Int. Agrophysics, 2007, 21, 73-79

INTERNATIONAL
Agrophysics
www.ipan.lublin.pl/int-agrophysics

Performance of earth pressure cell as grain pressure transducer in a model silo**

M. Molenda[1]*, *M.D. Montross*[2] *and J. Horabik*[1]

[1]Institute of Agrophysics, Polish Academy of Sciences, Doświadczalna 4, 20-290 Lublin 27, Poland
[2]Biosystems and Agricultural Engineering Department, University of Kentucky, Lexington, KY, USA

Received October 26, 2006; accepted December 30, 2006

A b s t r a c t. Numerous methods have been proposed for determining the pressure exerted by grain at discrete locations in a storage structure, but few satisfactory solutions have been found. Earth pressure cells were tested as potential measurement devices for grain bins. Earth pressure cells are commercial transducers designed for geotechnical applications. Calibration of the earth pressure cell was performed in a pressurized chamber filled with wheat under normal load as well as shear load. The cell was tested in a model grain silo 1.83 m in diameter d with a height h_c of 5.75 m. Vertical floor pressures and horizontal wall pressures were measured at different points in the model bin. The vertical floor pressure p_{vi} was measured at two different radial locations and horizontal wall pressure p_h was measured at four different wall heights. The vertical floor pressure obtained using the earth pressure cell was in good agreement with the mean floor pressure p_v calculated using load cells that supported the entire floor or the bin. Considerable variation in the vertical floor pressure along the silo floor radius was observed. The variation of the lateral-to-vertical pressure ratio, K, was monitored during each fill-unload cycle of the model silo. In the case of the maximum h/d ratio of 2, K increased during filling and stabilized after reaching a grain h/d ratio of 1.3. At the onset of discharge, the pressure ratio immediately increased up to value of approximately 0.7, and remained stable during unloading down to a h/d ratio of approximately 0.65 when K decreased rapidly.

K e y w o r d s: bulk solids, granular material, pressure ratio, pressure cell, silo loads

INTRODUCTION

Information on the level and distribution of pressures exerted by bulk solids on storage structures is of vital interest to structural and process engineers. In order to validate theories early theoretical considerations of storage pressures required pressure measurements. Ketchum (1919) gave an extensive review of the state of theory and technology at the beginning of 20th century. In the chapter concerning experiments on the pressure of grain in deep bins, this author reviewed results of nine projects, and in three of them authors used hydraulic pressure transducers. Ketchum (1919) reported that Jamieson and Lufft, used similar techniques independent of each other at approximately the same time. Jamieson performed his tests in Montreal, Canada in 1900 using a rubber diaphragm to transfer the grain pressure through water to a mercury gage. Lufft performed his experiments in full-size bins in Buenos Aires, Argentina in 1902 in which rubber diaphragms mounted inside the wall transferred the grain pressure to a mercury column through glycerine. Since that time, a significant amount of research has been performed using pressure transducers for bulk solids by structural and chemical engineers. In current transducers pressure exerted on a circular surface is measured. Two types of transducers are commonly employed: stiff plate supported on force transducer or an elastic membrane. Transducers for measuring pressure of bulk solids are not widespread on the market, but one solution are earth pressure cells (EPC). EPC are a closed hydraulic system with an elastic diaphragm where the deflection of the diaphragm creates fluid pressure that is converted by the pressure transducer into an electrical signal. Earth pressure cells are meant to provide a direct means of measuring total pressure in geotechnical applications.

The objective of this project was to validate the applicability of earth pressure cells for determination of grain pressure exerted on a silo wall and floor. Performance of the EPC in four experimental conditions were tested: radial distribution of vertical floor pressure, variation in the horizontal wall load during filling and discharge of the model silo, dynamic response of horizontal wall load at initiation of discharge and variation of lateral pressure ratio during a typical fill - unload cycle of a model silo.

*Corresponding author's e-mail: mmolenda@ipan.lublin.pl
**The investigations reported in this paper were made in College of Agriculture, University of Kentucky, USA.

PROCEDURE

Equipment

Geokon 3510 earth pressure cell with a diameter of 203 mm was used as the grain pressure transducer. The cell was calibrated in a Grain Friction Tester that allowed for measurement of normal load as well as shear load (Molenda *et. al.*, 2000). The pressure was produced using compressed air into an elastic membrane and a 7 cm thick layer of dry wheat. The transducer was attached to the sample tray of the apparatus. To produce a shear load the tray was pulled and the pulling force recorded. The test for the applied normal load was completed when the force required to slide grain across the surface of the transducer stabilized. Tests were performed with increasing and decreasing pressure in a range from zero to 48 kPa. The procedure was repeated three times and transducer output versus normal pressure recorded.

Additional tests were conducted in a cylindrical, flat floor, corrugated-wall steel grain silo. The silo was 1.83 m in diameter and 5.75 m high (Fig. 1). The wall corrugations were 13 mm high with a period of 67.7 mm. The cylindrical wall of the silo and the flat floor were each supported independently from each other to isolate the wall and floor loads. Both the wall and floor of the model grain silo were supported by 3 load cells spaced at an angle of 120° around the circumference of the silo. Load cells F_1, F_2 and F_3 support the floor of the bin, while load cells F_4, F_5 and F_6 support the walls of the bin. Soft red winter wheat with a moisture content of 11.3% (wet basis) and an uncompacted bulk density of 750 kg m^{-3} was used in the tests.

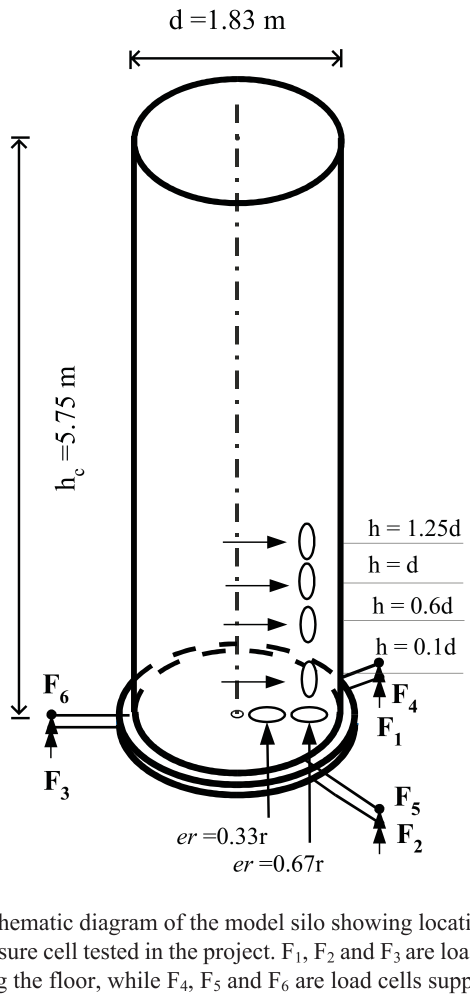

Fig. 1. Schematic diagram of the model silo showing locations of earth pressure cell tested in the project. F_1, F_2 and F_3 are load cells supporting the floor, while F_4, F_5 and F_6 are load cells supporting the wall.

All tests were conducted using centric filling and centric discharge. The silo was centrally filled at a flow rate of approximately 2600 N min^{-1} using a horizontal conveyor equipped with a discharge spout. After filling, the grain was allowed to equilibrate during a detention period of 0.5 h. Grain was discharged through a 7.2 cm diameter discharge orifice located in the center of the silo at a rate of 1100 N min^{-1}, which produced a sliding velocity of 2.8 m h^{-1} along the silo wall during mass flow. The wall and floor loads during loading, detention and discharge were measured at a 30 s interval until discharge was completed. To observe the dynamic response of the loads at the start of grain discharge, loads were measured at a frequency of 0.7 s prior to opening the unloading orifice and for one minute after the start of discharge. The loads were measured with an accuracy of ± 50 N.

Locations of the EPC within the model silo used in the experiments are shown in Fig. 1. Testing of the pressure cell under vertical floor pressure p_v in the model silo was performed at two radial locations of eccentricity ratios (*er* - distance from the silo center line axis expressed as a fraction of silo radius) of 0.33 and 0.67. Testing of the cell under horizontal wall pressure p_h was performed at four height-to-diameter (*h/d*) locations on the silo wall of 0.1, 0.6, 1 and 1.25. Each test was repeated two times, and in case of noted discrepancies between two replications a third test was conducted. Results of one of the two tests will be shown in this article.

Calibration of earth pressure cell under normal and shear load

The earth pressure cell was calibrated under a pressurized mass of grain under normal pressure only and under normal pressure with shear stress. The cell was loaded with eight levels of normal pressure from 0 to 48 kPa and then gradually unloaded. The procedure was repeated three times and the transducer output (mV) against normal pressure (kPa) recorded. Linear regression was performed and calibration parameters obtained. Coefficients of linear correlation were found higher than 0.999 and calibration under normal pressure only was found in close agreement with factory calibration. No significant hysteresis was observed during load increase – decrease cycles. Presence of shear stress during calibration resulted in pressure readings that were 1.023 greater than readings under pure normal load.

RESULTS

Vertical floor pressure during filing and discharge

Vertical floor pressure during filling and discharge as a function of grain height-to-diameter ratio are shown in Figs 2 and 3. Vertical floor pressure p_{vi} was measured with the EPC at two locations on the floor: *er*= 0.33 (0.305 m from the silo axis, Fig. 2) and at *er* = 0.67 (0.61 m from the silo axis, Fig. 3). The vertical floor pressures at discrete locations were compared to the mean vertical floor pressure p_v in the bin by summing the vertical floor load from the three load cells supporting the bin floor and then dividing by the silo floor area. At both test locations the EPC measured floor pressures (p_{v1} and p_{v2}) were higher during filling than the mean vertical floor pressure p_v. Maximum floor pressures p_{v1} of 19.2 and p_{v2} of 17.4 kPa were observed at the end of filling at *er* = 0.33 and *er* = 0.67, respectively. The mean vertical floor pressure p_v was found equal to 16.5 kPa at the end of filling. During discharge the mean pressure p_v was greater than the pressure p_{v1} and lower than p_{v2} , both measured using the EPC. This behavior confirmed earlier observations that the radial distribution of floor pressure in a bin was not constant, contrary to Janssen's assumption. Eurocode 1 (2003) does not address the radial distribution of pressures on a flat floor but recommend that the design vertical floor load in a bin is calculated using Janssen's and taken as uniform, except when the silo is squat or intermediate slenderness. Australian Standard AS 3774 (1996) recommended the following equation for determination of the pressure distribution on the base of a flat – bottomed silo:

$$p_{vix} = 1.25 p_v \left[1 - 1.6 \left(\frac{x}{d_c} \right) \right] \qquad (1)$$

where: p_{vix} – mean initial pressure on the base at distance x from center, kPa; x – radial coordinate in a circular container, meters; d_c – container diameter, meters; p_v – mean vertical floor pressure using Janssen's equation and the suggested grain coefficients.

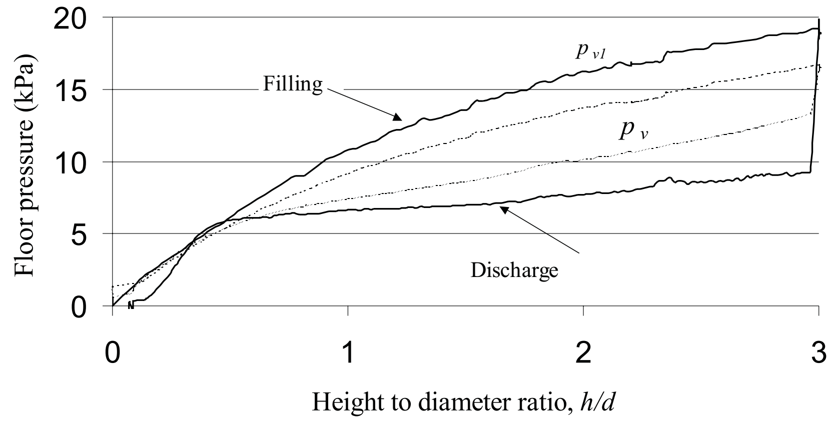

Fig. 2. Vertical floor pressure p_{v1} measured with the EPC during filling and discharge of the silo at a distance of 0.33 radius from centerline (*er* = 0.33) and mean vertical pressure p_v determined using the three load cells supporting the floor.

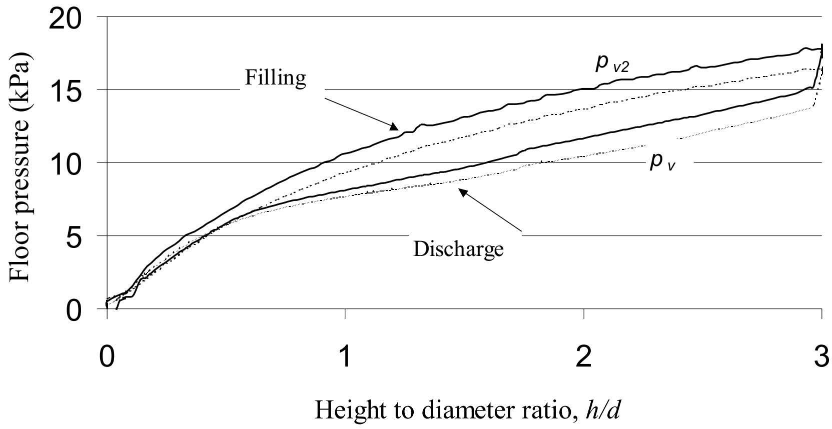

Fig. 3. Vertical floor pressure p_{v2} measured with the EPC during filling and discharge at a distance of 0.67 radius from centerline (*er* = 0.67) and mean vertical pressure p_v determined using three load cells supporting the floor.

Equation (1) with d_c = 1.83 m, p_v = 16.5 kPa (mean floor pressure) and radial coordinates of x_1 = 0.305 and x_2 = 0.61 resulted in predictive values of 19.7 kPa and 17.0 kPa for p_{v1} and p_{v2}, respectively. The predicted floor pressures were 0.5 kPa higher and 0.4 kPa lower than measured with the EPC. The pressure distribution observed in the experiment was flatter than the distribution suggested by the Australian standard. At the initiation of discharge a sharp decrease in the floor pressures was observed. The mean vertical floor pressure p_v decreased from 16.5 to 13.7 kPa. Vertical pressure at *er* = 0.67 (p_{v2}) decreased from 17.4 to 15.2 kPa, while at *er* = 0.33 the vertical pressure decreased from 19.2 to 9.2 kPa. A larger decrease in floor pressure closer to the discharge orifice is a typical response during discharge.

Dynamic response of vertical floor pressure to discharge initiation

Ratios of dynamic vertical floor pressure to static floor pressure (*dsr*) during the first minute of discharge are shown in Fig. 4 for two radial locations of the pressure cell at *er* of 0.33 and *er* of 0.67.

Distinct differences in the dynamic to static floor pressure ratio (*dsr*) for the two locations of the EPC were observed (Fig. 4). In the case of the EPC located closer to the silo axis the *dsr* decreased to 0.48 of its static value immediately (within 1.5 s of discharge), while at an *er* of 0.67 the vertical floor pressure was still 0.99 of its static value after 13 s of discharge. At the end of the recording period, *dsr*'s were relatively stable having values of 0.88 and 0.50 at *er* = 0.67 and at *er* = 0.33, respectively. These results illustrated the strong dampening action of stagnant grain covering the pressure cell. Change in stress state from static to dynamic after discharge initiation had little effect on the grain bulk located deeper in the stagnant zone. Propagation of pressure wave in the network of intergranular forces was weakened by friction between grains due to the increased distance from the source of disturbance.

Horizontal wall pressures at various vertical locations

This set of tests were performed with the pressure cell attached to the silo wall at height to diameter ratios (*h/d)* of 0.1, 0.6, 1 or 1.25. Measurements were taken during filling, detention and discharge of the silo. Characteristics of horizontal pressure p_h against the height to diameter ratio are shown in Fig. 5a for filling and in Fig. 5b for discharge.

During filling, fluctuations in horizontal pressure were observed due to the forming and collapsing of unstable structures in the top layer of wheat. During the detention period of 30 min horizontal pressure decreased by approximately 15% in all cases except *h/d* of 0.1. This was due to consolidation of grain in a direction of higher principal stress *ie* in the vertical direction. This decrease in horizontal pressure p_h was accompanied by an increase in vertical pressure p_v and floor load. At the initiation of discharge a sharp increase in horizontal pressure was observed. Maximum dynamic to static pressure ratios (*dsr*) recorded after 1 min of discharge at *h/d* locations of 0.1, 0.6, 1 and 1.25 were found to be 1.15, 1.5, 2.3 and 1.7, respectively. This result is in disagreement with the opinion that the highest increase in horizontal pressure occurred at the transition from parallel to converging flow (*h/d* of approximately 0.7). In addition previous work has indicated that a dynamic increase in horizontal pressure should not occur at initial grain heights of less than *h/d* of 2.0 (EP433, 1997). Relatively small dynamic increase in horizontal pressure p_h at the lowest *h/d* of 0.1 may be explained by the muffling action of stagnant grain covering the pressure cell in this case. At *h/d* of 0.6, 1 and 1.25 pressure fluctuations were observed from the initiation of discharge until the change in flow pattern from mass flow to funnel flow, at which time these pressure fluctuations ceased. Cessation of mass flow and initiation of funnel flow resulted in a steady decrease in horizontal pressure. During further unloading p_h

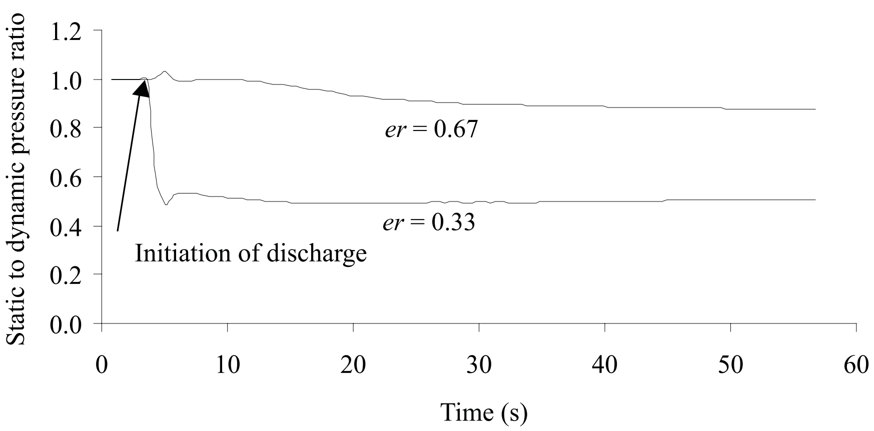

Fig. 4. Ratio of static to dynamic vertical floor pressure at the onset of discharge initiation recorded by EPC located at radial locations of *er* = 0.33 and *e r*= 0.67.

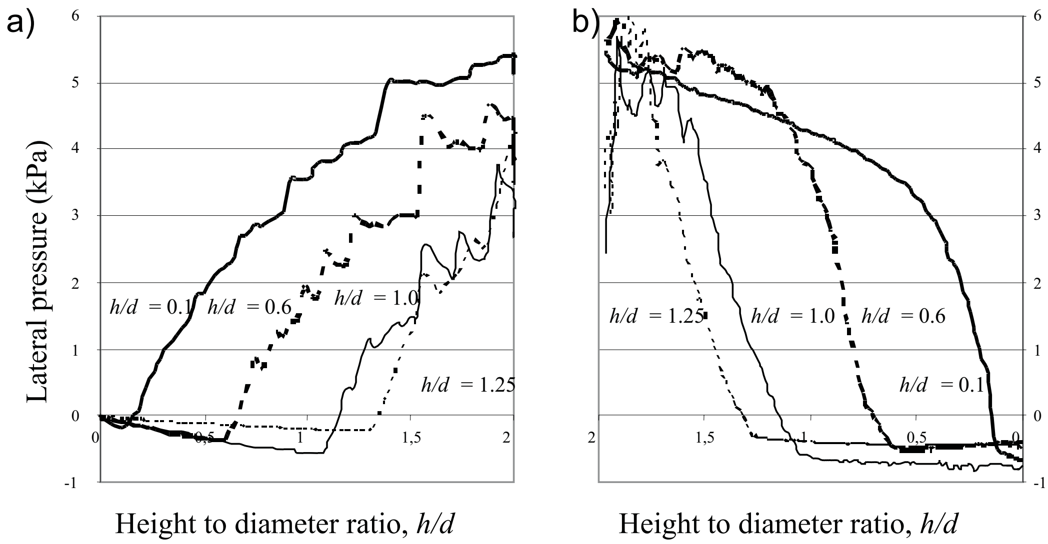

Fig. 5. Lateral wall pressure p_h during filling and discharge of the model silo at four vertical locations of the EPC at *h/d* of: 0.1, 0.6, 1 and 1.25. Arrows pointing to the right indicate filling, and arrows pointing to the left indicate discharge.

decreased smoothly to 0 at which time the EPC surface was uncovered. For the majority of tests after unloading the pressure cell returned value between 100 and 500 Pa. This inconsistency was probably due to the changes in barometric pressure and temperature during testing that would influence closed hydraulic system.

Dynamic pressure increase at the onset of discharge

The dynamic to static horizontal pressure ratios (*dsr*) measured at an interval of 0.7 s during the first minute of discharge and at four vertical locations of the pressure cell are shown in Fig. 6. For the location of the EPC closest to the floor ($h/d = 0.1$) the horizontal pressure p_h ramped up after discharge was initiated to 1.45 of the static value, and subsequently slowly decreased down to *dsr* of 1.15 after 50 s of discharge. The *dsr* for the cell location at $h/d = 0.6$ also increased steeply after discharge initiation up to value of 1.5 and remained approximately stable with some fluctuations not exceeding the initial dynamic value. The *dsr* measured at $h/d = 1$ demonstrated a very irregular path with several local extremes, with the largest 2.3 times the static value that was observed after 23 s of discharge. Smaller fluctuations in *dsr* were observed at the cell location of $h/d = 1.25$ where

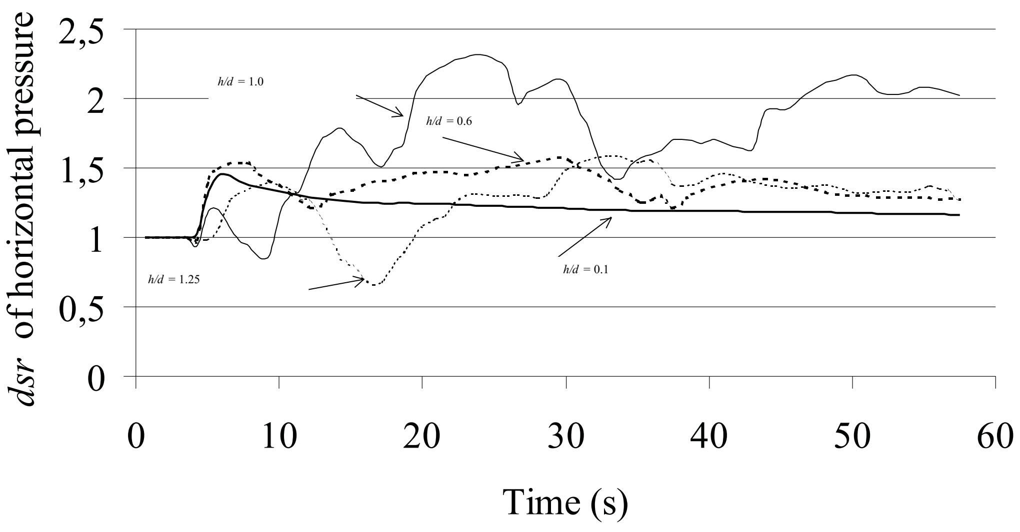

Fig. 6. Dynamic to static horizontal pressure ratio (*dsr*) at the onset of discharge recorded by EPC located at four *h/d* ratio levels of 0.1, 0.6, 1 and 1.25.

a minimum of 0.7 and a maximum of 1.6 were observed. Data presented in Fig. 6 were for individual tests and were representative of the duplicate. This silo discharged in mass flow until the grain level reached a value of *h*/*d* of approximately 1.5, and effective transition was observed at the level of 1.3 m from the floor that is at *h*/*d* of 0.7. Thus the smooth nature of the *dsr* at *h/d* of 0.1 was a result of cell location in stagnant grain. Greater fluctuation was observed for *h*/*d* of 0.6 because this was slightly below the transition. The largest *dsr* fluctuations were found in the area of mass flow (above *h*/*d* of 0.7) where grain was sliding against the wall (and the cell surface) and where fluctuations of stress state due to non-uniform wall shape and variation in wall friction occurred. Eurocode 1 (2003) recommended that increased discharge load should be used to account for possible transitory increases in pressure on the silo walls during discharge. The discharge factor C_h of 1.15 for horizontal pressure in slender silos and typical conditions has recommended. ASAE standard EP 433 (1997) recommended an overpressure factor of 1.4 and in flat bottom mass flow silos suggested application of this factor from the grain surface to within a distance of *d*/4 from the bottom. Results of the current tests have shown that values of local dynamic pressure increases were larger and occurred at a lower level than recommended by conventional design codes.

Lateral pressure ratio, *K*, during filling and discharge of the model silo

Eurocode 1 defines the lateral pressure ratio as the ratio of the horizontal pressure on the vertical wall of a silo to the mean vertical stress in the solid at the same level. Usually an active (or static) stress exists during filling, while a passive (or dynamic) stress field develops during discharge. The traditionally (after Rankine) used term active means the case when the higher principal stress σ_1 is oriented vertically, while σ_2 which is known as the passive stress is oriented horizontally (Drescher, 1991). These states of stress are accompanied by active and passive stress ratios. Figure 7 shows the stress ratio *K* against *h*/*d* ratio from experimental results for filling and discharge of the model silo. For calculation of *K*, values of lateral pressure measured at an *h*/*d* of 0.1 were used, while mean floor pressure was obtained as the ratio of vertical floor load to silo floor area. During filling of the silo, *K* increased with some fluctuations and slow local decreases until it stabilized at a value of approximately 0.43 at an *h*/*d* ratio of approximately 1.4. During the detention period of 30 min, *K* decreased slightly to a value of 0.41. After initiation of discharge, *K* immediately increased to a value of 0.63 and slowly increased during continuous unloading to a value of 0.73. After the grain level decreased down to an *h*/*d* of approximately 0.7, the pressure ratio decreased rapidly to 0. The value of *K* of 0.41 was lower than 0.5 that is recommended for wheat by EP 433 (1997) or 0.54 recommended by Eurocode 1. The dynamic to static wall pressure ratio measured was 0.73/0.41 = 1.78 that was also higher than the over pressure factor of 1.4 recommended by EP 433 or 1.15 recommended by Eurocode 1. This discrepancy in results may be attributed to the relatively low level of vertical pressure under which tests in the model silo were performed. For the case of a 1.83 m diameter silo and *h*/*d* of 2 the static floor pressure was 14 kPa. Thompson *et al*. (1996) reported that typical storage conditions in a full size corrugated bin with a 15 m grain height, a vertical floor pressure of approximately 100 kPa was observed. The floor pressure in the 1.83 in diameter model was more than seven times lower than in field conditions. Mechanical behaviour of particulate materials strongly depends on the degree of consolidation and this was considerably lower in the model silo.

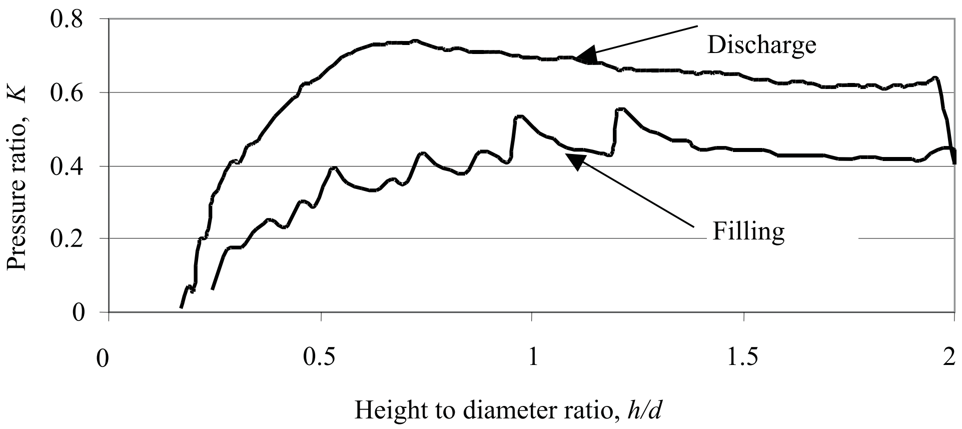

Fig. 7. Pressure ratio, *K,* produced during filling and discharge of the model silo.

CONCLUSIONS

1. The earth pressure cell (EPC) was found to be an efficient transducer for measuring pressures exerted by grain on the wall and floor of a model silo. Readouts from the EPC were reliable in calibration tests with shear stress present and when tested in a model silo. A limitation to field application of EPC as a grain pressure transducer may be its susceptibility to variation in reading due to ambient temperature and atmospheric pressure.

2. Radial distribution of static vertical floor pressure was found to vary contrary to Janssen's assumption. In the case of centric spout filling higher values of vertical pressure were found near the centerline.

3. Ramps in lateral pressure were observed in response to initiation of discharge for all locations of the pressure cell. Dynamic to static load ratios (*dsr*) at *h/d* locations of 0.1, 0.6, 1 and 1.25 were found of 1.15, 1.5, 2.3 and 1.7, respectively. This finding is in disagreement with the claim that the highest increase in lateral pressure occurred at the transition from mass to funnel flow, as well as with an opinion that dynamic increase in lateral pressure for silos with an *h/d* equal to 2 or lower would be negligible. Weaker dynamic increase in p_h for the lowest location of the pressure cell at *h/d* of 0.1 may be explained by muffling action of the stagnant bulk of grain covering the pressure cell.

4. The variation in the lateral-to-vertical pressure ratio, *K*, was monitored during filling and discharge of the model silo. *K* increased with small fluctuations during filling and stabilized at a value of 0.43 after reaching a grain *h/d* ratio of 1.3. At the onset of discharge, *K* immediately increased up to approximately 0.7, remained stable during unloading down to an *h/d* of approximately 0.65 and then decreased rapidly.

REFERENCES

AS 3774, **1996.** Australian Standard, Loads on bulk solids containers. Standards Association of Australia, 1 The Crescent, Homebush, NSW 2140.

Drescher A., 1991 Analytical Methods in Bin-Load Analysis. Elsevier, Amsterdam-Oxford-New York-Tokyo.

EP433, **2001**. Loads Exerted by Free-Flowing Grain on Bins. ASAE. 2950 Niles Road, Saint Joseph, MI 49085.

Eurocode 1, **2003.** Actions on structures. Part 4: Actions on silos and tanks. European Committee for Standardization, Brussels.

Ketchum M., 1919. The Design of Walls, Bins and Grain Elevators. McGraw-Hill Book Comp. Inc., New York.

Molenda M., Thompson S.A., and Ross I.J., 2000. Friction of wheat on corrugated and smooth galvanized stell surfaces. J. Agric. Eng. Res., 77(2), 209-219.

Thompson S. A., Galili N., and Williams R.A.. 1997. Lateral and vertical pressures in two different full-scale grain bins during loading. Food Sci. Technol. Int., 3(5), October, 371-379.