SETTLEMENT AND LOAD TRANSFER OF RING FOUNDATION FOR TOWER SILOS

D.E. Becker and K.Y. Lo

Faculty of Engineering Science, University of Western Ontario, London, Ontario N6A 5B9

Received 16 February 1979

Becker, D.E. and **K.Y. Lo**. 1979. Settlement and load transfer of ring foundation for tower silos. Can. Agric. Eng. 21: 97-110.

A research program on the foundation behavior of tower silos on clay deposits in Southwestern Ontario was initiated in 1976. The program consists of detailed instrumentation for one new silo and settlement observations for several other existing and newly-constructed silos. The results of field observations on settlement and tilt, silage density and pressure distribution beneath the silage and the ring footing are reported in this paper. The phenomenon of load transfer of the silage to the silage wall and thence to the ring footing was also studied. It was found that in spite of the relatively low factor of safety against bearing capacity failure and the considerable load transfer of 42% to the ring footing, the total maximum foundation settlement up to date was small (78 mm) and the differential settlement along the circumference of the ring footing was 9 mm. It may be concluded that the performance of the silo foundation is entirely satisfactory, in spite of the relatively low factor of safety compared to that commonly used in foundation design. The main reason for this is the beneficial effect of the stiff surficial crust and the relative geometry of the ring foundation layout with respect to the thickness of the crust below the foundation level. The results of settlement observations of other silos are also briefly reported and some significant observations are discussed.

INTRODUCTION

Current practice in construction of tower silo foundations is usually based on local experience without the benefit of a soils investigation. The trend towards the erection of larger and larger tower silos has led to serious foundation problems with these structures. A few failures of tower silos have occurred in Ontario (Bozozuk 1972; Eden and Bozozuk 1962) attributable to inadequate bearing capacity of the subsoil to support the superimposed load. Many others have tilted or settled appreciably, affecting their performance. On the other hand, silos up to 37 m in height have been constructed on soft clays of the Wallaceburg-Chatham-Windsor area without any serious distress.

In Southwestern Ontario alone, 7600 silos were constructed in the 5-yr period between 1972 and 1976. This represents an annual expenditure of some $18 million. Thus, a better understanding of the foundation behavior of tower silos leading ultimately to economical and adequate foundation design appears to be of economic significance.

As part of a comprehensive investigation on the behavior of tower silo foundations, a full scale concrete silo, 9.1 m in diameter and 21.9 m high, with a ring footing 0.9 m deep and 1.1 m wide was fully instrumented for pressure distribution, pore pressure response and settlements during construction, and the subsequent loading and unloading cycles. In addition, a general performance survey, with respect to settlement and tilt, of seven other silos in the Chatham-Wallaceburg area was conducted over the three loading cycles since 1976. This paper describes the subsoil conditions, the instrumentation, and the results of field observations. An analysis of these results, together with the favorable performance of the instrumented silo is also included.

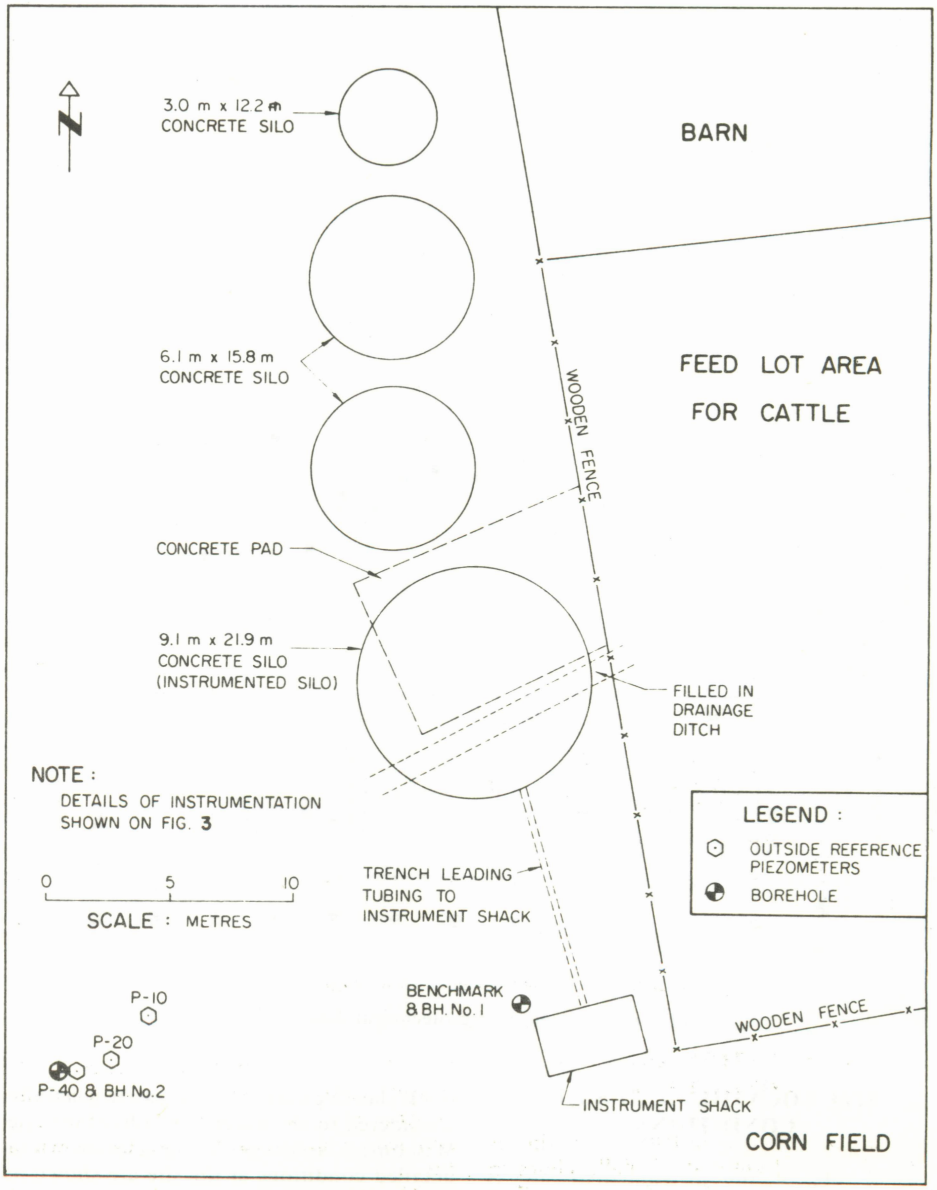
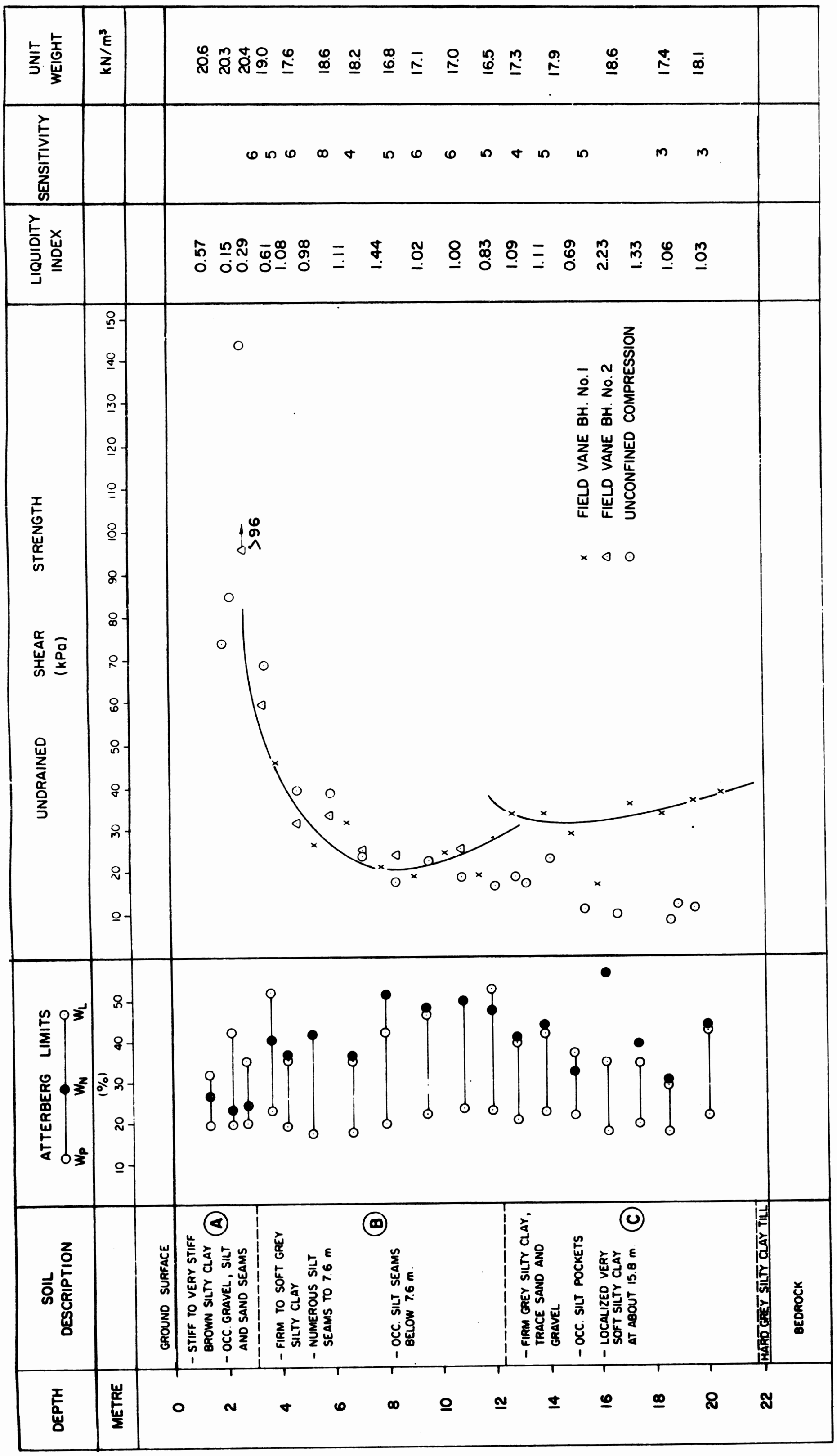


Figure 1. General layout of site, borings and reference instrumentation.



DEPTH (METRE)	LIQUIDITY INDEX	SENSITIVITY	UNIT WEIGHT (kN/m³)
	0.57		20.6
	0.15		20.3
	0.29	6	20.4
	0.61	5	19.0
	1.08	6	17.6
	0.98	8	18.6
	1.11	4	18.2
	1.44	5	16.8
	1.02	6	17.1
	1.00	6	17.0
	0.83	5	16.5
	1.09	4	17.3
	1.11	5	17.9
	0.69	5	
	2.23		18.6
	1.33		
	1.06	3	17.4
	1.03	3	18.1

Figure 2. Summary of geotechnical data.

SITE LOCATION AND SOIL CONDITIONS

The site of the instrumented silo is located about 2 km east of Wallaceburg in Ontario within the St. Clair Clay Plains. The thick clay deposits of this area are generally considered to be "water-lain" tills of the late Wisconsin substage of glaciation. The detailed conditions at the site are shown in Fig. 1.

The new instrumented silo was erected about 1.2 m from a row of three smaller existing silos built in 1969. Within the area encompassed by the new silo, the concrete pad was broken up and partially removed during construction. An old drainage ditch about 0.9 m wide and 1.2 m deep back-filled with loose material ran across the site. The existence of the concrete pad and drainage ditch complicated the location and installation of instrumentation somewhat.

A total of 10 borings were drilled to various depths. Borehole 1 was put down to a depth of 23.2 m for the purposes of detailed sampling and vane testing, proving bedrock and installation of permanent benchmark. Borehole 2 was advanced to a depth of 12.2 m for additional sampling and vane testing as well as installation of one of the three reference piezometers. (Piezometers are instruments used to monitor the groundwater conditions and excess groundwater pressures due to applied loading.) The remaining boreholes were advanced for installation of piezometers at various depths from 2.1 to 9.2 m. The depth of sampling and vane testing were staggered in order to effectively achieve continuous sampling and vane strength profile down to 12.2 m.

The principal stratigraphy of the subsoil consists of 3 m of stiff brown desiccated silty clay crust, followed by an 18.5-m thick deposit of soft to firm gray silty clay. The gray silty clay in turn overlies a thin veneer of hard gray silty clay till, which directly overlies the shale bedrock encountered at about 22 m below the ground surface. The detailed stratigraphy is shown in Fig. 2 along with a summary of pertinent geotechnical data. Details of these results may be found elsewhere (Lo and Becker 1978). The use of geotechnical data in silo foundation design has been outlined by Bozozuk (1974).

LAYOUT OF INSTRUMENTATION

The instrumented silo is a poured concrete type of silo 9.15 m in diameter and 21.94 m high. The silo was not supplied with a dome or a silage distributor. The foundation is a 1.07-m wide by 0.92-m deep reinforced ring footing founded at 0.92 m below the ground surface. (Note that in the southern quarter of the circumference, the depth is about 1.22 m due to the existence of some loose fill.) The 200-mm thick silo wall is uncoated and is located centrally on the ring footing. Consequently, the inner diameter of the ring footing is about 8.24 m and its outer diameter is about 10.36 m. Upon completion of the silo wall, a concrete slab about 150 mm in thickness was poured inside the silo with its edges resting on the foundation. The slab is not structurally joined to the silo wall, and hence may be considered as "floating." The concrete slab is not reinforced.

The layout of instrumentation of the silo in plan and cross section is shown in Figs. 3 and 4, respectively. As shown in these figures, the instrumentation consists of

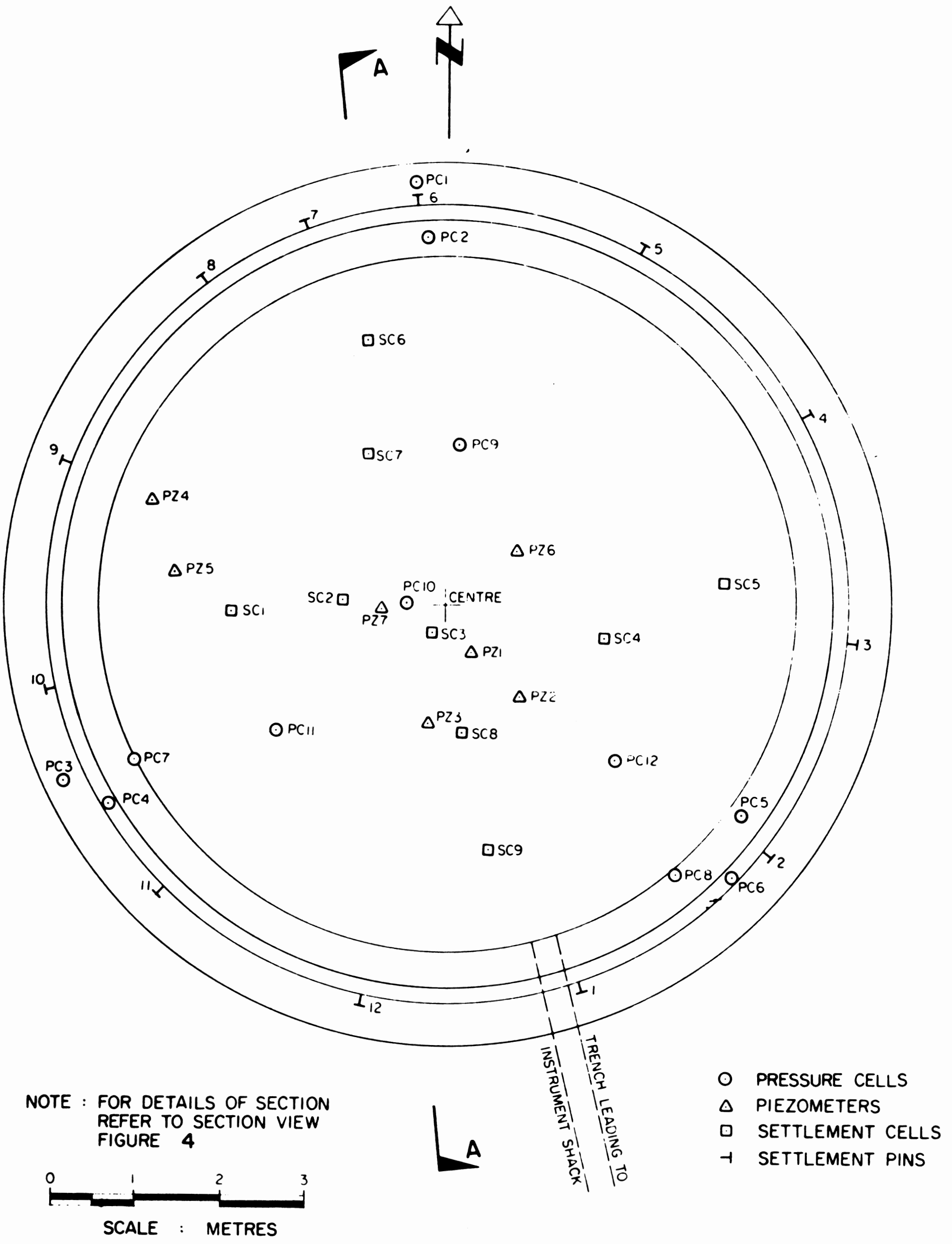


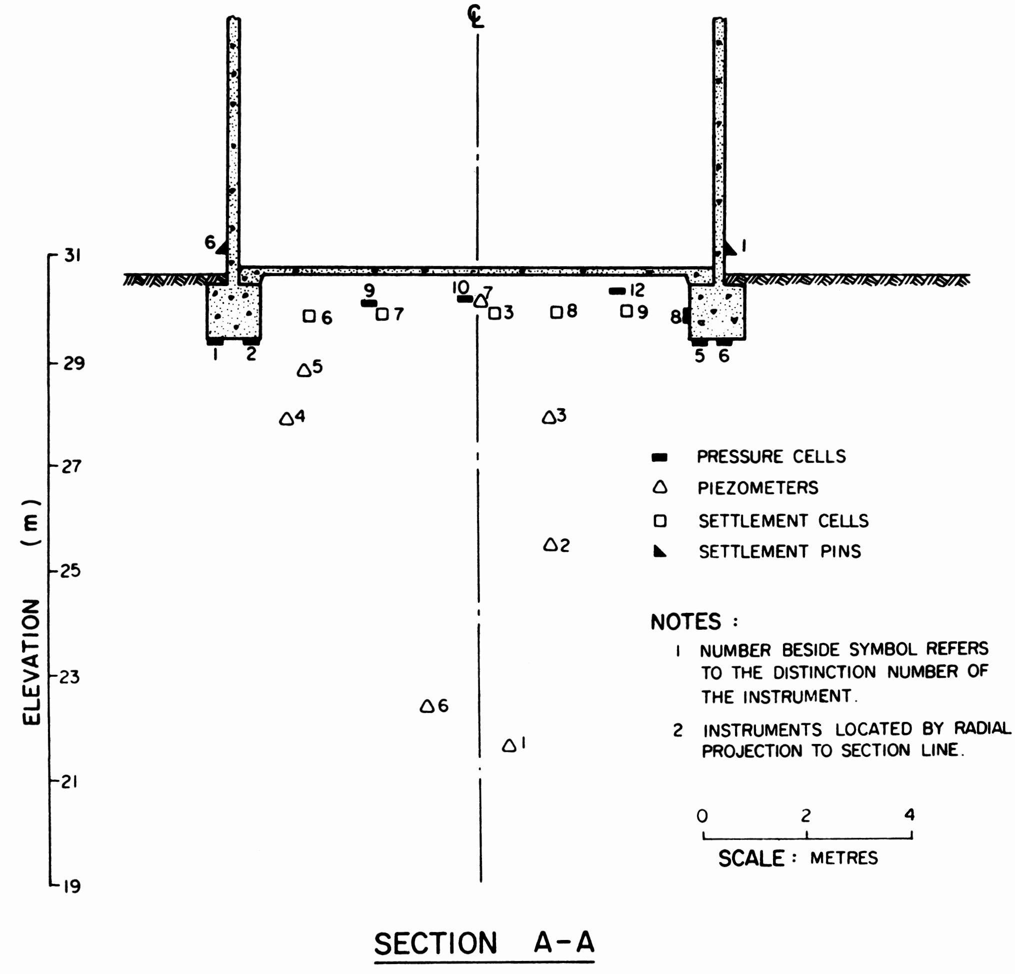
Figure 3. Plan of instrumentation of 9.1 x 21.9-m silo.

pressure cells below the ring foundation and silage, piezometers at different depths in the subsoil, settlement cells along two perpendicular diameters beneath the center slab and settlement pins along the wall circumference on both the new and adjacent silos. Details of installation and operation principles may be found elsewhere (Lo and Becker 1978).

LOADING CONDITIONS AND SILAGE DENSITY

Silage Load

To determine the weight of the whole-plant corn silage, it had been originally planned to use portable electronic weigh scales. The weigh scales, however, malfunctioned about a week prior to filling of the silo. It therefore became necessary to adopt a new weighing-in program by measuring the average density of silage in a wagon and the volume of each wagon load. The volume of the silage was determined by measurements with a 3-m pocket tape. The density of the silage was routinely determined by the following method: A box of known volume and mass was filled with silage and compacted to roughly simulate the effect of the wagon travelling across the field to the silo. The mass of the silage in the box was measured using a beam balance and the density of the silage calculated. The moisture content of the silage was also determined for each density measurement by oven-drying for 24 h at 100°C. Using this procedure, it was calculated that the total mass of the 56% moisture silage in the silo in the first loading cycle (1977) after two refillings was about 1170 t (tonnes). The total silage weight determined from the measured vertical pressures beneath the silage and foundation was calculated to be 9.9 MN. The National Silo Association (NSA 1974) reports capacity values of 850 t to 1220 t for silage at 50 and 65% moisture, respectively, for 9.1 x 21.3-m silos. Graphical interpolation of this data along with other published NSA capacity charts of



NOTES :

1 NUMBER BESIDE SYMBOL REFERS TO THE DISTINCTION NUMBER OF THE INSTRUMENT.

2 INSTRUMENTS LOCATED BY RADIAL PROJECTION TO SECTION LINE.

Figure 4. Typical section view of instrumentation of 9.1 x 21.9-m silo.

9.1-m diameter silos of varying heights yielded a capacity of 1020 t for silage at 56% moisture in a 9.1 m x 21.9 m silo. In 1978, only 12 m of fresh silage at an average moisture of 63% was put in the silo since the silo still contained 9.4 m of silage from 1977. Based upon the described density-volume procedure it was determined that 540 t of fresh silage was stored in the silo. The pressure cell observations indicated that 5.1 MN of fresh silage had been put in the silo in 1978. Graphical extrapolation of existing NSA capacity charts yielded a 1978 capacity of 530 t of fresh silage. Consequently, during the first two loading cycles (1977 and 1978), the total silage weight determined from the pressure cell observations are within 13% and 4%, respectively, of the total silage weight determined from the described density-volume procedure. In addition, the calculated capacity values agree quite favorably with NSA capacity charts. It is felt, therefore, that the method of weighing the silage into the silo has an accuracy within 10%.

Silage Density

The density of silage within a silo is not constant. Due to its very compressible nature, the density at a given location increases with height of silage above it. Consequently, only an average silage density may be determined. To determine this average silage density, the mass of silage and the volume it occupied inside the silo were routinely measured and recorded every morning and evening during filling of the silo. The average density can then be determined.

The results of these measurements are shown on Fig. 5 for the first two loading cycles. It may be seen from the figure that the silage density is highly dependent upon the silage moisture content. In 1977, the corn was harvested late in the year due to poor weather conditions. The corn therefore had been subjected to several frost exposures and was beginning to wither. The average moisture content was about 56% and, as confirmed by the farmer, lower than usual; whereas in 1978 the average moisture content was about 63% and increased densities, proportional to the increase in moisture content, were observed. The curve for 1978 spans over a silage height increase of only 12 m. This represents the fresh silage put in the silo from 9.4- to 22-m height, as the silo still contained 9.4 m of silage from 1977 prior to refilling in 1978.

From the 1977 curve, it may be seen that generally an increase of density of about 48 to 80 kg/m³, depending upon silage height, was observed upon settling overnight. The average density of silage increased from about 400 kg/m³ at a silage height of 5.5 m to an average density of 730 kg/m³ upon refilling the silo and subsequent silage settlement to 21 m; whereas in 1978 the corresponding average density was about 820 kg/m³ and agrees reasonably well with densities reported by Bozozuk (1972).

The relationship between unloading and average density is also plotted along with the refilling portion in 1978 on Fig. 5. During unloading, the average silage density in the silo increases. For example, when the silo

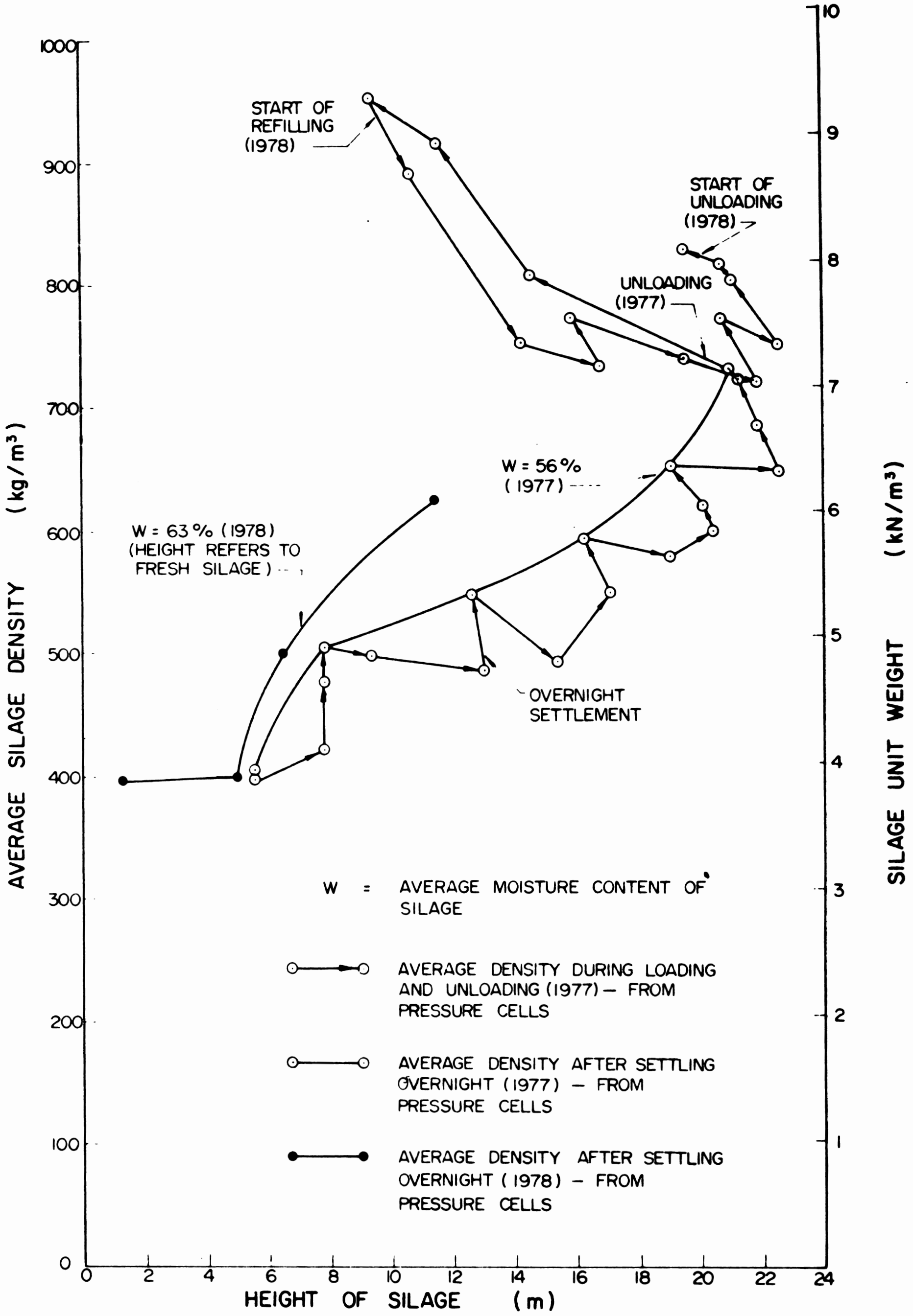


Figure 5. Relationship between average silage density and height of silage in a 9.1 x 21.9-m silo.

was full, the average density in the silo was about 730 kg/m³. However, when the silo had been unloaded to the 9.4-m height, the average silage density in the silo was 950 kg/m³.

The variation of the average density during refilling in the second loading cycle is also shown in Fig. 5. As fresh silage is put into the silo from the 9.4-m height and up, the average density decreases markedly until loading is interrupted or completed. Subsequently, as the silage in the silo settles, the average density once again increases and reaches a maximum value of 820 kg/m³ prior to starting of unloading operations in 1978. This behavior of the average silage density is consistent with its compressible nature.

LOADING CONDITIONS AND PRESSURE DISTRIBUTION

General

A silo is an intermittently-loaded structure subjected to cycles of loading and unloading. The components of loading consist of the dead weight of the structure and the varying load of the silage. The first component is known, but the load of the silage must be established by some type of direct weigh-in program, since the unit weight of silage varies with the moisture content and the superimposed load above the point under consideration. In addition, as the silage compresses, part of the load is transferred to the silo wall, thence to the foundation. As a result, the applied pressure on the foundation soil is generally non-uniform.

During Silo Construction

The reliability of the pressure cell measurements was first assessed by comparing the pressures registered with the computed average pressure during the

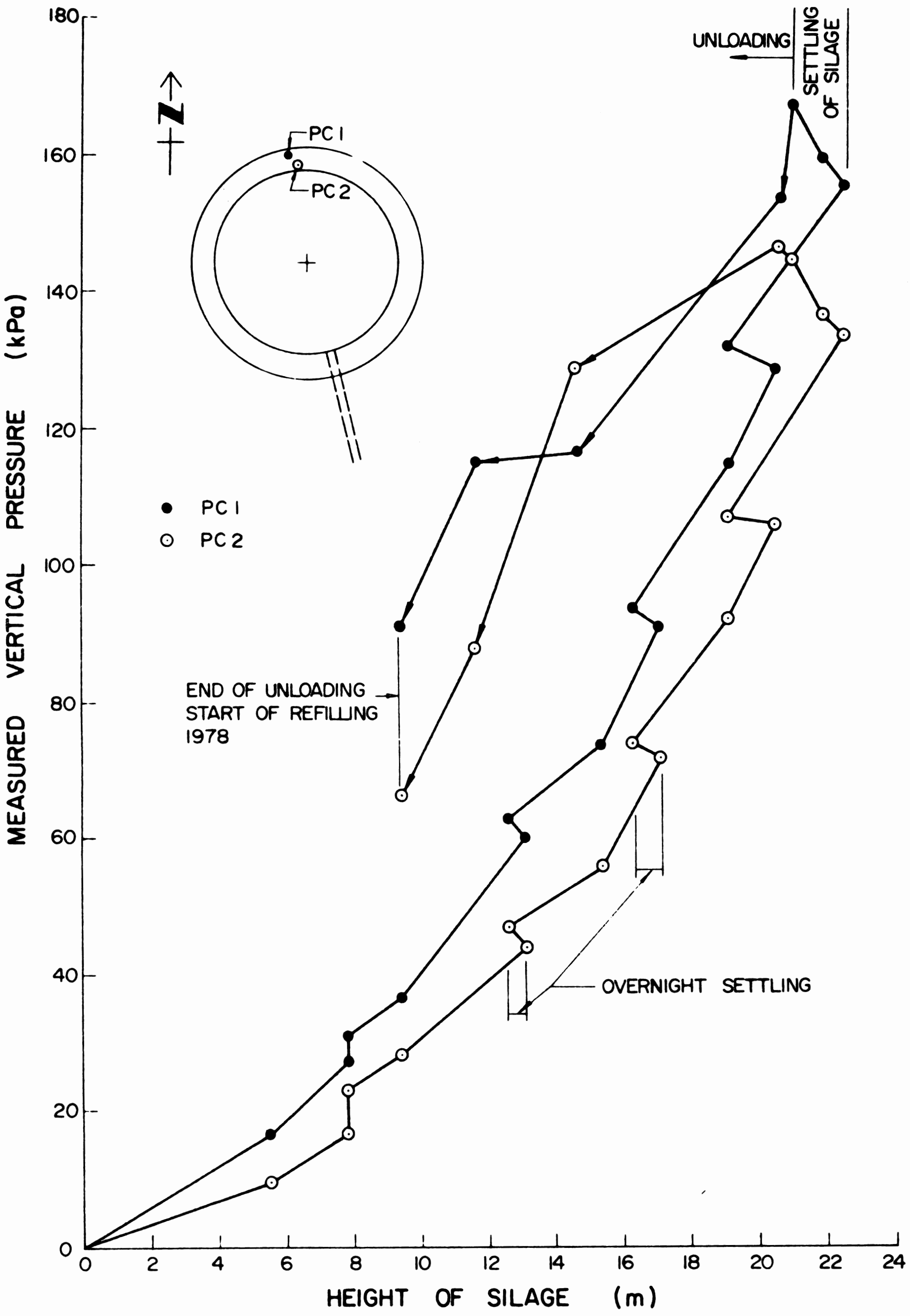


Figure 6. Relationship between measured vertical pressure and height of silage during the first loading cycle (1977) beneath the ring foundation.

successive stages of construction of the silo wall, taking the density of concrete to be 2330 kg/m^3. At full height of the wall, the average calculated pressure was 96.6 kPa compared to an average measured pressure from the six cells of 97.3 kPa. It was also found that the response of the pressure cells was practically instantaneous and the readings remained essentially constant at constant load. Based on the above observations, the performance of the pressure cells, as installed, is considered to be satisfactory. The total load of the structure (foundation and wall) was found to be 3.63 MN.

During the First Loading Cycle (1977)

A typical set of results of measurements from the pressure cells beneath the ring footing (cells 1 - 6) are shown in Fig. 6. The height of silage plotted is the equivalent height of the actual cone-shaped top of the silage. From these results, the following observations may be made:

(a) The rate of increase in pressure increases with silage height.

(b) At high silage loading, the silage settles when filling is temporarily interrupted. The measured pressure increases slightly under constant load with time, especially when silage was at full height.

(c) The measured pressures during unloading are greater than loading for the same silage height.

The results of the pressure cell measurements underneath the silage (cells 9 - 12) are plotted against the equivalent height of the silage in Fig. 7. It may be observed that:

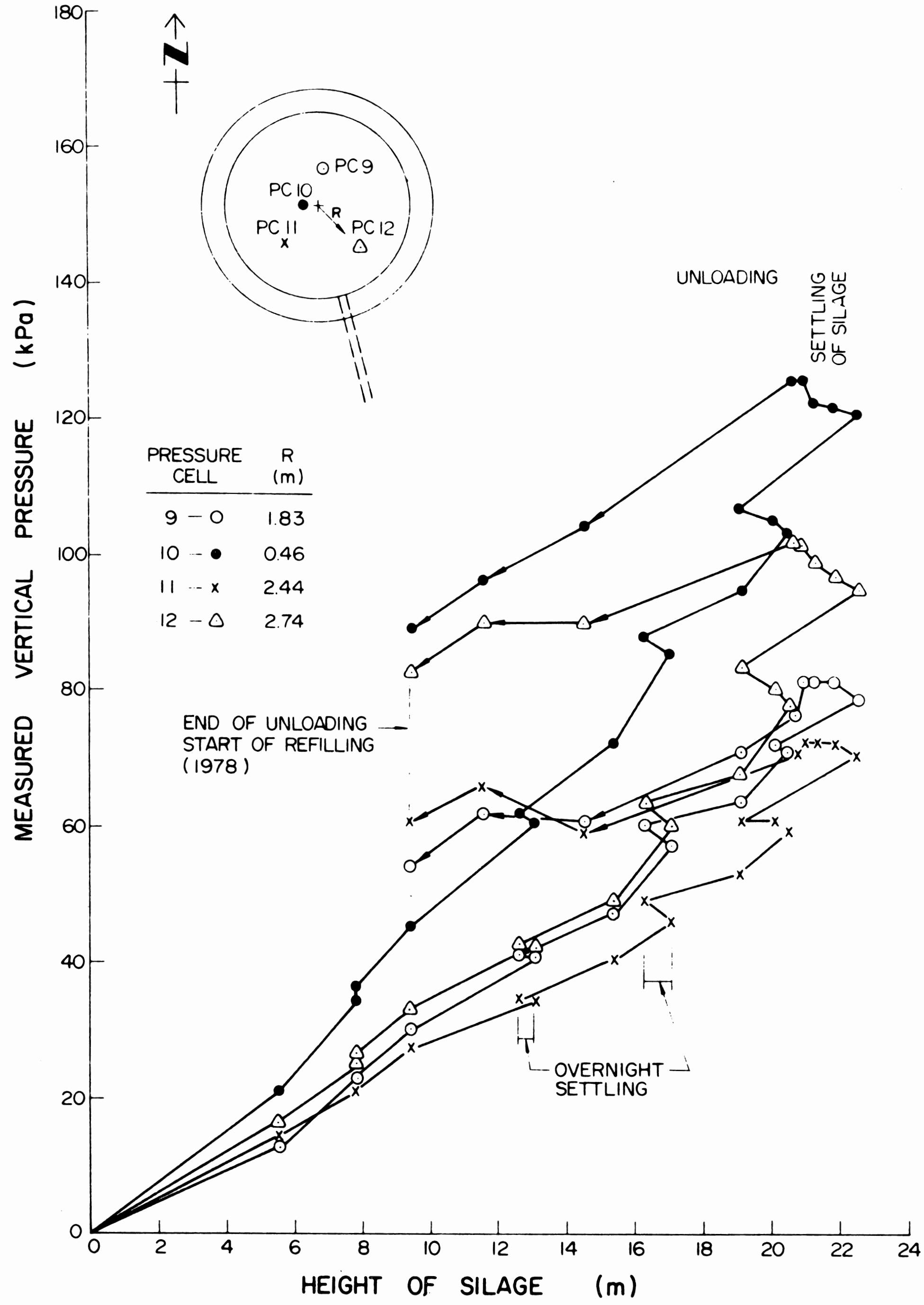


Figure 7. Relationship between measured vertical pressure and height of silage during the first loading cycle (1977) beneath the silage.

(a) The rate of increase in pressure increases at high silage loading.

(b) The pressure cell nearest to center (R = 0.46 m) recorded the highest pressure while the other cells at radial distances of 1.8 - 2.7 m recorded lower pressures.

(c) At constant silage load, the silage settles and the pressure increases slightly. This is particularly noticeable at greater silage height.

(d) The measured pressures during unloading are greater than during loading for the same height of silage.

Assuming that the pressures below the silage at equal radial distances from the center are the same due to axi-symmetric condition, the distribution of pressures measured along the radial distances is shown in Fig. 8 for three stages of filling. It may be seen that the pressure distribution is essentially uniform at one-third height of silage. At two-thirds full height, a distinct non-uniform distribution may be noticed, as a result of load transfer from silo wall to foundation. At full height, the minimum pressure measured beneath the silage is only half that of the foundation. Included in the figure are the measured pressures at full height in the second loading cycle (1978). It may be seen that the behavior is almost identical to that exhibited in the first loading cycle (1977). The higher magnitude of the measured pressures for the second loading season reflects the higher moisture content of the silage in 1978. Although the number of pressure cells is insufficient to define precisely the silage pressure distribution, it appears likely that the distribution of pressure below the silage may be

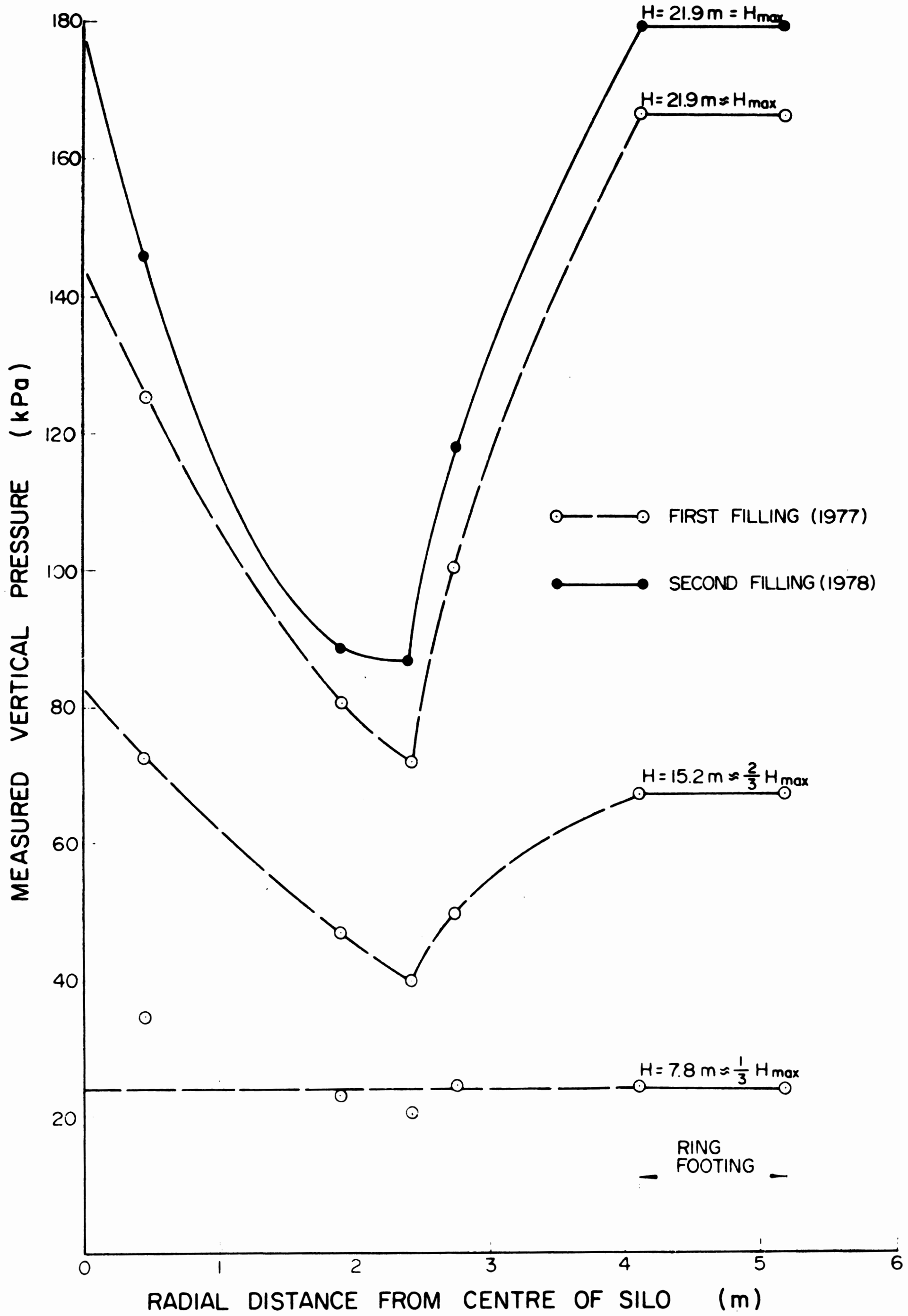


Figure 8. Relationship between measured vertical pressure and radial offset from center of silo.

approximately triangular.

The average measured pressures beneath the ring footing and that below the silage are plotted against the height of silage in Fig. 9. It may be seen that the average pressures are about the same up to about one-third of the wall height. Subsequently, the increase in pressure becomes more rapid beneath the ring footing, indicating that a greater proportion of silage load is being progressively transferred to the foundation. At full height of silage (22.6 m), the average pressure below the foundation is 148 kPa, while the average pressure below the silage is only 91 kPa. After refilling, the corresponding values were 155 kPa and 95.2 kPa.

The portion of the silage load carried by the ring foundation may be determined. The total silage load after refilling is 11.5 MN. The area of the ring foundation is 31.1 m^2. With an average pressure of 155 kPa, the load carried by the foundation is 4.82 MN. The load transfer to the foundation is thus 42% of the total silage load.

A secondary effect may be noticed in Fig. 9. Subsequent to the completion of the filling and refilling operations, the average pressure below the foundation increases by 10 kPa under constant load with accompanying silage settlement of 1.2 m. This suggests that the load transfer may be slightly time-dependent related to the settlement-time behavior of the silage.

During unloading, the average pressures at any silage height are greater than the pressures measured during loading. This reflects the fact that the density of silage within a silo is not constant. Consequently,

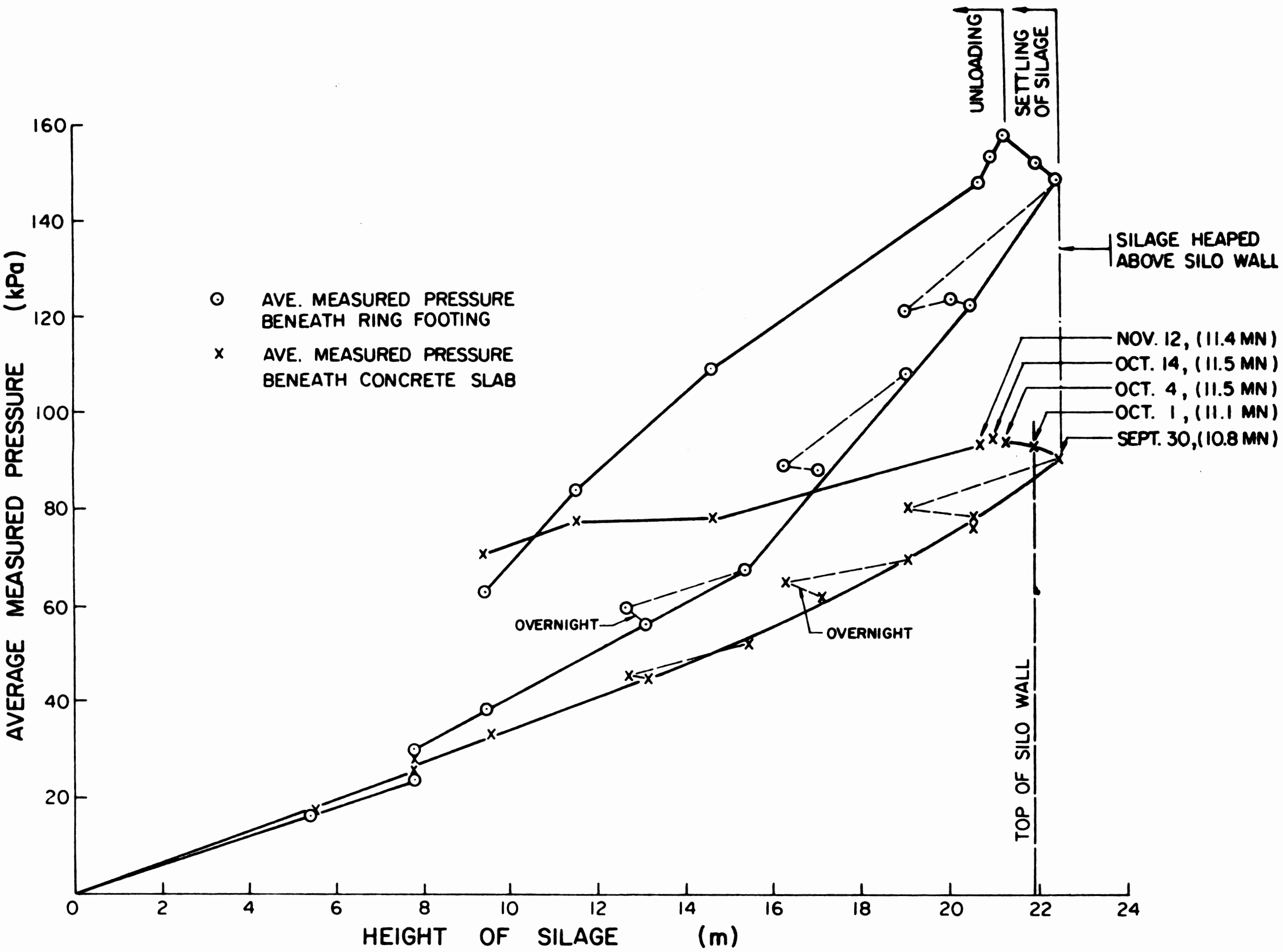


Figure 9. Relationship between average measured vertical pressure and height of silage.

during unloading, the average density at any given height will be greather than the density at the corresponding height during filling.

During the Second Loading Cycle (1978)

The relationships between measured pressures and silage height during the second loading of the silo are very similar in nature to that in the first loading cycle. It was observed, however, that the magnitude of the pressures was slightly greater than that in the first loading cycle. The reasons for this have previously been outlined.

The portion of the silage load carried by the ring foundation may be determined in the same manner as before. The load transfer to the ring foundation is 44% of the total silage load. This is consistent with the amount of load transfer in first loading. The slight difference probably reflects the different silage moisture contents and the 9.4 m of silage remaining in the silo from 1977.

Figure 10 shows the relationship between silage wall friction and the height/diameter ratio for concrete silos (Turnbull et al. 1978). The Canadian Farm Building Code (Standing Committee on Farm Building Standards 1977) recommends use of the curve associated with k = 4.72 based upon field measurements of load transfer. Turnbull points out that the curve should reasonably estimate the wall friction load for silage not over 70% moisture stored from 9- to 24-m depth. If the results of this case record are added to the above design curve, excellent agreement is obtained (Fig. 10). This agreement lends support to the validity of the design curve using k = 4.72 in the range of h/D of 2 - 3.

SETTLEMENTS AND TILT

Settlement of the Ring Foundation

The results of settlements measured by the settlement pins during the construction of the silo wall to the present date (19 Dec. 1978) are shown in Fig. 11. In the upper diagram, the loading history is shown. The pins were installed and initial readings obtained after the silo wall had reached one-half of its maximum height of 21.9 m. Thus, the first part of the settlement curve during construction of the silo was not recorded. However, from the settlement measured to the end of construction of the silo, the amount of settlement missed may be assessed to be about 7 mm. Thus, the settlement for the construction of the silo is about 13 mm. It also appears that the settlement is essentially "elastic."

In presenting the results of measurements, only the maximum and minimum settlements are shown for the sake of clarity. These two pins are diametrically opposite to each other. Results from other pins lie within these two bounding curves. From Fig. 11, the following observations may be made:

(a) The settlement of the silo due to silage loading (before unloading) in the first loading cycle is 43 mm and the maximum differential settlement is 5 mm.

(b) The maximum total settlement recorded in the first loading cycle is 56 mm.

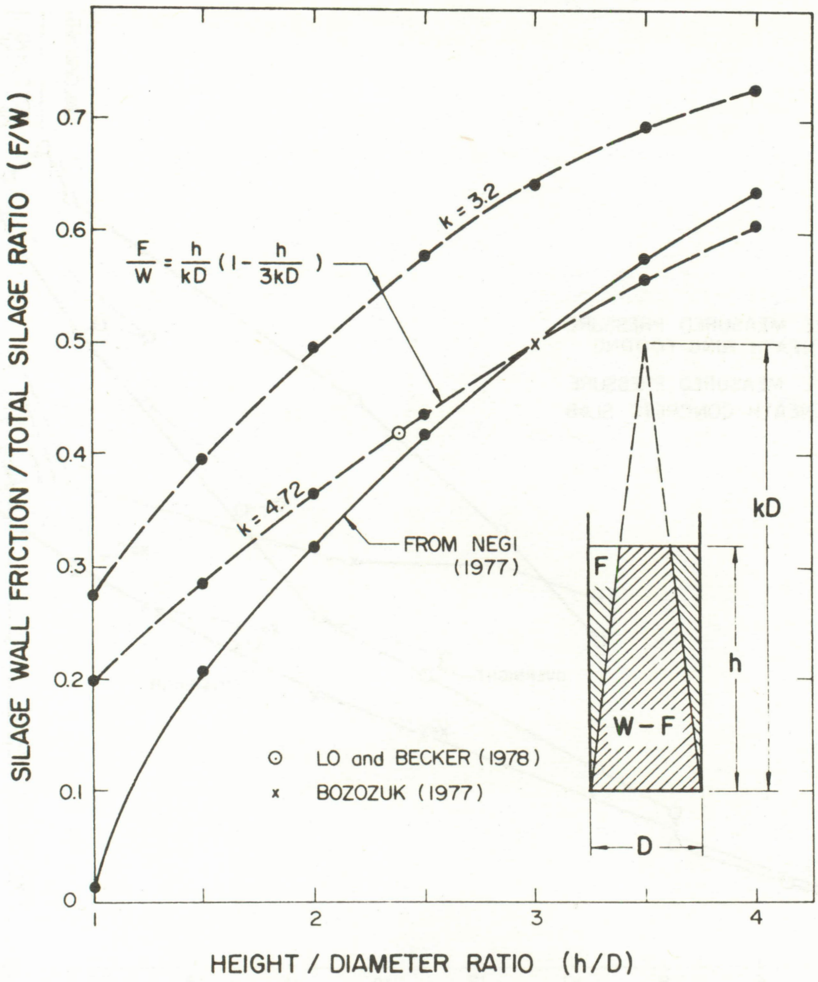


Figure 10. Silage wall friction versus height/diameter ratio for concrete tower silos (after Turnbull et al. 1978).

(c) No rebound of settlement occurred during unloading of the first cycle (i.e. time-dependent consolidation settlement occurs throughout the first loading cycle).

(d) In the second loading cycle, an additional settlement of 11 mm occurred prior to unloading.

(e) The total maximum settlement of the ring foundation to date is 78 mm with a differential settlement of 9 mm.

The distribution of settlement (based on the settlement pin measurements) around the circumference of the silo is fairly uniform. The tilt at the top of the silo during the first loading cycle is about 13 mm (corresponding to 5 mm differential settlement) towards the adjacent silo, whereas in the second loading cycle, the tilt is about 23 mm (based upon the 9-mm differential settlement). The modest amount of tilting is generally considered quite acceptable.

Influence of Settlement on Adjacent Silos

During the construction and filling of the new silo, the settlement of the closest adjacent silo was also monitored. It was observed that the consequent average settlement of the adjacent silo was about 5 mm. The greatest settlement, however, occurred immediately adjacent to the new silo (Fig. 11). An additional "immediate" settlement of 5 mm occurred when the old silo itself was filled. It may be further noted from Fig. 11 that the pin closest to the new silo (pin #15) continued to settle to a maximum of 20 mm, whereas the furthest pin (#19) only settled 6 mm.

The reasons for the above interaction effect being relatively small are:

(i) The increase in vertical stress on the ring foundation is largely carried by the stiff surficial crust and is therefore localized.

(ii) The relatively short loading period of the new silo so that the influence of consolidation settlement has not been fully affected.

Settlement Beneath the Silage

Settlements beneath the silage were measured remotely by the two lines of settlement cells shown in Figs. 3 and 4. Results of these measurements show that the surface settlement of the clay below the silage is greatest in the central portion of the loaded area. The maximum settlement during the first loading (1977) is 89 mm and is 51 mm greater than that of the ring foundation. Detailed analysis of these observed settlements may be found elsewhere (Lo and Becker 1978).

BEARING CAPACITY OF SILO FOUNDATION

It has been observed (Bozozuk 1972) that failure of tower silos occurred as a unit. It follows, therefore, that the factor of safety against bearing capacity failure may be determined by the conventional method using the total area encompassed by the external circumference of the ring footing as the bearing area.

The ultimate bearing capacity is given by

$$q_{ult} = N_c c_u + \gamma D \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

where

c_u = undrained shear strength, averaged over a depth of 2/3 diameter of the foundation

N_c = bearing capacity factor for circular foundation

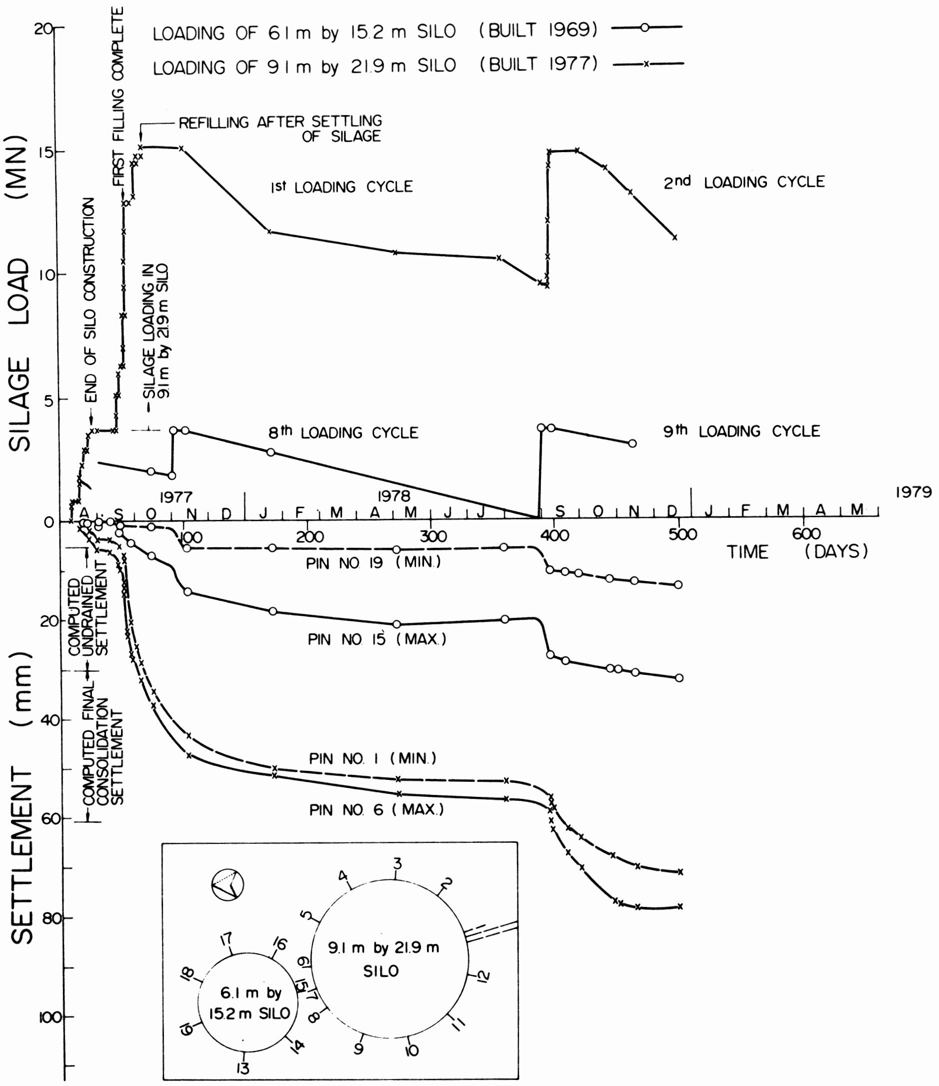


Figure 11. Observed settlements of silo foundations with time.

γ = total unit weight of the soil
D = depth of embedment of the foundation

For shallow depth of embedment, the term γD constitutes less than 5% of the total capacity and may therefore be neglected. The factor N_c is 6.6 for circular foundation. The weighted average undrained shear strength from results of field vane tests over a depth of 2/3 diameter is 53 kPa, and over a depth equal to diameter is 45 kPa. The ultimate capacity is therefore 345 kPa and 297 kPa, respectively.

While the undrained shear strength in Eq. 1 is usually taken as the average over 2/3 diameter (e.g. Skempton 1951), field observation (Bozozuk 1972) showed that silo foundations failed as a monolithic unit. This suggests that it might be more appropriate to take the average strength over a depth equal to the external diameter of the ring foundation. The total applied average pressure from the structure and silage is 179 kPa. The factor of safety is therefore about 1.7.

FOUNDATION SETTLEMENTS AT OTHER SITES

In addition to the fully instrumented silo at Wallaceburg, six other silos constructed and loaded in 1976 in the Chatham-Wallaceburg area were monitored for settlements of the ring foundation. Settlement measurements have been continuing since 1976 or generally over three consecutive loading seasons up to the present date (December 1978). Wherever there were other silos at a site, both the old and new silos were monitored to ascertain any interaction between two silos. Borings were carried out at two of the sites to determine the stratigraphy and subsoil conditions. For brevity, only the performance of silos at these two sites will be discussed.

Jack's Farm

This site is located about 6.4 km north of Chatham. The silos monitored at this site include a 9.1 x 31.1-m poured concrete silo built in August 1976 and an older 7.3 x 24.4-m concrete stave silo built in 1969. The new silo was built approximately 5.5 m away from the older silo in an open level area.

Based on information supplied by the owner and the contractor, it is understood that the foundation level of the new silo was to be at 1.5 m. However, upon excavating and encountering a wet sand layer, the contractor deepened the foundation to 3.1 m. The width of the ring footing was about 1.8 m and its thickness about 1.2 m. The footing was heavily reinforced. The full silage load is estimated to be about 17.35 MN and the weight of the structure itself to be 4.80 MN. In total, therefore, the maximum load supported by the subsoil is approximately 22.15 MN.

The sequence of soil strata consists of a 1.2-m thick stiff brown silty clay crust, a 0.46-m brown layer of silt, a 1.37-m compact water-bearing brown silty sand, followed by the main stratum of stiff to firm gray silty clay which extends to a depth of 17.8 m

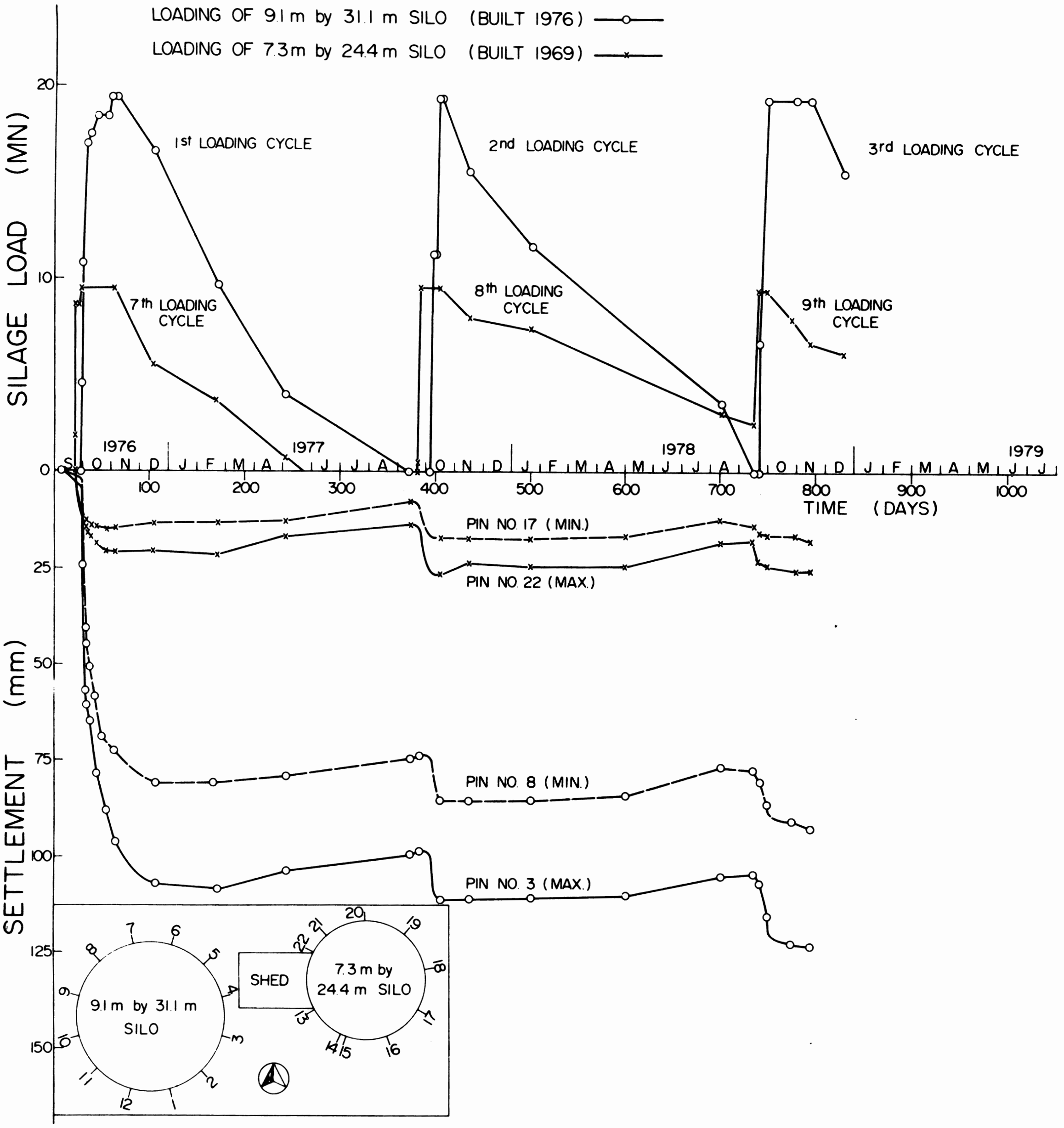


Figure 12. Observed settlements of silo foundation with time, Jack's farm.

below ground surface. A thin till layer overlies the shale bedrock which occurs generally at depths of 18.3 to 21.3 m in this area. Using the vane strength profile, the factor of safety against bearing capacity failure of the 9.1 x 31.1-m silo is 1.4.

Anderson's Farm

This site is located about 6 km southwest of Thamesville. The silos monitored include a 6.1 x 21.3-m poured concrete silo built in July 1976 and an older 7.3 x 21.9-m poured concrete silo built in 1969. The new silo was built adjacent to the older silo and separated by a distance of 1.13 m.

Based on information supplied by the contractor, it is understood that the top of the ring footing is flush with the ground surface, 1.1 m deep and 1.4 m wide. The weight of the structure is calculated to be 2.13 MN, and the weight of the ear corn to be stored in the silo is about 4.45 MN. In total, therefore, the maximum weight supported by the subsoil is about 6.58 MN.

In general, the subsoil consists of surficial layers of compact brown sandy silt to silty sand and stiff brown clay to 3.8-m depth below the ground surface. The silty sand is water-bearing and overlies a very stiff gray clayey silt which extends to 6.1-m depth. The clayey silt in turn is underlain by 1.8 m of very stiff gray silty clay. Below 8.1 m, the subsoil is a hard gray silty clay till. This layer was not fully penetrated when the boring was terminated at 12.6 m. The factor of safety cannot be calculated from the vane strength tests since the subsoil has a greater strength than the capacity of the vane. It is estimated, however, that the factor of safety is greater than 3.

Summary of Settlement Monitoring

The results of settlements measured by the settlement pins from September 1976 to the present date (19 Dec. 1978) are shown on Figs 12 and 13. In presenting the results of measurements, only the maximum and minimum settlements are shown for the sake of clarity. These two pins are diametrically opposite to each other. Results from the other pins lie within these two bounding curves.

The results of all the silos monitored for settlement are summarized in Table I. The values of maximum and minimum settlement are for the ring footing. It can be seen from the table that the maximum settlement of silos, subjected to first cycle of loading, varies from 30 to 109 mm; and the differential settlement generally increases with the absolute settlement. In addition, the majority of the total observed settlement (to

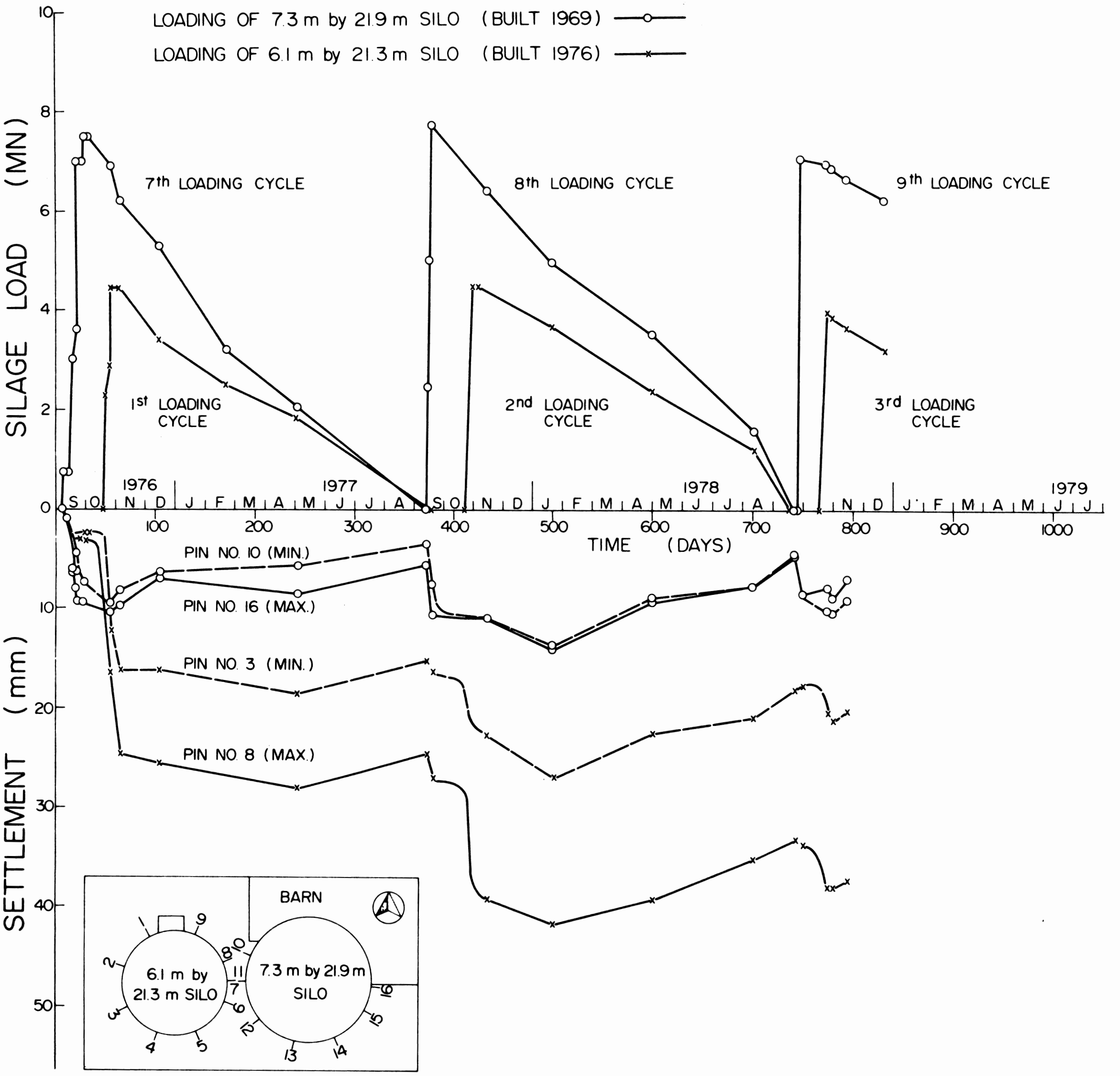


Figure 13. Observed settlements of silo foundations with time, B. Anderson's farm.

date) occurs in the first loading cycle. Furthermore, the differential settlement, once set up by first loading, appears to remain relatively constant thereafter. The tilting at the top of the silo wall computed from differential settlements varies from 23 to 101 mm and is generally consistent with transit measurements wherever the construction tilt is negligible. Furthermore, the tilt of two adjacent silos is towards each other.

CONCLUSIONS

The research program conducted consists of the instrumentation and observation of a new silo, and the performance survey of other silos. In summarizing the results of the investigation, those pertaining to the detailed instrumentation will be presented first, followed by observations from the other silos. Finally, the practical implications of the results of this study are discussed.

(1) The results of observations from the pressure cells show that average silage density increases with height of silage. The average silage density in the full silo, subsequent to silage settlement varied from 730 to 820 kg/m³ for silage moisture contents of 56 and 63%, respectively.

(2) The results of observations from the pressure cells show that the average stresses below the footing and the silage increase linearly by the same amount up to one-third of the full height. Thereafter, the increase in stress below the ring foundation occurred at a greater rate with silage loading. At full height, the average contact stress between soil and foundation due to silage load is 155 kPa which is 1.6 times that below the silage area, indicating important load transfer from the silage to the silo wall and thence to the foundation. The load transfer to the foundation is 42% of the total silage load which amounts to 11.5 MN in the first loading cycle. This behavior also took place in the second loading cycle with the load transfer amounting to 44% of the total silage weight. No measurable effect of wind load on the contact pressure has been observed.

(3) With respect to the settlement of the ring foundation measured by the settlement pins, the settlement, essentially elastic, due to the dead load of the silo wall and foundation is about 13 mm under an average pressure of 121 kPa. The total maximum settlement due to silage load observed to date is about 78 mm. The maximum differential settlement is only 9 mm and corresponds to a slight tilt of 23 mm

TABLE I. SUMMARY OF RESULTS FROM SETTLEMENT MONITORING

Silo	Dimensions	p_{max}† (mm)			p_{dif} (mm)			Rebound (mm) at end of		Tilt at top of silo wall (mm)		Factor of safety
		1st cycle	2nd cycle	3rd‡ cycle	1st cycle	2nd cycle	3rd cycle	1st cycle	2nd cycle	Calculated	Measured	
Burm's	9.1 x 21.9 m (1977)‖	56	78	—	5	9	—	0	—	23	—	1.7
Jack's	9.1 x 31.1 m (1976)‖	109	112	124	28	28	31	10	8	101	102	1.4
Jack's§	7.3 x 24.4 m (1969)‖	21	26	28	7	7	10	9	6	32	0	—
Anderson's	6.1 x 21.3 m (1976)‖	30	42	38	9	14	17	5	8	59	114	>3
Anderson's§	7.3 x 21.9 m (1969)‖	10	14	10	3	0	0	3	9	6	89	—

† Maximum settlement generally occurs at some stage during unloading, not at end of cycle.
‡ As of 14 Nov. 1978.
§ Reported values are for 7th, 8th and 9th loading cycles.
‖ Refers to year of construction.

towards the existing silos.

(4) Results of measurements by settlement cells below the silage show that a maximum settlement of 89 mm occurred at the center of the silo in the first loading cycle (1977). In addition, the near surface settlement of the subsoil below the silage area is approximately dish-shaped and the center settlement is 51 mm greater than that of the ring foundation.

(5) The factor of safety for bearing capacity is computed to be about 1.7.

(6) In spite of this relatively low factor of safety when compared to that commonly used for foundation design of other structures, the foundation performance has proved to be entirely satisfactory as indicated by the modest amount of settlement, differential settlement and tilt. The main factor for this is the beneficial effect of the surficial crust in relation to the geometry of the foundation.

From the performance survey of four other silos in the Chatham-Wallaceburg area, the following observations may be made:

(a) For silos subjected to first cycle of filling, the maximum settlement of the ring foundation varies from 30 to 109 mm. The differential settlement generally increases with the absolute settlement. The upper values of these quantities were measured for a 9.1 x 31.1-m silo. The computed factor of safety for bearing capacity of this structure is 1.4.

(b) The differential settlement, once set up by first loading, appears to remain relatively constant on unloading and reloading.

(c) The maximum tilting at the top of the silo wall measured by a transit is 114 mm and the range of values is generally consistent with those computed from differential settlement wherever the construction tilt is negligible. In addition, the tilt of two adjacent silos is towards each other.

Based on the above conclusions obtained from the detail instrumentation and analysis of the new silo and complemented by performance survey of other silos, an item of considerable importance in the design of tower silo foundations appears to emerge. Whenever a stiff surficial crust exists, and the depth of the ring foundation is so located that the depth of the crust below the bottom of the foundation is at least twice the foundation width, it is possible to design the foundation with a relatively low factor of safety of 1.7, with satisfactory performance with respect to settlement, differential settlement and tilting. The effect on adjacent silos will also be slight. The ring foundation, appropriately reinforced with the silo wall concentrically located above it, is an effective design to optimize the utilization of the beneficial effect of the crust which possesses high strength, low compressibility and a high coefficient of consolidation. The economic significance of using a low yet adequate factor of safety is evident in view of the large number of silos constructed annually in the general area of Southwestern Ontario.

ACKNOWLEDGMENTS

The research performed is supported by Supply and Services Canada under Contract No. 0SU76-00139. The Ontario and National Silo Associations also contributed to the financial support. Dr. M. Bozozuk, National Research Council, acted as scientific authority for the project and contributed many helpful discussions. Thanks are due to the following personnel for their valuable suggestions particularly regarding selection of sites for instrumentation: H. Bellman, Ontario Ministry of Agriculture and Food, R. Clayton, Agricultural Engineer, Ridgetown, Ontario Ministry of Agriculture and Food and J. Abercrombie and D. Rhoades, Ontario Silo Association. Appreciation is also expressed to F. Davidson of McCormick Silo Ltd. for his cooperation in installation of the instrumentation of the silo. Several University of Western Ontario personnel participated in the field and laboratory work involved in the project, including M. Johnson, G. Lusk, L. DiNardo, G. Fisher, S. Eccles, R. Wai and N. King. In addition, R. Carrington of Solinst Canada Limited helped with the pressure cell installations. Many thanks are also due to the farmers who allowed their silos to be instrumented and monitored.

BOZOZUK, M. 1972. Foundation failure of the Vankleek Hill tower silo. Proceedings of the Specialty Conference on Earth and Earth-Supported Structures, ASCE, Soil Mechanics and Foundations Division 1(2): 885-902.

BOZOZUK, M. 1974. Bearing capacity of clays for tower silos. Can. Agric. Eng. 16: (1) 13-17.

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

LO, K.Y. and D. BECKER. 1978. Tower silo foundations in Southern Ontario. University of Western Ontario, Faculty of Engineering Science Research Report, GEOT-1-78.

NATIONAL SILO ASSOCIATION. 1974. Silo operator's manual. The National Silo Association Inc., Cedar Falls, Iowa.

NEGI, S.C., J.R. OGILVIE, and E.R. NORRIS. 1977. Silage pressures in tower silos. Part 3. Experimental model studies and comparison with some silo theories. Can. Agric. Eng. 19(2): 107-110.

SKEMPTON, A.W. 1951. The bearing capacity of clays. Proceedings Building Research Congress, London. pp. 180-189.

TURNBULL, J.E., H.A. JACKSON, and D. LOWE. 1978. Reinforced extended ring foundations for top-unloading concrete tower silos. Contribution No. 529, Engineering and Statistical Research Institute, Agriculture Canada, Ottawa, Ont.