EXPERIMENTAL RESEARCH ON LATERAL PRESSURE OF GRANULAR MEDIA WITHIN CLOSELY SPACED WALLS CONSIDERING DIFFERENT FILLING CONDITIONS

Scientiffic paper / Znanstveni rad

Aleksej Aniskin
University North, Department of Civil Engineering, Senior Lecturer
Corresponding author: aaniskin@unin.hr

Abstract: This article presents the results of an original experimental research on the lateral pressure acting on closely spaced rigid walls at different angles of granular particle orientation to the horizontal line. Filling was performed at three different predominant angles of grain orientation with respect to the horizontal line: 0°, 45°, and 90°. The aim of the study is to determine the nature of the influence of the particle orientation achieved by filling on the characteristics and distribution of the lateral pressure. In the experiments, a composite medium, i.e. a mixture of quartz sand and flat shell particles in a volume ratio of 2:1, was used. The results of the experiments showed a significant difference in the lateral pressure at different angles of particle orientation. It was found that at an angle of 90°, the average lateral pressure was 44.2% more than that at an angle of 0°.

Keywords: granular media, closely spaced parallel walls, lateral pressure, model structure, particle orientation, fill in conditions

EKSPERIMENTALNO ISTRAŽIVANJE BOČNOG TLAKA ZRNATOG MATERIJALA NA BLISKO POSTAVLJENE STIJENKE U RAZLIČITIM UVJETIMA ZASIPAVANJA

Sažetak: U članku su predstavljeni rezultati originalnih eksperimentalnih istraživanja bočnih tlakova na blisko postavljene paralelne i krute stjenke modela, pri različitim kutovima orijentacije čestica zrnatog materijala u odnosu na horizontalu. Zasipavanje materijala u model izvodilo se na tri različita načina, tako da su dominantni kutovi orijentacije čestica u odnosu na horizontalu bili 0°, 45° i 90°. Svrha istraživanja je utvrditi karakter utjecaja orijentacije čestice ostvarene putem postupka zasipavanja na karakter i distribuciju bočnog tlaka. U eksperimentu je korišten kompozitni medij – mješavina kvarcnog pijeska i plosnatih školjki, u obujamskom omjeru 2 : 1. Rezultati istraživanja pokazali su značajne razlike u bočnim tlakovima pri različitim kutovima orijentacije čestica. Pri kutu od 90°, bočni tlak bio je u prosjeku 44.2 % viši nego pri 0°.

Ključne riječi: rasuti materijal, blisko postavljene paralelne stjenke, bočni tlak, model, orijentacija čestica, uvjeti nasipavanja

1 INTRODUCTION

Structures with parallel, vertical, closely spaced walls are very common in construction, especially in hydrotechnical engineering and particularly in marine ports. Examples of such structures are narrow piers, poole quay extensions, cofferdams, cellular sheet pile structures, and berthing and mooring dolphin structures.

The pressure on closely spaced parallel walls was first investigated in silo construction models. Therefore, this kind of pressure is commonly called silage pressure in the normative and regulatory literature [1].

In 1895, H.A Janssen [2] carried out several series of experiments to determine the pressure of wheat, corn, and sand in a model of a silo of a square cross-section. The lengths of the silo walls considered were 20, 30, 40, and 60 cm. In addition to the experiments, a theoretical study was carried out, which led to the theory being named after the author and this theory is still widely used in current international codes and standards [1, 3–5]. However, Janssen did not pay attention to the methods of filling and their influence on the lateral pressure in the closely spaced walls. This question was considered much later by scientists such as J. Nielsen [6], M. Molenda et al. [7, 8], G.K. Klein [9], and A.V. Shkola [10].

J. Nielsen [6] studied the effect of the filling method on the distribution of the lateral pressure in the grain silo. Measurements of the lateral pressure were conducted at seven different levels in a silo of diameter 7 m and height 46 m; at each level at least four pressure cells were placed. Three experiments were conducted with an eccentric filling of wheat, seven with an eccentric filling of barley, and three with a central filling of barley. The measurement results showed that the type of grain and the procedure for filling had a great influence on the lateral pressure; this influence was not considered in Janssen's theory [2]. The difference in the lateral pressures on the silo walls in the bottom half (up to 21 m from the bottom) varied from 12 to 48%, and it was higher by 30% on average than that in the case of central filling. The author concludes that the eccentric filling of the silo with elongated grains of oats leads to the uneven distribution of lateral pressure, which is explained by anisotropy and inhomogeneity in the medium, caused by a preferred orientation of particles that depends on the filling procedure.

The impact of the filling method on the pressure distribution in the silo model was investigated by M. Molenda et al. [7]. Experiments were conducted to determine the effect of the filling method and wall type on the radial distribution of the vertical pressure on the bottom of a model bin. The bin was 0.61 m in diameter and 0.62 m in height. In addition, the measurement of the mean lateral pressures was conducted to determine the lateral pressure coefficient λ. Filling was carried out in three ways (Figure 1.): (a) centrally from the top, (b) circumferentially along the perimeter, and (c) sprinkling through a sieve uniformly across the cross-section of the silo.

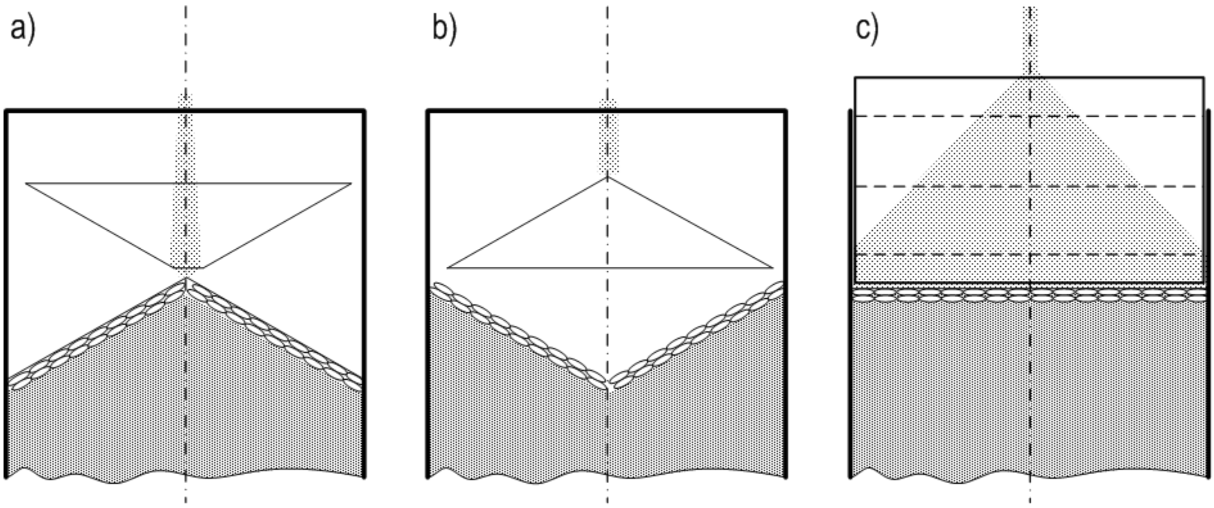

Figure 1 Different filling procedure, a) Central, b) Circumferential, c) Sprinkle

Six experiments were performed for each combination of the three filling methods and two wall types. The results showed significant differences in lateral pressures. The highest mean static lateral pressure (702 Pa) was obtained for the case of central filling while the lowest lateral pressure (579 Pa) was obtained for the case of sprinkle filling, with the difference between the two being 21%. In the case of circumferential filling, the pressure was 668 Pa, which was 15.4% more than that in the case of sprinkle filling. The authors in [8] attribute this difference in the pressure values to the different bulk densities in the various methods of filling, i.e. a greater angle of internal friction in the denser filling lowers the lateral pressure. As a result, it was concluded that the spatial arrangement of the solid particles constituting the bedding reflects the method of its formation, and the bulk mechanical behavior depends on the geometrical structure that defines the stress transmission path within the bedding. Further, experimental results confirmed the hypothesis that the bedding orientation in a massif of particles has an impact on the load transmitted to the walls and the bottom of structures.

Tong H. et al. [11] show the results of measurements of the vertical and lateral pressures at different orientations of the particles in the sample stacking. Two series of biaxial compression tests on an ellipse-shaped steel rod assembly were performed in a rectangular sample container, 240 mm in height and 120 mm in width. The sample consisted of iron rods that were 40 mm long with an oval cross-section and a ratio of principal axes of 1:2. The specimen of the aggregate was made by mixing rods of three major-axis lengths: 4 mm, 2 mm, and 1 mm. Their mass ratio was maintained as 8:2:1. A sample was filled into the container at various angles between the bedding plane and the plane of the major principal stress: 0°, 30°, 60°, and 90°. The horizontal (σ_3) and vertical (σ_1) stresses, and the horizontal walls movement were then measured. The lateral pressure was maintained at a constant level of 200 kPa. The maximum ratio of stresses σ_1/σ_3 was observed at an angle of 0°, and the minimum was observed at 60° and 90°, and the difference between the two ratios of stresses was about 36%. Therefore, a significant impact of the rod orientation on the characteristics of the stress changes was observed in the samples.

An extensive literature review on this topic is available in the work of G.K. Klein [9]. It was, therefore concluded that the majority of experimental results are qualitatively consistent with Janssen's theory, but often differed quantitatively i.e. the pressure is higher than that in Janssen's theory by up to two times, and in some cases up to five times that in Janssen's theory. In addition, the lateral pressure is influenced by an uneven pressure distribution in the cross-sections and the degree of activation of friction on the side walls. More recent studies [10] show that the filling technique affects the lateral pressure on the retaining walls. Consequently, the construction technology used for obtaining backfill formation i.e. the pattern and sequence of soil massif creation, which can be called technological factors, should be considered in the calculation and regulation of the construction works.

2 MATERIALS AND METHODS

The aim of this study is to determine the nature of influence of the particle orientation obtained owing to the method of filling on the characteristics and distribution of the lateral pressure in a silo. For this purpose, a composite medium with a volume ratio of 70% sand and 30% shell was used in this study as the test material; the characteristics of the medium are shown in Table 1. This material is often found in underwater sea quarries and river trade ports, and is used for filling cavities of hydrotechnical structures by dredging. The material was tested in a completely dry state.

Table 1 Basic physical and mechanical properties of a composite medium

Property	Standard	Value
Unit weight	HRN U.B1.016	γ = 16.81 kN/m^3
Specific weight of particles	HRN U.B1.014	γ_s = 27.00 kN/m^3
D_{10}		0.19
D_{30}		0.32
D_{60}		2.10
C_U		2.10
C_C		0.85

This material was filled in a model that was shaped as a steel cuboid the dimensions of which were 0.5 m _× 0.5 m with a height of 1.05 m. It had an opening at its upper end, as shown in Figure 2. The back wall of this structure was reinforced by reinforcement ribs (Figure 2b), which can be installed in four different positions, thus, causing the possible distance between the parallel walls to be 5, 10, 15, or 50 cm.

The lateral pressure values were measured along the axis of symmetry of the frontal wall at five measuring points (Figure 2a) using aluminum type-6530 single point load cells (Xi'an Ruijia Measurement Instruments Co. Ltd.) (shown in Figure 3a) that have a capacity of 10 kg, an input resistance of 406 Ω and a sensitivity of 2.0±0.15 mV/V.

At each measuring point, the load cell was fixed onto the external part of the frontal wall at its lower end, while a steel cylinder of diameter 48 mm, inserted at the 50-mm opening of the frontal wall (Figure 3b), was fixed onto the upper part of the cell. The cylinder was covered with a flexible thin polyethylene membrane to prevent particle entry into the radial gap between the cylinder and the opening.

Figure 2 General view of model structure: a) front, b) back, and c) top view in horizontal position

Signals obtained from the cells were read and recorded using an 8-channel quantum X data acquisition system (Hottinger Baldwin Messtechnik GmbH) (Figure 4). The measurement process was synchronized on all five channels of the device and carried out without interruption during the entire filling procedure.

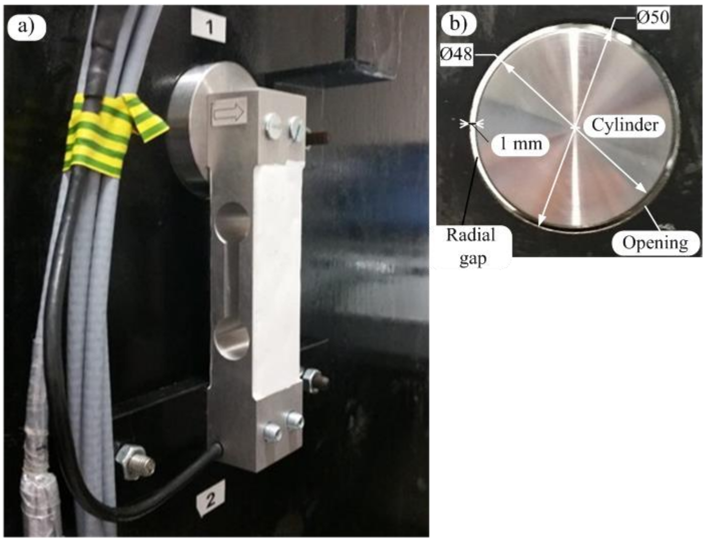

Figure 3 The setup of the load cell on the model: (a) outside, and (b) inside view

Before starting the experiments, the measuring system was calibrated by measuring the hydrostatic water pressure. The calibration was repeated three times. The measured average pressure was calculated as a ratio of the measured force that acts on the load cell and the surface of the cylinder. The average difference between the measured and calculated values of water pressure was 0.85%, and the averaged variation in the values around the arithmetic mean was ±0.86%.

In order to study the two dimensional problem, the distance between the walls was chosen as 5 cm. The ratio of the cross-section of the wall lengths was 1:5, while the ratio of the vertical cross-section was 1:20, which necessarily resulted in Janssen's effect of pressure saturation [2], i.e., lower increases in pressure with depth due to the wall friction.

The filling of material into the model was carried out in three modes depending on the predominant orientation of the grains to the horizontal line α, with the angles being 0°, 45°, and 90°. The model was filled with material evenly, with layers of an average thickness of 1 cm, up to a height of 1 m and the lateral pressure was then measured without an additional load, i.e. only under the influence of its own weight. Granular media was always filled from the top of model (Figure 3), but the position angle of the model was changed to achieve different angles of orientation α.

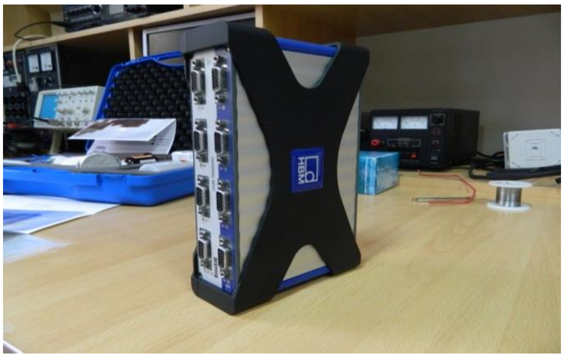

Figure 4 HBM data acquisition system

A filling angle of 0° was realized by filling from above while the model was in a vertical position (Figure 5a). Filling at angles of 45° and 90° was carried out using special technology, as shown in Figures 5b and 5c.

A filling angle of 45° was realized by fixing the structure onto a horizontal platform using special steel supporters (Figure 5b). The model was then filled vertically from above, with a majority of the falling particles ending up in a horizontal position because of their geometrical shape and the force of gravity. After the filling procedure was completed, the structure was very slowly returned to a vertical position.

Filling at an angle of 90° was realized by putting the model into a horizontal position on two horizontally arranged beams (Figure 5c), after which the back wall was uninstalled and a special steel bulkhead that was 5 cm in height was inserted at a distance of 1 m from the bottom. After the filling process, the surface was very carefully evened out, the back wall was re-installed, and the model was very slowly returned to a vertical position.

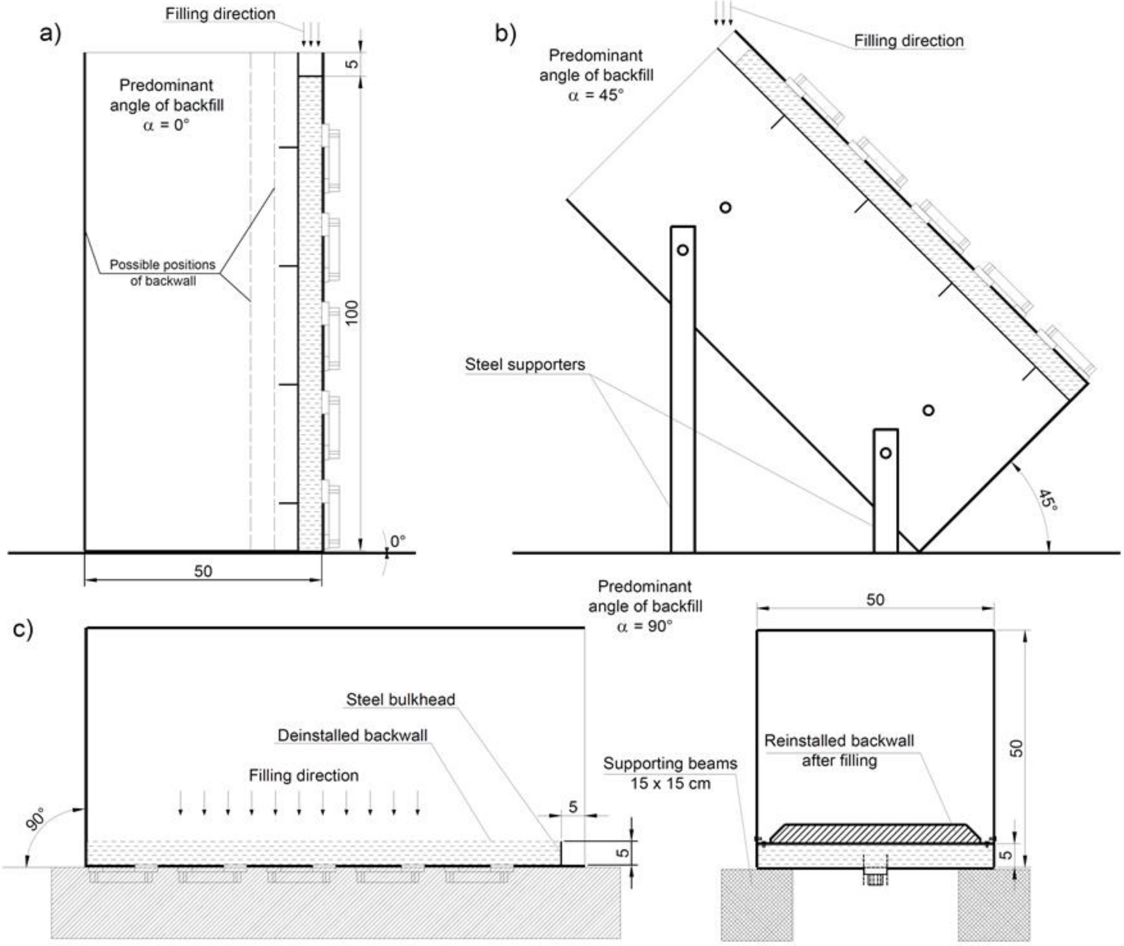

Figure 5 Technology used for filling the model for filling angles: a) 0°, b) 45°, and c) 90°

Each measuring procedure was carried out according to the following sequence:

- The functionality of each individual cell was inspected while the model was in a vertical position.
- The measuring process was initiated in the vertical position and was tracked during the whole filling process.
- The model was evenly and gradually filled with material without any sudden movement.
- After the filling process, the model was very carefully returned to a vertical position.
- A pause of approximately 5 to 10 min was introduced so as to wait for the measured values to stabilize.
- The values were then recorded.

The tests were carried out under laboratory conditions at a temperature of 20 °C and relative humidity of 50%. The loads were measured with an accuracy of ±0.05 N.

3 RESULTS AND DISCUSSION

To achieve consistency in the measured values, the testing was performed three times at each angle, with the total number of tests being nine. The sample unit weight measurement was performed for each experiment, and the measurement results are shown in Table 2.

Table 2 The average unit weight of the samples at various conditions of filling

Angle of orientation, α [°]	$\gamma = \gamma_d$ [kN/m³]
0	16.40
45	14.83
90	16.19

As expected, owing to the anisotropy of the material at different filling conditions, different lateral pressure values are obtained. The average measurement results of the lateral pressure values at different filling conditions are shown in Figure 6.

Under different filling conditions, changes in the material unit weight were observed. The data in Table 2 indicates that the difference in the lateral pressure values for filling angles 0° and 90° was insignificant, i.e. only 1.24%, but at angle of 45°, the filling unit weight was lower than that at an average angle of 0° by 9.54%. The deviation of the measured values from the arithmetic mean was ±1.34%.

At a filling angle of α = 0 ° (Figure 6, curve 1), the averaged measured data differs from that in Janssen's theory by 4.9%. The results are comparable to the measurements of well-known authors such as M.L. Reimbert et al. [12], G.K. Klein [9], D. Schulze [13] and Brown et al. [14], which further confirms the accuracy of the results.

In case of filling at α = 45°, at a depth of 0.5 m, the lateral pressure exceeds that at a filling angle of 0° by 19%; furthermore, with the increase in depth, the difference between the two pressures decreases, and the pressure at a depth of 0.88 m at α = 45° is less by 15% than in the case of α = 0°. This can be attributed to the influence of the rigid bottom, which is most expressed at α = 45°.

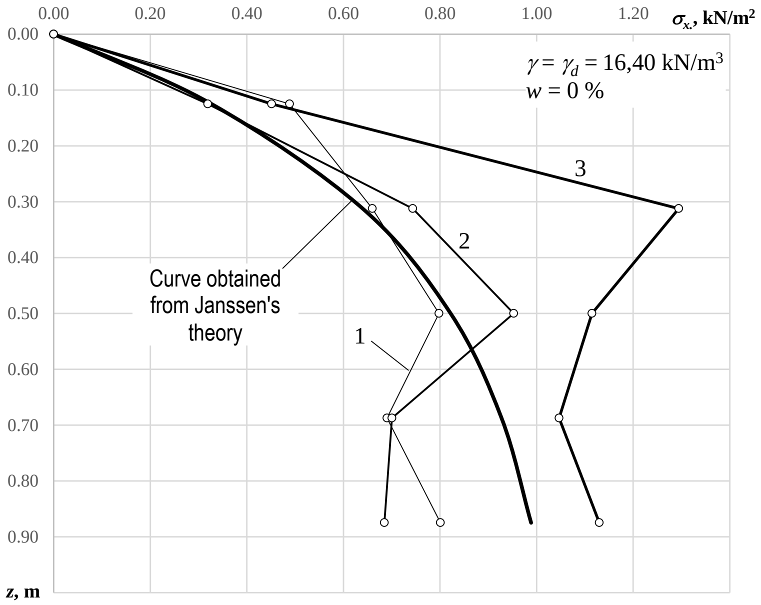

Figure 6 Diagrams of measured average lateral pressure values when using different filling technologies, 1 – 0°, 2 – 45°, 3- 90°

The pressure diagram at α = 90° (Figure 6, curve 3) is similar to that at α = 0° (Figure 6, curve 1), and the pressure is maximum at z = 0.3 m. At the filling angles of 0° and 90°, the average difference of the lateral pressures was 44.2%. The significant difference in the lateral pressures at α = 0° and 90° can be attributed to the effect of the predominant orientation of the grains, which contributes to the horizontal extension (wedging) caused by the indentation of the particles in the space between the grains under the influence of gravity. In addition, the influence of dynamic factors when the model was returned from the inclined position to the upright position is unavoidable.

When there are variations of approximately ±10% in the bulk density of the filling, the lateral pressure differs greatly (approximately 45%), which also indicates a change in the lateral pressure coefficient $k = \sigma_3/\sigma_1$; conversely, the lateral pressure rises with the increase in the angle α. Molenda et al. [7] and Tong et al. [11] have found similar tendencies with the change in lateral coefficient.

The average deviation in the measured pressure values was ±16.13%, which further confirms the accuracy of the measured data.

4 CONCLUSION

Based on the results of the testing of the lateral pressure for different filling conditions and predominant particle orientations α = 0°, 45°, and 90°, the following conclusions are derived:

1. The lateral pressure characteristics are nonlinear. Curves 1 and 3 are qualitatively similar, while curve 2 is different at the bottom of the graph.
2. The unit weight for different filling conditions is different; the most loose sample was observed at α = 45° (it was less than that at α = 0° by 9.54%), while the densest sample was observed at α = 90° (it was higher than that at α = 0° by 1.24%).
3. At an angle of α = 0°, the measured pressure values are comparable with the pressure values calculated by Janssen's theory, the average difference was only 4.9%;
4. The lateral pressure at α = 45° at a depth of 0.6 m is higher by 1% than in the case of α = 0°, while the lateral pressure in the remaining area is lower by 6% on average than that at α = 0°.
5. At a filling angle of α = 90°, the average lateral pressure is 44.2% higher than that at α= 0°.

Experimental research has shown that the technology used for filling silos significantly affects the value of the lateral pressure, and this finding is of great importance in the construction of various retaining structures that use filling procedures. Accordingly, the technology and the method of material filling should be analyzed and used to improve the reliability and economy of such structures. It may, therefore, be used for reducing the loads on supporting structures or increasing the bearing capacity of artificial beddings using optimal fill methods and technology.

References

[1] Instruktsiya po proyektirovaniyu morskikh prichal'nykh i beregoukrepitel'nykh sooruzheniy: RD 31.31.55-93. 1993: [Data vvedeniya 1993-06-01]. Soyuzmorniiproyekt. Moskva (In Russian)

[2] Janssen H.A. 1895: Getreidedruck in Silozellen, Z. Ver. Dt. Ing., 39. pp. 1045-1049.

[3] Pidpryyemstva, budivli ta sporudy po zberihannyu ta pererobtsi zerna: DBN V.2.2-8-98. 1988: Chynnyy vid 1998-01-07. Derzhbud Ukrayiny, Kiev (In Ukranian)

[4] Podpornye steny, sudokhodnye shlyuzy, rybopropusknye y rybozashchytnye sooruzhenyya: SNiP 2.06.07-87. 1989: Data vvedenyya 1988-01-01. TSYTP Gosstroya SSSR, Moskva (In Russian)

[5] Basis of design and actions on structures. Part 4: Actions in silos and tanks: prEN 1991-4. 2002: Eurocode 1. CEN.

[6] Nielsen J. 1983: Load distribution in silos influenced by anisotropic grain behavior//International Conference on Bulk Materials Storage, Handling and Transportation, New Castle, NSW, Australia.

[7] Molenda M.; Horabik J.; Ross I.J. 1996: Effect of Filling Method on Load Distribution in Model Grain Bins, Transaction of American Society of Agricultural Engineers, 39(1), pp. 219-224, https://doi.org/10.13031/2013.27501

[8] Molenda M.; Horabik J.; Ross I.J. 1993: Loads in model grain bins as affected by filling methods, Proc. of American Society of Agricultural Engineers, 36(3), pp. 915-919, https://doi.org/ 10.13031/2013.28416

[9] Kleyn G.K. 1977: Stroitel'naya mekhanika sypuchikh tel, 2-ye izd. pererab. i dop., Stroyizdat, Moskva (In Russian)

[10] Shkola A.V. 2012: Bokovoye davleniye anizotropnykh gruntov na sooruzheniya, MAG VT, Odessa (In Russian)

[11] Tong Z.; Zhang L.; Zhou M. 2013: DEM Simulation of Biaxial Compression Experiments of Inherently Anisotropic Granular Materials and the Boundary Effects, Journal of Applied Mathematics, Vol. 2013, Article ID 394372, pp. 1-13, https://doi.or/10.1155/2013/394372

[12] Reimbert M.L.;Reimbert A.M. 1976: Silos - Theory and Practice,Claustal, Trans Tech Publication, 1st Edition, Germany

[13] Schulze D. 1991:Untersuchungen zur gegen seitigen Beeinflussung von Silo und Austragorgan, Dissertation, Fakultät für Maschinenbau und Elektrotechnik der Technischen Universität Carolo-Wilhelmina zu Braunschweig

[14] Brown C.J.; Lahlouh E.H.; Rotter J.M. 2000: Experiments on a square platform steel silo, Chemical Engineering Science, 55, pp. 4399 – 4413, https://doi.org/10.1016/S0009-2509(99)00574-6