Wall and Bottom Loads in a Model Grain Bin During Discharge

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Abstract
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Keywords
Wheat, Dynamic, Loads, Friction, Model bins

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Comments
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WALL AND BOTTOM LOADS IN A MODEL GRAIN BIN DURING DISCHARGE

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ABSTRACT
It was found that elasticity of wheat significantly influences bin wall and bottom loads during discharge. A change in the direction of the resultant friction force against the bin wall was observed in the final stage of discharge. The observed relationship between the resultant friction force and the grain height results from the downward friction force of flowing grain and the upward friction force of the dead zone of the bin.

KEYWORDS. Wheat, Dynamic, Loads, Friction, Model bins.

INTRODUCTION
Compressibility of stored granular solids influences the vertical and horizontal pressures in bins. This is important especially in the case of relatively soft materials like grain. Ross et al. (1979) showed that by estimating the parameters of bulk density, the coefficient of friction of the grain on the bin wall and the ratio of lateral to vertical pressures as functions of both grain moisture content and vertical pressure, the discrepancy between experimentally observed static pressures in bin and those predicted by the classical Janssen equations can be explained. Similarly, Latinsics (1984) proposed to include the compressibility of granular solids into calculations of the stresses in a bin.

Horabik et al. (1988) found that during the final stage of discharge the total friction force of grain on the bin wall changed its direction from a downward direction to an upward direction. The viscoelastic response of grain to the decrease in vertical stress in the dead zone of the bin caused by the decrease in the height of the grain was considered a possible explanation of the frictional force reversal. Their experiment suggests that not only compressibility but also an elastic or viscoelastic recovery of grain after unloading may influence load distribution in bins. This recoverable part of the total volumetric strain (depending on the moisture content). Thompson and Ross (1983) have shown that, for wheat with a moisture content below 12% in a pressure range from 0 to 7 kPa, half of the total change in bulk density resulted from rearrangement of the grain particles and half from the deformation of individual kernels.

The purpose of the research reported in this article was to establish the source of the frictional force reversal process.

EQUIPMENT AND PROCEDURE
A laboratory scale cylindrical bin 0.4 m in diameter and 1.6 m high, equipped with a flat bottom or with a 60° conical hopper was used for this study. The wall and floor of the bin were made of smooth galvanized steel with a surface texture roughness of 3.6 μm. The model bin was centrally filled and unloaded. The total vertical wall load was determined from three load cells (F1, F2, F3) supporting the wall cylinder, and the total vertical bottom load was determined from three load cells (F4, F5, F6) supporting the bin bottom. A schematic diagram of the model bin and load cell arrangement is shown in figure 1.

Winter wheat (Grana variety) at moisture contents of 10, 15, and 18% wet basis was tested. Experimental data from the six load cells were collected and processed on an Amstrad CPC 6128 Microcomputer. Accuracy of the load measurement for each load cell was 1 N. Load values for each load cell were collected during the discharge process.

Figure 1—Schematic diagram of the model bin indicating the load cell support arrangement.

every 3 s. Load values reported each represent an average of 20 measurements. The duration of the discharge process ranged from 20 to 60 min depending on the discharge rate. Four orifice sizes (24, 26, 30, and 34 mm) were tested which had a discharge rate corresponding to a sliding velocity of wheat (with a 15% moisture content wet basis) down the bin wall of 1.8, 3.0, 4.8 and 5.8 m/h, respectively.

Vertical deflection of the bin wall and bin bottom was measured by a dial gauge during filling and emptying of the bin. A dial gauge was located near the center of the bin bottom and one gauge was positioned under the supporting frame of the bin wall. The vertical deflection of the bin wall resulting from the elasticity of the load cells and supporting frame was less than 0.06 mm, and the vertical deflection of the bin bottom was less than 0.20 mm. The influence of artificially increased deflection of the bin bottom on the load distribution was examined. This deflection was increased to 0.3, 0.5 and 0.9 mm by using an elastic support of the bin bottom.

Four sets of dynamic wall and bottom loads tests were conducted with the flat bottom bin. One set using a 24 mm orifice and a relative deflection of 0.15 mm varied the three levels of moisture content. Four levels of relative deflections were tested with a 34 mm orifice and a moisture content of 15%. Another set used a moisture content of 15%, relative deflection of 0.15 mm, and the four orifice sizes. The fourth set examined the influence of equilibrium time of 0.5 and 18 h prior to beginning a discharge test. A dynamic wall and bottom load test was conducted using a 60° hopper with a 30 mm orifice and grain at 15% moisture content. Each test was replicated three times.

Compression tests of wheat grain samples at 10, 15, and 18% m.c. were performed in a rigid cylindrical die 210 mm in diameter and 120 mm high. The wall of the cylinder had a surface texture roughness comparable to the model bin wall. The wheat was poured into the cylinder and covered with a cylindrical plate. The covering plate was compressed towards the base of the cylinder with a constant displacement rate of 1 mm/min using an Instron resistance testing machine. The force exerted by the crosshead of the Instron machine on the plate covering the wheat in the cylinder was measured by a load cell. The compression test continued until the compressive force reached 416 N which is equivalent to a mean vertical pressure of 12 kPa, the overburden pressure from 1.6 m of wheat in the bin. Immediately after reaching a compressive force of 416 N the covering plate was moved upward at a displacement rate of 1 mm/min until the compressive force decreased to 3 N. Duration of the loading process ranged from 2 to 3.6 min depending on moisture content of wheat. The duration of the unloading process lasted approximately 40 s. The compressive force vs. vertical displacement of the covering plate was recorded during loading-unloading cycle. The loading-unloading cycle was repeated three times for each level of moisture content.

RESULTS

The observed relationship of the dynamic vertical wall and bottom loads to the height-to-diameter ratio of grain in the flat bottom bin during discharge of wheat at different moisture contents is presented in figure 2. During each experiment, the reversal of the friction force on the bin wall was observed as the ratio of the grain height to the bin diameter (H/D) decreased below approximately 1. With increasing moisture content of grain, the maximum upward friction force on the bin wall increased from 40 N for moisture content of 10% wb to 96 N for moisture content of 18% wb. Also, the H/D ratio at which the friction force changed its direction (passed through a vertical wall load of zero) increased with increasing moisture content. Enveloping flow that was identified by visual observation of an inverted cone-shaped grain surface appeared when the H/D ratio decreased below 1.1 for a moisture content of 10% wb and below 2.5 for a moisture content of 18% wb. The height of the dead zone remaining in the bin at the end of the discharge process was 80 mm for moisture content of 10% wb and 150 mm for moisture content of 18% wb.

Both the relative deflection between the bottom and wall and the moisture content of grain influence the frictional force reversal. Vertical wall and bottom loads affected by different bottom deflections are shown in figure 3. The upward friction force increases with an increase in bottom deflection. For a bottom deflection of 0.5 mm, the friction force reversal occurs at the same H/D ratio as the observed development of enveloping flow. Increasing bottom deflection from 0.5 to 0.9 mm did not increase the magnitude of the maximum friction force reversal. The upper limit for the magnitude of the upward friction force is expected to occur when all grains in the dead zone are pushed upward. The vertical deflection of the bin wall resulting from the elasticity of the load cells and elasticity of the supporting frame was less than 0.06 mm and the bin bottom deflection was less than 0.20 mm. The maximum relative deflection between the bin wall and bottom was 0.14 mm. The deflection between the bin wall and bottom
was increased by using different elastic supports for the bin bottom. Figure 4 presents the magnitudes of deflection for the bin bottom relative to the bin wall as affected by height to diameter ratio. The magnitude of the relative deflections remains constant during the first 30 to 80% of the discharge process depending on the maximum deflection for the bin filled with grain.

Figure 5 presents the wall and bottom loads for different flow rates of grain from the bin using four different orifice sizes. Increasing the orifice size from 24 to 34 mm increases sliding velocity of grain down the bin wall from 1.8 to 5.8 m/h and slightly decreases the magnitude of the maximum friction force reversal. No difference in the loads was observed between orifice sizes of 30 and 34 mm. Height of the dead zone remaining in the bin after discharge decreased from 110 to 80 mm for an increase of orifice size from 24 to 34 mm, respectively. An approximately three-fold decrease in the discharge time resulted in a decreased viscoelastic response of wheat during unloading as illustrated in figure 5. This is congruent with the observations by Grundas and Horabik (1980) which showed that 70% of the total change in the volumetric strain of a wheat sample in the creep process occurs immediately after loading and the next 20% of this strain occurs within the first 30 s after loading the sample. Increasing the storage time of grain in the bin from 0.5 to 18 h before unloading did not influence the wall and bottom loads. During the initial phase of discharge, the difference between the static and dynamic wall and bottom loads was larger as storage time increased from 0 to 0.5 h.

Loading-unloading tests of a wheat sample were performed to estimate the value of elastic strain recovery after unloading. The effects of vertical pressure on volumetric strain are presented in figure 6. The elastic part of the total volumetric strain recovery was approximately 0.006. The value of elastic recovery corresponds to a displacement of about 0.6 mm for the 100 mm high dead zone in the test bin.

The discharge of the test bin when equipped with a conical hopper (wall slope of 60° to the horizon) was performed to observe the influence of the dead zone on the wall loads. Figure 7 illustrates that throughout the entire discharge process the friction force on the bin wall never reversed. This result is attributed to the absence of the dead zone which is composed of grain. The experimental curve of the vertical wall load nearly coincides with the shape predicted by the classical Janssen equation because the vertical wall load does not change directions.

**Summary and Conclusions**

These experiments indicate that a measured change in direction of the frictional force on the bin wall originates from the combination of the downward friction force of flowing grain and the upward friction force of the grain contained within the dead zone of the bin. This upward movement can be generated by the elasticity of grain and the elastic relative deflection between the bin bottom and the bin wall. The magnitude of the upward movement of grain is determined by the amount of overburden pressure removed. The contribution of the relative deflection to the upward grain displacement was approximately 0.15 mm, and the elastic recovery of grain was estimated to be about 0.6 mm.

A hypothesized frictional stress distribution (σf) along the bin height, as inferred from the results of this study, is illustrated in figure 8. During the plug flow phase of unloading, the height of the dead zone in the bin was constant. As H/D decreases, the height of the dead zone increases reaching the height of grain in the bin immediately after enveloping flow occurs. Such a change in the dead zone height could explain the relationship between the resultant friction force on the bin wall and quantity of grain in the bin.

A change in the direction of the resultant friction force on the bin wall from a downward direction to an upward direction was observed as the ratio of the grain height to the bin diameter (H/D) decreased below approximately 1.

Elasticity of wheat and the elastic relative deflection between the bin bottom and the bin wall will generate an upward movement of wheat located in the dead zone.
The moisture content of wheat grain influences its compressibility, height of the dead zone, discharge rate and, in consequence, the upward movement of grains in the dead zone of flat bottom bin during discharge.

No reversal was observed in the frictional force on the bin wall during discharge for a bin equipped with the conical hopper. Replacement of a dead zone composed of grain by a 60° hopper removes the frictional force reversal.

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REFERENCES