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BRIDGES AND TUNNELS: THEORY, RESEARCH, PRACTICE

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ANALYSIS OF THE PREREQUISITES FOR THE EXPERIMENTAL DETERMINATION OF THE PRESSURE OF BULK MATERIAL ON THE BOTTOM OF A SILO CONTAINER

Purpose. The main purpose of the publication is to describe the experience of preparing and planning an experiment to determine the pressure of bulk material on the bottom of a silo. It includes an analysis of global experience in conducting similar experiments, a review of potential problems and difficulties during the experiment's preparation, and the specifics of the material and technical base for conducting similar experiments in Ukraine. **Methodology.** To achieve the main objective, the global experience in conducting similar experiments was reviewed in detail. The advantages and disadvantages of existing methods for experimentally determining the pressure of bulk material on the bottom of a silo were examined. The availability of necessary technical means in Ukraine was analyzed. **Findings.** It was found that the main problems in preparing similar experiments are the inaccessibility of necessary equipment and the specific technological operations of most non-port elevators in Ukraine. An analysis of risks that may hinder the quality of the experiment was also conducted, and a methodology for preparing for the experiment was developed. **Originality.** This publication describes the process of planning and preparing for the experiment, potential methods for conducting the experiment, assessment of possible difficulties and risks during the experiment, and ways to mitigate these risks during preparation. For the first time, a method of using tensometric sensors to measure pressure inside a silo is proposed, including the selection and installation of these sensors. **Practical value.** The article provides a step-by-step guide for preparing for the experiment and describes possible methods for investigating the pressure of bulk material on the bottom of a silo, necessary tools, and calculations. The materials in the article will facilitate the process of organizing and conducting future experiments on measuring the pressure of bulk material on the bottom of a silo.

Keywords: grain silo; elevator; bulk material pressure; grain; pressure sensor; sweep auger; silo floor

Introduction

The largest export category of Ukraine over the past decade has been agricultural products. Ukraine is one of the world leaders in the grain market. To transport grain across the territory of Ukraine and abroad, a large number of grain storage facilities have been constructed, performing the functions of grain accumulation and its shipment by various types of transport, mainly rail, river, and sea. Efficient logistics in delivering grain to the end consumer are extremely important for maintaining our country's position in the global agricultural market. Proper and careful storage of grain at transshipment terminals is an essential factor in the logistics of this product.

The most modern method of storing and accumulating grain at an grain storage facility is steel silos. They make it possible to fully mechanize the processes of loading and unloading grain, provide its efficient storage, and monitor its condition during storage. At the same time, Ukraine is experiencing a significant shortage of grain storage capacity; therefore, in the near future, such facilities will be actively constructed and reconstructed (Лебідь, 2012).

At the same time, some grain storage facilities face problems related to the distress of these constructions (Bannikov, 2011). Part of the accidents may be associated with the imperfection of the method for calculating the pressure inside the silo. The present study aims to investigate conditions related to excessive settlement of the silo floor.

Those deformations do not allow for mechanized cleaning of the silo and, as a result, this work has to be carried out manually.

Deformations of this type occur in foundations with internal backfill due to its excessive compaction and settlement. Similar deformations were recorded during the inspection of six silos on a foundation with internal backfill at Kononivskyi Elevator LLC in the village of Pomynnyk, Mankivka district, Cherkasy region (Винников, Харченко, Кічасов, & Марченко, 2024). An example of such a foundation design is shown in Fig. 1.

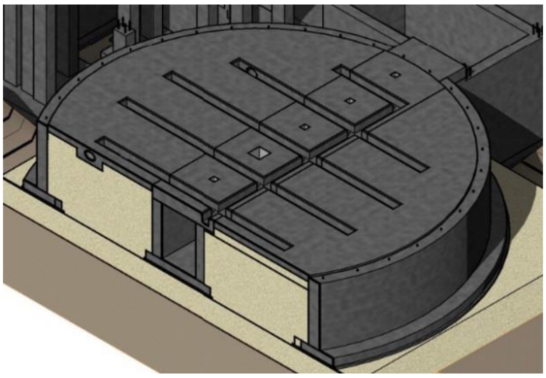

Fig. 1. Example of a foundation with internal backfill

The old approach, which minimized "wet" processes such as monolithic concreting, is no longer relevant due to changes in construction methods, as prefabricated elements are now rarely used in the construction of silo foundations (Alkhdour, Tiutkin, Bannikov & Heletiuk, 2023). Despite the fact that soil properties in a saturated state are considered in foundation calculations, excessive deformations are still observed. One of the reasons for such damage may be the imperfection of the commonly accepted theory for calculating pressure from bulk materials, described over 100 years ago in the article by the German engineer Janssen (Jansen, 1895). According to Janssen's equation, the pressure on the silo floor is uniform, equal across the entire floor area.

Janssen's equation has served as the basis for most international standards for silo design (EN 1991-4, 2006; ANSI/ASAE EP433, 2015; AS 3774, 1990) as well as the partly cancelled national standard (ДБН В.2.2-8-98, 2015). In the EU, US, and Ukrainian regulations (EN 1991-4, 2006; ANSI/ASAE EP433, 2015; ДБН В.2.2-8-98, 2015), the pressure on the silo floor is assumed to be uniform across the entire container area, unlike the Australian standard (AS 3774, 1990), where an additional empirical coefficient is introduced into the floor pressure calculation, depending on the ratio of the ordinate (the distance from the center of the silo to the point where the pressure is calculated) to the silo diameter (AS 3774, 1990, 6.2.3.2).

The vast majorities of silo manufacturers also use Janssen's equation in their calculations and assume the product pressure on the silo floor to be uniform.

There are a number of experimental studies that have found that the actual pressure on the silo floor is not uniform (Fank, do Nascimento, Cardoso, et al., 2018; Horabik & Molenda, 2017; Schwab, Ross, White, & Coliver, 1994). These studies indicate that in certain areas of the silo, the actual floor pressure can exceed the theoretical value calculated using Janssen's equation by more than 50 %. However, these pressure distribution studies are, unfortunately, not applied in practice and are not reflected in current calculation methodology, which may be one of the reasons for the occurrence of the deformations described above. One way to avoid such deformations may be the use of a pile foundation, as the uneven loads on the silo floor are distributed between the piles and the raft (Тімченко, Крішко, & Савенко, 2024). However, a pile foundation is significantly more expensive to construct compared to a foundation with internal backfill. Therefore, the foundation with internal backfill remains popular due to its economic feasibility. Using more accurate floor pressure values in calculations can provide the designer with a more precise picture of the stress-strain state of the foundation.

Purpose

Considering all of the above, in order to prevent excessive deformations of silo's floors, it is necessary to further develop the theory of pressure distribution on the floor of the silo. For a more detailed study of the distribution of vertical pressure on the floor, a larger number of experiments measuring floor pressure must be conducted. The influence of different types of products and various ratios of silo diameter to height (D/H) has to be taken into account. Based on the results of a significant number of experiments, the theory for calculating floor pressure in silos should be refined and im-

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plemented in the practice of designing grain storage facilities. This article presents the experience of preparing such an experiment.

Methodology

Experiments to determine the pressure on the silo floor were conducted using scaled models (Horabik, & Molenda, 2017) as well as full-scale silos (Schwab, Ross, White, & Coliver, 1994; Fank, do Nascimento, Cardoso, et al., 2018). Full-scale constructions allow for more realistic data, taking into account the interaction between the product and the silo structure. This article examines both the authors' own experience and that of previous experiments, presenting the preparation stages and highlighting the specific features of their implementation.

The following stages can be distinguished in the process of preparation for the experiment:

1, Selection of a site for the experiment

One of the greatest challenges in organizing this experiment is the time constraints, since the technological process at most grain storage facilities involves a rather long loading-unloading cycle of the silo, which can last up to a calendar year. Therefore, if the experimental site is chosen poorly, only one experiment per year can be conducted using a single set of equipment.

Grain storage facilities can be classified into three types based on their purpose:

а) farm facilities;

б) industrial facilities;

в) port and rail terminals.

Farm facilities in Ukraine usually have two loading periods during harvesting (May–June and August–November). The storage duration of grain in such facilities can range from six to twelve months.

Industrial facilities usually have a single harvesting period. The loading and unloading cycle of silos at such facilities ranges from three months to one year, depending on the number of silos and the ratio of storage capacity to processing volume.

Port and rail terminals specialize in providing services for the accumulation and transshipment of grain between different types of transport. Facilities of this profile receive products throughout the year. Such terminals can perform from two to twenty cycles per year, making rail and port terminals the most attractive sites for conducting experiments.

It should also be noted that filling a single silo can usually take from 5 days to several weeks. It is desirable to monitor the pressure throughout the entire loading period in order to obtain accurate data on the grain pressure distribution at different diameter-to-height ratios (D/H). Therefore, for proper observation, daily measurements must be recorded over several days or weeks. For this reason, preference should be given to facilities located as close as possible to the researcher's location, to simplify the organization of the scientific study.

Therefore, when selecting a facility for conducting the experiment, it is necessary to:

1. Give preference to port or rail terminals.
2. Choose facilities located as close as possible to the researchers.
3. Clarify the expected silo loading rate.
4. Determine whether elevator staff can be involved in the experiment and provide them with instructions on the procedure for conducting the measurements.

2. Choosing a method for measuring pressure

The measurement of the actual pressure on the silo floor was primarily carried out using two methods. The first method involves the installation of a second floor level, divided by expansion joints into several concentric rings, each mounted on sensors. This allows for the measurement of the total pressure on specific sections of the floor (Schwab, Ross, White & Coliver, 1994). The experimental setup is shown in Fig. 2.

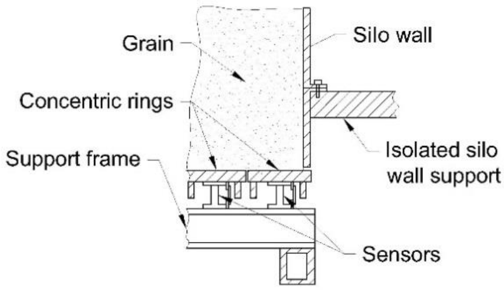

Fig. 2. The experimental setup for measuring floor pressure using a second-floor level arrangement

The second method is based on the installation of individual sensors to measure the local pressure on specific areas of the silo floor (Fank, do Nascimento, Cardoso, et al., 2018). Figure 3 shows a photo of the sensor placement inside the silo.

The first method requires a large amount of work to install a second floor level, which significantly increases the time for assembly and disassembly of the equipment, as well as the overall cost of the experiment. In addition, this method requires adapting the equipment whenever the silo diameter changes.

Fig. 3. Placement of sensors for measuring pressure on the silo floor

The second method offers quick and easy installation, requires much less expensive equipment, and allows sensors to be positioned freely, making it possible to measure pressure at any point on the silo floor. For these reasons, this method was selected for the experiment.

3. Choosing equipment for pressure measurement

The most suitable type of sensors for measuring pressure from bulk materials are hydraulic pressure sensors, commonly known as earth pressure cells. These sensors were originally developed to measure pressure within soil or the pressure exerted by soil on structures. They can also be used to measure the pressure of any bulk material (Instruction Manual, Model 3500 Series Earth Pressure Cells, GEOKON, 1984).

Unfortunately, it was not possible to find a supplier of hydraulic sensors in Ukraine. Therefore, strain-gauge sensors were chosen for the experiment.

Strain-gauge sensors available on the Ukrainian market are most often designed for use in weighing equipment and are primarily intended to measure point loads from beams, columns, or platforms.

Three types of sensors were considered for measuring pressure:

1. Strain-gauge bending sensor with a weighing range of 50 kg to 2 t, equipped with a damping support unit and a pressure collection surface diameter of 75 mm (Fig. 4).

2, Strain-gauge diaphragm sensor, with a weighing range of 50 kg to 2 ton, was featuring a point load application (Fig. 5).

3. Strain-gauge platform sensor, with a weighing capacity of either 2 t or 5 t, and a load collection plate diameter of 122 mm (Fig. 6).

Fig. 4. Strain-gauge bending sensor

The strain-gauge bending sensor required isolation of the space beneath the sensor from the grain to prevent the platform from resting directly on it. Therefore, it was decided to discard this option.

The strain-gauge diaphragm sensor required an enlarged load collection area, as it was designed to measure point loads and had a load plate with a diameter of only 10 mm. Therefore, the diaphragm sensor option was also discarded.

Fig. 5. Strain-gauge diaphragm sensor featuring a point load application

Fig. 6. Strain-gauge platform sensor

For the experiment, a platform-type strain-gauge sensor was selected. This type of sensor is already isolated from any grain getting beneath the platform and has a load collection area with a diameter of 122 mm. Among the drawbacks of these sensors are their limited availability in Ukraine, resulting in a four-month lead time. Another disadvantage was high maximum capacity (2 t and 5 t), which can lead to measurement errors at low pressure.

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It should be noted that, to record data from the sensors, they must also be equipped with a dedicated data acquisition terminal.

Findings

After completing the organizational stages, the practical preparation for the experiment began, taking into account the design of the chosen silo. This preparation consisted of the following stages:

1. Calculation of the expected pressure

One of the key factors in selecting a sensor is the expected pressure. On one hand, the product pressure should not exceed the sensor's maximum allowable load; on the other hand, the expected pressure should be as close as possible to the sensor's optimal working range to ensure the most accurate measurements.

The maximum expected pressure can be determined according to the European standard (EN 1991-4, 2006) under hydrostatic conditions. None of the experiments mentioned above recorded values exceeding the hydrostatic pressure.

The pressure under frictionless conditions (hydrostatic conditions) can be calculated using the following formula:

$$P_{\max} = gH, \tag{1}$$

$P_{\max}$ – pressure on the silo floor, t/m^2; g – bulk density of the product stored in the silo, t/m^3; H – maximum silo filling height, m.

When conducting an experiment in a silo with a diameter greater than 12 m, it is also necessary to account for one-third of the cone height. In this case, the height can be calculated using the following formula (2):

$$H = h + \frac{D}{6}\mathrm{tg}\alpha, \tag{2}$$

h – silo wall height, m; α – angle of repose; D – silo diameter, m.

The heaviest of the products that can be stored in grain silos is wheat, with the following characteristics: g = 0.8 t/m^3; α = 25°.

Thus, the final formula for the maximum expected pressure will be:

$$P_{\max} = g\left(h + \frac{D\mathrm{tg}\alpha}{6}\right). \tag{3}$$

For the experiment, the Agro-KMR LLC grain storage facility in Bohuslav, Pavlohrad District, Dnipropetrovsk Region, was selected. This grain elevator is equipped with silos manufactured by Frame (Italy), model FP 21/23, with the following dimensions: wall height, h = 20.29 m; wall diameter D = 19.2 m.

The maximum expected pressure was calculated for wheat:

$$P_{\max} = 0.8\left(20.29 + \frac{19.2\mathrm{tg}25^\circ}{6}\right) = 17.43\ \text{t/m}^2.$$

The sensor purchased for the experiment has a diameter of 122 mm. The load collection area for this sensor is:

$$A = \frac{0.122^2 \cdot 3.14}{4} = 0.0117\ \text{m}^2.$$

Thus, the maximum expected force will be:

$$F_{\max} = 0.0117 \cdot 17.43 = 0.2039\ \text{tf}.$$

Thus, of the two available sensor models (2 t and 5 t), the 2 t model was chosen, as the expected load is closer to the sensor's optimal working range.

However, the maximum expected pressure is only about 10 % of the sensors' maximum capacity. Therefore, it was decided to increase the load collection area in order to raise the expected maximum force to approximately 70 % of the sensors' allowable limit.

The required area for expansion can be calculated using the following formula:

$$A_p = \frac{0{,}5F_{\max}}{P_{\max}}, \tag{4}$$

A_p – expanded load collection area, m^2; $F_{\max}$ – maximum load for the selected sensor, t. In our case, $F_{\max}$ = 2 t.

It should be noted that this value depends on the product to be stored in the silo and must be calculated for each specific experiment. In our case, the silo is expected to be filled with wheat, so the previously determined value can be used. $P_{\max}$ = 17.43 t/m^2.

$$A_p = \frac{0.5 \cdot 2}{17.43} = 0.0574\ \text{m}^2.$$

The radius of the plate for expanding the load collection area should be R=0.135 m.

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To expand the load collection area, it was decided to fabricate a steel disc. To isolate the space beneath the expansion plate, a section of welded pipe was used, with a diameter 2 mm larger than that of the expansion plate. A preliminary schematic of the sensor installation with the expansion plate is shown in Fig. 7.

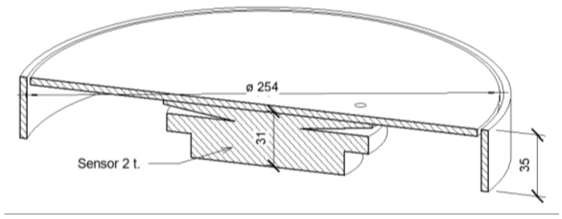

Fig. 7. Sensor setup with the expansion plate

In addition, the expected sensor readings for each fill level were calculated in advance. For the experiment, the expected values can be determined using Jansen's equation, as well as according to the Australian standard. (AS 3774, 1990).

The experiment is planned using wheat with the following characteristics: bulk density – 0.705 t/m³; bulk density with 2 % compaction – 0.719 t/m³; silo wall friction coefficient – 0.4; internal friction angle – 24°; silo diameter – 19.1 m.

The calculated expected values are presented in the table 1.

The calculations were performed in Mathcad using the input data provided above.

Table 1

Expected sensor readings

Fill height *Z*, m	Expected sensor readings, kg					
	According to Jansen	For AS 3774 (1990)				
	All sensors	Sensor 1 (0.117 *R*)	Sensor 2 (0.341 *R*)	Sensor 3 (0.598 *R*)	Sensor 4 (0.813 *R*)	Sensor 5 (0.948 *R*)
1	84	105	101	90	78	68
2	117	146	140	126	108	94
3	149	185	178	160	137	119
4	180	223	214	192	165	144
5	209	260	249	224	192	167
6	238	295	283	255	219	190
7	265	330	316	284	244	212
8	292	363	348	313	268	234
9	317	395	378	340	292	254
10	342	425	408	367	315	274
11	366	455	436	392	337	293
12	389	484	464	417	358	312
13	411	511	490	441	378	329
14	433	538	516	464	398	347
15	454	564	541	486	417	363
16	474	589	565	507	436	379
17	493	613	588	528	453	395
18	507	630	604	543	466	406
19	530	659	631	568	487	424
20	547	680	652	586	503	438

2. Installation of the sensor inside the silo

Factors influencing the choice of the sensor installation location include both design and structural considerations.

Design considerations refer to the preferred sensor installation locations where changes in pressure, local decreases, or local increases are expected. Based on the experience of previous experiments, it is recommended to have five pressure measurement points (Schwab, Ross, White, & Coliver, 1994; Fank, do Nascimento, Cardoso, et al., 2018; Horabik, & Molenda, 2017). Analysis of these three experiments shows that different pressure values can be observed at all five points. By examining the experimental results, conclusions can be drawn regarding the optimal sensor installation locations.

The highest pressure is expected at the center of the silo. Moving away from the center, the pressure gradually decreases until approximately 0.69*R* … 0.85*R*, where a local increase is observed. To capture this local pressure rise in the experimental results, one or two sensors should be placed just before the pressure increase zone. Therefore, the recommended range is 0.4*R* … 0.7*R*.

The next sensor should be installed in the area where a local pressure increase is expected, at approximately 0.82*R* … 0.84*R*.

The final zone, where previous experiments showed a sharp drop in pressure, is around 0.95*R*.The next important factor in selecting sensor locations is structural. The sensors must be removable before the sweep auger is activated.

The first area to be cleared of grain during silo unloading is the zone along the unloading axis, where the initial position of the loading auger is located. To clear this area from the grain, discharge outlets are provided in the silo floor (Fig. 8).

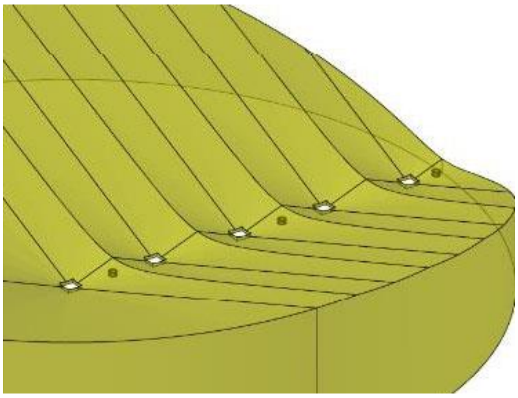

Fig. 8. Sensor installation layout between the discharge outlets

It is recommended to place the sensors along the silo's unloading axis. This allows the sensors to be removed before the auger is activated. If sensors are positioned outside the unloading axis, they may be at risk of being damaged when the auger starts operating.

It should also be noted that significant forces are developed during grain unloading. If a sensor is placed too close to the discharge hopper, it could be swept into the hopper along with the grain flow, potentially damaging the unloading conveyor. Therefore, the sensor installation zone was chosen to be midway between the discharge openings, where small ridges of grain remain before the auger is activated. These ridges help to protect the sensors from being dragged into the hopper (see Fig. 8).

In the case of the silo chosen for our experiment (*D*=19.1 m), with sensors positioned midway between the discharge openings, they can be installed at the following locations (Fig. 9).

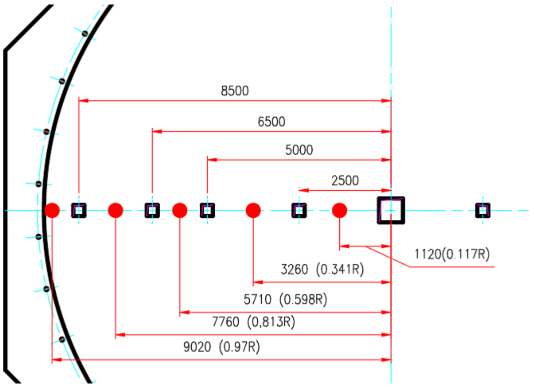

Fig. 9. Sensors placement layout for the experiment

Cables from the sensors to the outside of the silo need to be routed to connect to the terminal. This can be done along the path of the loading auger cables, which are typically laid in the undersilo tunnel.

When routing cables inside the silo, they must also be securely fastened to the floor to prevent the equipment from being drawn into the discharge outlets. Additionally, the cables should be laid at a distance of 0.5 … 1.0 m from the discharge openings (Fig. 10).

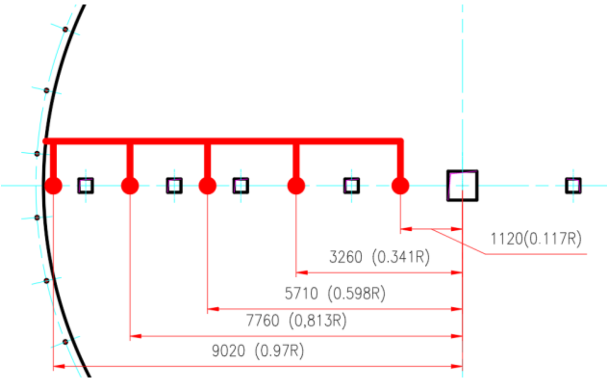

Fig. 10. Cable routing layout inside the silo

Outside the silo, the cables should be numbered according to the sensor numbers to prevent mistakes. The connectors for the terminal and the sensor labels must be protected from rain and dust.

3. Preliminary preparation for the experiment.

Before starting the experiment, it is recommended to prepare a logbook in advance, where the measurements will be recorded.

Prior to the experiment, data should be collected on the stored product and the characteristics of the silo, including:

– product name;

– measured bulk density of the product;

– measured internal friction angle of the product;

– measured friction coefficient of the product against the silo walls;

– silo wall diameter and height;

– sensor layout inside the silo and their numbering.

Next, a table is created for further analysis with the following columns:

1. Date and time of measurement.
2. Amount of product received in the silo, t (data from the facility laboratory).
3. Amount of grain waste separated from the product loaded into the silo, t (data from the facility laboratory).
4. Measured bulk density of the product after drying and cleaning.
5. Height of the product pile along the silo wall at the time of measurement, m.
6. Whether the measurement was taken during silo filling or emptying, or if the product was static, since pressure during loading or unloading can differ from static conditions (Gandia, Gomes, de Paula, de Oliveira Jr., & Rodriguez, 2021).
7. Sensor readings (1 … 5), kg.
8. Status of the ventilation system during measurement (on or off).

Originality and practical value

The process of preparing for the experiment demonstrated the complexity of this work. Considering the difficulties and high costs associated with the experiment, thorough preparation is essential to prevent potential complications. As noted earlier in the article, Janssen's equation for calculating pressure inside a silo does not fully reflect the actual pressure distribution; therefore, the theory of pressure calculation requires further refinement and development. Unfortunately, due to the organizational challenges of such experiments, they have been conducted insufficiently worldwide. This article aims to assist in organizing similar experiments, accelerate research, reduce experimental costs, and expand the experimental database for the further development of pressure calculation theory for bulk materials in silos.

Conclusions

1. Due to the technological features of grain storage facilities operations, special attention should be given to the selecting grain elevator for the experiment. Selecting an inappropriate site may result in only one experiment per year with a single set of sensors.
2. The article presents pressure measurement methods used in previous experiments and identifies the optimal method.
3. The analysis of the equipment market for such experiments revealed a lack of necessary sensors for conducting these studies. However, a modification of the equipment available on the Ukrainian market is proposed to meet the experimental requirements.
4. Based on the analysis of data from previous experiments, optimal sensor locations were selected to provide the most accurate representation of the pressure distribution curve.
5. The paper proposes and describes a method for mounting sensors inside a grain silo.
6. The article details the preparatory work conducted in the office prior to the experiment.

A Conflict of Interest Statement

The author is a Deputy Editor of the journal, and therefore the article was entirely handled and edited by another member of the Editorial Team.

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АНАЛІЗ ПЕРЕДУМОВ ЕКСПЕРИМЕНТАЛЬНОГО ВИЗНАЧЕННЯ ТИСКУ СИПУЧОГО МАТЕРІАЛУ НА ДНИЩЕ СИЛОСНОЇ ЄМНОСТІ

Мета. Основною метою публікації є опис досвіду підготовки та планування експерименту з визначення тиску сипучого матеріалу на днище силосної ємності. Аналіз світового досвіду з проведення аналогічних експериментів, аналіз можливих проблем та ускладнень при підготовці до експерименту, особливості матеріально-технічної бази для проведення аналогічних експериментів в Україні. **Методика.** Для досягнення основної мети було детально розглянуто світовий досвід з проведення аналогічних експериментів. Вивчено переваги й недоліки наявних способів експериментального визначення тиску сипучого матеріалу на днище силосу. Проаналізовано доступність в Україні необхідних технічних засобів. **Результати.** Виявлено, що основними проблемами підготовки аналогічних експериментів є важкодоступність необхідного обладнання, особливості технологічної роботи більшості не портових елеваторів в Україні. Також було проведено аналіз ризиків, які можуть завадити якісному проведенню експерименту, розроблено методику підготовки до експерименту. **Наукова новизна.** У публікації виконано опис процесу планування та підготовки експерименту, можливі методи його проведення, оцінка можливих складнощів і ризиків при проведенні експерименту, шляхи усунення цих ризиків при підготовці до експерименту. Уперше запропоновано спосіб використання тензометричних датчиків для вимірювання тиску всередині силосу, описано спосіб їх підбору та встановлення. **Практична значимість.** У статті розроблено покрокову інструкцію підготовки до експерименту та описані можливі методи дослідження тиску сипучого матеріалу на днище силосної ємності. Наведені необхідні інструменти та розрахунки. Матеріали статті спростять процес організації та проведення майбутніх

експериментів із вимірювання тиску сипучого матеріалу на днище силосної ємності.

Ключові слова: зерновий силос; елеватор; тиск сипучого продукту; зерно; датчик тиску; зачисний шнек; підлога силосу

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