for the foundation, the factor of safety against failure was 1.2. Because the concrete footing cracked before failure occurred, the actual factor of safety could not be determined. If the contact area was reduced to 70.1 m², the cross-sectional area of the tower, the factor of safety would be 0.8. A value of 1.0 would have been obtained if the effective contact area was 91 m², which was a realistic contact area at the time of failure.

Discussion

It is difficult to understand why a structure as high as a 10-storey building should be constructed on clay soils without a soils investigation. Furthermore, it is equally difficult to understand why foundations for such an immense structure should be constructed without steel reinforcing. The evidence for the cause of the failure points to inadequate foundations. When the ring foundation cracked during loading, the contact area was reduced and failure occurred when the bearing capacity of the soil was exceeded.

The failure at this stage of loading may

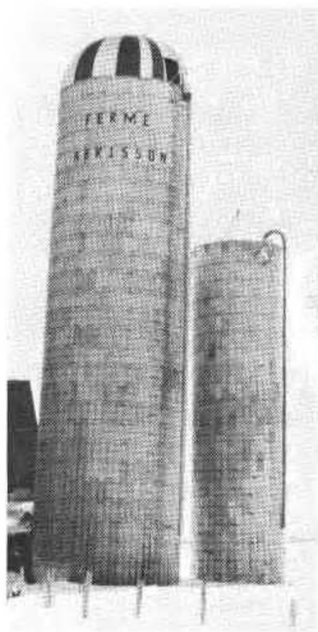

Figure 4. Casselman silo, 6.10 m diameter, 21.34 m high, leaning 765 mm from the vertical, 31 Jan. 1978.

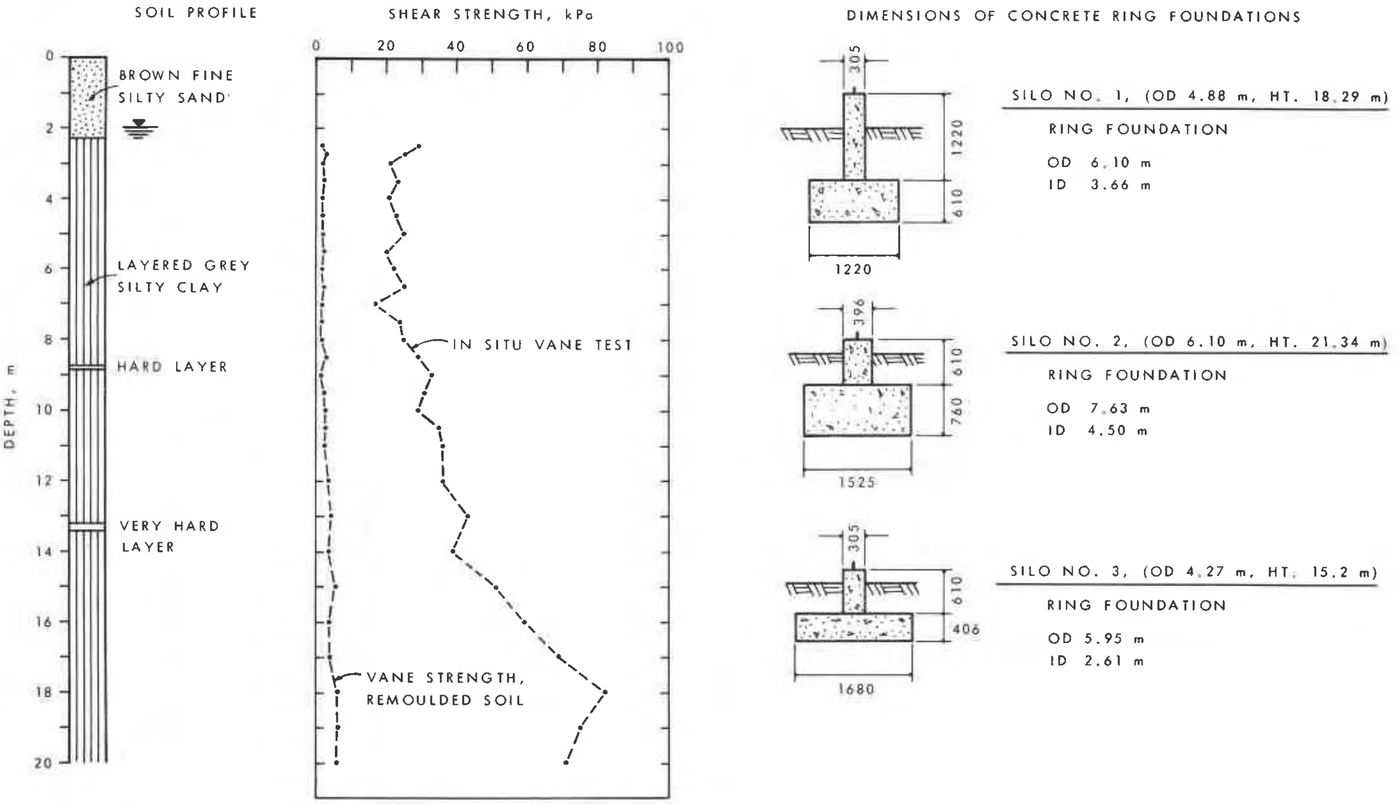

Figure 5. Soil profile, in situ vane shear strength and dimensions of concrete foundations for silos at Casselman.

have been a blessing in disguise. If the foundation had remained intact, the silo might have been filled to capacity. Because of the very low factor of safety, however, a much more catastrophic failure could have occurred. There is little doubt that even if the concrete foundation had been reinforced, it was still inadequate for the structure and the soils at the site.

CASSELMAN

Three concrete stave silos were constructed in a row on a marine clay plain about 40 km east of Ottawa. Number 1 was a 4.88-m diameter silo, constructed 6 yr ago to a height of 12.2 m. In 1977 it was raised to a height of 18.29 m. Number 2 was a 6.10-m diameter silo, 21.34 m high, constructed in 1975. Number 3 was 4.27 m in diameter, 15.2 m high, erected in 1977, and was empty. Number 1 performed well, even after its height was raised in 1977. Number 2 performed well but was never filled until 1977 when it was filled to capacity for the first time with wet grass silage to a height of 16 m, and topped with wet corn silage. Following this loading it started to lean drastically as shown in Fig. 4.

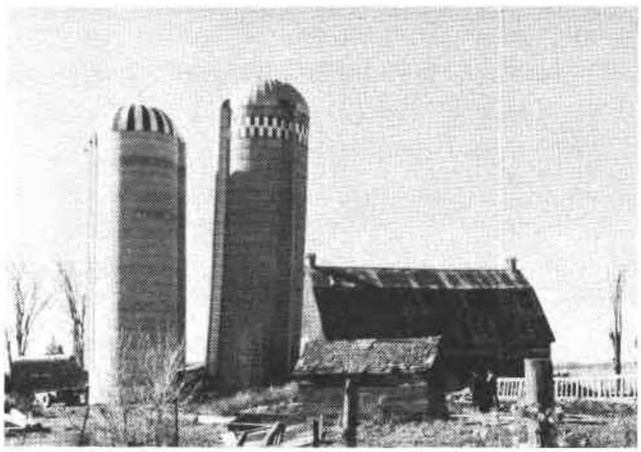

Figure 6. Foresters Falls silo, 6.10 m diameter, 21.34 m high, leaning 1213 mm from the vertical, 3 Nov. 1978.

The Problem

Silo No. 2 had settled vertically about 20 cm and was tilting 765 mm (2.05°) from the vertical, whereas Nos. 1 and 3 were performing satisfactorily. To determine what caused the settlement and tilting, a detailed inspection of the foundation was carried out.

The ring foundations for Nos. 1 and 3 were nonreinforced cast-in-place concrete with the dimensions given in Fig. 5. Drains were included in No. 1 to handle the silage juices.

The ring foundation for No. 2 was similar in design but larger (Fig. 5). Steel reinforcing was not used and drains were not installed. This foundation was constructed by the owner, who excavated a circular trench to the required dimensions using a backhoe. When the concrete was placed water was added to it to encourage the concrete mix to "flow" around the trench easily. It was not possible to see whether the foundation was cracked because it was buried with backfill.

Soil Investigation

Soil borings and in situ vane tests were performed in May 1978. Although samples were not taken for testing, the borings indicated 2.3 m of fine brown silty sand over layered gray silty clay (Fig. 5). The groundwater table was at a depth of 2 m.

The in situ vane shear strength (Fig. 5)

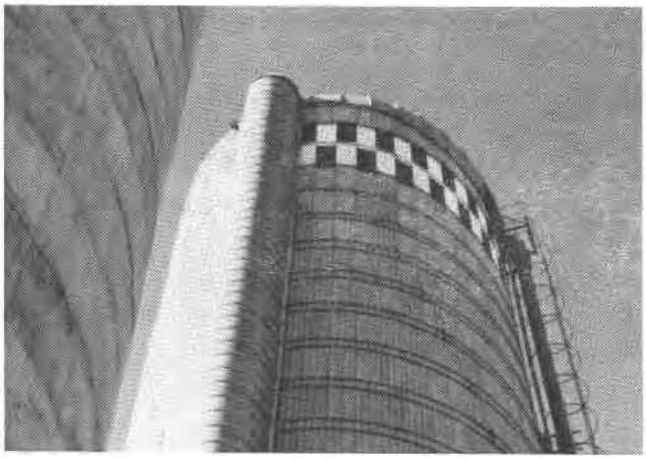

Figure 7a. Effects of structural distortion on silo: Overlapping bulge of roof due to distortion of stave.

Figure 7b. Effects of structural distortion on silo: Horizontal cracks in concrete staves.

Figure 7c. Effects of structural distortion on silo: Diagonal cracks in staves.

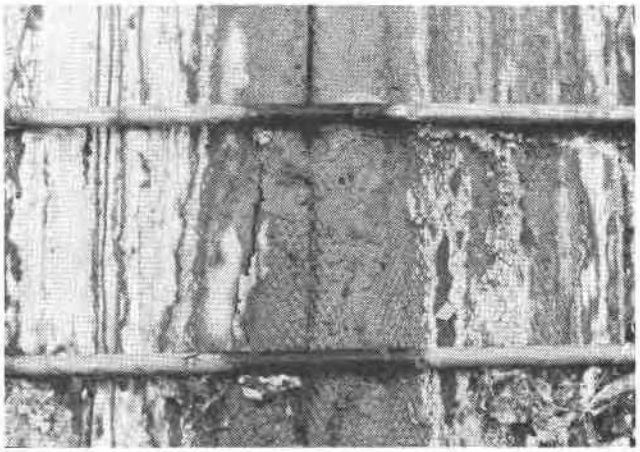

Figure 7d. Effects of structural distortion on silo: Vertical splitting and spalling of staves.

was relatively constant at about 23 kPa to a depth of 7.5 m. It then increased with depth to 67 kPa at 17 m. The average shear strength of the soil below the footing to a depth equal to two-thirds of the outside diameter of the ring foundation was 25.0 kPa.

Bearing Capacity

The ultimate bearing capacity of the soil based on the average in situ vane shear strength (Skempton 1951) was 165 kPa. When loaded to capacity the factor of safety against a bearing capacity failure for silos No. 1 and No. 2 was 1.6 and 1.3, respectively.

Discussion

This case record illustrates the "trap" many silo builders and farmers fall into. Silo No. 1 performed very well when it was 12.2 m high. It continued to perform well even after its height was raised to 18.3 m in 1977. The fact that the foundation had drains to control the silage juices probably accounted for its good performance even though the factor of safety was 1.6 when the height was 18.3 m. This good performance was probably the basic reason for the construction of silo No. 2 to a height of 21.3 m without a soils investigation. When it was erected in 1975 it performed well for a couple of years because it was never filled. In fact, in 1975 and 1976 the maximum height of silage in No. 2 was about 18 m, and this accounted for its good performance. In 1977, however, it was filled to capacity for the first time. The silo settled vertically and started to tilt. The estimated factor of safety from the soils analysis was 1.3, which is unacceptable for good engineering design. Eliminating the drains from the foundation probably reduced the factor of safety even more because the silage juices started seeping out from under the foundation. Considering all these facts, it is fortunate that the structure and its foundation did not overturn. For this type and size of foundation the limiting height of a stave silo on this soil would be about 18 m.

FORESTERS FALLS

In 1975, a concrete stave silo 6.10 m in diameter, 21.34 m high, was erected for corn silage on a marine clay plain south of the Ottawa River about 120 km west of Ottawa. A second silo, a cast-in-place concrete structure, 5.49 m in diameter, 18.29 m high, was erected adjacent to it for haylage in 1978. When the silos were filled in 1978, the cast-in-place structure behaved well, but the larger stave silo bulged and started leaning, and threatened to fall on the neighboring barn (Fig. 6). This was the first sign of any trouble since the silo had been built.

Site Investigation

On 3 Nov. 1978, measurements on the silo showed that it was leaning 1178 mm (3.16°) from the vertical in a direction away from the concrete silo and towards the barn. The spherical roof had flattened on two sides and bulged over the walls of the silo on the other two sides by about 20 cm (Fig. 7a) because the top part of the silo had deformed from a circle to an ellipse. Many of the concrete staves had cracked. These cracks were horizontal (Fig. 7b), diagonal (Fig. 7c) and vertical (Fig. 7d). They were caused by the stresses imposed on the staves as the silo leaned, twisted and bulged on its foundation. Two steel hoops near the base of the silo were also broken. Silage juices were seen bubbling up through the soil around the foundation and were leaking through the vertical joints between the staves at the bottom of the structure.

The foundation for the stave silo was a cast-in-place concrete ring, 1.1 - 1.5 m wide and 1.5 - 2.0 m thick, without steel reinforcing and without drains. The excavation for the foundation was made with a backhoe. Some large boulders had been thrown into the excavation to reduce the volume of concrete. At the time of the visit there was a differential settlement of the foundation of about 75 mm, the greatest settlement being on the side of the tilt.

A bedrock controlled stream cut a gulley 5 m deep through the marine clay about 100 m north of the silos. The exposed soil formations were firm gray silty clays. A well dug on the property encountered bedrock at 7.3 m. These observations indicate a well drained competent soil, varying in depth from 5 to 7 m at the site.

Danger of Collapse

It was evident that the structure was near collapse. If it fell it would destroy the barn, and the heaved soil from the rotation of the foundation could overturn the new cast-in-place silo located immediately behind it (Fig. 6). It had to be unloaded and dismantled as quickly as possible. Attempts to start the unloader located at the top of the silo were to no avail. Because the silo was no longer circular, the unloader would not work. It could be made to work with constant attention and adjustments, but was it safe to enter the silo? Was the silo still moving; how far could it lean before it fell over?

Measurements taken late in the afternoon of 3 Nov. showed that after 3½ h, the tilt had increased by 35 mm to 1213 mm (3.25°) from the vertical. It was not safe to climb the silo. To stop this rapid movement and perhaps prevent the silo from overturning, a steel cable was fastened to one of the steel hoops, 15 m above the base, and anchored to two large trees 80 m away. A few days later a second cable was attached to the silo 18 m above the base. The movements, as shown in Fig. 8, were drastically reduced, enabling the owner to modify the unloader and start removing the silage. The additional movement measured after the cables were attached was partly due to the upper part of the silo flattening out into a flatter ellipse because the steel cables were anchored to the flexible steel hoops at one point only.

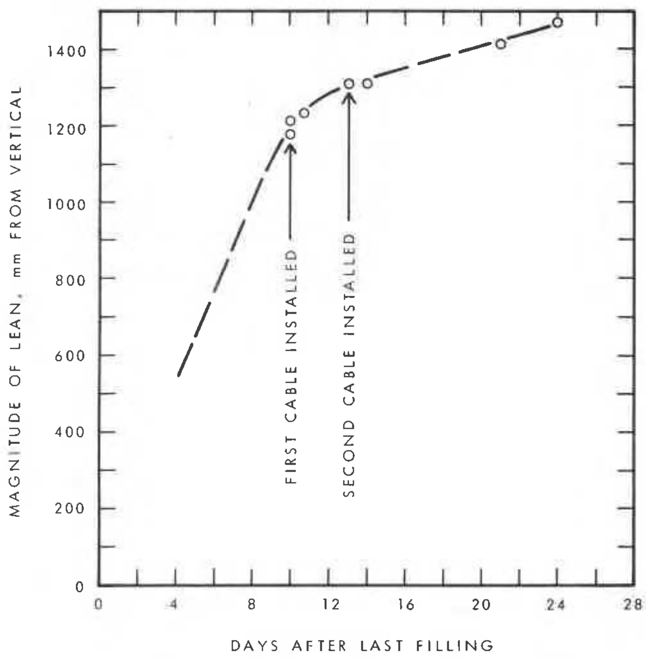

Figure 8. Tilt measured on leaning silo at Foresters Falls.

Discussion

The stave silo performed well before 1978 because the maximum height of silage placed in it was about 18 m. In 1978 it was filled completely and retopped five times. The last load was more than 40% greater than in previous years and caused the movements of the silo. Although the distributor was used to place the silage uniformly during filling, the bulge in the structure indicated that a core of high density silage had shifted against the walls of the structure. As the silo leaned, twisted and flattened into an elliptical shape, cracks appeared in the staves, and two of the steel hoops around the base failed.

The soil had adequate bearing capacity to support the silo filled once to a height of 18 m. When the 21-m stave silo was retopped five times, it started to tilt under the increased load, and the foundation settled differentially 75 mm more on the side of the tilt. A number of factors contributed to this differential settlement. The ring foundation varied in width and thickness, which could cause non-uniform pressures applied to the soil. It was not known whether the foundation was cracked. When the silage shifted and the structure started to lean, it also caused a non-uniform loading of the soil, with the pressures being greatest on the side of the lean. The fact that there were no drains forced the silage juices to seep out from under the foundation and this invariably weakened the soil. The combination of all these factors, together with the 40% increase in load, contributed to the differential settlement and the severe tilting of the structure. The installation of the arresting cables most probably prevented a catastrophic failure and permitted the silo to be unloaded.

EMBRUN

Two concrete stave silos 7.32 m in diameter, 24.38 m high, and a third smaller one were located on a farm 5 km south of Embrun, 40 km southeast of Ottawa. During filling with corn silage in 1978 (a distributor was used), one of the two larger structures bulged and tilted from the vertical

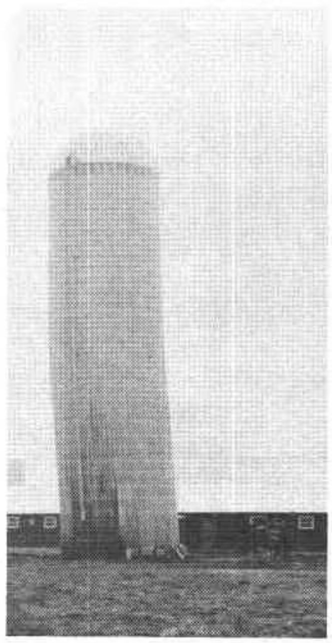

Figure 9. Embrun silo, 7.32 m diameter, 24.38 m high, leaning 1475 mm from the vertical, 7 Nov. 1978.

(Fig. 9). As the two structures were identical in design, construction and loading, a brief investigation was carried out to find the cause of the problem.

Site Investigation

The foundation soils were geologically the same marine clays as those at Casselman. The soil investigation for the structure was performed by the Ontario Ministry of Agriculture and Food in the region, and the foundations were designed for the allowable bearing capacity of the soil. The ring foundation was cast-in-place concrete adequately reinforced with radial and circumferential steel. Drains were included to control the silage juices.

Measurements on the structure showed that the silo had tilted 1475 mm (3.46°) from the vertical, and that the foundation had settled differentially 130 mm on the side of the lean. The foundation was not cracked and the drains were working well.

The structure was erected and partially filled in 1976, and remained empty in 1977. In 1978 when it was time to fill the silo, it was observed that the steel hoops were not as tight as they had been when the silo was erected. They were not tightened but filling proceeded just the same. After 3 days when the height of silage was about 22 m it was noticed that the silo was leaning. This was surprising because the other identical silo, which was loaded with the same material using the same kind of distributor, behaved perfectly. Nevertheless, no additional silage was placed in the silo.

Discussion

This study demonstrates that a well constructed foundation, designed for the allowable bearing capacity of the soil and with drains to control the silage juices, is capable of supporting a filled silo even after it leans 1475 mm (3.46°) from the vertical. The large eccentric load caused the small differential settlement of the foundation, but there was no bearing capacity failure of the soil.

The study also shows that the steel hoops binding the silo together may relax with time and thus weaken the superstructure. The silo is then more vulnerable to a shifting hard core of silage. Consequently, even though a distributor is used during filling, any shift in the core of silage may cause a weakened silo to deform and tilt as observed. This can occur even though the foundations provide adequate support for the structure. The problem could have been prevented if the steel hoops had been tightened to the same stresses as were applied during construction.

Figure 10. Mallorytown silo, 4.88 m diameter, 18.29 m high, leaning 737 mm from the vertical, 29 Sept. 1978. Rock escarpment behind barn.

MALLORYTOWN

In May 1978, a small concrete stave silo 4.88 m in diameter, 18.29 m high, was constructed on the north shore of the St. Lawrence River, 20 km west of Brockville. During the summer it was partially filled with hay, and when it was completely filled with corn silage in September, it tilted from the vertical as shown in Fig. 10. This is a case of unsatisfactory performance of a small silo on very strong soil.

Site Investigation

Measurements on the silo showed that it was leaning 737 mm (2.31°) from the vertical, and that the foundation had settled more on the side of the tilt by about 175 mm. The concrete ring foundation was 610 mm wide, 1370 mm thick, with drains.

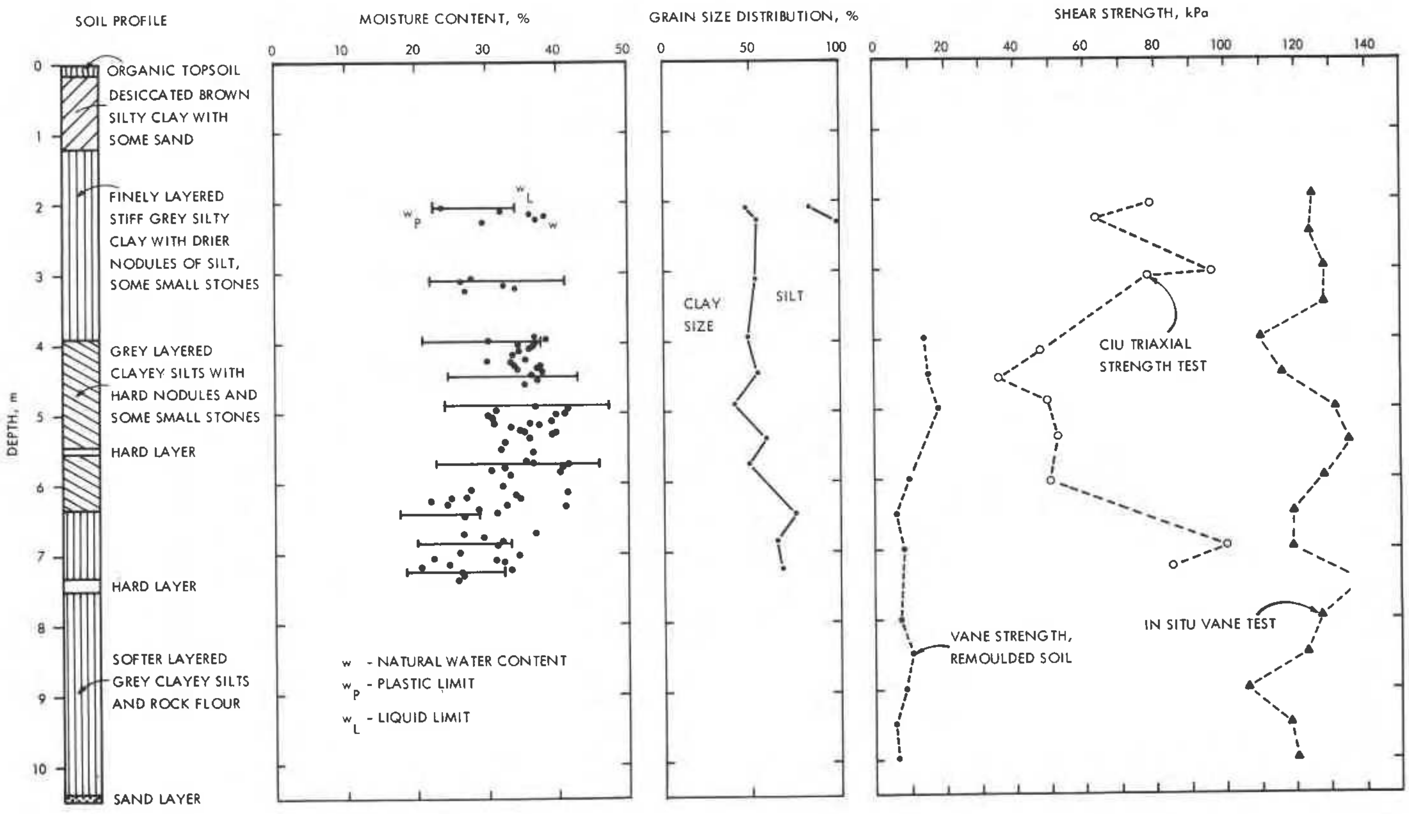

Figure 11. Engineering properties of soil at Mallorytown.

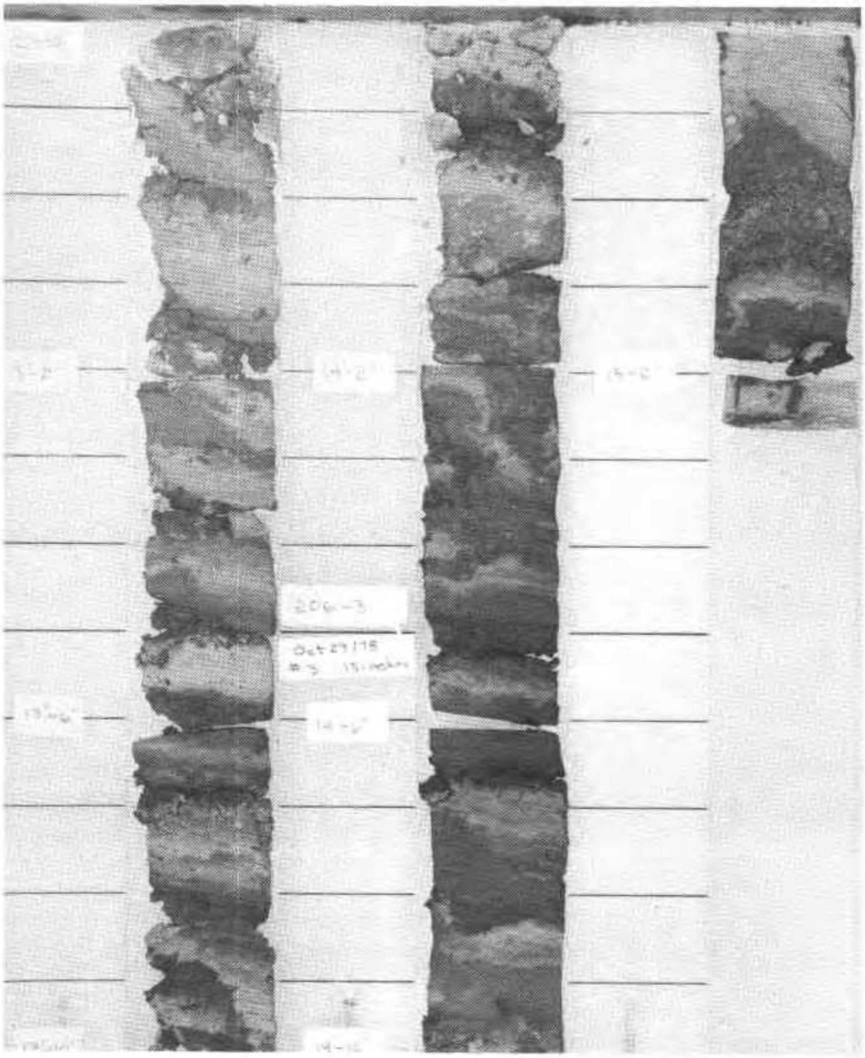

Figure 12. Layered soil formations at Mallorytown silo.

Figure 13. Effect of acid attack on staves in collapsed silo near Harriston, 1974. Photo courtesy H.E. Bellman, OMAF, Walkerton, Ont.

The location was in the Thousand Islands region where bedrock was near the surface and often covered with competent granular tills. The site was a gently rolling relatively flat plain bordered by rock outcrops. The silo was situated about 25 m south of a rock escarpment near an old barn. About 0.3 m of granular fill was placed around it to form a road.

Soil Investigation

The soils investigation consisted of three borings for soil samples and in situ vane strength tests. Boring No. 1, 11 m south of the silo, encountered layered silty soils to a depth of 10 m, the maximum depth of the borehole. Number 2, located 6 m west of the silo, also penetrated through layered silty soil but it encountered bedrock at 4.9-m depth. Number 3, which was 5.6 m east of the structure passed through the same silty soil to a depth of 12.2 m without encountering bedrock. The groundwater table rose to within 0.13 m of the ground surface in the boreholes.

An examination of the undisturbed soil samples showed that the soils were extremely layered. The results of the soil tests (Fig. 11) indicated a soil of low plasticity, with an average plasticity index of 16%. The natural water content varied from 21 to 41% and was generally less than the liquid limit of the soil. Based on the grain size analysis and the plasticity index, the soils were mainly finely ground rock flour, which behaves as a pure silt.

The in situ shear strength of the soil measured with the NGI vane (Fig. 11) varied with depth from 107 to 135 kPa. The average strength below the foundation to a depth of two-thirds of the outside diameter of the foundation was 120 kPa.

The shear strength measured in the laboratory on the soil samples with the consolidated isotropically undrained triaxial (CIU) test was significantly lower than that measured in situ with the NGI vane, giving an average of 72 kPa for bearing capacity analysis. As these soils were highly layered (Fig. 12) it was very difficult to obtain high quality, undisturbed soil samples for testing. Because of the disturbance from sampling, these laboratory tests underestimated the true strength of the soil.

Bearing Capacity

Based on the average shear strength measured in situ with the vane, the ultimate bearing capacity of the soil (Skempton 1951) was 790 kPa, giving a factor of safety against a bearing capacity failure greater than 5. Using the shear strength measured with the triaxial test, the factor of safety was still more than 3. As the results from the triaxial tests were known to be conservative, the actual factor of safety against a bearing capacity failure was considerably greater than that normally used for good engineering design.

Discussion

According to the owner, every spring, groundwater seeping from the upland made the farm road leading to the barn adjacent to the silo impassable at many places. When seepage stopped the road would dry up and become passable again.

The soils near the silo were very silty and therefore vulnerable to groundwater seepage. Local soft spots develop easily in this type of soil, which may consolidate or collapse when loaded. A soft wet spot was detected when the excavation was being prepared for the foundation. It is more than a coincidence that the maximum settlement and tilt occurred over the wet spot.

Placing concrete over loose soil left in the base of the excavation or over uncompacted loose fill can also cause differential settlements if the excavation is too wet and the working conditions unfavorable at the time of construction. After the silo is filled the applied load will compress the loose uncompacted soil, and the foundation will settle non-uniformly causing the silo to lean.

HARRISTON — PORT ELGIN

In 1974, a 10 yr-old concrete stave silo

Figure 14. Port Elgin silo, 7.32 m diameter, 21.34 m high. Collapse due to acid attack on staves at base of silo, 1978. Photo courtesy H.E. Bellman, OMAF, Walkerton, Ont.

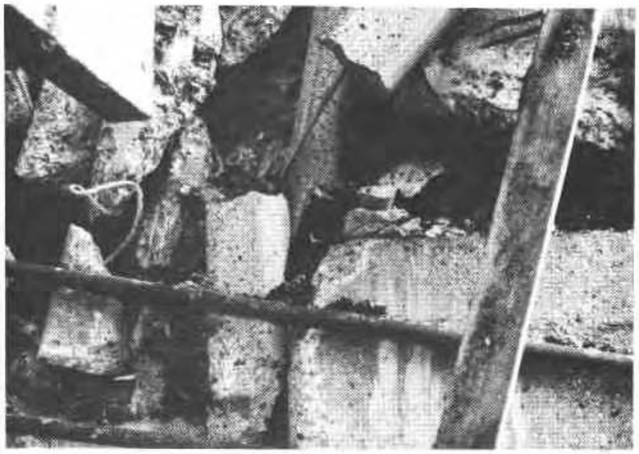

Figure 15. Port Elgin silo, condition of staves in collapsed silo, showing deterioration from acid attack. Photo courtesy H.E. Bellman, OMAF, Walkerton, Ont.

9.14 m in diameter, 24.38 m high, near Harriston, Ontario, fell over. Visual inspection of the failure indicated that silage acids had attacked the concrete and reduced the effective thickness of some staves at the base of the structure from 51 to about 38 mm (Fig. 13). Structural tests were not performed on the staves, but it is probable that the loss in strength was proportionally greater than the reduction in thickness. The owner reported that some of the staves had buckled and crushed prior to the collapse.

In 1978, a 12-yr-old stave silo 7.32 m in diameter, 21.34 m high, collapsed near Port Elgin about 2 wk after being refilled for the second time (Fig. 14). Visual inspection of the staves near the base of the silo showed that a considerable amount of deterioration had occurred due to chemical attack from silage acids (Fig. 15). The standard 51-mm thick concrete staves were reduced to less than 41 mm thick, and had an extremely crumbly and porous interior surface. It was practically impossible to locate an unbroken stave in the debris at the base of the silo.

This silo was badly treated early in its life. Silage was placed in a very wet condition, and for about 8 yr hay-crop silage was left in the bottom 1.2 - 1.5 m of the silo. The interior was not coated at the time of construction or at any later time to protect the walls from acid attack. Consequently the concrete staves deteriorated at such a rate that the silo collapsed from structural failure 12 yr later.

Discussion

One of the major problems with concrete silos is the deterioration of concrete walls that are in direct contact with silage juice acids (primarily lactic and acetic) over prolonged periods of time. Juices form when the silage is placed at moisture contents that are too high for the size of the structure and consequently are squeezed out from the ensiling mass. In addition, the pressures forcing the silage acids in contact with the cement walls at the base of a silo increase with increasing height of the silo. These acid juices under pressure etch the concrete walls leading to their deterioration with time. Because the trend over the past decade has been toward larger concrete tower silos, this problem has become very significant. The problem can be controlled in part by ensuring that the moisture content of the silage is compatible with the size of the silo, thus preventing the formation of silage juices (Daynard et al. 1978).

Because it is often impossible to prevent the formation of silage juices, there is an urgent need to protect the silo walls with special coatings, and to maintain this protection during the life of the structure. Concrete staves vary from 51 to 64 mm thick, and if deterioration from acid attack occurs, the problem can become critical with respect to loss of structural strength. This applies also to cast-in-place concrete silos. The concrete covering the steel reinforcing in the walls of these structures may not be more than the thickness of a concrete stave in front of steel hooping. Since the quality of cast-in-place concrete is often not as high as factory-produced staves, these structures are equally vulnerable to deterioration from acid attack and to structural collapse in time.

Some research on the suitability of certain coating materials for concrete silos has been done (Jofriet 1977), but more work is required.

SUMMARY AND RECOMMENDATIONS

This paper presented six case histories of the performance of tower silos, chosen to illustrate particular current problems with these structures. These dealt with bearing capacity failures; inadequate and unreinforced foundations; omission of drains for silage juices; relaxation of circular steel hoops causing deformation of the silo and overstressing of the staves; consequences of non-uniform placement of silage during filling; consequences of inadequate site investigations; deterioration of concrete with time; and danger inherent in building larger silos on a site than those dictated by experience, without expert advice.

A review of these problems led to the following recommendations:

1. A soils investigation should be performed by a qualified engineer to determine the allowable bearing capacity of the soil for all large silos. The investigation should include an engineering appraisal of the site to detect potential soft spots at the proposed location of the structure.
2. The foundations for tower silos should be designed for the allowable bearing capacity of the soil. They should be constructed with steel reinforcing and contain drains to handle the silage juices. A well designed and constructed foundation should support a silo that may be refilled or retopped many times, and resist any eccentric loading that may develop during the lifetime of the structure.
3. The placement of silage during filling should be carefully controlled to eliminate the possibility of creating

high density cores that could shift and deform the structure.

4. Silo walls should be made of good quality concrete to resist deterioration from acid attack. Deterioration can be reduced by placing silage at a moisture content not greater than that recommended for the size of the structure to prevent the formation of silage juices. The interior walls should also be coated for protection from acid attack.
5. A regular maintenance program should be instituted to: (a) check on the deterioration of the concrete; (b) check on the tension of the steel hoops which provide the structural strength of the silo.

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ANDRESEN, A. and L. BJERRUM. 1956. Vane testing in Norway. ASTM, Spec. Tech. Publ. 193. pp. 54-60.

BOZOZUK, M. 1972. Foundation failure of the Vankleek Hill tower silo. Proc. Spec. Conf. Earth and Earth-Supported Structures, ASCE, Soil Mech. Found. Div. 1(2): 885-902.

BOZOZUK, M. 1977. Evaluating strength tests from foundation failures. Proc. 9th Int. Conf. Soil Mech. Found. Eng. 1: 55-59.

DAYNARD, T.B., R.F. ARNOLD, and H.E. BELLMAN. 1978. Density-pressure seepage relationships of whole-plant corn (*Zea mays* L.) silage. Can. Agric. Eng. 20: 45-52.

EDEN, W.J. and M. BOZOZUK. 1962. Foundation failure of a silo on varved clay. Eng. J. 45(9): 54-57.

JOFRIET, J.C. 1977. Corrosion protection for concrete farm silos. Can. Agric. Eng. 19(2): 59-64.

LAMBE, T.W. 1951. Soil testing for engineers. The Massachusetts Institute of Technology, New York, N.Y. John Wiley and Sons. 165 pp.

SKEMPTON, A.W. 1951. The bearing capacity of clays. Proc. Build. Res. Congr., London. pp. 180-189.