Effects of grain moisture content on dynamic loads during discharge in a model corrugated steel bin

D. HAO, Q. ZHANG and M.G. BRITTON

Department of Agricultural Engineering, University of Manitoba, Winnipeg, MB, Canada R3T 5V6. Received 21 July 1993: accepted 24 March 1994.

Hao, D., Zhang, Q. and Britton, M.G. 1994. Effects of grain moisture content on dynamic loads during discharge in a model corrugated steel bin. Can. Agric. Eng. 36:103-108. Tests were performed using a model corrugated steel bin to study the effect of grain moisture content on static and dynamic loads. Lateral pressures on the bin wall were measured at six depths during filling and emptying (discharge). Static and dynamic vertical resultant forces on the bin wall and on the bin floor were measured independently. Hard red spring wheat was tested at three moisture contents of 9%, 12%, and 16% wb. With increasing moisture content, static lateral pressure on the bin wall decreased, whereas static vertical resultant force on the bin wall increased. During discharge, a lower dynamic lateral pressure was observed for grain with higher moisture content. Dynamic vertical force on the wall was in the same order of magnitude (0.7 kN) for 9% and 12% moisture contents. No dynamic vertical force was observed for 16% moisture content.

KEYWORDS: grain, bin, dynamic loads, discharge, moisture content.

Des expériences ont été effectuées avec un réservoir modèle en acier ondulé afin d’étudier l’effet du contenu en eau de grain sur les charges statiques et dynamiques. Les pressions latérales sur les murs du réservoir ont été mesurées à six profondeurs durant le remplissage et le vidage. Les forces verticales statiques et dynamiques exercées sur le mur du réservoir et sur le plancher du réservoir ont été mesurées indépendamment. Des tests ont été effectués avec du blé de force roux de printemps à trois teneurs en humidité différentes: 9%, 12% et 16% (base humide). En augmentant la teneur en eau, la pression latérale statique sur le mur du réservoir a diminué, alors que la force statique verticale résultante sur le mur a augmenté. Durant le vidage, une pression dynamique latérale plus petite a été observée avec le grain possédant la plus grande teneur en eau. L’ordre de grandeur de la force dynamique verticale sur le mur a été le même (0.7 kN) pour des teneurs en eau de 9% à 12%. Aucune force dynamique verticale n’a été observée avec une teneur en eau de 16%.

INTRODUCTION

Bulk solids storage structures are subjected to a much higher failure rate than most other building structures (Blight 1986). The majority of failures occurs during discharge of stored materials (Theimer 1969). When the stored material is discharged from a bin, loads exerted on the wall increase. These increases in loads are defined as dynamic loads during discharge. The ratio of the peak dynamic pressure to the static pressure is defined as the overpressure factor (OPF), which has commonly been used to estimate dynamic loads in design practice. Although much research has shown the importance of dynamic loads in bin design, the mechanism by which dynamic loads are introduced is still not clearly understood. Overpressure factors recommended by design standards and codes (ACI 1977; ASAE 1991b; NRC 1990) are essentially design safety factors.

Haaker and Scott (1983) showed that a wide disparity existed among the various design theories, methods, standards, and codes of practice that have been proposed for estimating dynamic loads during discharge. They illustrated this point by using six widely known methods, Jenike and Johanson (1968), Jenike (1980), Reimbert and Reimbert (1976), Richards (1977), ACI (1977), and DIN (1977), to predict a set of lateral pressures on walls for a silo filled with polyethylene pellets. The hopper bottomed silo had a square cross section with sides of 2.8 m and height of 19.5 m. The discharge hopper had a square orifice of 0.5 m x 0.5 m and a hopper angle about 50°. The material that they used in their example had a bulk density of 580 kg/m³, an average particle size of 3.5 mm, an angle of effective internal friction of 33.8°, and an angle of wall friction of 24.7°. The maximum dynamic pressure during discharge predicted by these six methods were 25, 12, 21, 33, 15, and 11 kPa, respectively. They showed that if other factors, like discharge methods, temperature, and variation in material properties throughout the silo were taken into account, the existing theories all had significant shortcomings.

Wide disparity among theories and design standards and codes is due to the fact that there are so many variables involved in predicting dynamic loads, including, but not limited to, internal friction, material-structure interaction, bulk density, moisture content, discharge rate, and location of discharge outlet. The effects of most of these variables on dynamic loads are still not well understood.

The present study was aimed at exploring the effects of grain moisture content on dynamic loads in grain storage bins. Grain moisture content affects both particle and bulk properties of grain, as well as grain-wall interactions, thus it affects bin loads. This effect of grain moisture on loads has not been considered in any design standards and codes. The specific objective of the present study was to measure dynamic loads in a model grain bin for different grain moisture contents.
EXPERIMENTAL METHODOLOGY
The experiment was conducted using a 1.0 m diameter by 1.5 m high model bin made of 0.97 mm thick corrugated galvanized steel sheet. The horizontal corrugations of the bin wall were 64 mm in pitch and 13 mm deep. The bin floor was suspended by three steel rods, each with a load transducer, to measure the entire mass of the bin and grain (Fig. 1). The bin wall was supported about 5 mm above the floor by three load transducers placed 120° apart. These transducers measured the vertical resultant force carried by the bin wall. Eight diaphragm pressure sensors were mounted on the inside surface of the wall to measure lateral pressures. Six transducers were placed in a vertical line and spaced at 192 mm with the first transducer 197 mm above the bin floor. Two were mounted 120° apart around a bin circumference 389 mm above the floor (Fig. 1). Details of the model bin and load sensors were discussed by Zhang et al. (1993).

The presence of the diaphragm pressure sensors on the inside surface of the wall might disturb the local stress field and the grain flow in the bin during discharge, thus altering loads on the wall. Preliminary tests were performed to investigate the significance of the effect of the pressure sensors on the static and dynamic vertical wall forces. Details of preliminary tests were discussed by Hao et al. (1994). The results showed that mounting pressure sensors on the wall had no significant effect (P < 0.05) on either vertical static or dynamic forces (Hao et al. 1994).

Hard red spring wheat was tested at three moisture contents: 9%, 12%, and 16% wb. The initial moisture content of wheat was 12%. The grain was dried to achieve a moisture content of 9% and water was added to the grain to obtain a moisture content of 16%. After the grain was mixed with a calculated amount of water, it was kept in a storage bin and covered with a plastic sheet for 24 hours. A humidifier was used to generate moisture in the laboratory to keep the relative humidity above 70% for the 16% moisture content tests. Grain moisture content was measured before and after tests using the air oven method outlined by ASAE (1991a). Measured grain moisture contents are summarized in Table I, along with other physical properties. The bulk density was determined from the measured in-bin volume and the total mass of wheat in the bin. Both angle of internal friction and the friction coefficient of grain on a corrugated wall were measured by using a direct shear device (ASTM 1992). Internal friction and grain-wall friction may not have been the same as those in the bin because the stress state in the bin was different from that in the shear box of the direct shear apparatus. They were used here to indicate the trend of changes in properties as grain moisture content changes. All physical property measurements were replicated four times.

Table I. Physical properties of wheat used in the experiment

<table>
<thead>
<tr>
<th>Property</th>
<th>Moisture content, % wb</th>
<th>Bulk density, kg/m³</th>
<th>Angle of internal friction</th>
<th>Coefficient of grain-wall friction</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>9% (0.1)**</td>
<td>12 (0.1)</td>
<td>16 (0.3)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>824 (6)</td>
<td>797 (15)</td>
<td>781 (3)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>21.3° (0.5)</td>
<td>25.2° (0.2)</td>
<td>29.2° (0.7)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.36 (0.02)</td>
<td>0.43 (0.03)</td>
<td>0.54 (0.03)</td>
<td></td>
</tr>
</tbody>
</table>

* means of four replicates
** Values in parentheses are standard deviations.

Tests were replicated four times for each of the three grain moisture contents. In each test, the conditioned wheat was centrally filled into the bin from a surge hopper located 0.8 m above the bin. After filling, the grain was allowed to settle for 2.5 h and then central discharge was started. The vertical resultant force and lateral pressures on the bin wall were recorded from the beginning of filling to the end of discharge using a high-speed data acquisition system (HP 8352A, Hewlett-Packard, Palo Alto, CA). Sensor outputs were recorded every second during filling and settling. The recording rate was increased to 20 readings per second per channel for the first 87 s of discharge, and then decreased to one reading per 2 seconds until the end of discharge.

A 60-mm diameter orifice was used to discharge grain from the bin in all tests. This orifice produced grain flow rates of 67.9, 65.4, and 62.5 kg/min for moisture contents 9%, 12%, and 16%, respectively.

RESULTS AND DISCUSSION
Variation in lateral pressure around the bin circumference was monitored at a height of 389 mm above the floor to confirm that filling and discharging of grain was centric (eccentric filling or discharging would cause large variation in lateral pressure around the bin circumference). The results are summarized in Table II. Analysis of variance showed that pressure variation around the bin circumference was insignificant for all tests. Therefore, in the following discussion of pressure variation along the bin depth, a uniform pressure distribution around the bin circumference was assumed.

Static loads
With increasing moisture content, static lateral pressure decreased at all six measuring depths (Fig. 2). Decreases in lateral pressure were much greater as the moisture content
Table II. Measured lateral pressures at three locations (A, B and C) around the bin circumference 389 mm above the bin floor

<table>
<thead>
<tr>
<th>Moisture Content</th>
<th>Location</th>
<th>Measured pressure (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Static</td>
</tr>
<tr>
<td>9%</td>
<td>A</td>
<td>2.60 (0.29)</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>2.65 (0.15)</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>2.58 (0.19)</td>
</tr>
<tr>
<td>12%</td>
<td>A</td>
<td>2.39 (0.29)</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>2.40 (0.12)</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>2.43 (0.31)</td>
</tr>
<tr>
<td>16%</td>
<td>A</td>
<td>1.48 (0.31)</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>1.45 (0.08)</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>1.47 (0.25)</td>
</tr>
</tbody>
</table>

* Means of four replicates  
** Values in parentheses are standard deviations.

increased from 12% to 16% than those from 9% to 12%. For example, the lateral pressure near the floor (197 mm from the floor) remained almost unchanged when the grain moisture content changed from 9% to 12%, whereas it decreased from 2.72 to 1.63, or 40%, when the moisture increased from 12% to 16%. The effect of moisture content on the vertical resultant force was negligible in the moisture range from 9% to 12% (changes in vertical force were less than 2%). When the moisture content increased from 12% to 16%, however, the vertical resultant force increased from 3.1 to 3.7 kN, or 19%.

Decrease in lateral pressure with increasing moisture content was attributed to greater internal friction and grain to wall friction, as well as lower bulk density for higher moisture grain (Table I). Softening of grain kernels due to high moisture content might also have contributed to the decrease in lateral pressure because of reduced contact forces between grain kernels and between grain kernels and the bin wall. Vertical resultant force on the wall responded to grain moisture change in a different fashion compared with lateral pressure because the internal friction and wall friction have an opposite effect on vertical force, i.e., a greater internal friction angle results in a lower vertical force on the wall while a higher wall friction causes a higher vertical force. When the moisture content increased from 9 to 12%, the angle of internal friction increased from 21.3° to 25.2°, or 18%, and the coefficient of grain to wall friction increased from 0.36 to 0.43 or 19%. Apparently, the effect of increased internal friction angle was compensated by the increased wall friction, thus little change in the vertical resultant force was observed. When the moisture content increased from 12 to 16%, the angle of internal friction increased from 25.2° to 29.2°, or 16%, while the coefficient of grain to wall friction increased from 0.43 to 0.54, or 26%. In this case, a greater increase in grain to wall friction resulted in a noticeable increase in vertical resultant force.

Dynamic loads

Measured dynamic lateral pressures during the initial 87 s of discharge are shown in Fig. 3 for three depths. The top, middle and bottom levels represent depths of 1157, 581, and 197 mm from the bin floor, respectively. For 9% and 12% moisture contents, lateral pressure in the lower part of the bin increased noticeably after discharge started and little change

Fig. 2. Variation of measured static lateral pressures with grain depth.

Fig. 3. Measured lateral pressures at three depths: 1157 (top), 581 (middle) and 197 mm (bottom) from the bin floor.
Fig. 4. Measured increases in lateral pressure during discharge (overpressures).

at the top layer was observed. Fluctuations in lateral pressure at the top and middle layers might be attributed to "stick-slip" effects as the grain moved down along the bin wall. The moving grain might proceed in a series of intermittent jerks referred to as "stick-slip" (Mohsenin 1986). The frequent stick and slip caused the lateral pressure to fluctuate. For 16% moisture content, grain stuck on the wall all the time (Fig. 5), resulting in smooth pressure curves (Fig. 3). Small gradual increases in lateral pressure were observed for 16% moisture content at all three layers.

For all three moisture contents, the lateral pressure at the bottom layer reached the peak first, then the middle layer and the top layer. This agrees with Jenike and Johanson's (1968) hypothesis which states that the dynamic pressure occurs at a pressure switch zone which is initiated near the discharge outlet and travels upwards as discharge progresses.

Dynamic overpressure (maximum net increase in pressure during discharge) increased with grain depth for 9% and 12% moisture contents, whereas, it decreased slightly with grain depth for 16% moisture content (Fig. 4). In the lower portion of the bin, dynamic overpressure was lower for higher grain moisture content. For example, at the bottom measuring level, overpressure decreased from 1.52 to 0.85 to 0.63 kPa when the moisture content increased from 9% to 12% to 16%. A total decrease of 0.89 kPa, or 59%, resulted from a 7% increase in moisture content.

Lower overpressure at high moisture contents might be attributed to reduction in the mass flow region caused by high moisture grain which did not flow well. An attempt was made to observe the flow mode by inserting twenty 2 mm diameter, 45 mm long steel rods into the grain mass through small holes in the bin wall. The rods were placed at heights from 197 to 1477 mm (measured from the bin floor), evenly spaced 64 mm apart. Tilting of steel rods indicated that the grain near the wall moved, or mass-flow occurred. Figure 5 shows the observed flow modes for the initial 20 s of discharge for the three moisture contents. When the moisture content increased from 9% to 12% to 16%, height of the stagnant region of grain mass increased from 580 to 790 to 1450 mm. Increase in the height of the stagnant region meant reduction in the mass-flow region, which would result in lower dynamic loads. Because of a larger funnel flow region for 16% moisture content, more grain mass at the bin top started to move when the discharge gate opened, therefore higher overpressure was observed in the top region for 16% moisture content grain (Fig. 4).

Overpressure factors OPF varied slightly with the grain depth for moisture contents of 9% and 12% (Fig. 6). OPF's averaged from all six measuring levels were 1.41 and 1.33 for 9% and 12% moisture contents, respectively. In comparison, the OPF for 16% moisture content was higher in the upper portion of the bin and lower in the lower portion of the bin.

Fig. 5. Observed flow modes during the initial 200 s of discharge for grain moisture contents: (a) 9%, (b) 12% and (c) 16%.
Fig. 8. Effect of ridge opening length.

Fig. 9. Effect of openings in endwalls; (a) wind at 60°; (b) wind at 30°; and (c) wind at 0°.

Fig. 10. Effect of doors open only on leeward side; (a) wind at 90°; (b) wind at 30°.

closed and sealed to prevent infiltration. Figure 10 shows, that for wind at 90°, air entered near the mid-length of the barn and exhausted at both ends. The ridge acted as an exhaust over its entire length. Wind directions other than 90° caused a horizontal rotational air movement from the leeward end to the windward end. The windward end of the ridge acted as an exhaust while the leeward end was not consistent and at times acted as either an inlet or exhaust. The same airflow patterns were observed for both ridge opening widths (150 and 300 mm full scale). However, observations indicated that the rate of smoke decay was higher with the wider ridge opening.

CONCLUSIONS

A scale model of a naturally ventilated swine finishing building was used to study the effect of structural modifications and wind angle of incidence on interior airflow patterns under isothermal conditions. The results showed that:

1. Wind perpendicular to the building (90°) provided the most uniform airflow patterns along and across the building.
2. Wind at 0°, 30°, and 60° created horizontal rotational air movements within the building.
3. The airflow pattern over a barn cross-section varied along the length of the building for winds other than at 90°.
4. With no endwall windows, zones of slow smoke dispersion were always observed at the windward end for winds at 0°, 30°, and 60°.
5. Changing opening angle of the sidewall rotating doors did not greatly influence the airflow patterns, in spite of changes in effective sidewall opening areas.
6. Centre versus side alley layouts, with solid pen fronts, had limited influence on the air flow patterns.

7. The addition of a wall across the midlength of the model created similar airflow patterns in the two rooms. Observations showed that the rate of smoke decay was greater in the windward room as compared to the leeward.

8. The addition of two windows in this central wall reduced the zones of slow smoke dispersion observed in the leeward room.

9. The ridge opening width had a limited influence on the primary airflow patterns. Observations indicated that the rate of smoke decay increased with the use of wider ridge openings.

10. Opening the ridge over the total length of the building as opposed to having it closed for a short distance at each end reduced the size of the zone of slow smoke dispersion at the windward end.

11. The addition of two endwall windows reduced or eliminated the zones of slow smoke dispersion in the windward end especially for wind at 0° and 30°.

12. It is possible (but not recommended) to ventilate a building using only leeward sidewall doors and a continuous ridge opening.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge K. Boyd, Education and Research, G. Garland, Resources and Regulation, C. Weil and M. Paulhus, Collège de technologie agricole et alimentaire d’Alfred, all of the Ontario Ministry of Agriculture, Food and Rural Affairs, and Dr. A. Lachance, Director, Centre for Food and Animal Research, Agriculture Canada, Ottawa, for their support and funding. Thanks are also extended to A. Olson and R. Pella, Centre for Food and Animal Research, Agriculture Canada, and F. Blais, D. Larose, and H. Dubois, Collège d’Alfred for their assistance.

REFERENCES


Canada Plan Service. 1990. Plan M-3433: Naturally ventilated grower-finisher barn. Canada Plan Service Coordination Unit, Centre for Food and Animal Research, Agriculture Canada, Ottawa, ON.


Choinière, Y. 1991. Wind induced natural ventilation of low-rise buildings for livestock housing by the pressure difference method and concentration decay method. Unpublished M.A.Sc thesis, Civil Engineering Department, University of Ottawa, Ottawa, ON.


Fig. 7. Vertical resultant force measured by one transducer, which is one third of the total vertical force on the bin wall.

than those for 9% and 12% moisture contents. Higher OPF in the upper portion of the bin for 16% moisture content was due to low static pressures.

Since variation of load around the bin circumference was insignificant, the vertical force measured by a single transducer was examined (Fig. 7). It should be noted that the force measured by one transducer represents the pattern of variation in the total vertical force, however its magnitude is one third of the total vertical force on the wall. For moisture contents of 9% and 12%, the vertical force on the wall increased sharply when discharge started, but for 16% moisture content, a sudden decrease was observed. The maximum increases in vertical resultant forces (the total of three transducers) were about 0.7 kN, or 24%, for the moisture contents of 9% and 12%, whereas there was no increase in vertical force during discharge for the 16% moisture content.

Change in the ratio of dynamic to static vertical forces (DSR) was negligible (1%) when the moisture content increased from 9 to 12%, while DSR decreased from 1.25 to 1.01, or 19%, for the moisture content increase from 12% to 16%.

SUMMARY AND CONCLUSIONS

An experiment was performed using a 1.5 m high by 1.0 m diameter corrugated steel bin to investigate the effects of grain moisture content on dynamic loads during discharge. Diaphragm pressure sensors were installed on the inside surface of the bin wall at six elevations: 197, 389, 581, 773, 965, and 1157 mm from the bin floor. Vertical resultant forces on the bin wall were measured by using three load transducers. Hard red spring wheat was tested at three moisture contents of 9%, 12%, and 16% wb. All tests were performed with central filling and discharging. Experimental results showed:

1. With increasing moisture content, static lateral pressure on the bin wall decreased, whereas static vertical resultant force on the bin wall increased.
2. In the lower portion of the bin, the lower the moisture content, the higher the dynamic overpressure. No pat-

term of variation of dynamic overpressure with moisture content was observed in the upper portion of the bin. The vertical resultant force on the bin wall increased about 24% during discharge for 9% and 12% moisture contents, whereas negligible dynamic vertical force during discharge was observed for 16% moisture content grain.

3. The effects of grain moisture on both static and dynamic loads were more pronounced in the moisture content range from 12% to 16% than from 9% to 12%.

ACKNOWLEDGEMENT

The financial assistance by the Natural Science and Engineering Research Council of Canada is gratefully acknowledged.

REFERENCES

ACI. 1977. Recommended practice for design and construction of concrete bins, silos, and bunkers for storage of granular materials and commentary. ACI 313. American Concrete Institute, Detroit, MI.


