1991

Calibration of a Model for Packing Whole Grains

Sidney A. Thompson
University of Georgia

Charles V. Schwab
Iowa State University, cvschwab@iastate.edu

I. Joe Ross
University of Kentucky

Calibration of a Model for Packing Whole Grains

Abstract
The computer program WPACKING was validated using bin data for three different bin conditions: 1) a smooth-walled bin filled with wheat, 2) a corrugated-walled bin filled with wheat, and 3) a corrugated-walled bin filled with corn. WPACKING is a computer program which utilizes the differential form of Janssen's equation to predict the pressures and amount of material stored in a bin. The differential form of Janssen's equation allows the material properties in the equation to vary as a function of different properties. The material properties suggested for use in the WPACKING program were based upon previous experimental work by various researchers. From using the WPACKING program, it was apparent that a change in grain height has a greater effect in increasing the amount of packing than does a change in bin diameter or moisture content of the stored material.

Keywords
Grain, Packing, Storage bins

Disciplines
Agriculture | Bioresource and Agricultural Engineering

Comments
This article is from *Applied Engineering in Agriculture* 7, no. 4 (1991): 450–456.

Calibration of a Model for Packing Whole Grains

S. A. Thompson, C. V. Schwab, I. J. Ross
Assoc. Member ASAE, Assoc. Member ASAE, Fellow ASAE

Abstract

The computer program WPACKING was validated using bin data for three different bin conditions: 1) a smooth-walled bin filled with wheat, 2) a corrugated-walled bin filled with wheat, and 3) a corrugated-walled bin filled with corn. WPACKING is a computer program which utilizes the differential form of Janssen's equation to predict the pressures and amount of material stored in a bin. The differential form of Janssen's equation allows the material properties in the equation to vary as a function of different properties. The material properties suggested for use in the WPACKING program were based upon previous experimental work by various researchers. From using the WPACKING program, it was apparent that a change in grain height has a greater effect in increasing the amount of packing than does a change in bin diameter or moisture content of the stored material. **Keywords.** Grain, Packing, Storage bins.

Introduction

The task of estimating the amount of materials in a bin is difficult and requires information on how materials pack and compress under load. Packing is affected by parameters associated both with the properties of the stored granular material and the geometry of the storage structure. WPACKING, a computer program developed by Thompson et al. (1987), which utilizes the differential form of Janssen's equation to predict packing, will be validated and then used to predict the packing for full-sized grain bins of a number of different geometries. The computer program will be validated using data collected by Schwab (1989), Thompson and Prather (1984), and Williams et al. (1989) in bins of different heights, diameters and side-wall geometries.

Background

It is difficult to predict the manner in which grain might compact or compress because bulk grain consists of a complex matrix of irregular-shaped particles each with its own characteristics. Therefore, most work which relates directly to the packing of whole grains and feeds has been empirical rather than theoretical.

Bates (1925) described a method for estimating the quantity of materials in storage bins and packing of granular materials. Bates suggested that the amount of material in a bin is dependent on the dimension and shape of a bin, the depth of material, and the test weight of the stored material.

A more detailed method published by the Illinois Agricultural Auditing Association (IAAA, 1980) can be used for estimating the packing factors of granular materials in a storage bin. Packing factors were provided for seven varieties of grain based on the initial test weight of the material and the bushels per foot of depth in the storage structure.

Malm and Baker (1985) tried to determine on-site compaction factors of granular materials by measuring the height of the material in a bin at 7 to 14 days after filling and again at 23 to 40 days after filling. However, difficulties were encountered in accurately measuring the amount of settlement of the grain as the surface of the grain was sometimes disturbed by the person sampling the stored crop.

Chang et al. (1981, 1983) determined that when a spreader was used, the in-bin bulk density of wheat was approximately 5 to 9% higher than when a spreader was not used. Similar results were found by Stephens and Foster (1976) who determined that grain spouted into a bin increased the average bulk density of the samples test weight by an average of 3.7%.

Description of the Computer Program

The computer program, WPACKING, utilizes the differential form of Janssen's equation (Ross 1979) to predict the variation in material properties and pressures within a storage bin. The differential form of Janssen's equation (1895) varies from the classical equation by allowing variable material properties. The values of k (the lateral-to-vertical pressure ratio) and u (coefficient of friction of grain on bin wall) are assumed to be constant throughout, while w (bulk density of the granular material) is allowed to vary. The variation in bulk density of the granular material is described by a function which varies with overburden pressure and moisture content when under uniaxial compression (Thompson et al., 1987).

The functions used to describe the variation in bulk density were determined experimentally (Thompson et al., 1987). Experiments were conducted to determine the variation in bulk density as a function of overburden pressure and moisture content for six different types of whole grains: soft red winter wheat (SRWW), hard red

Article was submitted for publication in September 1990; reviewed and approved for publication by the Structures and Environment Div. of ASAE in February 1991. Presented as ASAE Paper No. 89-4547.

This research is supported by State and Hatch funds allocated to the Georgia Agricultural Experiment Station.

The authors are **S. A. Thompson**, Associate Professor, Agricultural Engineering Dept., University of Georgia, Athens; **C. V. Schwab**, Assistant Professor, Agricultural Engineering Dept., Iowa State University, Ames; and **I. J. Ross**, Professor and Chairman, Agricultural Engineering Dept., University of Kentucky, Lexington.

winter wheat (HRWW), corn, soybean, rice, and sorghum. Mathematical expressions which predicted the variation in bulk density as a function of overburden pressure and moisture content were developed based upon the experimental tests. The predicted variation in bulk density of the granular material for each whole grain at a moisture content of 12% (wb) is shown in figure 1.

The computer program, WPACKING, has nine different user inputs which are used to predict the packing of whole grains in storage structures. A list of these inputs is shown in Table 1. A more detailed explanation of the user inputs can be found in Thompson et al. (1987). The computer program predicts the amount of packing of the granular material in the bin and the number of standard bushels contained in a bin based on the user inputs.

Description of Full-Scale and Model Bin Data

WPACKING predicts, based on the differential form of Janssen's equation, both the amount of packing and the vertical pressures which occurs in a bin. If particle packing is a function of the vertical stress variation that exists within a given stack or pile of material, then accurate estimates of the vertical pressures in a bin are required. To validate the computer model, WPACKING, the vertical pressures predicted by WPACKING in a bin were compared to experimental values previously listed in the literature. From this comparison values of u and k required to predict vertical pressures for packing were determined.

Full-scale and model bin data by Schwab (1989), Thompson and Prather (1984), and Williams et al. (1989) were used in the validation of the computer model WPACKING for three different conditions: 1) soft red winter wheat in a smooth-walled grain bin; 2) soft red winter wheat in a corrugated-walled grain bin; and 3) corn in a corrugated-walled grain bin. A description of the bin geometry and storage conditions for each of these experiments is shown in Table 2.

Schwab (1989) performed experiments in a smooth-walled flat bottomed grain bin constructed such that the loads on the bin walls and bottom could be measured separately. Vertical floor pressures were measured using a system of ring beams supported by load cells which measured the vertical pressures on the floor of the bin. Tests were conducted for two different grain heights.

Williams et al. (1989) performed experiments in a full-scale corrugated grain bin. For all tests, vertical pressures on the floors of the bin were measured using load cells as described by Galili et al. (1989). Vertical pressures were measured along four different radial lines at grain heights of approximately 0.45 m (18 in.) intervals.

Thompson and Prather (1984) performed tests in a corrugated-walled flat bottomed model grain bin. The floor of the bin was supported by four beams which were used to determine the total load which acted on the floor of the bin. Floor loads were measured in the bin in increments of 0.15 m (6 in.) up to a grain height of 2.74 m (9 ft).

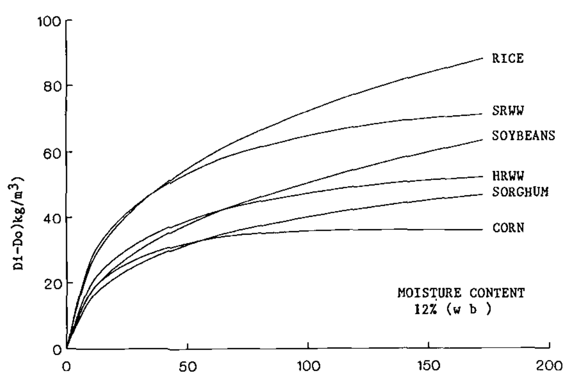

Figure 1–Variation in bulk density of six whole grains for a moisture content (wb) of 12% (Thompson et al., 1987).

TABLE 1. User inputs for the computer program needed to predict the packing of whole grains in storage structures

1. Type of grain.
2. Moisture content of the grain (wb).
3. Lateral to vertical pressure coefficient (k).*
4. Type of interior wall surface.
5. Coefficient of friction of the grain on the bin wall.*
6. Grain height, m (ft).
7. Bin diameter, m (ft).
8. Method used to fill the bin.
9. Test weight of the stored material, kg/m ^{3} (lb/bushel).

* Default values are assumed by the program unless the user chooses to input these values.

TABLE 2. Descriptive parameters of the grain bins and test conditions used in the validation of the computer program WPACKING

Source	Bin diameter (m)	Bin diameter (ft)	Bin height (m)	Bin height (ft)	Bin wall geometry	Stored material
Schwab (1989)	3.08	13.4	21.1	69.3	Smooth-walled galvanized steel	Wheat
Williams et al. (1989)	12.8	42	17.1	56.1	Corrugated-walled galvanized steel	Corn
Thompson and Prather (1984)	0.91	3	2.7	9	Corrugated-walled galvanized steel	Wheat

Material Properties

Janssen's (1895) equation is still the most commonly used method for predicting pressures in grain bins. However, both the differential and/or classical form of Janssen's equation rely on the magnitude of the values of u (coefficient of friction of the grain on the bin sidewall), k (lateral-to-vertical pressures ratio), and w (bulk density of the stored material) for predicting pressures in grain bins. By using different values of u, k, and w, entirely different pressures can be achieved. As an example, eight different values of u and k were used in combination with a bulk density of 834 kg/m^3 (52 lb/ft^3) in Janssen's equation to compare predicted pressures with the vertical pressures measured by Schwab (1989) in a smooth-walled grain bin (see Table 3). This bulk density corresponds with that suggested by ASAE EP433 (1989). For these values the sum of the squares of the error (SSE) varied from 1266 to 19 for a grain height of 12.2 m (40 ft) and from 202 to 5.9 for a grain height of 7.7 m (25 ft). While significant improvement can be made in the fit of the predicted values to that of the measured values, none of these eight conditions were based upon measured values of either u or k.

A possible solution to this problem would be to use realistic material properties determined through experimentation. However, many of the experiments previously cited in the literature were conducted under conditions which do not correlate well with those normally found in grain bins. Therefore, it is still difficult to determine what values of u and k should be used in Janssen's equation for different bin conditions and stored material. However, below are listed the descriptions of experiments and values of u and k which appear to correlate well with those conditions found in grain bins and can be used for the three storage conditions mentioned in this article to validate the packing in grain bins.

Lateral-to-Vertical Pressure Ratio In Corn and Soft Red Winter Wheat

To determine the lateral-to-vertical pressure ratio, k, for both soft red winter wheat and corn as a function of pressure, limited experiments were conducted with load cells tested in both the vertical and lateral positions in an apparatus described by Galili et al. (1989). The apparatus can exert a vertical pressure on the grain which simulates overbearing grain in a grain bin. An example of the strains measured by the load cells in the vertical and lateral positions for soft red winter wheat are shown in figure 2. Values of k of 0.42 and 0.45 were determined for soft red winter wheat and corn, respectively.

TABLE 3. Sum of the squares of the error for variations in the bulk density, lateral to vertical pressure ratio, and the coefficient of friction for smooth-walled bin data (Schwab, 1989)

Material Properties			SSE
Bulk Density (kg/m ^{3}) (w)	Lateral to Vertical Pressure Ratio (k)	Coefficient of Friction (u)	
For tests with a grain height of 12.2 m (40 ft)			
	0.5	0.3	1266 (531153)
	0.5	0.25	720 (293154)
	0.5	0.2	298 (112412)
834 (52 lb/ft ^{3})	0.4	0.3	632 (254952)
	0.4	0.25	292 (109764)
	0.4	0.2	76 (22538)
	0.4	0.15	38 (15034)
	0.4	0.175	19 (7947)
Based on predictions from the WPACKING program:			
724 (45.2 lb/ft ^{3})	0.42	0.14	24.9
For tests with a grain height of 7.7 m (25 ft)			
	0.5	0.3	202 (88186)
	0.5	0.25	102 (44558)
	0.5	0.2	36 (15473)
834 (52 lb/ft ^{3})	0.4	0.3	88 (38439)
	0.4	0.25	34 (14819)
	0.4	0.2	7.3 (3178)
	0.4	0.15	14 (5958)
	0.4	0.175	5.9 (2565)
Based on the predictions from the WPACKING program:			
724 (45.2 lb/ft ^{3})	0.42	0.14	11.8 (5147)

Coefficient of Friction of Wheat and Corn on Galvanized Steel Surfaces

Thompson et al. (1988) and Thompson and Ross (1983) performed experiments with soft red winter wheat on galvanized surfaces. In these experiments galvanized steel blades, which simulated the walls of a smooth-walled grain bin, were pulled through a steel box filled with grain. Pressure diaphragms mounted in the box were used to exert a lateral pressure, similar to that found in a grain bin, on the galvanized steel blade. An example of the variation in the coefficient of friction for a sample of galvanized steel can be observed in figure 3. It was determined that the coefficient of friction decreased by over 42% when the galvanized steel blades were pulled through the grain mass 16 times. This decrease was attributed to the coating of the

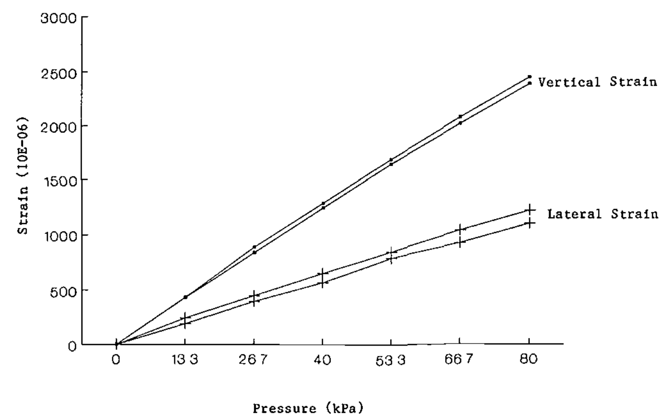

Figure 2–Vertical and lateral strains of soft red winter wheat within a grain pressure apparatus using a diaphragm pressure cell.

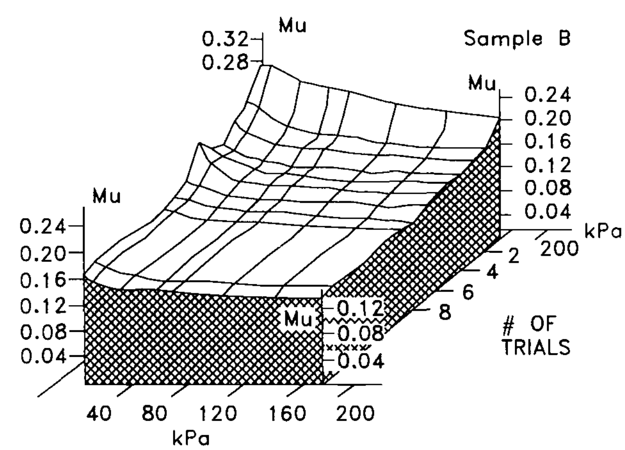

Figure 3–Variation in the coefficient of friction of wheat on galvanized steel as a function of lateral pressure and the number of trials (Thompson et al., 1988).

blades by long-chained alcohols, which are found on the seedcoat of the grain, as grain slides on the galvanized surface. In a grain bin, coating of the walls by these alcohols would result in a decrease in the wall loads and an increase in the vertical pressures on the floor. These experiments suggest that for a new galvanized steel surface the average coefficient of friction for lateral pressures between 0 and 68 kPa (0 to 10 psi) is 0.27, and for a galvanized steel surface well-coated by these alcohols the average coefficient of friction would be 0.14.

Moore et al. (1984) conducted tests to determine the coefficient of friction of soft red winter wheat on galvanized steel corrugated surfaces. For corrugated wall surfaces, both a grain-on-grain and grain-on-steel sliding situation was thought to occur. Using Moore's data, the average coefficient of friction was determined to be 0.46 for a galvanized steel corrugated surface for all test conditions. Assuming that a corrugated-walled surface is effected by a similar 42% decrease in the coefficient of friction, caused by the deposition of oils, a coefficient of friction of 0.27 would be expected on a corrugated wall surface.

Tests similar to those conducted by Moore et al. (1984) on the coefficient of friction of corn on corrugated galvanized steel surfaces were not found in the literature. However, tests have been conducted by Thompson (1986) and Brubaker and Pos (1965) on the coefficient of friction of corn on smooth galvanized surfaces. In both cases, it was determined that the coefficient of friction of corn on galvanized steel surfaces was approximately 25 to 30% higher than that for wheat on galvanized steel surfaces. Using this idea and assuming that similar effects caused by coating of oils on galvanized steel surfaces occur for corn, it is believed that a well-coated galvanized steel corrugated surface would then have a coefficient of friction of approximately 0.34.

Suggested values of u and k, as shown in Table 4, based on the above experimental results for different wall surfaces and stored materials were used in the computer program WPACKING to predict packing in bins under different storage conditions.

Validation of WPACKING Using Full-Scale and Model Bin Data

Using the proposed material properties shown in Table 4 and the computer program WPACKING, estimated values of vertical pressure were determined and compared to the pressures measured by Schwab (1989), Thompson and Prather (1984), and Williams et al. (1989) in full-size and model grain bins to validate the computer program WPACKING.

Smooth-Walled Grain Bin Storing Wheat

The vertical pressures reported by Schwab (1989) for a smooth-walled grain bin are shown in figures 4 and 5 for grain heights of 7.7 (25 ft) and 12.2 m (40 ft). In addition, the vertical pressures predicted by the classical Janssen equation using the suggested material properties listed in ASAE EP433 and the vertical pressures estimated by the WPACKING program using the suggested values in Table 4 are shown. For a test height of 12.2 m (40 ft) and a test height of 7.7 m (25 ft) the WPACKING program had SSE of 24.5 and 11.8, respectively (See Table 2). The material properties suggested by ASAE EP433 had the largest SSE for both test conditions.

TABLE 4. Material properties used to predict the packing of soft red winter wheat and corn in various storage conditions

Galvanized Wall Surface	Stored Material	u	k
Smooth-wall	Wheat	0.14	0.42
Corrugated-wall	Wheat	0.27	0.42
Corrugated-wall	Corn	0.34	0.45

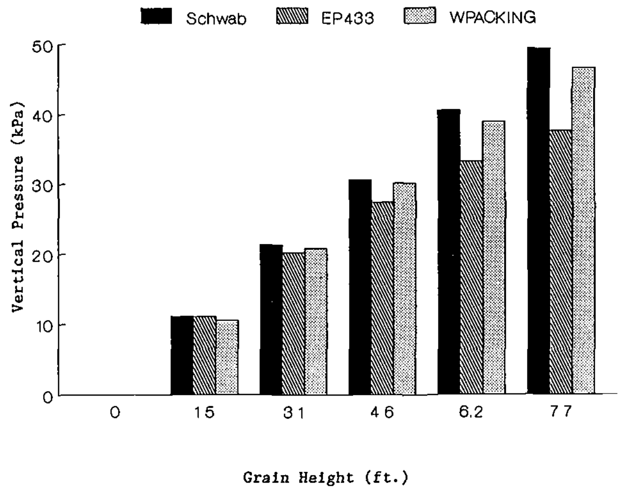

Figure 4–Vertical pressures in a 4.08 m (13.4 ft) diameter smooth-walled grain bin storing soft red winter wheat with a height-to-diameter ratio of H/d=1.8 [WPACKING-k=0.42, u=0.14, and w=724 kg/m³ (45.2 lb/ft³); EP433-k=0.5, u=0.3 and, w=834 kg/m³ (52 lb/ft³)].

Corrugated-Walled Grain Bin Storing Wheat

The measured vertical pressures for a corrugated-walled model grain bin 2.74 m (9 ft) tall and 0.91 m (3 ft) in diameter are shown in figure 6. The average vertical pressures which exist on the floor of this bin are shown in Table 5. The vertical pressures were measured using four cantilever beams as described in Thompson and Prather

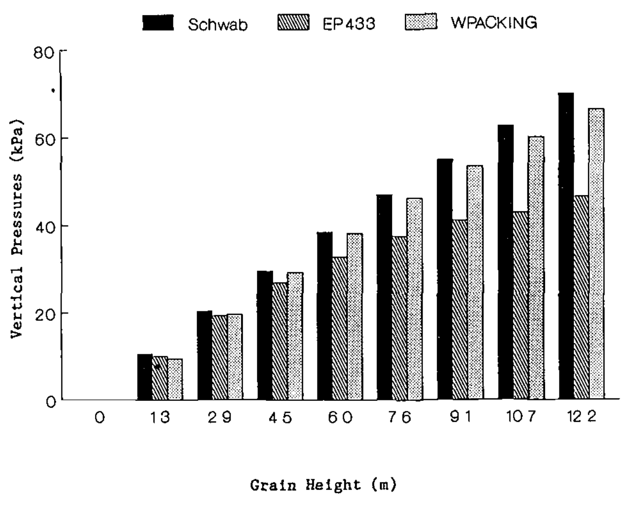

Figure 5–Vertical pressures in a 5.08 m (13.4 ft) diameter smooth-walled grain bin storing soft red winter wheat with a height-to-diameter ratio H.d=3.0 [WPACKING-k=0.42, u=0.14, and w=724 kg/m³ (45.2 lb/ft³); EP433-k=0.5, u=0.3, and w=834 kg/m³ (52 lb/ft³)].

(1984). An equivalent floor pressure was estimated by dividing the total load supported by the four beams by the area of the bin bottom. These floor pressures compare favorably with the average pressures measured by Williams et al. (1989) in the model bin using load cells.

Also shown in figure 6 are the vertical pressures estimated by the WPACKING program using the material properties shown in Table 3 for a corrugated grain bin, and the classical Janssen equation using the material properties listed in ASAE EP433. The WPACKING program used the actual bulk density of the stored grain as determined by the Winchester Bushel Test (USDA Inspection Division, 1977). The SSE for these conditions are shown in Table 6. When the equivalent floor pressures in the model bin were compared to the values suggested by Janssen's equation, the SSE were much smaller using the WPACKING program and the material properties shown in Table 4 than those suggested by the classical Janssen equation and ASAE EP433.

TABLE 5. Measured vertical floor pressure in a 0.91 m (3 ft) diameter corrugated model grain bin

Grain Height		Average Pressure on Bin Floor	
(m)	(ft)	(kPa)	(psi)
0.99	3.25	5.19	0.75
1.91	6.25	8.32	1.21
2.21	7.25	9.06	1.31
2.51	8.25	9.82	1.42
2.82	9.25	10.52	1.53

TABLE 6. Sum of the squares of the error for a model corrugated-walled grain bin storing soft red winter wheat

Comparison	SSE
Average pressures vs. ASAE*	4.52 (1959)
Average pressures vs. WPACKIN†	1.80 (789)

* ASAE EP433 suggests values of w = 834 kg/m^3 (52 lb/ft^3), k = 0.5, and u = 0.375 for a corrugated-walled grain bin.

† Values of w = 724 kg/m^3 (45.2 lb/ft^3), k = 0.42, and u = 0.268 were used in the differential form of Janssen's equation used by the computer program WPACKING.

Corrugated-Walled Grain Bin Storing Corn

The average vertical pressures in the 12.8 m (42 ft) diameter grain bin are shown in figure 7. During these tests, large vertical pressures were measured at grain heights of less than 4 m (13.1 ft). Much larger than any vertical pressure normally estimated by using combinations of u, k, and w in the classical Janssen equation. This is believed to be caused by the methods in which the grain was spouted into the bin. A more detailed description of this test can be found in Williams et al. (1989).

A comparison of the vertical pressures estimated by the WPACKING program and the vertical pressures predicted by the classical Janssen equation are shown in figure 7. For stored materials other than wheat, ASAE EP433 suggests that the results from the Winchester Bushel test be used, increased by a compaction factor of 1.08. Therefore, the WPACKING program used an initial bulk density of 724 kg/m^3 (45.2 lb/ft^3) while ASAE EP433 used an initial bulk density of 775 kg/m^3 (48.4 lb/ft^3) in calculating the vertical pressures in this bin. The SSE are shown in Table 7 for this test condition. A SSE of 263 was determined for the WPACKING program while a SSE of 540 was determined for the ASAE EP433 values. For the WPACKING program, 90% of the error was associated with the first three grain heights shown in figure 7. This error at the lower grain heights may not be caused so much by the error in the coefficients of u and k, as assumed by the WPACKING program, as by the manner in which the bin was filled. In this particular bin the grain spout was located in the center of the bin, but the manner in which the grain moves down the downspout and into the bin creates an eccentric loading situation at the lower grain heights. However, as the height of grain in the bin increases, the eccentricity of the grain peak becomes smaller and smaller until it approximates a centrally loaded bin when full. The effect which this filling technique has on the vertical pressures within the bin is not known.

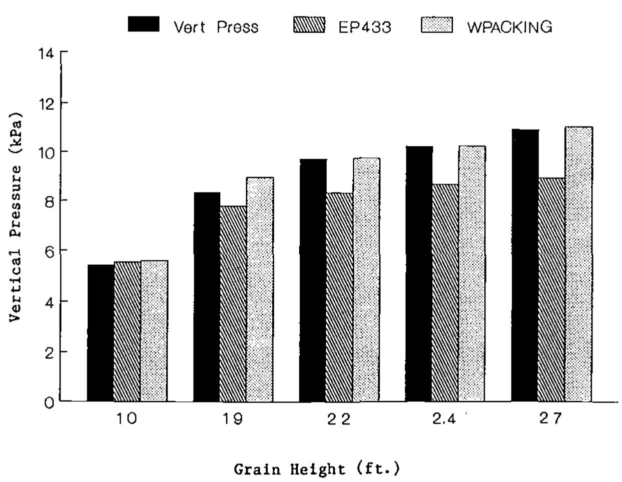

Figure 6–Vertical pressures in a 0.91 m (3 ft) diameter corrugated-walled model grain bin storing soft red winter wheat [WPACKING-k=0.421, u=0.27, and w=724 kg/m³ (45,2 lb/ft³; EP433-k=0.5, u=0.37, and w=834 kg/m³ (52 lb/ft³)].

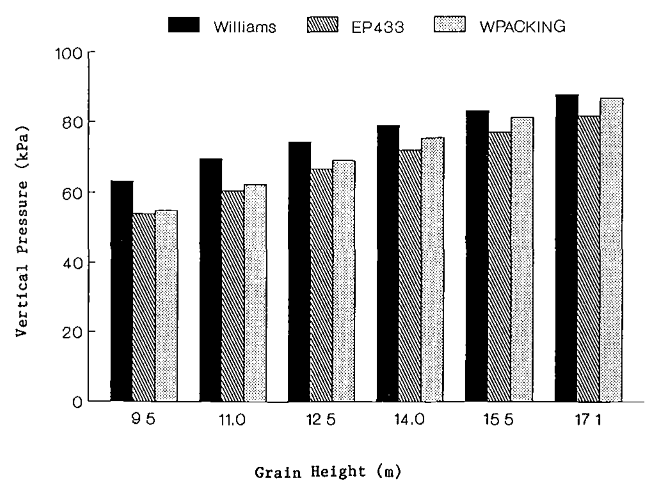

Figure 7–Vertical pressures in a 12.8 m (42 ft diameter corrugated-walled grain bin storing corn [WPACKING-k=0.45, u=0.34, and w-720 kg/m³ (45 lb/ft³); EP433-k=0.5, u=0.37, and w=775 kg/md³; EP 433-k=0.5, u=0.317, and w=775 kg/m³ (48.4 lb/ft³)].

TABLE 7. Sum of the squares of the error for a 12.8 m (42 ft) diameter corrugated-walled bin storing corn (Williams et al., 1989)

Comparison	SSE
Average floor pressure vs. ASAE*	540 (235600)
Average floor pressure vs. WPACKING†	263 (114736)

* ASAE EP433 suggests that for commodities other than wheat, that the bulk density determined by the Winchester Bushel tests be used increased by a compaction factor of 1.08. Therefore, the bulk density used in Janssen's equation was w = 775 kg/m ^{3} (48.4 lb/ft ^{3}). EP433 suggests values of u = 0.37 and k = 0.5 for a corrugated steel bin.

† Values of w = 724 kg/ m ^{3} (45.2 lb/ft ^{3}), k = 0.45 and u = 0.34 were used in the differential form of Janssen's equation used by the computer program WPACKING. Suggested values of u = 0.34 and k = 0.45 as shown in Table 4 for a corrugated steel bin filled with corn were used.

VALIDATION SUMMARY

For each storage condition the vertical pressures estimated by the WPACKING program approximated the measured vertical pressures closely. Therefore, it is believed that by using the proposed material properties in Table 4 that the vertical pressures and in turn the packing in grain bins can be determined for these three different storage conditions using the WPACKING program.

While the estimated pressures predicted by the material properties in ASAE EP433 did not agree well with those measured for these conditions, it is not suggested by the authors that the values of u and k in ASAE EP433 be changed to those values shown in Table 4. Using the WPACKING program, the values in Table 4 appear to predict reasonably well the vertical floor pressures found in galvanized walled grain bins which have been coated by the sliding grain. It should be remembered that during this coating process the vertical wall loads decrease while the vertical pressures on the floor increase. Therefore, based on these results it is believed that in the design of a grain bin the values of u and k in ASAE EP433 should be used to predict the lateral pressures and vertical wall loads in a grain bin while the values in Table 4 should be used to predict the vertical floor pressures in a grain bin.

PROGRAM OUTPUT

Packing factors for the three different storage conditions for variations in the moisture content of the stored material, grain height and bin diameter are shown in Tables 8 to 10. A more detailed description of the effects of changes in u and k were described in Thompson et al. (1987).

The results in Tables 8 to 10 show that changes in both bin diameters and grain height have an effect on the predicted packing factors. It is apparent that a change in grain height has a greater effect on the packing factor than does a change in bin diameter. For a change in grain height of from 6.1 m (20 ft) to 12.2 m (40 ft), an average increase of 1.2 percentage points was observed for wheat while an average increase of 0.7 percentage points was observed for corn. For a corresponding change in diameter of from 6.1 m (20 ft) to 12.2 m (40 ft), an average change of 0.23 percentage points was observed for wheat while an average increase of 0.2 percentage points was observed for corn.

The moisture content of the granular material had an effect on the packing factors of grain as evidenced by the predicted values shown in Tables 8 to 10. As the moisture content of the material increases, the particles become much more compressible and, therefore, increased particle packing would be expected to occur. For the example bins shown in Tables 8 and 9, increases of approximately 0.4 to 0.9 percentage points were observed for increases in moisture content from 10 to 16% (wb) moisture content. For corn, a slightly larger increase was observed for similar changes in bin size and moisture content. For the sample bins, an increase of 1.0 to 1.8 percentage points was observed for increases in moisture content.

It is apparent in looking at Tables 9 and 10 that a variation does exist in packing between different whole grains. Soft red winter wheat undergoes much more packing than does corn. In Tables 9 and 10, wheat was observed to have packing factors from 2.8 percentage points higher than for similar storage conditions with corn.

TABLE 8. Predicted packing factors for soft red winter wheat in a smooth-walled grain bin as a function of bin diameter, grain height, and moisture content

Packing Factors for a Smooth-Walled Grain Bin*						
Bin Diameter		Grain Height		Moisture Content (% wb)		
(m)	(ft)	(m)	(ft)	10%	13%	16%
6.1	20	6.1	20	5.0	5.2	5.4
6.1	20	12.2	40	6.1	6.5	6.9
12.2	40	12.2	40	6.2	6.7	7.1

* The packing factors were determined assuming an initial bulk density of 770 kg/m ^{3} (48 lb/ft ^{3}), k = 0.42, and u = 0.14.

SUMMARY

The computer program, WPACKING, has been developed based on the differential form of Janssen's equation to predict the packing factors of whole grains in bins of variable height and diameter (Thompson et al., 1987). The computer program was validated for a: 1)

TABLE 9. Predicted packing factors for soft red winter wheat in a corrugated-walled grain bin as a function of bin diameter, grain height, and moisture content

Packing Factors for a Corrugated-Walled Grain Bin*						
Bin Diameter		Grain Height		Moisture Content (% wb)		
(m)	(ft)	(m)	(ft)	10%	13%	16%
6.1	20	6.1	20	4.9	5.1	5.3
6.1	20	12.2	40	5.9	6.3	6.6
12.2	40	12.2	40	6.1	6.5	6.9

* The packing factors were determined assuming an initial bulk density of 770 kg/m ^{3} (48 lb/ft ^{3}), k = 0.42, and u = 0.268.

TABLE 10. Predicted packing factors for corn in a corrugated-walled grain bin as a function of bin diameter, grain height, and moisture content

Packing Factors for a Corrugated-Walled Grain Bin*						
Bin Diameter		Grain Height		Moisture Content (% wb)		
(m)	(ft)	(m)	(ft)	10%	13%	16%
6.1	20	6.1	20	2.8	3.3	3.8
6.1	20	12.2	40	3.2	4.0	4.8
12.2	40	12.2	40	3.3	4.2	5.1

* The packing factors were determined assuming an initial bulk density of 718 kg/m ^{3} (44.8 lb/ft ^{3}), k = 0.45, and u = 0.34.

smooth-walled galvanized steel grain bin storing wheat; 2) corrugated-walled galvanized steel grain bin storing wheat; and 3) corrugated-walled galvanized steel grain bin storing corn using the material properties listed in Table 4. The values of the lateral-to-vertical pressure ratio were determined experimentally using a load cell tested in the vertical and lateral position. The experimental values of the coefficient of friction were determined using techniques designed to simulate the stress conditions found in grain bins.

When utilizing the computer program, WPACKING, it was determined that variations exist in the predicted packing factors for variations in type of grains, moisture content of the stored material, properties of the stored material, grain height, and bin diameter. A change in grain height had a larger effect on packing than does a change in bin diameter or moisture content of the stored material.

REFERENCES

ASAE Standards, 36th ed. 1989. EP433. Loads exerted by free flowing grains on bins. St. Joseph, MI: ASAE.

Bates, E.N. 1925. Estimating the quantity of grain in bins. United States Department of Agriculture, Miscellaneous Circular No. 41.

Brubaker, J.E. and J. Pos. 1965. Determining static coefficients of friction of grains on structural surfaces. *Transactions of the ASAE* 8(1):53-55.

Chang, C.S., L.E. Shackelford, F.S. Lai, C.R. Martin and B.S. Miller. 1981. Bulk Properties of corn as affected by multiple point grain spreaders. *Transactions of the ASAE* 26(6):1632-1636.

Chang, C.S., H.H. Converse and C.R. Martin. 1983. Bulk properties of grain as affected by self-propelled type grain spreaders. *Transactions of the ASAE* 26(5):1543-1550.

Galili, N., S.A. Thompson and R.A. Williams. 1989. Accurate strain measurement in granular media. ASAE Paper No. 89-4540. St. Joseph, MI: ASAE.

Illinois Agricultural Auditing Association. 1980. *Test Pack Factor Tables*. Bloomington, IL: IAAA.

Janssen, H.A. 1895. Verrsuche uber quitreidedruck in silozellen. *VDI Zeitschrift* V. 39:1045-1049.

Malm, J.K. and L.F. Baker. 1985. Compaction factors for six crops. *Transactions of the ASAE* 28(5):1634-1636.

Moore, D.W., G.M. White and I.J. Ross. 1984. Friction of wheat on corrugated metal surfaces. *Transactions of the ASAE* 27(6):1842-1847.

Ross, I.J., T.C. Bridges, O.J. Loewer and J.N. Walker. 1979. Grain loads as affected by grain moisture and vertical pressure. *Transactions of the ASAE* 22(3):592-597.

Schwab, C.V. 1989. Grain pressure phenomenon in a circular flat bottom bin. Ph.D. diss., University of Kentucky, Lexington.

Stephens, L.E. and G.H. Foster. 1976. Grain bulk properties as affected by mechanical grain spreader. *Transactions of the ASAE* 19(2):358, 363.

Thompson, S.A. 1986. Compressibility and frictional coefficients of corn. 1st World Congress Particle Technology, Nurnberg, West Germany. April.

Thompson, S.A. and I.J. Ross. 1983. Compressibility and frictional coefficients of wheat. *Transactions of the ASAE* 26(4):1171-1176, 1180.

Thompson, S.A. and T.G. Prather. 1984. Dynamic wall loads in a corrugated walled model grain bin. *Transactions of the ASAE* 27(3):875-878.

Thompson, S.A., S.G. McNeill, I.J. Ross and T.C. Bridges. 1987. Packing factors of whole grains in storage structures. *Applied Engineering in Agriculture* 3(2):215-221.

Thompson, S.A., R.A. Bucklin, C.D. Batich and I.J. Ross. 1988. Variation in the apparent coefficient of friction of wheat on galvanized steel. *Transactions of the ASAE* 31(5):1518-1524.

USDA Inspection Division. 1977. *Grain inspection manual*. United States Federal Grain Inspection Service.

Williams, R.A., S.A. Thompson and N. Galili. 1989. Vertical pressures in full-size and model corrugated bins. ASAE Paper No. 89-4537. St. Joseph, MI: ASAE.