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THE increased heights and diameters of grain storage bins that are now being designed and constructed pose new structural problems. Inadequate foundations, inexperienced planning and statical analysis, and faulty structural work have all contributed to these problems.

An equation of static equilibrium multiplied by an overpressure factor usually in the range of 1 to 2 is presently used by some engineers as an estimator for horizontal and vertical sidewall pressures for tall bins. Many design problems can be attributed to a lack of understanding of the magnitude and position of dynamic overpressures caused by plug flow from grain bins and how they relate to bin design.

Ross et al. (1979) proposed a method for using a differential form of Janssen's (1895) equation for predicting pressures in bins containing ground shelled corn in which variable material properties were defined as functions of certain varying grain parameters. The Ross study showed that the variation in physical properties of materials may explain the higher pressures which occur during plug flow of granular materials from bins. At that time, no attempt was made to measure the actual stresses in bins in which ground shelled corn was stored or to compare the results to those proposed by the method of varying grain properties.

The results of the experiments conducted for this study are compared to calculated values based on Janssen's equation using constant values of the grain properties in the equations. Also, using regression equations determined for the physical properties of soft red winter wheat, the prediction method developed by Ross is compared to values obtained by measuring wall loads on a model grain bin. Wall loading was also characterized during bin loading and unloading after periods of quiescent storage.

EQUIPMENT AND PROCEDURE

A smooth walled grain bin 0.61 m in diameter and 2.44 m tall made of galvanized steel was used for these tests. A diagram of the grain bin and grain distribution system is shown in Fig. 1. The main cylinder of the grain bin was supported independently from the bottom to obtain an independent measure of the total wall and bottom loads. Interchangeable hoppers of different included angles were tested. Each bin component was supported by four cantilever beams equipped with bonded strain gages. The loads were determined from the deflection of the cantilever beams supporting the two bin components with an accuracy of approximately plus or minus 0.18 kg.

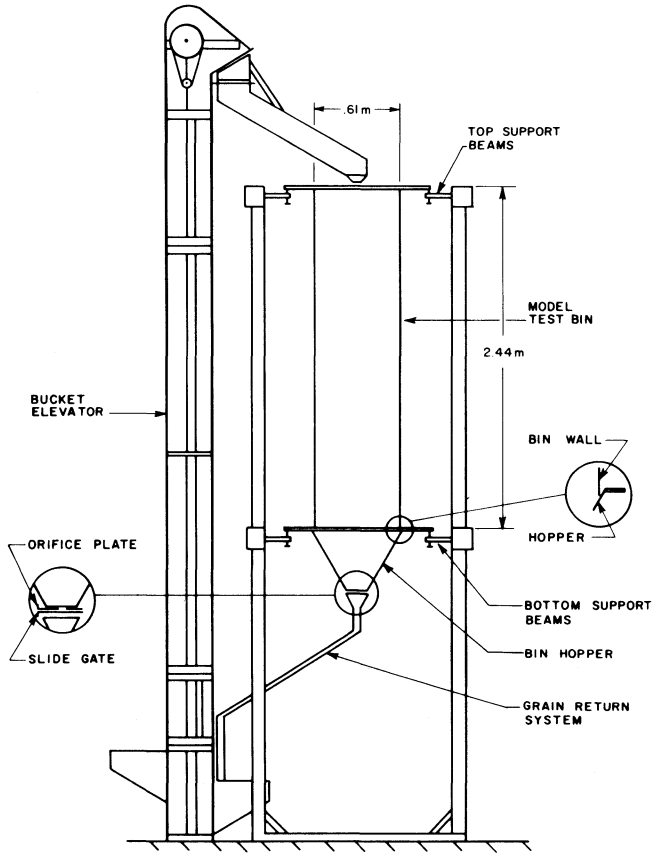

FIG. 1 Model bin and bucket elevator system.

Wheat at a moisture content of 12 percent (w.b.) was used for all tests. Two hopper bottoms (0 deg, (or flat), and 60 deg) and three orifice sizes (2.54, 3.18, and 3.81 cm) with each bottom were tested. The size of the orifices were chosen to give discharge rates which resulted in a sliding velocity of the grain down the wall during plug flow discharge of between 1.46 and 4.94 m/h, i.e., the range of values normally observed during plug flow discharge in farm and commercial grain bins. Nine replications in a balanced design were performed for each independent variable: grain height, hopper angle, and discharge rate of grain. A replication consisted of the measurement of the total dynamic wall and total bottom loads which occurred during the discharge mode in the grain bin. By continuous circulation of the grain by a bucket elevator, the beginning depth of the grain was maintained during the dynamic flow tests. This was done to allow the flow and pressure conditions to stabilize in the grain bin and distribution system prior to measuring

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the bin loads for a given test condition.

The test bin was filled to a specified height with grain prior to beginning a test and allowed to equilibrate. Upon equilibration, the static wall and bottom loads were measured.

Total wall and bottom loads were also measured for circular orifices of 5.08, 6.35, and 7.62 cm in diameter. These results will not be compared to those computed in the differential form of Janssen's equation using variable grain properties, because the grain flow velocities down the wall of the bin using these orifices were much higher than the velocities used in the tests to determine the effect of velocity on the variable coefficients.

RESULTS: GRAIN PROPERTIES EQUATIONS

Experiments were conducted in which sidewall friction coefficients, μ, and bulk density, w, were measured as a function of sliding velocity, overburden pressure and moisture content for soft red winter wheat. Multiple Regression techniques were used to develop empirical equations which characterize the measured relationships. The equations are as follow:

$$\mu = 0.108 + 1.69\,P/10^5 + 1.084\,(1/\sqrt{P}) + 0.194\,(M^4/10^6) - 0.025\,(Me^M/10^{11}) - 0.566\,(\ln M)(1/\sqrt{P}) + 0.014\,[(M\ln M)(1/\sqrt{P})] + 0.399\,(M^4/10^6)\sqrt{SP} - 0.011\,M\,(e^M/10^{11})\ln(SP) - 4.90\,P\sqrt{SP}/10^5 \quad [1]$$

where

μ = sidewall friction coefficient

P = vertical pressure, kPa

M = percent moisture content, % w.b.

SP = sliding velocity, m/h

R^2 = 0.802

The bulk density of grain was calculated by:

$$w = 826.01 + 0.523P + 1.750\sqrt{P} - 14.236\,(M^3/1000) + 31.964\,(e^M/10^{10}) - 0.258\,P\,(\ln M) + 1.712\,M^3\sqrt{P}/1000 \quad [2]$$

where

w = bulk density, kg/m^3

P = vertical pressure, kPa

M = moisture content, % w.b.

R^2 = 0.992

Equations [1] and [2] provided a convenient means of incorporating measured variations in material properties into the differential form of Janssen's equation. Details of the experiments and analysis resulting in equations [1] and [2] are given by Thompson (1980).

The equation for μ and w were valid for overburden pressure up to 172 kPa, moisture contents in the range of 8 to 24 percent, and sliding velocities of 0.06 to 6 m/h. The variable material functions were then inserted into the differential form of Janssen's equation to solve for the dynamic vertical pressures which occur at discrete points in the grain bin. The differential form of Janssen's equation used was:

$$\frac{dP}{dy} = wg - \frac{kP\mu}{R}$$

where

P = vertical pressure in the bin at a given depth y

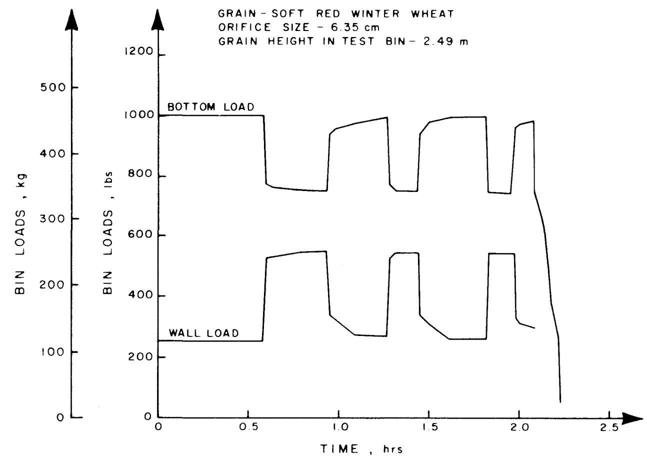

FIG. 2 Bin component loads during the dynamic discharge mode.

y = depth of overbearing grain at a discrete point in a grain bin—measured from the top of the material surface down

R = hydraulic radius of the grain bin

w = bulk density of the stored material

k = lateral to vertical pressure coefficient

μ = coefficient of sidewall friction

g = gravitational acceleration constant

RESULTS: MODEL BIN

The variation in both the static and dynamic bin loads were measured in the test bin. They were found to vary with grain height, hopper angle, and discharge rates of the grain.

The test bin was filled three times for a given test condition with three unloading cycles performed each time the bin was filled. An example of the resulting total loads for an orifice size of 6.35 cm is shown in Fig. 2. The bin component loads varied with time for both the static and dynamic grain flow conditions. An equilibrium period of 0.5 h was taken between each unloading cycle. Immediately prior to discharging grain, 20 percent of the total load in the test bin was supported by the walls while 80 percent of the total load was supported by the bottom. Immediately after opening the discharge gate in the test bin, a large portion of the total bin load shifted from the bottom to the walls. In the discharge mode, 44 percent of the total load was supported by the walls of the bin; the remainder was supported by the bottom. Therefore, under these conditions, the dynamic-static load ratio (as defined by the ratio of the total wall loads in the dynamic to static condition) of 2.2 was observed. Upon closing of the discharge gate, an instantaneous change in the bin loads was again observed with only 26 percent of the total load in the bin supported by the walls.

The loads carried by the walls of the test bin varied with a change in the height of stored grain. For a 6.35 cm orifice, it can be observed in Fig. 3 that the change in wall loads in the test bin is exponential. This effect is predicted by both the Janssen (1895) and Reimbert (1976) equations. However, the height of stored grain in the test bin at which zero wall loads occurred was found to be not at a height of zero inches, as assumed in the formulation of the Janssen equation, but rather at a grain height of 25 to 30 cm.

The discharge rate has a statistically significant effect at the 0.05 significance level on the wall loads measured

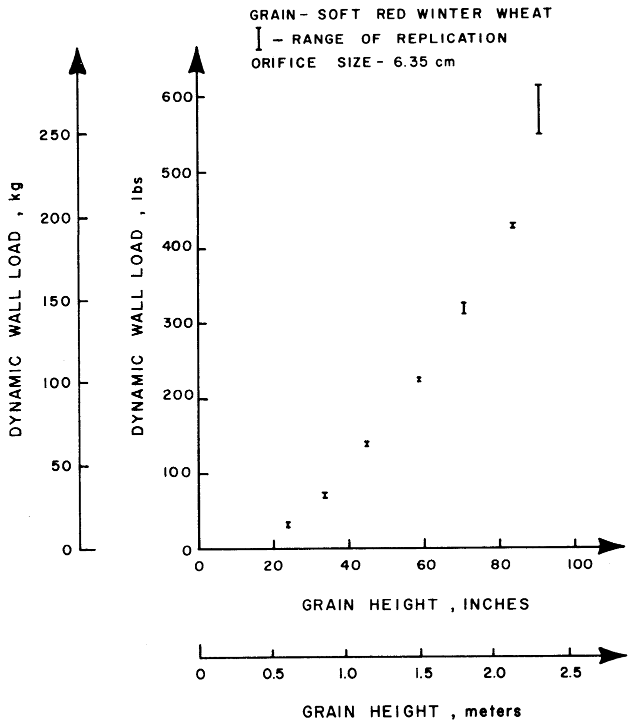

FIG. 3 Wall loads measured in the test bin as a function of grain height for an Orifice Diameter of 6.35 cm.

in the test bin. This variation is shown in the graphs presented in Fig. 4 for 0 deg and 60 deg hoppers. An increase in orifice size and the resulting increase in discharge rate resulted in an increased wall load. A linear regression analysis of the wall loads for a grain height of 2.44 m, using a 0 deg hopper bottom with orifice diameters ranging from 2.54 to 6.35 cm showed that the slope of the regression line was 13.7, or that the total wall load increased 13.7 kg for each m^3/h increase in the discharge rate.

The average dynamic wall load and the average height of the grain column in the test bin increased slightly following each successive discharge event or test replication. Two examples of this phenomenon are presented in Table 1, in which the average wall loads were observed to vary with the packing of grain. The same amount of grain was used in each replication within the two hopper configurations. This indicates that the configuration and packing of the grain mass changes following each successive discharge or test replication, with larger dynamic wall loads observed in the test bin for less compact material. The Reimberts (1943) and Turitzin (1963) interpreted this same phenomena as the result of the formation and ultimate collapse of grain arches formed in the grain mass, which upon failure produced shock waves in the walls and bottom of the grain bin. They proposed that the behavior of the grain mass during discharge was a function of both the degree of packing and the method in which the grain bin had been previously filled. Using a jet method, the grain was deposited in a narrow stream in the middle of the bin, with the grain particles sliding to and being loosely deposited on one another at the outermost regions of the bin adjacent to the walls. They also tested a shower method in which the grain was evenly spread over the entire bin, thereby evenly compacting the entire grain mass. For the compact material, very few irregularities were observed within the grain mass and emptying proceeded without hammering and vibration, while in a non-compact material rupturing of the grain arches occurred during emptying with violent vibrations observed in the bottom and walls of the grain bin. Vibrations and hammering were not observed during any of the unloading tests conducted in the model bin as part of this research. However, the compacting and wall loading

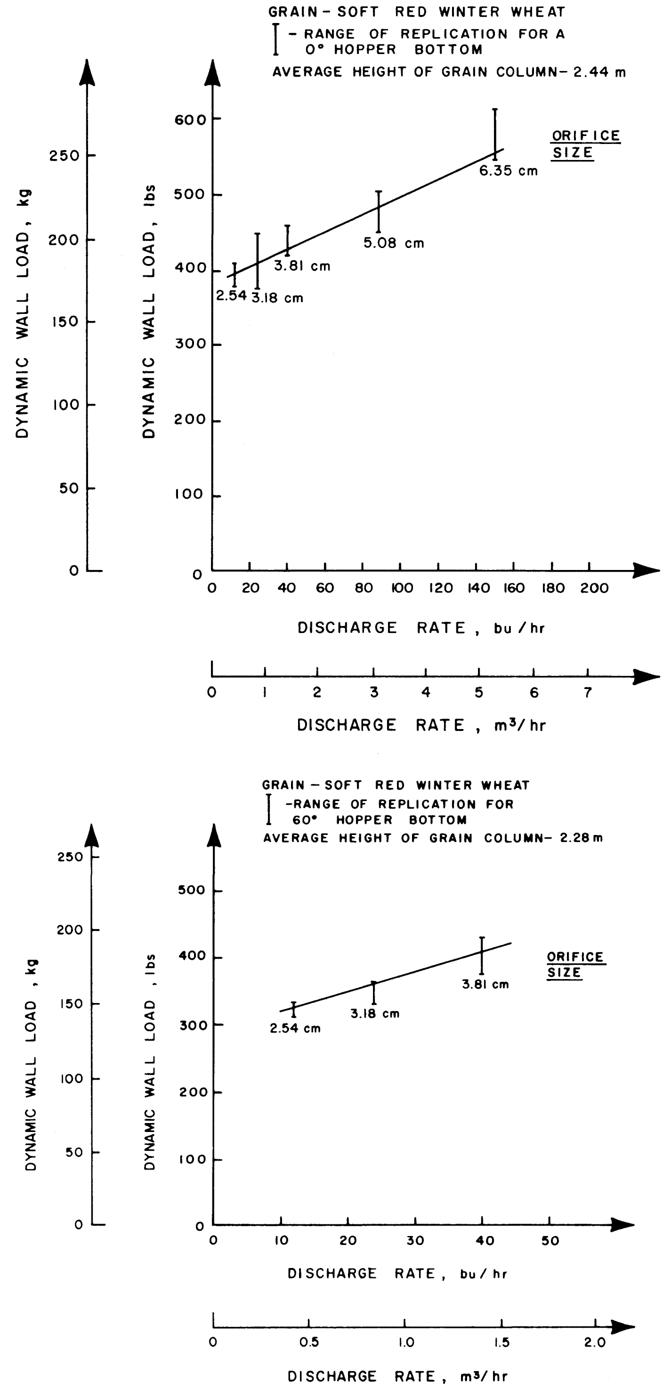

FIG. 4 Wall loads measured in the test bin as a function of discharge rate.

TABLE 1. AVERAGE DYNAMIC WALL LOADS FOR SUCCESSIVE REPLICATIONS.

Hopper bottom	Orifice size	Replication	Grain height	Average wall load
		1	120.7 cm	49.4 kg
0°	2.54 cm	2	123.2 cm	52.1 kg
		3	123.8 cm	55.1 kg
		1	220.0 cm	158.1 kg
60°	3.18 cm	2	222.9 cm	163.2 kg
		3	224.2 cm	165.3 kg

TABLE 2. DYNAMIC-STATIC LOAD RATIOS FOR THE TEST BIN AS AFFECTED BY DISCHARGE RATE, GRAIN HEIGHT, AND BOTTOM CONFIGURATION.

Flow rate, m^3/h	Height*	Dynamic-static load ratio (dsr) Bottom configuration: Flat	60° hopper
0.42	Hi	1.47	1.64
	Lo	2.09	1.78
0.82	Hi	1.64	1.61
	Lo	1.83	1.77
1.43	Hi	1.87	1.85
	Lo	1.92	1.71

*Height ranges: Hi — from 222.0 to 248.9 cm
Lo — from 117.1 to 120.9 cm

concepts of the Reimberts may explain at least, in part, some of the observed results.

Averages of the dynamic-static load ratios (dsr) which existed in the test bin during discharge are presented in Table 2 with the ratios in this case defined as the average total dynamic wall loads measured during the discharge mode divided by the minimum static load which existed prior to discharge. The minimum static loads vary as a function of the equilibration period allowed prior to recirculation of the grain in the discharge mode, therefore, these values are only examples of the dsr factors which may exist in the grain bin, with a possibility that the dsr factors defined in Table 2 may be slightly larger in some cases. It was determined that at a 0.05 significance level, the dsr varied both with grain height and orifice size, with the dsr for a particular orifice being larger for a smaller grain height than for a larger grain height. These results are similar to those proposed in the German Standard, DIN 1055 B1.6 (1964), in which larger dynamic overpressure factors were suggested in the upper sections of the bin as compared to the lower sections of the bin.

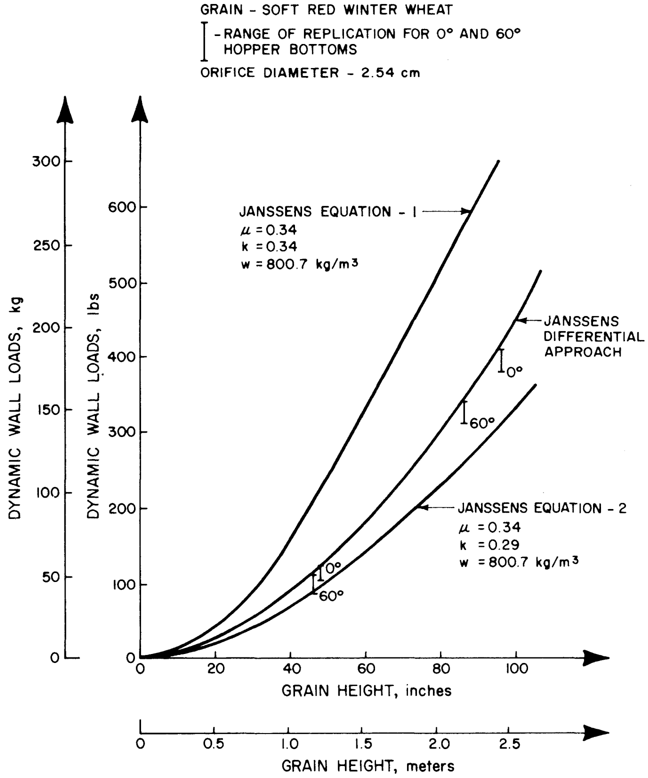

FIG. 5 Dynamic wall loads measured in the test bin as a function of grain height for an Orifice Diameter of 2.54 cm.

COMPARISON OF PREDICTION TECHNIQUE

The dynamic wall loads measured in the test bin were compared to calculated results using the differential form of Janssen's equation with variable material properties and with Janssen's equation using constant values of the material properties. These comparisons are shown in Figs. 5, 6 and 7 for three grain discharge rates obtained with the discharge orifice diameters of 2.54, 3.18 and

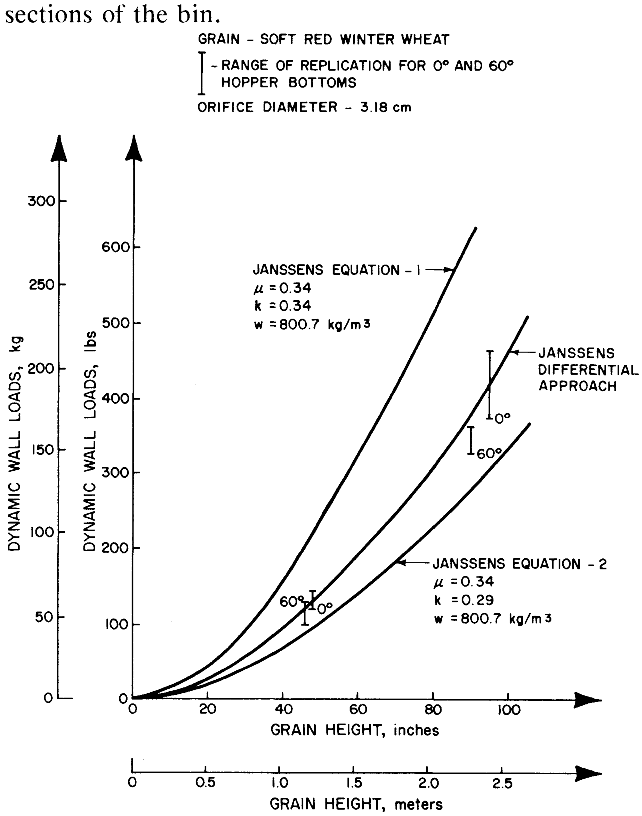

FIG. 6 Dynamic wall loads measured in the test bin as a function of grain height for an Orifice Diameter of 3.18 cm.

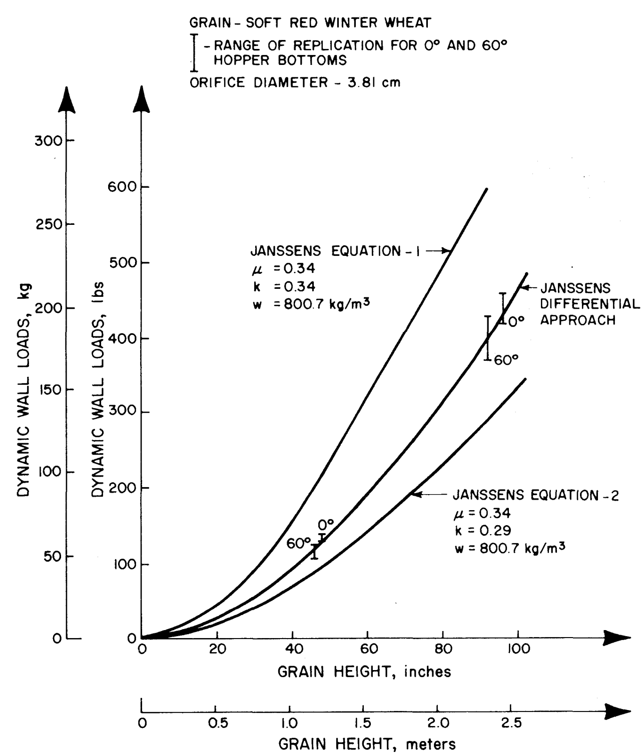

FIG. 7 Dynamic wall loads measured in the test bin as a function of grain height for an Orifice Diameter of 3.81 cm.

3.81 cm, respectively. The range of experimentally determined values for the flat bottom, 0 deg and the 60 deg hopper bottom are presented for each of the orifice diameters.

The curves in each of the figures labeled Janssen's Differential Approach represent the calculated values using the computer technique with variable material properties for μ and w as defined by equations [1] and [2], respectively. A constant value of k equal to 0.29 was used for these calculations. This value of k was a best-fit value chosen on the basis of the comparison of wall loads predicted by the differential form of Janssen's equation and the wall loads obtained from measurements in the test bin for orifice sizes of 2.54, 3.18 and 3.81 cm.

The curves labeled Janssen Equation-1 and Janssen Equation-2 represent the calculated values using constant values of the physical properties. For Janssen's Equation-1, the values used for μ and k are the average of the range of values for these properties suggested for grains by Committee 313 of the ACI (1975). These values were 0.34 for both μ and k. For Janssen's Equation-2, a value of μ equal to 0.34 (average of the ACI suggested range) and a value of k equal to 0.29 (the best-fit value obtained from these experiments) was used. A constant value of w equal to 800.7 kg/m^3 was used in the calculations for both Janssen's Equations-1 and -2. This value is the measured bulk density for the wheat used in these experiments subjected to a pressure of approximately 7 kPa.

The predicted wall loads using the differential approach of Janssen's Equation with variable material properties compared favorably with those measured in the test bin. The sliding velocities shown in Figs. 5 to 7 vary from 1.46 to 4.94 m/h or over much of the range of the sliding velocities normally found in grain bins. The predicted results using this method was somewhat poorer when compared to the wall loads measured in the test bin equipped with a 60 deg hopper, with the prediction method overestimating the wall loads for an orifice diameter of 2.54 and 3.18 cm while underestimating the wall loads for an orifice diameter of 3.81 cm. However, these generally favorable results would be anticipated since the predicted values were determined using a best-fit value of 0.29 for k. A comparison of the predicted curves using Janssen's Equation-2 and the Janssen differential approach in which the same k-value (0.29) was used indicates the difference between these prediction methods. In general, the predicted values shown for the Janssen's Equation-2 curve are approximately 0.75 of the predicted values shown for the Janssen differential approach.

The prediction method using the constant physical properties represented by the average of the range of values suggested by ACI (Janssen's Equation-1) overestimated the wall loads in the test bin by a factor of approximately 1.7, that is, the predicted wall loads were 1.7 times as large as those measured in the test bin. This overestimation occurred prior to the application of the dynamic overpressure factors to the bin loads which are suggested by ACI Standard (1975) to accommodate the increased wall loads which occur during the discharge mode in a grain bin. Following the application of the dynamic overpressure factors, the predicted wall loads would be 2.3 to 3.2 times the values of those measured in the test bin, indicating that in this case for the constant material properties used, the method suggested by the ACI grossly overestimated the wall loads in the test bin.

SUMMARY

The sidewall friction coefficient, μ, and the bulk density, w, have been determined for soft red winter wheat as affected by grain moisture content, pressure, and sliding velocity over a galvanized metal surface. These values were used in a differential form of Janssen's equation (1895) to predict the total wall and bottom loads in a 0.61 m diameter by a 2.44 m high test bin to determine if the variability of grain properties could be used to explain the dynamic overpressures which occur in grain bins during discharge.

The total wall and bottom loads in the test bin were measured for both the static and dynamic conditions for variations in grain height, grain bin hopper configurations, and grain discharge rate. Wall loads and bottom loads were measured for grain heights of approximately 1.22 and 2.44 m, for hopper configurations of 0 deg (or flat) and 60 deg, and or grain discharge rates from 0.43 to 5.50 m^3/h.

Total wall loads increased as the discharge rate increased but were not affected by filling rate. Because of the geometry of the test bin, the rate but not the method of filling could be altered. Packed grain produces smaller total wall loads than those of a non-compacted grain. Total wall loads increased exponentially with grain height, as was assumed by both Janssen (1895) and Reimbert and Reimbert (1976). The dynamic-static load ratio (dsr) was larger for lower grain heights than higher grain heights, as suggested by the German design code DIN 1055 B1.6 (1966) in which dynamic overpressures were slightly larger for smaller grain heights.

The differential form of Janssen's equation used with the variable material properties for bulk density and sidewall friction and a best fit value of 0.29 for the lateral to vertical pressure coefficient predicted wall loads in the test bin to within 5 to 10 percent of the measured values. The values suggested by Committee 313 of the ACI (1975) overestimated the measured wall loads by approximately a factor of 1.7. These results indicate that the prediction method using the differential form of Janssen's equation with variable properties may be a viable method for the prediction of loads in grain bins.

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