VERTICAL PRESSURES OF DRY AND FLOODED GRAINS STORED IN DEEP BINS

by

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INTRODUCTION

Two important questions regarding the vertical pressures of grain stored in deep bins seem to have been left unanswered by the literature. The first has to do with normal dry grain and the second with grain submerged in water as when storage bins are flooded.

Many workers in the past 60 years, by a variety of experimental methods, have measured vertical and lateral pressures of dry grains in bins of different size, shape and construction materials. The results of these many experiments are in general agreement.

However, in measuring vertical pressures, each investigator measured the total vertical pressure across the entire cross sectional area of the bin bottom. In practice no storage bins are built with bottom openings as large as the bin itself. Bins in grain elevators have discharge holes in the bottom with areas from o.5 - 6.0 per cent of the cross sectional area of the bin. Usually grain storage bins have enclosed spouts fastened to the underside of these holes in the bin bottom. These spouts carry the grain by gravity to belt conveyors for horizontal transfer or to bucket elevators for vertical elevation.

When emptying grain from a bin through a relatively small hole in the bottom it soon becomes evident that the grain on top of the bin is working its way down through the mass of granular material below it. First an imaginary column of grain, having a height equal to the total height and an area approximating that of the bin opening, will empty out. As this imaginary column of grain draws down through the hole, the grain from the top fills the void. Subsequent to the disappearance of this imaginary column of grain above the hole, the last grain placed in the bin is the first out. This behavior of grain when being withdrawn by gravity from bins is most noticeable when the holes are centrally located with respect to the bin walls. Does this commonly observed phenomenon indicate that, under static conditions, a greater vertical pressure exists at the center of a grain storage bin than at points closer to the bin walls?

The importance of the second problem was suggested by the effects of flood waters on grain stored in bins at the time of the historic flood of 1951 which was so disastrous to Kansas and Missouri rural and urban property. Many grain storage elevators were known to have been flooded and some damage to bins, hopper bottoms and spouts was reported. This raises the question whether additional pressure is exerted on a centrally located discharge opening in the bottom of a bin when the lowest portion of the grain stored therein has been soaked in water for a considerable period of time. If flooded grain exerts additional pressure on the bins, hopper bottoms and spouts, what is the nature and magnitude of this additional pressure? Can reliable data be collected to be of value to engineers designing grain storage units to be located in districts subject to possible floods?

No work was attempted to measure the lateral pressures of either dry or soaked grain in a bin. The lateral pressures of dry grain in bins are already adequately investigated. The lateral pressures of grain soaked after storage are important and interesting but the measurement of these pressures requires equipment and time beyond the scope of this project.

PREVIOUS INVESTIGATIONS

Forces in Bins Due to Dry Grain

Many investigations of both vertical and lateral pressures exerted by grain in bins have been carried out. As early as 1882 Roberts (11) in England reported on work with wheat in bins, the largest of which was hexagonal, 12 inches on a side, and 8 feet high. The vertical pressure on the bottom of the bin was found to remain constant after the bin was filled beyond a height of about 2 1/2 times the diameter. Both horizontal and vertical pressures were measured.

Janssen (6) in Germany in 1895, made tests on wheat and corn in wooden model bins 8 inches, 12 inches, 16 inches, and 24 inches square, each having a height of 5.95 feet. The vertical pressures on the entire bottoms were measured by weighing. Janssen developed formulas for the solution of lateral and vertical pressures which have been very widely used by bin designers. These formulas are still the standard for engineers in the United States engaged in grain storage design. These tests and the calculations based upon them yielded results comparable with those obtained by Roberts. For the derivations of these formulas see Appendix A.

In England in 1898 Airy (1) reported on an investigation to determine the coefficient of friction of various grains. He developed equations for grain pressures which yielded results in agreement with those of Roberts and Janssen. Airy's formulas are reported to be the standards in English engineering practice.

Jamieson (5), in 1903 conducted a series of experiments on a full-size bin of the Canadian Pacific Railway Elevator, West St. John, N.B. The timber crib construction bin was 12 feet 0 inches by 13 feet 6 inches in cross section and 67 feet 6 inches high. Hard red spring wheat weighing 61.7 pounds per bushel was used. Calculated pressures using Janssen's formulas were found to check closely with observed bottom and side pressures.

Pleissner (10), in 1902-1905 experimented extensively on the pressures exerted by grain in deep bins. Various sizes of bins and types of materials were used in these investigations. The calculated pressures, using Janssen's equations, were in close agreement with measured vertical and lateral pressures.

Ketchem (7) summarized the reports of the above investigators as follows:

> 1. The pressure of grain on bin walls and bottoms follows a law which is entirely different from the law of the pressure of fluids.
>
> 2. The lateral pressure of grain on bin walls is less than the vertical pressure (0.3 to 0.6 of the vertical pressure depending on the grain etc.) and

increases very little after a depth of 2 1/2 to 3 times the width or diameter of the bin is reached.

3. The ratio of lateral to vertical pressures, k, is not a constant, but varies with different grains and bins. The value of k can only be determined by experiment.

4. The pressure of moving grain is very slightly greater than the pressure of grain at rest (maximum variation for ordinary conditions is probably 10 per cent).

5. The calculated pressures by either Janssen's or Airy's formulas agree very closely with actual pressures.

6. The unit pressures determined on small surfaces agree very closely with unit pressures on large surfaces.

Caughey, et al. (2) in 1951 using a model concrete bin 1.5 feet in diameter and 5 feet high investigated vertical and lateral pressures exerted by wheat, shelled corn, soybeans, cement, sand and pea gravel. Vertical forces acting through a movable bottom resting on a platform scale were recorded and translated into pressures by calculation. Lateral pressures were measured by electric resistance strain gages connected to a Baldwin Portable Strain Indicator, Model K. This method of measuring pressures was new since the investigations of previous workers. These men reported that vertical and lateral pressures exerted by wheat agreed favorably with results of calculations using Janssen's formulas but that the vertical and lateral pressures exerted by shelled corn, soybeans, sand, and pea gravel did not agree with results of calculations using Janssen's formulas. However, the value of k (below) used in the formulas, yielded results which were in excess of measured pressures and therefore calculations using Janssen's formulas contained a safety factor when used for bin design.

The ratio of lateral to vertical pressure k and the coefficient of friction μ' between granular material and concrete are as follows:

Material	k	μ'
Wheat	.612	.35
Shelled Corn	.599	.25
Soybeans	.383	.27
Cement	.400	.55
Sand	.391	.48
Pea Gravel	.325	.45

Behavior of Grain When Dampened

No specific information on the forces produced by thorough wetting of grain in bins was found in the literature. Many workers refer to changes of wheat characteristics caused by additions of only small amounts of water (2-5 per cent), a practice which is a part of the process of tempering or conditioning wheat for milling. Thus Pence (9) measured the increase in volume of three small lots of wheat having moistures of 9.5 per cent, 12.0 per cent, and 14.9 per cent which had been freshly wetted with sufficient water to raise the moisture of each to 16.0 per cent and stored in half filled glass jars. Temperatures of the wheat samples varied from 53.6°F. to 80.6° F. A rapid increase in volume occurred in the first 40 minutes after which a very slow rate of increase in volume continued for one to three hours. A maximum increase in volume of 9.5 per cent was found for the wheat tempered from 9.5 per cent to 16.0 per cent moisture at 27° C. Elevated temperature and increased amounts of added water produced the higher increases in volume.

Fisher and Hines (3) in 1939 discussed the effects of wetting wheat as follows:

> It is well known that when dry wool, cotton, gelatin, wheat or flour is mixed with water, heat is evolved as indicated by a rise in temperature. The drier the wool or the wheat the greater is the heat evolution. This heat evolution is an indication of some kind of union, which may be either chemical or physical, between the solid material and at least some of the water. ...It must be pointed out that in this connection the surface of wheat is not merely the outer surface of the berry, but, since water can penetrate wheat, it includes also the enormously greater internal surfaces. Heat is liberated progressively as water penetrates the wheat berry and so comes in contact with the internal surfaces.
>
> When a collodial material such as wool, cotton, gelatin or wheat is mixed with water and allowed to stand at constant temperature a progressive shrinkage of the mixture occurs. Thus if x c.c. of wheat and y c.c. of water are mixed the volume of the mixture will be slightly less than (x plus y) c.c. and the shrinkage will increase progressively until the water is uniformly distributed throughout the wheat.

Thomas (15) in 1917 showed that test weight in pounds per bushel of wheat containing average moisture decreased as water was added to the wheat. Upon re-drying to the original moisture, the wheat in every instance tested a lower bushel weight than it had before wetting. The following are data he obtained:

Moisture content Per Cent	Weight per bushel Pounds	Moisture content after re-drying Per Cent	Bushel weight after re-drying Pounds
11.4	63.0	--	--
13.2	61.0	11.1	62.0
15.2	60.0	11.3	61.5
18.8	56.0	11.0	61.0
22.2	53.0	11.0	60.5
25.2	52.0	11.4	60.0

Sharp (12) in 1927 showed that not only the bushel weight but also the specific gravity of dry wheat decreased as increasing quantities of water were added in the following manner:

Moisture percentage	Density or specific gravity	Moisture percentage	Density or specific gravity
6.5	1.426	13.4	1.391
8.8	1.423	15.0	1.381
10.1	1.416	16.7	1.365
11.4	1.402	19.8	1.347
12.2	1.399	26.4	1.302

Swanson (14) experimented extensively with wheat to determine the influence of adding water to dry wheat. His results corroborate the conclusions of both Thomas and Sharp.

The phenomenon of swelling pressures due to water inhibition by colloidal biological materials has been discussed to some extent in the literature.

Gortner (4) mentions a historical demonstration of the force of swelling:

> The process of taking up water by strongly dried hydrogels.......will occur against very high pressures. A method used by the Egyptians to quarry stone consisted in drilling a series of holes in the face of the stone

> along the line of desired fracture, pounding dry wooden pegs into the holes and then keeping the pegs moistened. Water is taken up with such force as to cause the stone to be broken apart by the pressure generated as the wood (a gel) swells.

Shull (13) reported on experiments which revealed how enormous swelling pressures can become under specified conditions.

> The internal forces causing entrance of water into air-dry xanthium seeds must be at the initial moment in the neighborhood of 965 atmospheres. From saturated solutions of sodium chloride these air-dry seeds will imbibe 7 per cent of their air dry weight. The imbibition force is 965 atmospheres. Rodewald states that dry starch on swelling develops a pressure of 2523 atmospheres. Seeds become greatly swollen in a number of solutions until in many instances they are perfectly cylindrical and stretched to inordinate size.

It may be noted that one atmosphere is equivalent to approximately 15 pounds pressure per square inch.

A dramatic experiment is described by Meyer and Anderson (8) to show that a dry grain does exert great pressure when swelling under conditions where the initial volume of the dry grain is forcibly maintained for a time.

> Pressures sometimes of enormous magnitude develop during the swelling of imbibing substances. Such pressures only become evident if the imbibant is confined in some way during the process of imbibition.
>
> A demonstration of this may be accomplished as follows:
>
> A glass funnel lined with filter paper is partly filled with moist plaster of Paris paste. The surface of the plaster of Paris is then strewn with a number of seeds after which more paste is added until the funnel is full. In a few minutes the moist matrix containing the seeds will have set. The resulting solid cone is removed from the funnel and its base immersed in a dish of water. Water moves up through the porous gypsum cone by capillarity and permits a continued imbibition by the seeds. Within a few hours the pressure developed by the swelling seeds is sufficiently great to rupture the gypsum block.

Summary of the Literature

The vertical (bottom) and lateral (side) pressures of dry grains have been determined by many investigators and reasonable agreement in results is evident. The vertical pressures reported were for the entire bin bottom and not for various zones across the bin bottom. No reference was made to experiments to determine vertical pressures on centrally located openings of various sizes or of the influence of hoppering the bin bottom to a centrally located opening compared to a flat bin bottom with the same size and location of opening.

Dampened grains are known to swell if stored under normal conditions. Bushel weights and the true density of dry grains decrease when their moisture content is increased and do not return to their original volumetric test weight upon redrying to their original moistures. The swelling pressures have not been evaluated.

Grains are colloids which imbibe water. Reports exist of enormous swelling pressures exerted by air dry colloids and seeds when they imbibe water. Quantitative data concerning swelling pressures produced by soaked grains are lacking.

STATEMENT OF THE PROBLEM

One objective of the present study was to determine whether vertical pressures exerted by dry grain on the bottom of the bin were of equal intensity at various points in the cross section. It was also of interest to determine whether these vertical pressures bearing on centrally located openings differ when the bin bottom or hopper is sloping instead of flat.

Because of reported damage to bin bottoms coincident with flood conditions, it was pertinent to determine the extent of the vertical pressures which are developed when grain in a bin is soaked with water and to what extent the vertical pressures are related to depth of flooding. It appeared important also to inquire whether a detectable upward movement of grain can occur when the tendency toward expansion downward due to pressure following wetting is restrained by a greater force. Another question of interest was the extent of migration of moisture from the surface of water or soaked grain in contact with the water surface to grains immediately above the damp grain.

MATERIALS

Hard red winter wheat (test weight 61.3 pounds per bushel), yellow corn (test weight 57.4 pounds per bushel) and mixed sorghum (test weight 53.1 pounds per bushel) were the grains used for the many vertical pressure tests. Tap water from the college water supply lines was used in the flooding tests.

APPARATUS USED

A model bin was constructed from a used 50 gallon hot water supply tank for the dry and wet grain tests. The ends of the tank were cut off with the precaution that one end (the bottom) would be precisely perpendicular to the sides at all points. This work was done with a lathe to insure accuracy and resulted in a steel cylinder 15.75 inches diameter by 50.125 inches high. Because of its previous use the inside wall of this tank was coated with a deposit of lime making it rougher than if it had been made with new sheet steel. This was desirable because the coefficient of friction between grain and this bin wall material closely approaches the conditions existing in concrete grain storage bins. The cylinder was supported vertically by 2 inches by 2 inches by 1/4 inch steel angles fastened to an overhead 10 inch by 10 inch wood beam at a point 2 feet from a 10 inch by 10 inch column. It was braced rigidly in a plumb position by an adjustable steel arm between the bin and the column. Figure 1a shows the details of the bin and the method of attaching it to the beam.

Figures 1a, 1b, and 1c show the different bin bottoms used. Each bin bottom in turn could be bolted securely to the bin making it part of the bin supported by the building. To permit the transmission of pressures to the platform scale, galvanized sheet metal pans indicated as Pan 1 and Pan 2 were made with inside diameters slightly greater than the outside diameters of the short vertical pipes at the bottom of hopper A and hopper B respectively (Figs. 1a and 1b). The purpose of this was to obtain a close fit between the pan and hopper without their binding or rubbing together. Pan 3 is the water tight container used to hold the water when flooding was desired. Plate I is a photograph of the large model bin, pan and scale as set up for an exploratory experiment to determine swelling pressure.

Figure 1c shows the flat bin bottom used in experiments to determine the vertical pressures through the opening of a bin bottom with no hopper.

A Fairbanks 250 pound platform scale resting on a steel plate adjustable vertically was located upon a small wood table below the bin.

Figure 1d shows a glass tube of 3 23/32 inches diameter used as a model bin. This was supported by two 3 inch wide steel bands clamped around the glass at two points using 3 inch wide leather inserts to protect the glass and prevent breakage. These clamps were bolted to two 1 inch by 1/4 inch flat steel hangers supported by the same 10 inch by 10 inch overhead beam shown in Fig. 1a. Pan No. 4 was used to hold the water. Four overflow drains were installed so that the effect of water depths of 4 inches, 8 inches, 12 inches, or 16 inches could be studied in relation to vertical pressures of both dry and flooded wheat.

Glass cylinders were used as shown in Plate II to permit a photographic record of the difference in appearance between a two pound sample of air dry wheat and a two pound sample of wheat soaked for 24 hours in two pounds of water.

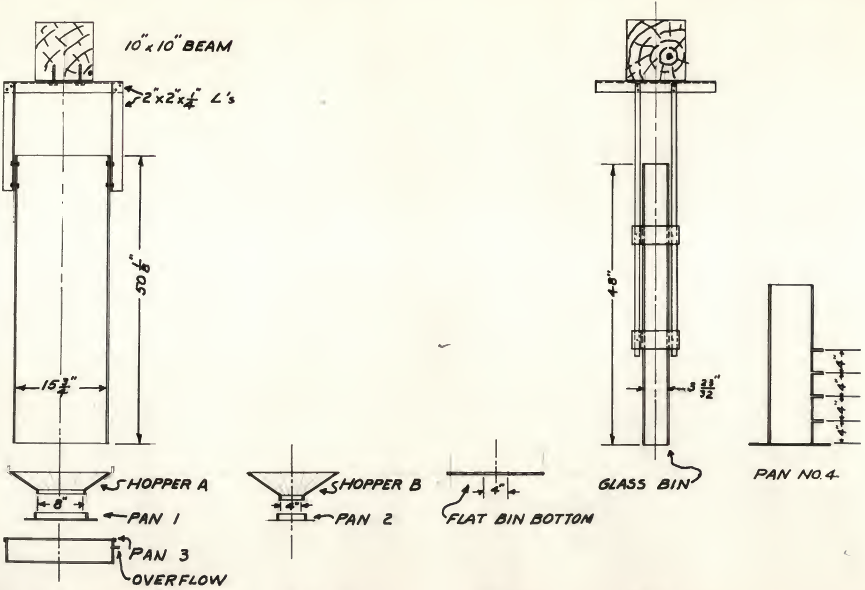


FIG 1-a FIG 1-b FIG. 1-c FIG 1-d

Fig. 1. Diagrams of model bins and bin bottoms used in the experiments.

EXPLANATION OF PLATE I

Photograph of 15.75 inch diameter model bin together with scale and water pans.

PLATE I

For the determination of moisture distribution in stored grain near water surfaces the apparatus shown in Fig. 2 was used. This figure shows three 1 1/2 inch diameter glass tubes and their contents standing in glass beakers. Glass wool was used for porous plugs to keep the grain in the tubes while each filter paper shown acted as a porous means of separating small portions of the grain into two inch high compartments.

PROCEDURE

Determination of Pressures Exerted by Dry Grains

The procedure followed in all experiments with dry grains was essentially the same. The desired bin bottom was bolted rigidly to the bin. The scale was placed on the adjustable steel platform resting on the table under the bin and was carefully raised into position by turning the adjusting bolts at each corner of the steel platform until any additional lift by any of the four bolts caused the scale to contact the bin bottom. Each bolt was then turned back one fourth turn thus lowering the scale 1/64 inch below the point where it touched the bin bottom.

Grain in small lots of .5 pound, 1 pound, 2 pounds, 3 pounds, 5 pounds, or 10 pounds were added to the bin. The scale reading and the depth of grain in the center of the bin were recorded after each increment.

Multiple tests were made using each of the three bin bottoms,

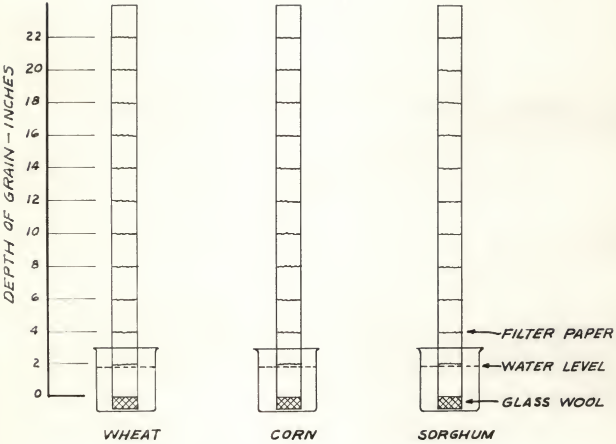


Fig. 2. Diagram of apparatus used to determine extent of vertical migration of water from flooded grains to the dry grains stored above them.

hopper A, hopper B, and the flat bin bottom (Fig. 1c) which had a 4 inch diameter hole at first and later had a 7 inch diameter opening. In a similar manner dry wheat pressure tests were made with the glass tube model bin with no bin bottom. The platform of the scale was adjusted until it almost touched the bottom of the glass tube. Vertical pressure readings were taken after each .5 or 1.0 pound increment of wheat had been added.

Swelling Pressure Experiments

With hopper A bolted in place and the scale resting on its steel platform, the small Pan No. 1 and large Pan No. 3 were positioned. The scale was adjusted vertically until the pans were very close to, but not touching, the bin hopper. A scale reading indicated the dead weight of the pans. Two hundred pounds of dry wheat were poured into the bin and the scale reading taken which indicated the weight of the pans and the dry grain pressure through the opening in the bin. A known amount of water was added to Pan No. 3 until overflowing commenced. The weight of the excess water was deducted from the original weight of the water supply to determine the amount of water initially added, and a scale reading was taken at this time. A supply can of water with a bottom outlet was connected by rubber hose to the water pan on the scale and the water flow was adjusted to drip slowly by means of a screw clamp to maintain a constant level of water in the grain column. Any excess overflowed. Scale readings were recorded at short time intervals between which the scale beam was held down until the next reading. Care was taken to avoid jarring the scale, scale supports or bin during an experimental run.

The increase in force (pounds) through the bin opening was determined by subtracting the sum of the initial forces exerted by (1) weight of the pans, (2) the dry grain force (pounds), and (3) the weight of water added, from each scale reading taken at time intervals after filling the pan with water. Each value of force in excess of the dry force conditions plus the weight of water added was considered to be the swelling force exerted for the corresponding time interval after flooding. The swelling pressure in pounds per square foot was calculated for each reading by dividing the recorded swelling force (pounds) by the area of the opening (square feet).

Vertical Migration of Water in a Column of Grain Partially Soaked

For this determination, apparatus indicated in Fig. 2 was used. The bottom of the glass tube was plugged with glass wool and a two inch layer of dry grain was poured in the tube which was then covered with a circular piece of filter paper. Another two inches of grain was dropped in and covered with a filter paper divider. In all, eleven such loosely compartmented layers of grain were placed in the tube. The tube was supported by clamps and adjusted vertically so that the bottom cleared the bottom of the glass beaker which was placed around and under the glass tube. Water was added to a level of 2 inches.

The grain compartment at the bottom of each tube was left to soak for one week after which the grain in each compartment was removed one at a time and placed in sealed containers. The moisture content of each portion was determined by the official 130° C. air oven method. The two stages method was used for the obviously high moisture samples.

EXPERIMENTAL RESULTS

Vertical Pressures of Dry Grains

The results obtained in the investigation of vertical pressures exerted by dry grain are summarized in Figs. 3 to 9 and Tables 1 to 5.

The four curves showing the vertical pressures exerted by dry wheat through the same four inch diameter hoppered bin bottom indicate great similarity. (Fig. 3). Vertical pressure increased in nearly a straight line function until the depth of 1.5 feet of wheat was reached. This depth of wheat was the equivalent of about 1.14 diameters of the bin itself. After this point was reached, subsequent increases in depth of grain caused less and less increases in vertical pressures. For instance, the vertical pressure was approximately 38 pounds per square foot at a grain depth of 1.0 feet (.76 diameters), 70 pounds per square foot at a depth of 2.0 feet (1.52 diameters), and only 84.6 pounds per square foot at a depth of 3.0 feet (2.28 diameters). The maximum vertical pressure under the conditions of these tests would be 85-90 pounds per square foot.

The slight divergence of the curve for experiment 14 at the top of Fig. 3 (3 foot grain level) indicates some variation in either procedure or materials. As nearly as possible the procedures used for the four tests were identical. The wheat itself could have changed somewhat in character since different 200 pound quantities of wheat were used in each of the four tests having been withdrawn by gravity from a 500 bushel storage bin in the Kansas State College Mill. It seems probable that each curve would have been just as similar to the other at the top half of the graph as all four curves are similar at the lower half of the graph if the experiments had been carried out with more grain resulting in a depth of grain more nearly 3 times the bin diameter. The results plotted stop at 2.28 times the bin diameter.

Figure 4 shows the results of duplicate experiments 15 and 16 with dry wheat as the material and using a flat bin bottom with a 4 inch diameter hole in the center. Close agreement of results is indicated between these two duplicate experiments.

Comparing the vertical pressures on the bin bottom hoppered to a 4 inch diameter hole with the vertical pressures on the 4 inch diameter opening of the flat bin bottom, the vertical pressures appeared to be very nearly equal, as Fig. 5 graphically illustrates. Calculated values obtained by use of Janssen's

Table 1. Vertical pressures of dry wheat through a four inch diameter hoppered bin bottom.

Total wheat added lbs.	Depth of wheat ft.	Vertical pressure (pounds per square foot)				
		Test 11	Test 12	Test 13	Test 14	Average
2.0	.2396	10.00	11.4	8.6	--	10.0
4.0	.3125	17.90	12.90	11.45	--	14.08
5.0	--	--	--	--	12.9	--
6.0	.3854	21.5	13.6	13.6	--	16.2
8.0	.3958	21.5	14.3	15.0	--	16.9
10.0	.4792	21.5	15.7	16.5	17.9	17.9
15.0	.5417	23.6	20.0	20.0	--	21.2
20.0	.625	25.8	22.9	22.9-	24.3	24.0
25.0	.6979	27.9	25.8	25.8	26.5	26.5
30.0	.750	29.3	27.9	27.9	27.2	28.1
35.0	.8333	31.5	30.8	--	--	31.1
40.0	.9063	34.4	33.6	32.2	31.5	32.9
45.0	.9792	36.5	35.1	--	--	35.8
50.0	1.0625	38.7	37.2	36.5	37.2	37.4
60.0	1.1771	41.5	41.5	--	--	41.5
70.0	1.3229	45.8	45.8	47.2	--	46.3
80.0	1.4583	48.7	50.1	--	54.4	51.1
90.0	1.5729	51.6	57.2	54.4	--	54.4
100.0	1.7708	57.2	61.6	--	60.1	59.6
110.0	--	60.8	--	61.0	--	60.9
120.0	--	64.4	--	--	--	--
125.0	2.0833	--	74.4	65.4	75.8	71.9
130.0	--	67.3	--	--	--	--
140.0	--	70.2	--	--	--	--
150.0	2.4688	71.6	76.6	74.4	86.0	77.1
160.0	--	73.0	--	--	--	--
170.0	--	74.2	--	--	--	--
175.0	2.8229	--	78.0	83.0	93.0	84.6
180.0	--	75.6	--	--	--	--
190.0	--	77.3	--	--	--	--
200.0	3.1667	77.3	78.0	85.8	96.0	84.3

formula were plotted to check with actual pressures as measured in experiments 11 to 16.

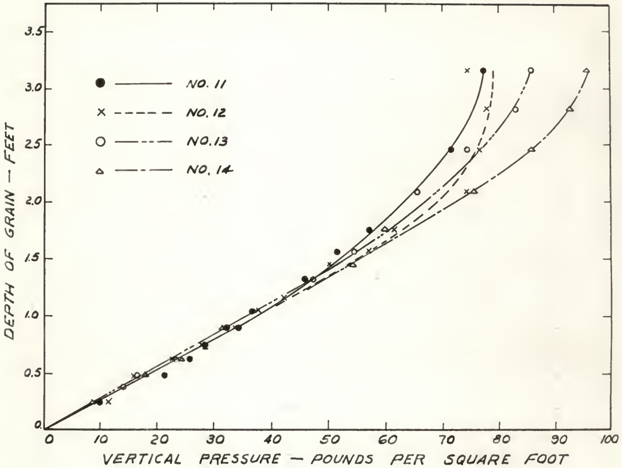


Fig. 3. Vertical pressures of dry wheat through 4 inch diameter opening in hoppered bin bottom.

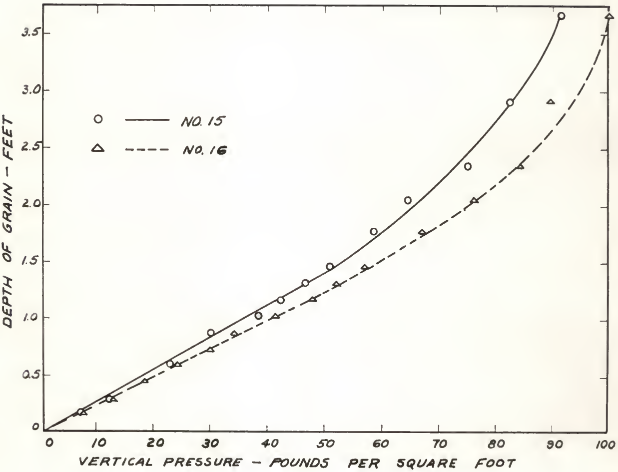


Fig. 4. Vertical pressures of dry wheat through 4 inch diameter opening in flat bin bottom.

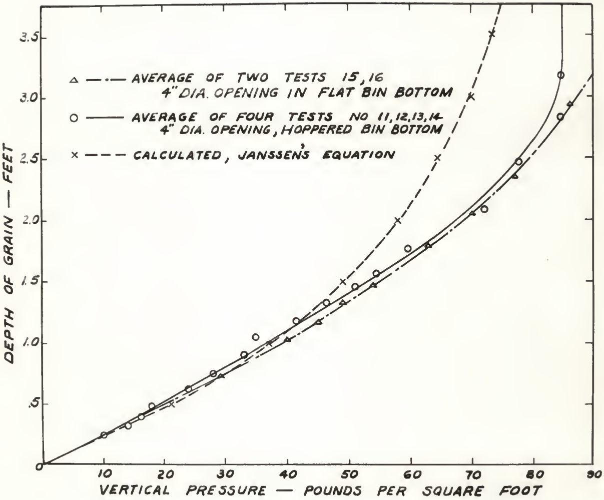


Fig. 5. Comparison of vertical pressures of dry wheat through 4 inch diameter opening in hoppered and flat bin bottoms.

Table 2. Vertical pressures of dry wheat through a four inch diameter hole in a flat bin bottom.

Wheat added lbs.	Total wheat added lbs.	Depth of grain ft.	Test 15	Test 16	Average
5	5	--	--	3.51	--
5	10	.1771	7.16	7.16	7.16
10	20	.3021	12.2	12.9	12.5
10	30	.4479	17.9	18.6	18.2
10	40	.5833	22.9	24.3	23.6
10	50	.7279	28.6	30.0	29.3
10	60	.8854	33.6	34.0	36.8
10	70	1.0313	38.6	41.5	40.0
10	80	1.1771	42.2	48.0	45.1
10	90	1.3229	46.5	52.0	49.2
10	100	1.4688	50.8	57.0	53.9
20	120	1.7813	58.6	67.0	62.8
20	140	2.0625	64.4	76.0	70.2
20	160	2.3542	70.0	84.0	77.0
20	180	--	77.3	86.5	81.9
20	200	2.9271	82.3	89.5	85.9
20	220	--	84.4	91.5	87.9
20	240	--	--	94.5	--
10	250	3.6771	91.6	100.0	95.8

Experiments 17 and 18 were duplicate tests using dry wheat and the bin with hopper A, which had an 8 inch diameter opening in the center. Figure 6 shows the results of the two tests to be in such complete agreement that a single curve fits the two sets of data. Maximum vertical pressure reached at the grain depth of 3 feet was 70 pounds per square foot and at 3.5 feet the vertical pressure was 77 pounds per square foot.

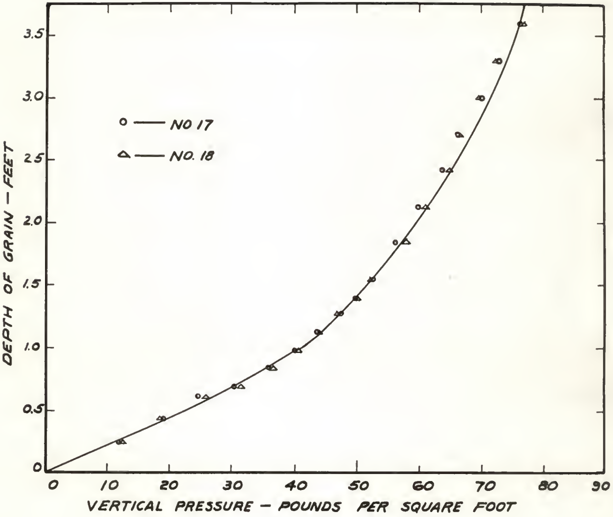


Fig. 6. Vertical pressures of dry wheat through 8 inch diameter opening in hoppered bin bottom.

Table 3. Vertical pressures of dry wheat through an eight inch diameter hoppered bin bottom.

Wheat added lbs.	Total wheat added lbs.	Depth of grain ft.	Test 17	Test 18	Average
10	10	.2396	11.8	11.8	11.8
10	20	.4427	19.0	18.6	18.8
10	30	.6198	24.7	25.8	25.25
10	40	.6875	30.4	31.5	30.95
10	50	.8385	36.0	36.5	36.25
10	60	.9792	40.0	40.5	40.25
10	70	1.1302	43.6	43.6	43.6
10	80	1.2812	47.4	46.9	47.65
10	90	1.3958	49.7	49.7	49.7
10	100	1.5521	52.6	52.2	52.4
20	120	1.8281	56.2	58.0	57.1
20	140	2.1198	59.8	61.2	60.5
20	160	2.4167	63.7	64.9	64.3
20	180	2.7135	67.2	67.0	67.1
20	200	3.0104	70.2	69.7	69.95
20	220	3.3073	73.0	72.3	72.65
20	240	3.5938	76.4	76.8	75.6
10	250	3.7708	77.3	76.0	76.65

Figure 7 shows that the vertical pressures of dry wheat upon the opening of a bin bottom hoppered to an 8 inch diameter hole and that of a flat bin bottom with a 7 inch diameter hole were so nearly the same that they might have been equal. The values for the 7 inch diameter opening were slightly greater than those for the 8 inch diameter hoppered bin bottom. It appears that the sloping sides of the hopper contributed nothing to increase the vertical pressure at the hole. Calculations using Janssen's formula yielded results in agreement with actual measured pressures.

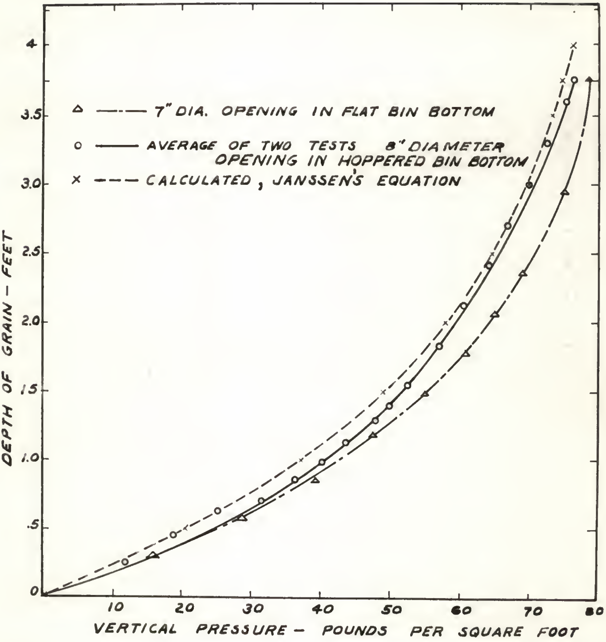


Fig. 7. Comparison of vertical pressures of dry wheat through 7 inch diameter opening in flat bin bottom with those through 8 inch diameter opening in hoppered bin bottom.

Table 4. Vertical pressure of dry wheat through a seven inch diameter hole in a flat bin bottom.

Wheat added lbs.	Total wheat added lbs.	Depth of wheat ft.	Vertical pressure lb./sq.ft.
10.0	10.0	.1771	6.8
10.0	20.0	.3021	15.7
20.0	40.0	.5833	28.6
20.0	60.0	.8854	39.3
20.0	80.0	1.1771	47.7
20.0	100.0	1.4688	54.8
20.0	120.0	1.7813	61.0
20.0	140.0	2.0625	65.0
20.0	160.0	2.3542	68.8
20.0	180.0	--	72.4
20.0	200.0	2.9271	75.2
20.0	240.0	--	78.0
10.0	250.0	3.6771	78.6

When the 3 23/32 inch diameter glass tube was used as a model bin in experiments 20A to 23A, vertical pressures were found to follow the pattern typical of all previous vertical pressure tests with dry wheat. (Fig. 8). However, the maximum vertical pressure reached (60 pounds per square foot) was less than the maximum vertical pressures (85 pounds per square foot) found when using the 15.75 inch diameter model bin with the 4 inch, the 7 inch, or the 8 inch diameter openings. This result was not expected because the glass tube model bin was much smoother than the lime-incrusted steel bin. However, the relatively small diameter of the bin, 3.72 inches, provided so little cross sectional area in relation to depth of grain measured that the wheat probably arranged itself somewhat differently than it did in larger bins.

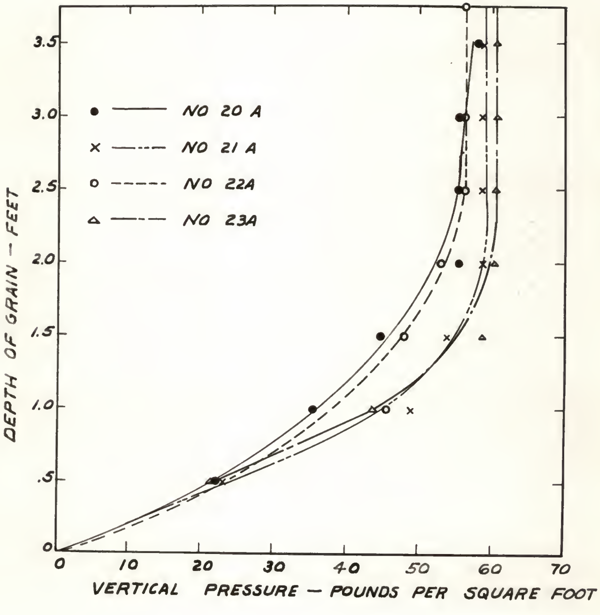


Fig. 8. Vertical pressures of dry wheat through bottom of 3 23/32 inch diameter glass bin.

Little practical significance is attached to this surprising though not too great difference between maximum vertical pressures of the dry grain in the glass bin and those of the larger model bin. Plotted results of calculations using Janssen's formula again indicate substantial agreement between calculated and actual values for vertical pressures under the conditions of this test. For this comparison of calculated and measured results with the glass model bin see Fig. 9.

Table 5. Vertical pressures of dry wheat at bottom of 3.72 inch diameter glass bin.

Depth of wheat ft.	Wheat added lbs.	Vertical Pressure in Pounds Per Square Foot					
		Test #20A	Test #21A	Test #22A	Test #23A	Average four tests	Calculated pressure
	.5	5.8	5.8	5.7	6.6	--	--
	.5	10.8	11.6	8.7	11.6	--	--
	.5	15.7	19.9	15.7	16.5	--	--
.5	.5	22.3	23.2	22.3	21.5	22.3	19.8
	.5	26.5	30.6	30.6	28.2	--	--
	.5	29.8	38.1	37.2	33.1	--	--
	.5	29.8	43.9	43.2	38.1	--	--
1.0	.5	35.5	48.9	45.5	43.9	43.4	33.1
	.5	35.5	47.2	48.9	46.3	--	--
	.5	35.5	52.1	50.5	51.4	--	--
	.5	35.5	52.1	50.5	56.3	--	--
1.5	.5	44.7	53.8	48.0	58.7	51.3	41.7
	.5	49.7	53.8	53.0	59.5	--	--
	.5	53.0	53.8	53.0	60.4	--	--
	.5	55.5	58.7	53.0	60.4	--	--
2.0	.5	55.5	58.7	53.0	60.4	56.4	47.3
	1.0	55.5	58.7	53.0	60.4	--	--
	1.0	55.5	58.7	56.3	60.4	57.7	51.0
	1.0	55.5	58.7	56.3	60.4	--	--
3.0	1.0	55.5	58.7	56.3	60.4	57.7	53.2
	1.0	57.0	58.7	56.3	60.4	--	--
3.5	1.0	57.0	58.7	53.0	60.4	--	54.8
3.75	1.0	58.7	58.7	53.0	60.4	57.7	55.4
4.0							56.0

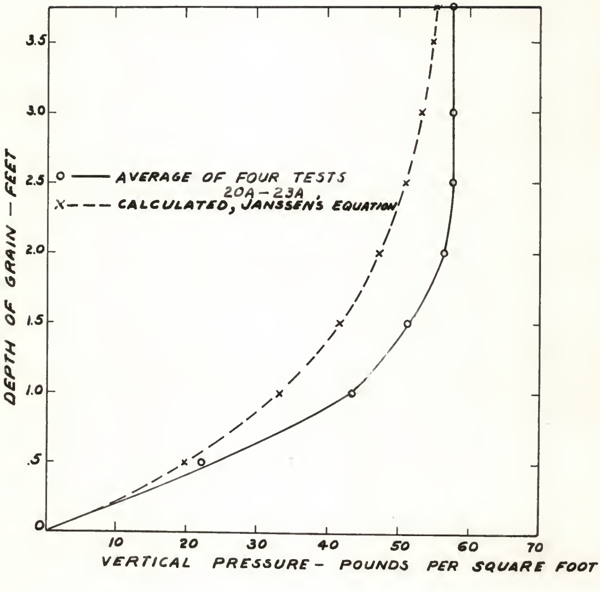


Fig. 9. Comparison of average vertical pressures of dry wheat at bottom of 3 23/32 inch diameter glass bin with calculated vertical pressures using Janssen's equation.

Swelling Pressures of Submerged Grain

Figure 10 graphically summarizes the swelling pressures measured when wheat was immersed to a depth of 2 3/8 inches above the bottom of the 15.75 inch diameter steel bin. Test No. 5 was conducted using the 8 inch diameter hopper bottom while tests No. 6, 7 and 8 were made using the four-inch diameter hopper bottom. The rapid build-up of swelling pressure on the bottom due to the flooding of the wheat at the lowest part of the bin is clearly demonstrated by Fig. 10. Following this rapid increase in swelling pressure, occurring over the first eight hours, swelling pressure continued to develop at a slower rate until about 24 hours had elapsed. After this, the total swelling pressure tended to fall slowly and regularly with time, approximating a straight line on a graph. The swelling pressures in pounds per square foot through the 8 inch diameter opening in the hoppered bin bottom were similar in value to those measured with the bin bottom hoppered to a 4 inch diameter opening. Average maximum swelling pressure was 300 pounds per square foot when the flood waters rose 2 3/8 inches into the wheat.

Comparing the average swelling pressures of wheat with two other grains, corn and sorghum, Fig. 11 shows that there was the same tendency of other grains to exert a rapid build-up of swelling pressure for the first eight hours. This was followed by a more slowly developing increase in swelling pressure for about 16 hours and a slow decrease in total swelling pressure thereafter continuing for at least 72 hours. This tendency of slow reduction in total swelling pressure after 24 hours occurred whether the water was drained from the wheat at the end of 30 hours or left in the pans around the wheat.

The swelling pressure of corn was substantially greater than that of wheat or sorghum. The early high rate of increase in pressure for corn was greater than that for wheat or sorghum and the peak pressure was 41 per cent greater than that for sorghum and 60 per cent greater than the average of four experiments with flooded wheat.

Table 6. Increase in vertical pressure at the bottom of 15.75 inch diameter model bin caused by wheat submerged to a depth of 2 3/8 inches vs. time.

Time after flooding hrs.	Increase in pressure lb./sq. ft. 1/				
	Test 5 2/	Test 6 3/	Test 7 3/	Test 8 3/	Average
1	50	70	70	117	82
2	103	107	137	185	133
3	136	136	200	228	175
4	165	152	252	252	205
5	185	165	280	268	224
6	202	175	298	280	239
7	216	185	312	288	250
8	228	192	323	296	260
9	238	198	332	300	267
10	247	205	338	304	275
12	255	215	349	305	281
16	270	234	356	305	291
20	281	247	356	305	297
24	285	255	356	305	300
28	285	255	348	300	297
32	285	255	342	295	294

1/ Readings taken from Fig. 10.
2/ 8 inch diameter concentric hole in 34° hopper.
3/ 4 inch diameter concentric hole in 34° hopper.

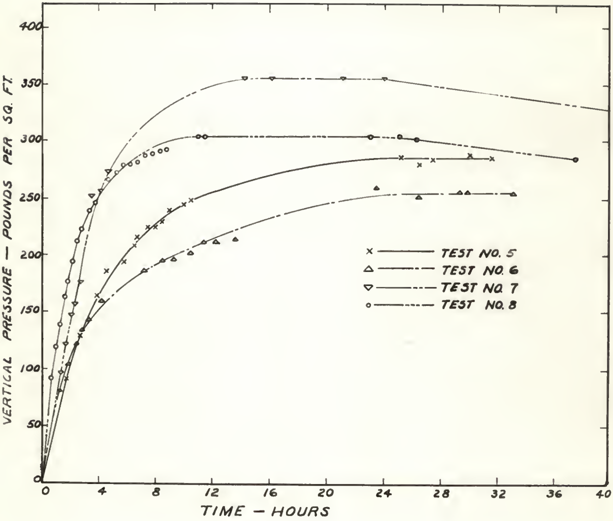


Fig. 10. Increase in vertical pressures of partially flooded wheat vs. time after flooding.

Table 7. Increase in vertical pressure through a 4 inch diameter opening in hoppered bin bottom caused by corn submerged to a depth of 2 3/8 inches vs. time.

Time	Scale reading lbs.-oz.	Increase in scale reading lbs. 1/	Increase in pressure 2/ lbs./sq.ft.	Time min.	Time hrs.
8:20 AM	6 - 0	--	--	--	--
8:25 "	30 - 0	5.44	62.4	5	.08
8:34 "	32 - 8	7.31	84	14	.23
8:42 "	34 - 5	9.75	112	22	.37
8:52 "	35 - 15	11.38	130	32	.53
9:02 "	37 - 10	13.06	150	42	.70
9:14 "	39 - 2	14.56	167	54	.90
9:32 "	41 - 10	17.06	196	72	1.20
9:51 "	43 - 12	19.19	220	91	1.52
10:12 "	45 - 11	21.13	242	112	1.87
10:32 "	46 - 13	22.4	257	132	2.2
10:51 "	48 - 1	23.5	269	151	2.5
11:12 "	49 - 8	24.94	286	172	2.86
11:34 "	50 - 11	26.13	299	194	3.23
11:51 "	51 - 8	26.94	309	211	3.52
12:38 PM	53 - 10	29.06	332	258	4.30
1:02 "	54 - 4	29.69	340	282	4.70
2:01 "	56 - 4	31.69	362	341	5.67
2:30 "	57 - 1	32.50	372	370	6.15
2:55 "	57 - 13	33.25	381	395	6.58
3:35 "	58 - 10	34.06	390	435	7.25
4:04 "	59 - 5	34.75	398	464	7.74
4:31 "	59 - 14	35.31	405	491	8.17
4:57 "	60 - 7	35.87	411	517	8.60
7:50 "	63 - 8	38.94	446	690	11.50
9:00 "	64 - 8	39.94	458	760	12.66
8:15 AM	66 - 10	42.06	482	1435	23.9
9:25 "	66 - 5	41.75	479	1505	25.1
10:12 "	64 - 12	40.19	461	1552	25.8
11:17 "	64 - 10	40.06	459	1617	26.9
1:07 PM	64 - 8	39.94	458	1727	28.8
4:31 "	64 - 7	39.87	457	1931	32.2
11:23 "	64 - 7	39.87	457	2343	39.0
8:30 AM	63 - 8	38.94	458	2890	48.1
11:00 "	63 - 8	38.94	458	3040	50.6
1:00 PM	63 - 4	38.69	444	3160	52.6
5:00 "	62 - 10	37.44	430	3400	56.6

1/ Scale reading minus weight of pan + dry corn on opening + water added.

2/ Increase in weight divided by .0872 sq. ft. (area of opening).

Table 8. Increase in vertical pressure through a four-inch diameter opening in hoppered bin bottom caused by sorghum submerged to a depth of 2 3/8 inches vs. time.

Date	Time	Time after submersion min.	Increase in scale reading	Increase in vertical pressure lbs./sq.ft.
4-11-53	8:45 AM	0	0 - 0	--
	9:00 "	15	7 - 10	87
	9:12 "	27	10 - 7	120
	9:42 "	57	13 - 15	160
	10:00 "	75	15 - 5	176
	10:15 "	90	15 - 7	177
	11:00 "	135	17 - 3	197
	11:25 "	160	18 - 1	207
	1:30 PM	285	21 - 9	247
	3:00 "	375	23 - 3	266
	3:30 "	405	23 - 9	270
	4:00 "	435	24 - 3	277
	8:00 "	675	26 - 11	304
	8:30 "	705	26 - 13	307
	9:00 "	735	26 - 15	309
	9:45 "	780	27 - 13	312
4-12-53	11:30 AM	1605	28 - 13	342
	2:00 PM	1755	28 - 9	328
	4:50 "	1925	28 - 5	324
4-13-53	8:35 AM	2870	26 - 15	309
	11:50 "	3065	26 - 15	309
	4:00 PM	3315	25 - 15	298
	5:15 "	3390	25 - 13	296
4-14-53	9:45 AM	4380	24 - 15	286

Effects of Depth of Flooding

Figure 12 shows the influence of height of flooding of a wheat column upon the vertical swelling pressure at the bottom. These tests were conducted with the glass tube model bin 3 23/32 inches inside diameter. The results indicate that in a bin of this size

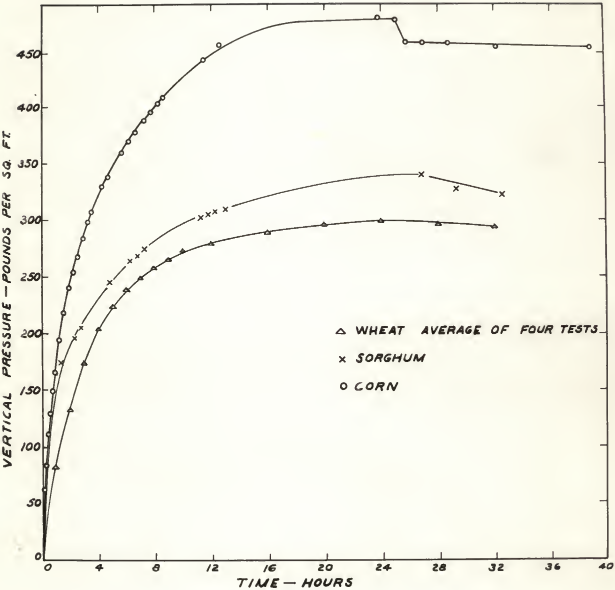


Fig. 11. Increase in vertical pressures of partially flooded wheat, corn, and sorghum vs. time after flooding.

and shape, the vertical swelling pressure on the bottom was great and increased until water reached a depth of 12 inches above the bottom of the wheat. After that, additional depths of flooding produced no increase in vertical pressure due to swelling.

The maximum vertical swelling pressure at 4 inch depth of flood water was 333 per cent greater than that obtained using the large bin with the flood water2 3/8 inches above the bottom of the grain. However, the swelling pressure of the wheat submerged to a depth of 8 inches was only 48 per cent greater than that at 4 inches depth of water and the swelling pressure of wheat submerged to a depth of 12 inches was only 8.0 per cent greater at 12 inches than it was at 8 inches depth of water. Figure 13 indicates that vertical pressure from swelling increased with depth of flood water up to 12 inches of depth.

The glass tube permitted visual examination of the wheat after swelling had reached its maximum. The wheat kernels exposed to water had swelled until they occupied all the interseed air space initially present in the dry grain. It was very tightly packed. After removing the pan of water only a few kernels of wheat fell from the glass tube which now had no bottom. The dry wheat above the soaked wheat was removed with a vacuum cleaner. When two liters of water were poured on top of the swollen grain no visible movement of the water through the plug of wet wheat was observed during the first hour. Overnight the wheat and water fell into a can on the floor beneath it.

Table 9. Increase in vertical pressure of submerged wheat vs. time at different depths of water. 3 23/32 inch diameter glass bin.

Time after flooding Min.	Increase in vertical pressure lbs./sq.ft. Depth of flood water inches			
	4 inches	8 inches	12 inches	16 inches
5	--	59.6	106	123
10	--	129.0	164	195
15	--	--	--	248
20	193	219	259	300
30	286	312	--	395
40	375	398	444	490
50	442	490	537	590
60	522	574	630	675
90	699	789	870	882
120	834	946	1058	--
150	925	1087	1210	1195
180	982	1194	1312	1322
210	1035	1275	1395	1380
240	1052	--	1458	1450
270	--	--	1488	1500
300	--	1395	1529	1525
360	1098	--	1560	--
440	--	1482	--	--
480	1070	--	--	--
540	--	--	--	1542
660	--	--	1583	--
720	1088	1462	--	--
800	--	1462	--	--
1330	--	--	1602	--
1485	--	--	1585	--
1600	1095	--	--	1515
2000	962	--	--	--
2900	736	--	--	--
3075	714	--	--	--
3345	677	--	--	--

Migration of Moisture to Dry Grain Above High Water Line

There was little capillary force to carry the water to the wheat above the level of the water in the pan. The wheat 1 to 2 inches above the water line appeared to be dry and undamaged.

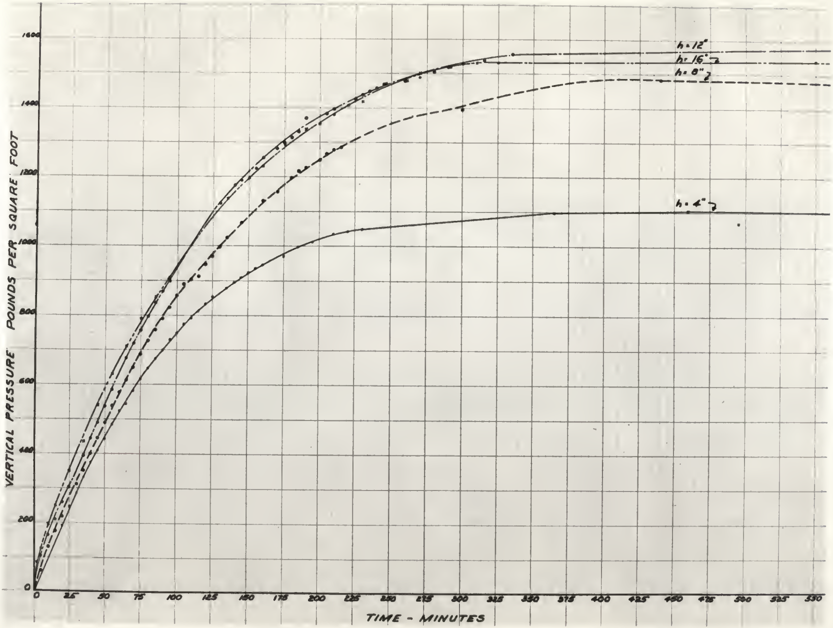


Fig. 12. Increase in vertical pressures of wheat, flooded to heights of 4, 8, 12 and 16 inches vs time after flooding.

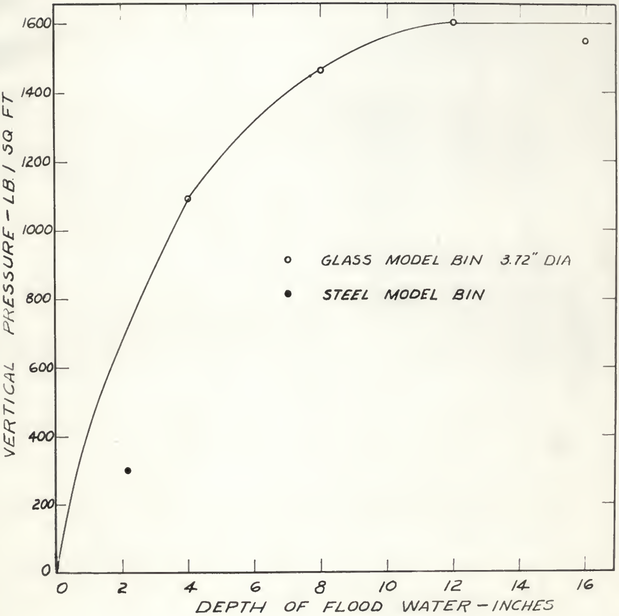


Fig. 13. Comparison of maximum vertical swelling pressures developed at different depths of flood water.

There occurred a limited upward migration of moisture above the water line of a column of wheat,corn or sorghum. Table 10 shows that there was practically no change in the moisture of the grain 2 inches or more above the high level mark of the flood water. Capillary forces were of a low order. Diffusion of water vapor seemed to have had no noticeable influence upon moisture transfer upward under these conditions and there could be no movement of air from the bottom through the water or the tightly packed wet grain.

Table 10. Distribution of moisture in columns of grain after immersion of the lower ends in water for seven days at room temperature.

Distance of sample above water surface inches	Moisture content, per cent		
	wheat	corn	sorghum
18-20	9.9	12.4	8.6
16-18	10.0	14.1	9.8
14-16	10.4	14.2	9.9
12-14	10.3	14.3	9.9
10-12	10.5	14.3	10.0
8-10	10.9	14.2	9.8
6- 8	10.1	14.5	9.9
4- 6	10.4	14.0	8.6
2- 4	10.8	15.0	10.2
0- 2	23.3	22.9	16.0
In water	44.4	41.9	35.4

Plate II shows the difference in appearance between 2 pounds of dry wheat and 2 pounds of the same kind of wheat soaked for 24 hours in 2 pounds of water. There was no visible free water in the flooded wheat after 24 hours, but when the top of the wet wheat was pressed down, water rose to the surface. The wet wheat

PLATE II

Photograph of a sample of dry wheat beside a sample of wheat soaked for 24 hours.

PLATE II

P EXHIBIT 95
DORC[illegible] FARIOW
Dist. [illegible] Court
JA[illegible]

CLERK U. S. DISTRICT COURT
NO.
MA[illegible]D FOR IDENTIFICATION
OC 12 1953
PLAINTIFF 59
[illegible]NT'S

was easily compressed to the higher of the two horizontal black lines which was the mark used to record the volume of dry wheat plus water immediately after the water was added. The color of the wheat after soaking changed to a light yellow and the kernels were visibly expanded. The wet wheat was more closely packed in the bottom than it was higher up in the glass cylinder. The milky white material looked like starch dissolved from the broken kernels which were in the original sample.

DISCUSSION

When dry grains are stored in a deep bin, it seems that vertical pressure will not be uniform across the greater part of the cross sectional area of a bin bottom and that a bin bottom hoppered to a slope of 34° or less will not cause an increase in vertical pressure upon the centrally located discharge opening. Conceivably a hopper built with greater slope would add somewhat to the pressure on the opening toward which it is pitched.

Millers and grain men have commonly observed that when grain is withdrawn from a centrally located hole in a bin the grain falls down through the center. Soon after the grain has started running out the bottom hole, a half cone will be observed at the top of the bin. The grain on top finds its way down through column of grain in the bin and runs out. The last grain in the bin is nearly the first out. This established phenomenon led to a hypothesis that the vertical pressure at the center of the bin was greater than it was at points farther toward the outside wall. This theory has been given support by the observation that the pressure of dry wheat was 84.3 pounds per square foot through the four-inch diameter centrally located hole at a 3 foot grain depth while only 76.65 pounds per square foot was recorded through the 8 inch diameter centrally located hole at 3 foot grain depth.

The swelling pressures as exerted vertically through the bottom opening are sufficiently powerful that bin hoppers and the spouts attached to the hoppers should be designed with considerably more strength than usual when it is known that flooding could occur. There is no apparent reason to believe that the lateral pressure against the sides of a spout, hopper or bin would be any less than the vertical pressures through or against the bottom when flood waters reach the grain and swelling takes place. Therefore bin walls should be designed to withstand the extra pressure if flooding can happen.

For example, in a 20 foot diameter concrete bin 100 feet high, full of wheat weighing 61.3 pounds per bushel, the maximum calculated vertical pressure for dry grain would be 1150 pounds per square foot. The maximum swelling pressure equalling 1600 pounds per square foot would increase the total load upon the bin bottom from 1150 pounds per square foot to 1150 plus 1600 = 2750 pounds per square foot, an increase of 240 per cent.

On the model bin it was observed that the swelling pressures transmitted through the 8 inch diameter hopper bottom were approximately equal to the average swelling pressures measured through the 4 inch diameter hopper bottom. The 8 inch diameter hole has an area 4 times the area of the 4 inch diameter hole but the unit pressures were in close agreement. It seems that in contrast to pressures of dry wheat the vertical pressures due to swelling will be uniform across the horizontal plane of the bin bottom. More experimental work is required before it can be known whether the vertical swelling pressures do behave as suggested.

Is there swelling pressure exerted vertically upward as well as downward when wheat in storage is flooded? It seems probable that swelling pressure is exerted equally in all directions. In the experiments the flooded wheat was covered by a column of dry wheat from 2.9 to 11.5 times the height of the wheat which was flooded. There was no noticeable change in elevation at the top of the dry wheat to indicate that upward movement had occurred even in the glass model bin, although it is probable that movement due to upward pressures would be dissipated by tighter packing of the dry grain immediately above the soaked area.

There was a downward acting vertical pressure of the dry grain upon the soaked and swelling grain but this had a relatively small total value compared to the swelling pressures measured at the bottom. When there is room for expansion or when the tendency to expand is resisted by lesser forces which yield, the swelling pressure does not reach high numerical values. A column of dry grain in a bin filled by gravity leaves about 44 per cent of free air space. When a quart can is filled to overflowing with wheat by gravity and the top surface is leveled by gently pushing a smooth board across its top, the can seems full. If the side of the can is tapped gently the individual kernels rearrange themselves and grain level drops below the top of the can. Therefore the absence of upward movement of the top of the dry grain does not indicate that there was no swelling pressure exerted vertically upward.

Swelling pressure of flooded wheat, as measured at the bottom of the bin, will be reduced for a time if more volume is made available for expansion. It was found that after 33 hours of soaking (test No. 6), by lowering the scale 1/64 inch, the swelling pressure was immediately reduced from 255 pounds per square foot to 220 pounds per square foot. Although this was done when the swelling pressure was decreasing at a slow rate, the pressure thereafter slowly increased from 220 pounds per square foot to 245 pounds per square foot at 48 hours after flooding. This value of 245 pounds per square foot is probably the pressure that would have been acting at the end of 48 hours had there been no increase in volume. It took 15 hours for this regain of swelling pressure to reach the amount it would have had if the scale had not been lowered.

The slow decrease in swelling pressure after about 24 hours might be due to the phenomenon of syneresis, the squeezing out of some of the liquid phase from the gel structure. Gortner (4) states:

> This process (syneresis) is variously explained as due (1) to the slow increase in the number or strength or both of the bonds existing between the structural elements of the gel (progressive flocculation) or (2) to a slow decrease in the attraction of the structural elements for the solvent (progressive desolvation).

The second explanation seems to offer a reason for the decreasing swelling pressures after 24 hours.

None of these tests was intended to be a measure of the imbibition pressure of wheat or other grains. The considerable volume of air in the interseed space of the dry grain (44 per cent) and the relatively low vertical pressure of the dry grains upon the flooded wheat permitted expansion in volume of the soaked grains and thus the low resistances to expansion did not permit testing for the imbibition pressures.

More studies of the swelling pressures of flooded grain should be undertaken. In particular, lateral pressures should be measured, for not all flood waters stop at a height below the top of the hopper. Implications might be drawn from facts discovered about swelling pressures that could be applied in a positive manner such as in the improvement of wheat, corn or other grains for milling.

SUMMARY AND CONCLUSIONS

Experimental evidence was obtained which indicate that:

1. With bin bottom shape the only known variable, it was found that equal vertical pressures were exerted by dry wheat through similar openings whether the bin bottom was flat or hoppered to the opening at a slope of 34° from the horizontal.

2. Equal heights of dry wheat exert greater vertical pressure upon smaller concentrically located holes in a bin bottom than they do upon larger holes similarly located.

3. The measured vertical pressures of different heights of dry wheat check reasonably well with vertical pressures calculated using Janssen's formula.

4. Stored wheat imbibes water freely when it is flooded with water. Wheat soaked in water for several hours, will imbibe water until its moisture is about 44 per cent of the sample weight.

5. Wheat, corn, and sorghum swell when they imbibe water.

6. If grains are stored under normal conditions, most of the potential swelling pressure is dissipated by forcing the grain kernels into the interseed air space.

7. As soon as the bottom of stored grain is immersed in water, vertical pressures upon the bottom increase rapidly and continue to do so for about 8 hours. Vertical pressure continues to increase at a slow rate for another 16 hours. At the end of approximately 24 hours, vertical pressure slowly decreases at a regular rate.

8. Under the same conditions, corn in a deep bin, which is flooded with water at the bottom exerts greater vertical pressure than wheat or sorghum. The swelling pressures vertically downward of wheat or sorghum flooded to the same depth are approximately equal.

9. The vertical pressure on the bottom due to swelling increased with depth of flooding only until the water stood 12 inches deep around the grain in the bin bottom. Flooding to a greater depth did not result in greater vertical pressures than the maximum of 1600 pounds per square foot.

10. Scarcely more than 2 inches of the grain above the peak flood line will increase in moisture sufficiently to become a storage hazard.

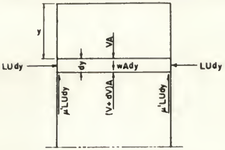
11. Mold growth commences at the surfaces of the soaked grain exposed to the air soon after draining the water from the bottom of a deep bin in which grain has been flooded.

PLATE III

Photographic reproduction of the development of Janssen's formulas

APPENDIX A

DERIVATION OF JANSSEN'S EQUATIONS



V = unit vertical pressure at any elevation (lb per sq. ft.)
L = unit lateral pressure at any elevation (lb per sq. ft.)
R = "hydraulic radius" = area of horizontal cross section of bin (sq ft) divided by the inside perimeter of bin (ft.)
w = weight of stored material (lb per cu ft)
μ' = coefficient of friction between stored material and bin wall
y = depth from top of bin to point under consideration (ft)
k = ratio of lateral to vertical pressure at any point
A = area of horizontal cross section of bin (sq ft)
U = inside perimeter of bin (ft)

$\Sigma V = 0$:

$$(V + dV)A + \mu' LUdy - VA - wAdy = 0$$

$$VA + AdV + \mu' LUdy - VA - wAdy = 0$$

$$AdV = wAdy - \mu' LUdy$$

$$AdV = wAdy - \mu' L \frac{A}{R} dy \qquad (R = \frac{A}{U} \quad \therefore \quad U = \frac{A}{R})$$

$$dV = wdy - \frac{\mu' L}{R} dy$$

$$dy = \frac{dV}{w - \frac{\mu' L}{R}} = \frac{dV}{w - \frac{\mu' L}{R} V}$$

Integrating

$$y = -\frac{R}{\mu' k} \log (w - \frac{\mu' k}{R} V) + C$$

When $y = 0$, $V = 0$

$$0 = -\frac{R}{\mu' k} \log w + C$$

$$C = \frac{R}{\mu' k} \log w$$

$$y = -\frac{R}{\mu' k} \log (w - \frac{\mu' k}{R} V) + \frac{R}{\mu' k} \log w$$

Multiplying by $-\frac{\mu' k}{R}$:

$$-\frac{\mu' ky}{R} = \log (w - \frac{\mu' kV}{R}) - \log w = \log (\frac{w - \frac{\mu' kV}{R}}{w})$$

$$e^{-\frac{\mu' ky}{R}} = \frac{w - \frac{\mu' kV}{R}}{w}$$

Solving for V:

$$we^{-\frac{\mu' ky}{R}} = w - \frac{\mu' kV}{R}$$

$$\frac{\mu' kV}{R} = w - we^{-\frac{\mu' ky}{R}}$$

$$\mu' kV = Rw (1 - e^{-\frac{\mu' ky}{R}})$$

$$V = \frac{Rw}{\mu' k} (1 - e^{-\frac{\mu' ky}{R}})$$

$$L = kV = \frac{Rw}{\mu'} (1 - e^{-\frac{\mu' ky}{R}})$$

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