SILAGE PRESSURES IN TOWER SILOS. PART 3.
EXPERIMENTAL MODEL STUDIES AND COMPARISON WITH SOME SILO THEORIES

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Experimental data on pressure distributions on the base and walls, and the total load carried by the base of a model silo are presented in this paper. The results of the model tests are shown to be in fair agreement with the predicted values. Good agreement is found between the theoretical results and available experimental data on silage pressures in full-scale tower silos. Further, the proposed solution not only compares favorably with the Jansen theory, but it seems to predict more realistically the wall pressures beyond a depth of one and a half times the silo diameter.

INTRODUCTION

An analytical method for determining silage pressures in tower silos was developed by the authors in Part 1. Computed results to illustrate the effects of silo characteristics on silage pressures and laboratory data on the related physical properties were presented by the authors in Part 2. In this paper, experimental data on model and full-scale silos are compared with the predictions based on some existing silo theories and the proposed theory.

EXPERIMENTAL EQUIPMENT AND PROCEDURE

The experimental work described in this section was intended to provide information on three points. Firstly, to investigate the vertical and lateral wall pressures developed by silage materials in a model silo under static conditions, and to compare the practical results with those predicted by the present theory. Secondly, to determine the distribution of vertical pressure on the silo base for different depths of fill. Finally, to study the variation of load carried by the base and walls of the silo with depth of fill.

A 115-cm high model silo was constructed from a 30-gage galvanized steel sheet rolled to a diameter of 28 cm. The sheet was held together by a hook or lock joint which was subsequently soldered. Double-fold rims and rolled ribs were provided at the top and bottom of the cylinder to supplement its strength. The base of the silo was made of 20-gage galvanized steel sheet attached at the bottom of the cylinder by soldering. Adjustable clamps were fitted into each end of the cylinder to hold it in proper shape.

The silage pressures were measured by the slight deflections of stiff diaphragm-type, bonded-strain-gage transducers. The proportions of the transducer were obtained by using the general biaxial stress-strain relation as well as the radial stress, tangential stress and deflection formulas for a flat-diaphragm clamped at the edges (Doebling 1966). A hard steel shim stock of 0.005-cm thickness and 2.7-cm diameter was found to give the best compromise of sensitivity and linearity. It also satisfied the assumptions of small deflections and perfectly elastic behavior.

A 107-cm high model silo was filled with grass silage to increasing depths in pre-selected increments and measured by the transducers at various levels. The pressure cell was supported by a Plexiglas block glued to the inside surface of the transducers. The lateral pressures were measured by horizontal-facing diaphragm pressure transducers installed flush with the inner wall surface of the model silo. These transducers were mounted at elevations of 10, 25, 40, 55, 70 and 85 cm from the bottom of the silo. Each pressure transducer was closely fitted in the cutout provided in the silo wall. The pressure cell was supported by a Plexiglas block glued to the outside face of the cylinder. The cell was held tightly in position by screws.

The vertical pressures were measured at the aforementioned levels by vertical-facing diaphragm assemblies placed adjacent to the walls of the silo. The transducers were clamped against the silo wall by adjusting screws passing through slots made in the wall. These slots, six in number, were spaced 60° horizontally from the cutouts provided for wall pressure measurements. After the silo was filled with silage, the clamps were loosened, and the pressure cells were allowed to float within the static particulate solid.

The calibration of a pressure transducer was carried out in a cast acrylic cylinder in which the pressure was varied by changing the head of water. A hole was drilled in the base of the cylinder so that the transducer could be inserted with the diaphragm flush with the inner base surface. The diaphragm-strain gage assembly was supported by a Plexiglas block glued to the cylinder base and then held in position by screws. All joints were sealed by tape to prevent leaks. The hydrostatic head was increased in 4-cm increments up to a maximum of 40 cm. The gage output in microinches per inch against pressure in grams per cm² was plotted.

In order to measure the vertical and lateral pressures, the transducers were mounted in the appropriate cutouts. All lead wires were brought through terminal blocks (Jones 10-140) to the bottom of the silo where they were connected to a 10-channel switch and balance unit (Budd Model SB-1). The switching and balancing circuits were in turn connected to a strain indicator (Budd Model P-350) using 9-volt internal batteries as a power source.

The silage was loaded into the model silo in layers and periodically leveled and compressed, up to the top of the silo. In all of these tests, the silo was filled with 28.3 kg of grass silage at an average moisture content of 68.2%. The average unit weight of silage was 400 kg/m³. This was determined from the “average unit weight for entire depth” curve presented by Aldrich (1963). Once the silo was completely filled, the pressures measured by the transducers at various levels were recorded.

To determine the distribution of vertical pressure on the silo base, five pressure transducers were placed in the floor of the model silo. The test procedure consisted of filling the silo with grass silage to increasing depths in pre-selected increments and measuring the pressure distribution across the base. The amount of silage required to give an average unit weight of 400 kg/m² for a given depth was weighed and deposited in the silo. The silage was distributed evenly and periodically compressed until the desired depth was obtained. The top surface was then gently leveled off and strain readings were recorded. The vertical pres-
sure distribution on the base was measured for four different depths of fill. The corresponding values of the ratio of silage depth to silo diameter ($z/D$) were 1, 2, 3 and 4.

The final series of tests were conducted to study the variation of load carried by the silo base with depth of silage fill. The compression load cell of the testing machine (Instron Model TM-M) was utilized as the sensing element. The solder fastening the cylindrical silo to its base was melted using a propane torch. This silo base was replaced by a slightly smaller (27.5-cm diam) false bottom. The compression cell, which employed an extension cable for connecting the load cell to the recording device, was removed from the base of the testing machine and set on two blocks. A 36-cm square table with a centrally-located hole was placed around the cell such that the top of the cell was slightly above the table. The false silo bottom was mounted on the cell and then the cylindrical silo was set upon the table concentrically around the hole. The test setup is shown in Fig. 1.

In conducting a test, the silo was filled to a given depth with a pre-determined quantity of silage to obtain an average unit weight of 400 kg/m$^3$. The total load on the silo base for each depth of fill was noted from the Instron recorder chart. The load measurements corresponding to $z/D$ values of 0.25, 0.50, 0.75, 1.00, 1.50, 2.50, 3.50 and 4.11 were made.

RESULTS AND DISCUSSION
Silage Pressures in Model Silo

The measured vertical and lateral pressures in the model silo are shown in Fig. 2 compared with those predicted by the proposed theory for the active case. Points plotted for the measured pressures are averages of five tests. In general, there is reasonably good agreement between the theoretical and experimental results. It can be seen that the measured pressures were usually somewhat less than the predicted values. However, it is to be noted that the measured vertical and lateral pressures were not reproducible. Large variations, typically of the order of ± 20% occurred between tests.

Variability among observations was presumably caused by not accounting for those errors that were inherent in the testing equipment, other experimentally induced errors due to difficulties in the test procedure, and perhaps additional factors both known and unknown. The principal sources of error in measurement of pressure due to experimental equipment included slight deviation of the model silo from a perfect cylinder, some disparity in surface roughness of pressure gages and walls of the silo, impracticability of attaining perfectly rigid edge clamping, and relatively small deflection of the transducer diaphragm which would inevitably alter the stress conditions. Also, errors were probably induced in conducting experiments due to filling difficulties which led to variations in the silage density throughout the depth of the silo as well as in the immediate vicinity of the transducers. The diversity of silage constituents, the effects of slight variations in moisture content, temperature and humidity on silage characteristics, are some of the other factors that may have contributed to the discrepancies in these measurements. However, modifications in the instrumentation and controlled environment are desirable to acquire a greater precision of measurements.

It can be seen from Fig. 2 that the measured vertical and lateral pressures were attenuated near the base of the silo. This is ascribed to the increased angle of internal friction of silage resulting from higher consolidating pressures near the silo bottom. Further, there are some indications of a bulge in the wall pressure curve which is rather inconspicuous and inconclusive from these limited data. However, this bulging appears to start at the 45-cm depth and ends at the 90-cm depth. It is believed that the bulge in this zone was caused by the arching effect of silage.

Figure 3 shows the distribution of vertical pressure on the base of the model silo for various depths of silage. The curves represent the mean values of five tests for each depth ratio. The scatter in these tests was of the order of ± 12%.
of base pressure was quite erratic, but the only general pattern emerging from these results is that the pressure was maximum at the center of the silo and attenuated towards the walls. The only exception was at a depth ratio of 3 wherein the base pressure was higher near the walls. The observed decrease in base pressures from center to points in the near vicinity of the walls was apparently caused by the pressure-reducing effect of wall friction.

The observed variation of the load on the base of the model silo with depth of silage is shown in Fig. 5. A typical recorder chart of these measurements is presented in Fig. 4. Each point shown on the curve "load carried by silo base" (Fig. 5) is the average of five tests. The scatter in these tests was of the order of ± 3%. This rather good precision of measurement is attributed to the high accuracy (± 0.1% of full scale range of 200 kg) of the load weighing system of the testing machine.

The results of these experiments show that the weight of the stored silage was carried entirely by the silo base up to a depth of one-half the silo diameter. Thereafter, the walls began to carry a part of the total load. The proportion of the load carried by the walls increased with the depth of fill. When the depth-to-diameter ratio was approximately 3, the load carried by the walls equalled that carried by the base. The load on the base increased at a decreasing rate and rapidly approached a finite limiting value at a depth ratio of 3.5. Additional weight of the stored material (z/Z ≳ 3.5) was carried completely by the walls of the model silo.

Comparison of Experimental Data on Full-Scale Silos with Some Silo Theories

The lateral pressures predicted by some silo theories and the proposed formula are plotted in Fig. 6 together with the available experimental data on silage pressures in full-scale tower silos. The lateral pressures developed by corn silage in the moisture content range of 64.9 - 71.7% were measured by Boyd and his co-workers (Boyd and Yu 1961; Yu et al. 1962) for 3 successive yr (1960-62) in a concrete stave silo 9.14 m in diameter and 18.3 m tall. The theoretical curves for the Janssen (1895), Walker (1966), American Concrete Institute (ACI) (1946), and Canadian Code (1970) formulas were calculated from the respective equations reported in the literature. The proposed pressure-depth curve was obtained from the equations presented in Part 1. The numerical computations were based on the following set of input parameters: corn silage, φ = 38°, M = 67.7%; concrete stave silo, δ = 21°, D = 9.14 m.

It is seen from Fig. 6 that the proposed pressure-depth curve is very close to the mean lateral pressures measured in 1960. The pressures observed in 1962 are somewhat lower than the predicted values. However, the wall pressures measured in 1961 are significantly lower than those obtained by the proposed formula. The experimental data (1961) do not depart appreciably from the theoretical curve up to a depth of about 10 m, but do considerably in the lower portions of the silo.

If the experimental results are regarded as the basis for comparison, the validity of the predictions based on the proposed formula and the theories of Janssen and Walker is confirmed in Fig. 6. The theoretical wall pressure curve obtained from Walker's formula compares favorably with the measured values up to a depth of about 10 m. Beyond the 10-m depth, the theory underestimates the wall pressures and the discrepancy increases with depth of fill. The pressures calculated by the Janssen formula are somewhat higher than those predicted by Walker's theory, the percentage increase diminishing with depth of silage. But the Janssen solution provides lower evaluation than the present theory in the critical zone beyond 14 m. It is this upper position of the proposed solution in the lower zone that makes it superior to the theories of Janssen and Walker.

A further advantage of the proposed formula is that it is more explicit than Janssen's and Walker's equations; the variables involved can be determined by simple laboratory tests. Also, it has been demonstrated that the moisture content of silage materials exerts a profound influence on the relevant properties, namely, φ, δ and γ. This effect of moisture variation can be incorporated in the present theory.

As seen in Fig. 6, the predictions based on the Canadian Code and ACI formulas are, in general, exaggerated in comparison to the
observed lateral pressures. According to the empirical formula listed in the 1970 Canadian Code for Farm Buildings, the wall pressure increases in linear proportion with the depth. This method, although it may lead to overdesign of the silo, is acceptable on the ground that it will place the designer reasonably on the safe side. The pressures calculated from the ACI formula, commonly used in professional practice, are far in excess of the measured values.

From the foregoing data and description it may be concluded that the order of the wall pressures which will be developed by silage materials in full-scale tower silos can be calculated using the proposed theory for the active pressure condition.


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