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Pressure of agricultural bulk solids under eccentric discharging of cylindrical concrete silo bin*

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A b s t r a c t. The paper presents selected results and discussion of model investigations of horizontal silo pressure distribution during eccentric discharging for an outlet located in the lower part of a silo wall conducted at the Białystok University of Technology using a ferrocement circular silo model. Tests were conducted using white mustard seeds were used as the agricultural bulk solid. Pressure were measured using a system of embedded pressure cells. The model studies revealed dynamic characteristics of eccentric pressure changes. Results were compared with the theoretical bulk solid pressures calculated on the basis of Eurocode 1 provisions. The results of these studies confirmed that a non-uniform distribution of discharge pressures occured in the silo wall in the very early stages of the eccentric discharging process. Continuation of eccentric discharge leads to a more uniform pressure distribution.

K e y w o r d s: agricultural bulk solids, pressure, eccentric discharging, silo

INTRODUCTION

Eccentric discharge occurs in silos when the silo bottom outlet is located at any eccentricity from the centre of gravity of silo bin cross-section. For such a case the bulk solid flow channel during discharge forms eccentrically to the vertical axis of the silo bin and moves to the internal surface of the silo wall. In many cases this phenomena is thought to be the reason for a significant redistribution of horizontal bulk solid pressure at the silo wall height and along the silo wall perimeter. In some cases this type discharge condition can create pressure distributions which cause serious damage to the silo structure, as firstly reported Jenike (1967).

Some of the first detailed experimental studies on the eccentric silo unloading were performed by Pieper and Wagner (1968) in Germany using silo model. Since then, many other researchers have tried to precisely measure the bulk solid pressure on silo walls during eccentric discharging *eg* Reimbert and Reimbert (1980), Wood (1983), Hamdy (1991), Molenda *et al*. (2000) and many others. Investigations have also been performed 'in-situ' on full-scale eccentrically unloaded silos storing cement *eg* Hamdy (1991) and grain (Łapko and Wójcik, 2004). However, the results of these studies have shown large amounts of variation depending not only on eccentricity but many others factors, as well.

Eccentric unloading in silos is an important design factor which must be taken into account. Eccentric unloading causes the redistribution of vertical and horizontal forces in the silo and produces bending moments in the cylindrical silo wall cross-sections, which should be taken into account by numerical analysis (Guaita *et al*., 2003; Łapko and Prusiel, 2004; Łapko and Wójcik, 2004).

Based on experimental model studies as well as investigation on real silo structures some idealized models for evaluation of eccentric pressure distribution have been presented in the last two decades (Martens, 1988; Safarian, 2001). Some of these propositions have been introduced into a few national Silo Codes (DIN 1055, 1987; AS 3774, 1996; PN-B-03262, 2002) and finally introduced into Eurocode 1 (EN 1991-4, 2006). In the European Silo Standard a non-uniform load distribution is specified on the silo wall perimeter for silos which discharge eccentrically. The load distribution is a function of reliability class of structure (called here Action Assessment Class) depending on the silo bin slenderness, its capacity and the eccentricity of the discharge outlet.

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According to Eurocode 1 (2006) the idealized model of eccentric pressure is governed by the bulk and the solid flow channel eccentricity e_c. The standard distribution is shown in Fig.1 consisting of the high channel edge pressure *Phae* in the zone adjacent to the flow channel, the decreased pressure *Phce* in the flowing zone and the static pressure *Phse* far from the flowing channel. The standard design procedure is intended to identify conditions that are the most demanding for each silo geometry and structural arrangement. The flow channel is assumed to be a circular arch with the location and radius of the flow channel based on a minimization of the total frictional drag at the channel perimeter of the solid in the channel.

Experimental studies were performed using agriculture bulk solids at Białystok University of Technology to assess the Eurocode provisions concerning the minimum and maximum pressures in eccentrically unloaded silos. These studies are an extension of previous studies done by Łapko and Konopacki (2001).

Experimental studies were conducted in both cylindrical silo models as well as in real grain silos equipped with eccentric outlets. The results are presented and discussed herein showing the dynamic characteristics and time dependent redistribution of bulk solid pressure due to eccentric discharging process. The experimentally measured pressures were compared with appropriate theoretical values based on Eurocode 1 (2006) procedures for silo structures classified into the Action Assessment Class No. 3.

EXPERIMENTAL MODELLING OF LATERAL ECCENTRIC PRESSURE

Model investigation on lateral silo pressure during eccentric discharging were conducted at the Faculty of Civil and Environmetal Engineering of Białystok University of Technology on a large ferrocement cylindrical silo bin model (total height H= 2500 mm, diameter D = 800 mm and wall thickness t =14 mm), arranged on a separate stand (Łapko and Konopacki, 2006). Silo wall pressure were measured using a system of embedded pressure cells. The silo was equipped with an eccentric silo discharge outlet located in the side wall of the model silo (e_0 equal to the radius of the cross-section of the silo model, e_0 = 0.5 D). Tests were conducted using white mustard seeds whose properties are given in Table 1.

Horizontal pressures caused by the particulate solid were measured during both filling and eccentric discharge of the silo bin model using originally designed pressure disc cells suspended inside the bulk solids in the bin model. The cells were positioned at a depth of 20 cm above the level of the discharge outlet. The locations of the cells in the silo bin cross-section are shown in Fig. 2. The pressures cells were located to measure the theoretical maximum and minimum horizontal pressures predicted by Eurocode 1 (2006). Pressure cell A was located within the flow channel (minimum pressure) while pressure cells B – were located near the flow channel edges (in the zone of maximum pressure).

A detailed view of the lower part of ferrocement silo bin model and of the embedded pressure cell are shown in Fig.3. The wireless computerized measurement system was previously used to measure pressure values in bins, described in the paper by Łapko and Kołłątaj (2003).

Filling of the model bin required approximately 40 min while discharging of the bin required approximately 35 min. Pressure readings were measured from each load cells during both loading and unloading of the model bin. Pressure readings were converted into horizontal pressures by a computer. Selected diagrams of horizontal pressure registrations against time during filling and discharging are presented in Fig. 4a (for the first filling-discharging cycle) and in Fig. 4b (for the second similar cycle).

T a b l e 1. Properties of the bulk solids

Property	Mustard seeds
Effective friction angle (°)	27
Bulk density (kN m^{-3})	7.30
Colour	white
Particle diameter (mm)	1÷2

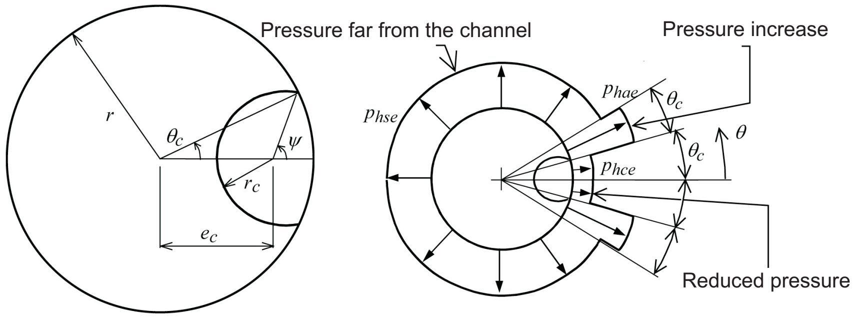

Fig. 1. Flow channel during eccentric discharging of silo bin and pressure distribution on silo bin perimeter according to Eurocode 1.

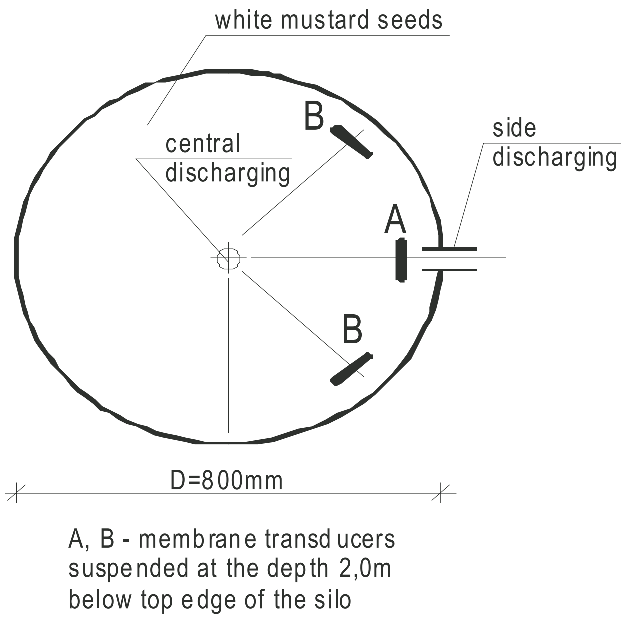

Fig. 2. Cross-section of silo bin model showing location of cells and position of side outlet.

Fig. 3. View of silo model with side outlet and embedded cell details: 1 – membrane, 2 – base, 3 – wire.

Horizontal pressures during the initial stages of eccentric discharge (1 min after the start of discharge) are shown in Fig. 5a for pressure cell A (located in the flow channel) and for pressure cells B (two cells which were located outside of the flow channel). The pressures within the flow channel were significantly smaller than those on the edge of the flow channel (pressure A/pressure B = 0.17). In Fig. 5b are shown the pressures measured (20 min after the start of discharge).The pressures measured within the flow channel were still smaller than those measured outside of the flow channel however the pressure differences between the two locations are not quite as significant (pressure A/ pressure B = 0.33). Pressures values predicted using the

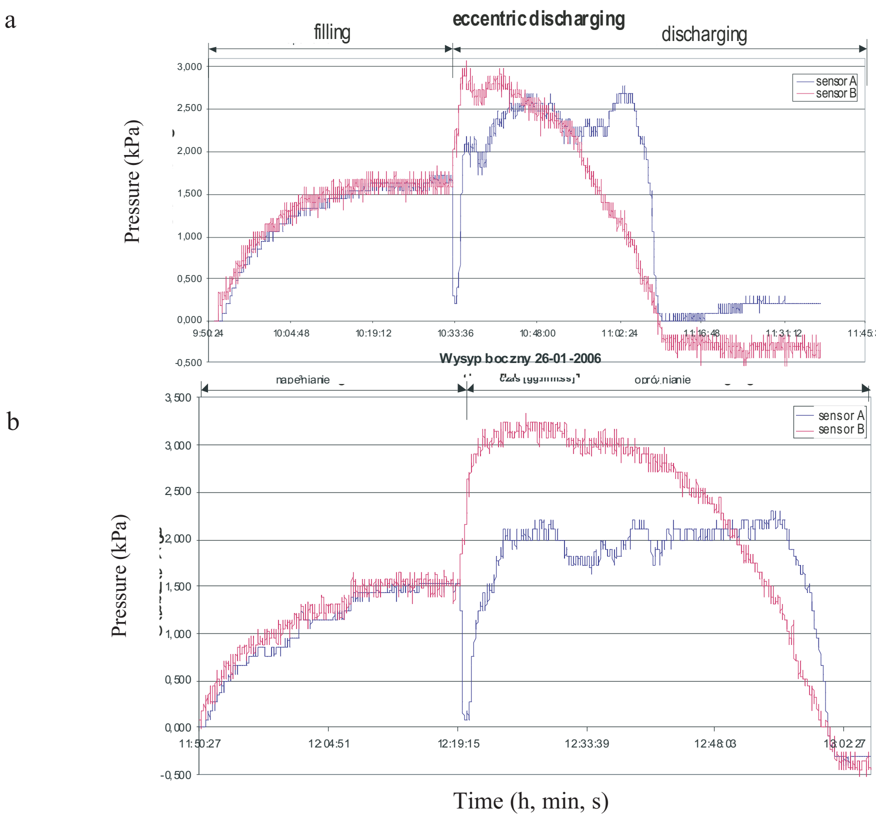

Fig. 4. Changes of pressure during filling and discharging phases of the silo model filled with white mustard seeds: a – for cycle 1, b – for cycle 2.

design procedures described in Euocode 1 (Silo Action Assessment Class 3) are shown in both Figs 5a and 5b. The pressure distribution predicted by Eurocode 1 matched closely the shape of the pressures observed immediately after discharge started (Fig. 5a). Euorcode 1 did not predict as well the pressure distribution observed during the advanced stages of eccentric discharge (Fig. 5b). For this condition a more uniform distribution of pressure was observed.

Bulk solid pressure diagrams shown in Fig. 4a,b during eccentric discharging revealed visible dynamic characteristics. Dynamic effects on silo wall structure can be described for design purposes by dynamic coefficients. In a given time of eccentric pressure the static horizontal loads on the silo bin wall may be converted into dynamic values using a dynamic coefficient χ, expressed as the ratio:

$$\chi = \frac{P_{he}(t)}{P_{hf\ \max}}, \qquad (1)$$

where: $P_{he}(t)$ – horizontal dynamic values of pressure measured at a given time t during eccentric discharging of the silo bin model, $P_{hf\ \max}$ – horizontal static pressure measured after the end of the filling process.

The time dependent changes of dynamic coefficients calculated as mean values from two test cycles during eccentric discharging through the side outlet are presented in Fig. 6.

In the initial phase of eccentric discharging, the value of coefficient computed on the basis of cell A measurements (in the flow channel) was $\chi = 0.11$, whereas the same coefficient computed from the registration using cells B (outside the flow channel) were $\chi = 1.78$ some 16 times larger.

The results of model tests indicating the dynamic bulk solids pressure characteristic revealed the possibility of fatigue effects in silo wall structure which may strong influence the level of silo structure reliability.

More precise analysis of such dynamic effects and structural influences needs to be verified on a real silo structure during operation.

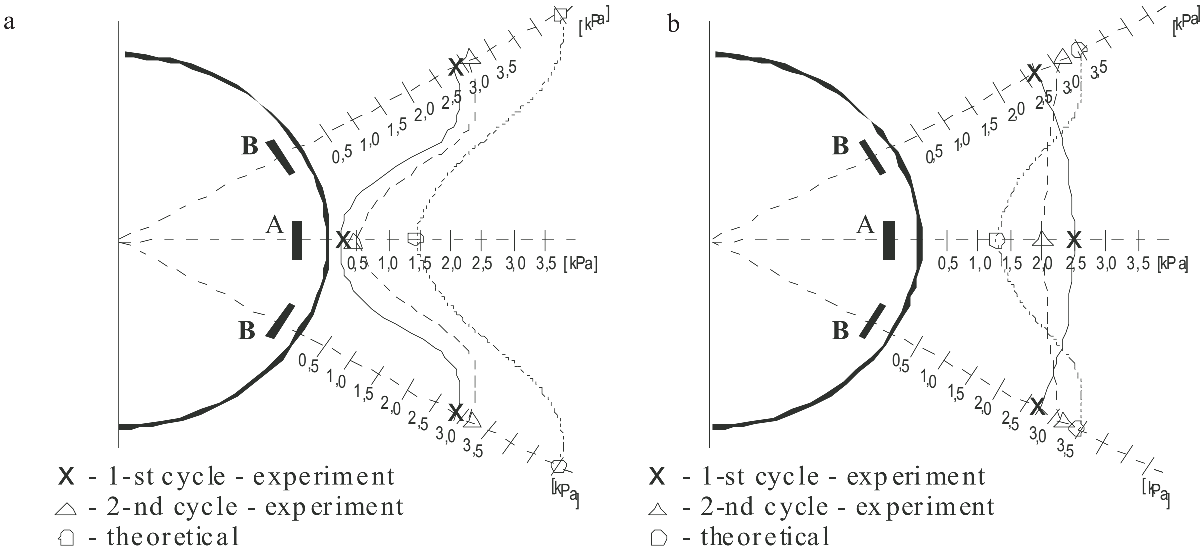

Fig. 5. Comparison of experimental and theoretical lateral pressure values predicted for eccentric discharging of the silo model: a – 1 min after opening of outlet , b – 20 min after.

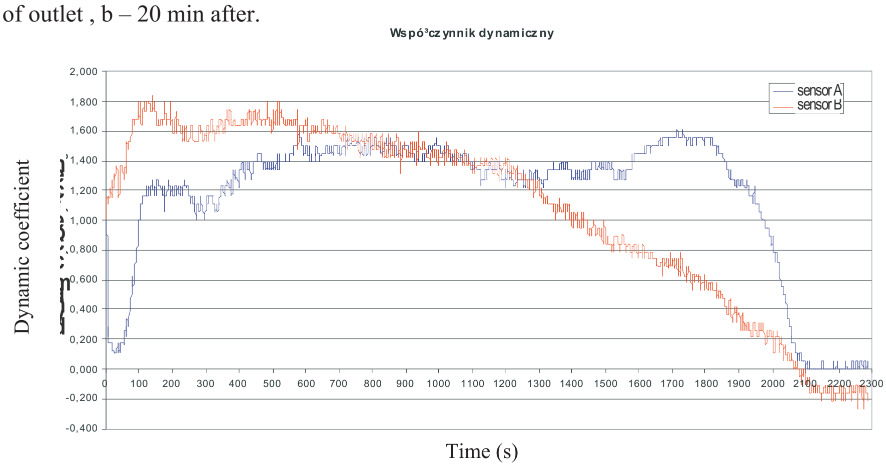

Fig. 6. Changes of dynamic pressure coefficient during discharging process for silo model filled with white mustard seeds.

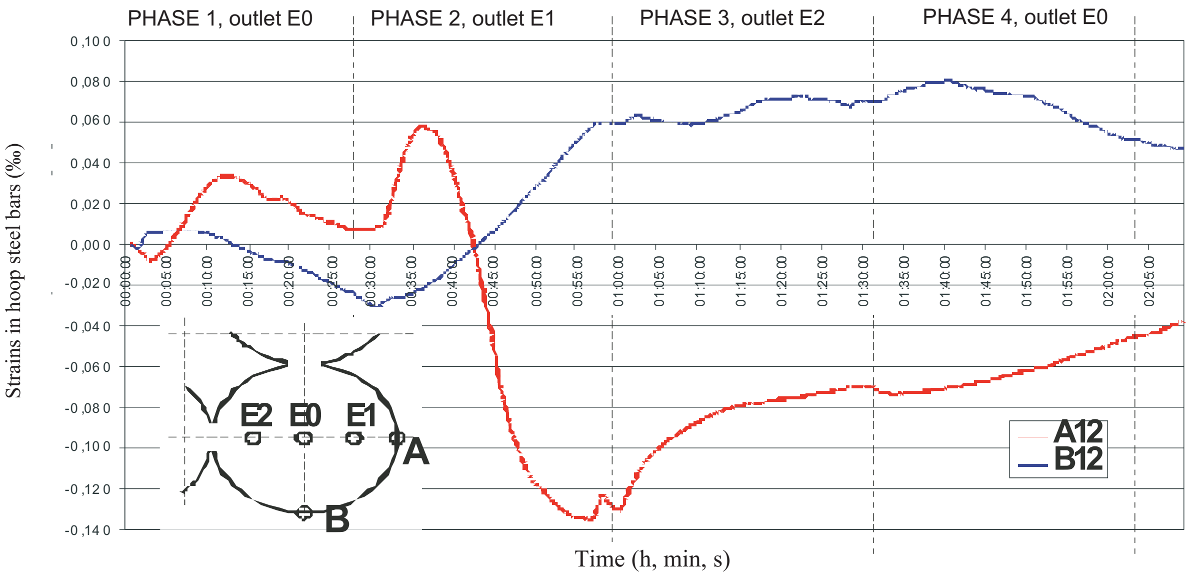

Fig. 7. Strain changes in the real grain silo wall structure due to different modes of discharging.

DYNAMIC EFFECTS OF ECCENTRIC PRESSURE IN REAL SILO

Tests were conducted in a full-scale grain elevator in Poland to determine the dynamic pressure effects during eccentric unloading. The reinforced concrete silo was 8.00 m in diameter and 29.5 m tall and was part of a grouped silo. The silo was equipped with one centric and two eccentric outlets located in the center region of the silo as shown in Fig. 7. Strains were measured using electric resistance strain gages attached to the circumferential reinforcement in the silo wall. The strain gages were located 12.0 m above the floor of the silo on lines A and B as shown in Fig. 7.

The measurements of strains in wall structure were conducted in the initial phase of discharging, lasting for 120 min, immediately after the end of the process of silo filling with grain. In the tests a wireless computer system was used.

Strains were measured using a wireless computer system. Strains were monitored during four different phases of discharge with each phase lasting approximately 30 min. Discharging of the silo started immediately after filling of the silo ended. The four different phases of discharge were:
1. central outlet E0,
2. eccentric outlet E1 (close to the location of gauges),
3. eccentric outlet E2 (opposite to the location of gauges),
4. repeated discharging by central outlet E0.

Significant redistribution of horizontal strains within the reinforcing steel were observed during phase E1 (discharging closer to line A) in which eccentric unloading of the bin occurred. During this phase a non-uniform horizontal pressure distribution was observed around the wall perimeter with similar dynamic overpressures observed in both the real and model bin. These results validated the pressure distribution model given in Eurocode 1 (2006).

CONCLUSIONS

1. Experimental studies concerning eccentric silo bin pressures conducted in cylindrical silo bin models confirmed that a non-uniform horizontal pressure distribution occurs around the wall perimeter, similar to that proposed for design in Eurocode 1. However, this non-uniform pressure distribution only occurred during the initial phases of the discharging process. In the advanced stage of eccentric discharge the pressure distribution had a different, more symmetric shape, with strong increased pressures in the flow channel.

2. Dynamic overpressures were measured during eccentric discharge with the magnitude of these dynamic overpressures varying depending on the location of the pressure measurement and the period of discharging. The maximum dynamic overpressure value of 1.78 was measured during the initial stages of discharge and was located outside of the flow channel, whereas in the zone of flow channel its value was equal to 0.11 only.

3. In full scale tests conducted in real grain silos, redistribution of strains and stresses (the cause of bending moments in the silo wall) were observed in the silo wall closet to the eccentric flow channel during the initial stages of eccentric discharging. During discharge stains were measured in the silo wall that appeared to produce dynamic characteristics within the structure which could affect the silo structure reliability.

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