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Analysis of horizontal silo pressure distribution by filling method based on experimental data

Abstract. The work presents an analysis of the results of the fill-in condition influence of particle inclination on horizontal silage pressure. Analyzed data were obtained from experiments on a rectangular silo model with rigid walls in a different fill-in condition. The filler was a composite mixture of sand and flat shell particles (2:1). The analysis of the results concluded that the volume weight of the composite mixture depends on the fill-in method, which affects the horizontal silage pressures. At filling of 0° and 45°, the pressure is slightly different from Jansen's theory (max 19%) which can be neglectable. Horizontal silage pressures are functionally dependent on the filling method (up to 44%), which should definitely be taken into account.

Keywords: Lateral silage pressure, confined walls, non-coherent material, particle orientation, fill-in method.

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Introduction

H.A Jansen [1] carried out a series of experiments on the silage pressure of wheat, corn, and sand in a silo model with a square cross-section. The experiments and a theoretical study were carried out, which is still used in current international codes and standards [2–8]. However, Jansen did not analyze fill-in methods and their influence on the silage pressure. The influence of the fill-in method was noticed much later by scientists such as J. Nielsen [9], M. Molenda and J.A. Horabik [10-11], G.K. Klein [12], A.V. Shkola [13].

The effect of the filling method on the distribution of the lateral pressure in the grain silo was studied by J. Nielsen [9]. Measurements of silage pressure were conducted in a real dimension silo with a diameter of 7m and 46m in height, at seven different levels with four or more sensors on each level. The experiments were carried out with eccentrically filling on wheat and barley, and with a central filling of barley. The conclusion was that the type of grain and the fill-in method had a noticeable impact on silage pressure [8]. The difference in the silage pressures on silo walls at the bottom varied from 12 to 48% and averaged 30% depending on the fillin method. The conclusion was that the difference in fill-in method with elongated grains caused a non-uniform distribution of silage pressure. The fill-in method caused different orientations of particles which as a consequence leads to anisotropy and inhomogeneity of the grain medium.

In the work of M. Molenda et al. [11] the impact of the fill in method on silage pressure was investigated. The effect of the filling method and wall type on the radial distribution of vertical pressure on the bottom of a silo model was determined. The silo model was 0.61 m in diameter and 0.62 m high. The coefficient of lateral pressure λ was determined from experimental data. It was used three types of fill in methods (Fig. 1) – from the top centrally (a), along the perimeter (b) and uniformly over the entire surface through a sieve (c).

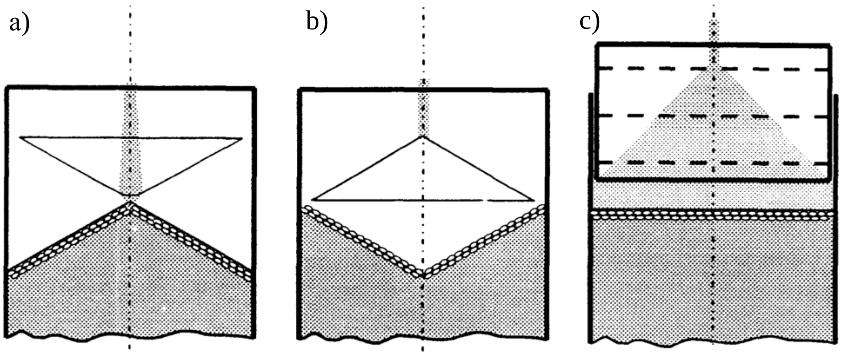

Figure 1. Different fill in methods: a) central, b) along perimeter, c) uniformly

Three filling methods and two wall types was used in experiments. The highest average silage pressure (702 Pa) was obtained for the central method while the lowest silage pressure (579 Pa) was obtained for the uniform fill-in method, with a significant difference of 21%. In the case of fill in along the perimeter, obtained pressure was 668 Pa which is 15.4% in regard to uniformly filling. The authors [10] explain the difference in value by the different bulk density at various ways of fill in conditions which cause a larger angle of friction in the denser filling and leads to lover silage pressure. In conclusion, the authors emphasize that the spatial arrangement of the grain particles which makes bedding, represents the formation method, and mechanical characteristics depends on the geometrical structure.

Klein G.K. [12] researched many sources of literature on the topic. The final conclusion was that the larger part of experimental results is consistent with Janssen's theory qualitatively, but in some cases differ by 2, and in some cases up to 5 times, sometimes the pressure was lower. Also, silage pressure affects non-uniform pressure distribution in the cross sections and the rate of activation of wall friction. Studies [13] show that the fill-in method affects the silage pressure on the walls.

In work [14] presented results of vertical and horizontal pressures measurements at a different inclination of the particles in the sample. The biaxial compression tests on steel roads sample with elliptical cross section (with a ratio of the principal axes of 1:2) were carried out in a rectangular sample container. The dimensions of the container was 240mm x 120mm. The sample consisted of three kinds of rods with their major axis length of 4mm, 2mm, and 1mm with mass ratio was 8:2:1. A sample was composed at a different angle between the bedding plane and the plane of the major principal stress, 0°, 30°, 60°, and 90°.

In experiment vertical (σ_1) and horizontal (σ_3) stress and displacement was measured. Lateral pressure was constant 200 kPa. At an angle of 0° the maximum ratio of σ_1/σ_3 stresses was observed and the minimum at 60° and 90° with the difference about 36%. The authors indicate that the rod orientation substantially impact stress changes in the samples.

According to currently available literature, fill in methods should be considered in the calculation and regulation of the construction work.

Experimental materials and methods

The medium used in experiment is composite mixture with a volume ratio of 70% of sand and 30% shell. The physical and mechanical characteristics are shown in Table 1. The material was tested in a dry state.

Table 1. Physical and mechanical properties of a composite mixture

Property	Standard	Value
Volume weight	HRN U.B1.016	γ = 16,81 кН/м^3
Specific weight of particles	HRN U.B1.014	γ_s = 27,00 кН/м^3
C_U =		2,10
C_C =		0,85
D_{10} =		0,19
D_{30} =		0,32
D_{60} =		2,10

The experimental model construction of the silo is shown in Figure 2. Horizontal-pressure values were measured on the middle of the foreground wall at 5 measuring places (Fig. 2a) using single-point load cells – aluminum type-6530 by Xi'an Ruijia Measurement Instruments Co. Ltd. (Table 2.). The forces were measured and recorded using a data acquisition system CATMAN Easy. The experiment was carried out three times on three fill-in methods [15].

Table 2. Characteristics of used load cells

Manufacturer	Xi'an Ruijia Measurement Instruments Co. Ltd.
Type	6530
Capacity	10kg
Input resistance	406 Ω
Sensitivity	2.0 ± 0.15 mV/V
Accuracy	±0,05 N

Calibrated of the system was carried out by hydrostatic water pressure measurements, 3 times. The average difference between measured and theoretical pressures was 0,85%, with averaged variation from the arithmetic mean ± 0,86%.

The dimensions of cross section of the silo model was chosen so that the test results could be observed and compared with the plane theoretical solution.

Electrical signals of the load cells were red using the 8-channel HBM Quantum X measurement device. Measuring was carried out simultaneously on all five measurement places during the entire filling procedure.

There were used three different fill-in methods. The construction was placed at a different angle to the horizontal – 0°, 45°, and 90°, while filling was always done from above [15].

The angle of backfill 0° was achieved by filling from above while the model was in a vertical position. Filling at angles of 45° and 90° was done when the model was at 45° and horizontal position.

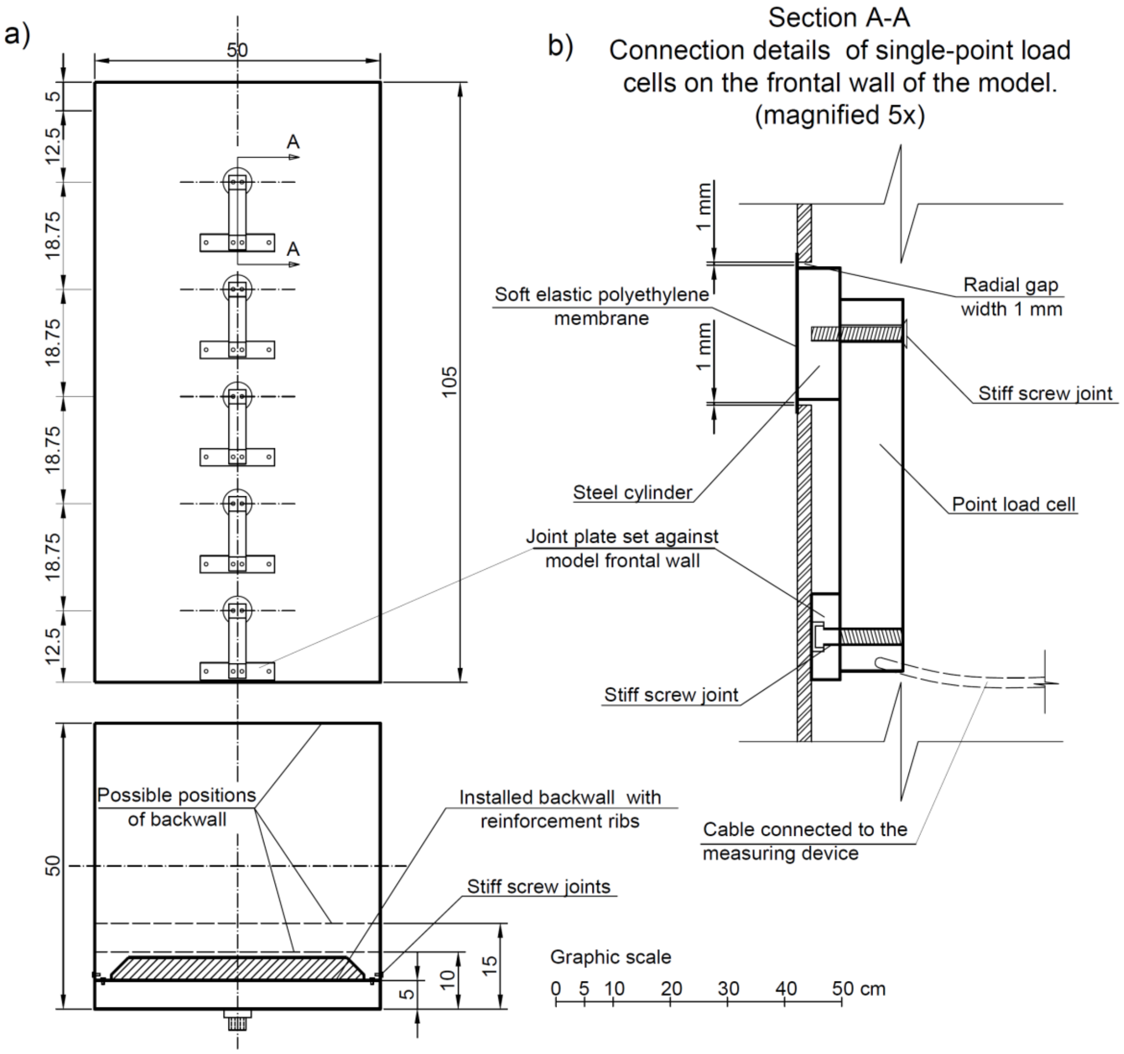

Figure 2. The rectangular silo model (a) foreground wall and cross section (b) detail of load cell mounts

Results and Discussion

Consistency of the measured results was achieved by repeating the test 3 times at each angle. Furthermore, the sample weight measurement was carried out for each experiment, the measurement results are shown in Table 3.

Table 3. The average volume weight of the samples at various conditions of filling

Angle of orientation, α	$\gamma = \gamma_d$, [kN/m^3]
0°	16,40
45°	14,83
90°	16,19

It was noted that due to the anisotropy of the material at different filling conditions, there are obtained different horizontal silage pressure values. The average measurement results of the horizontal pressure values at different filling conditions are shown in Figure 3.

Different filling conditions caused different average volume weight which impact pressures values. The data in Table 3 shows that at angles 0° and 90° the difference was only 1.24%, but at angle 45°

volume weight was lower than at angle 0° and 90° by 9.54% on average.

At a filling angle of 0° (Fig. 3, curve 1), the measured data is fits well with Jansen's theory to the middle of the depth (a difference of only 4.9%). The results are similar and comparable to Reimbert [16], Klein [12], Schulze [17], and Brown [18].

It was observed that the lower the mean depth of the model, the pressures are lower than the theoretical. This fact can be explained by the influence of the rigid bottom.

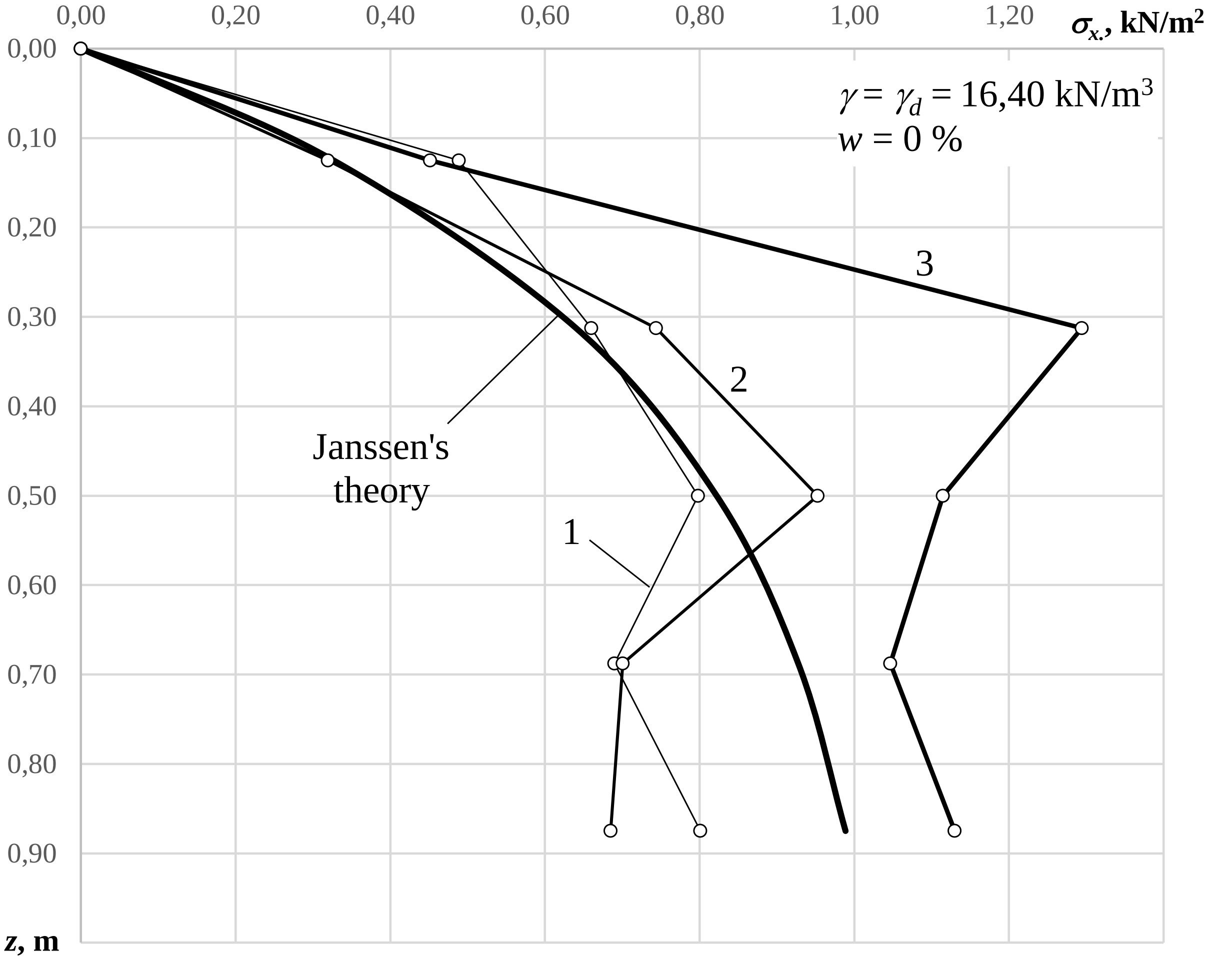

Figure 3. Experimental distribution of the silage horizontal pressure at different fill in methods 1 – 0°, 2 – 45°, 3 - 90°

As expected, pressure at 90° was the highest one, it is average deferens from 0° was 44.2%. [15]. Filling at an angle 0° and 45 °, relatively in close fit, difference up to 19%, which can be neglected for this ratio of plane particles (30% shells in sand).

This differences in pressures can be explained by the inclination angles of the particles in space (Figure 4.)

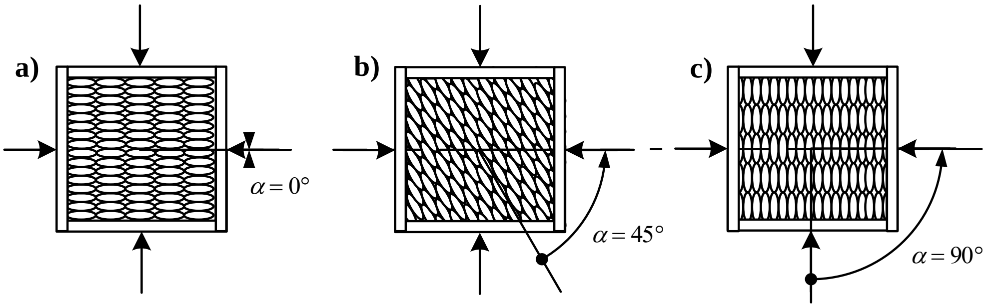

Figure 4. Different inclination of the particles in structure of the massif a)0°, b)45°, c)90°

The remaining potential of the friction force is zero in the case of 90° (Fig. 4 c), so the pressure is the highest, while the potential of the friction force at 0° and 45° is higher, so the horizontal pressure is lower (Fig. 4 a and b). Furthermore, the vertical wedging of the particles produces additional lateral pressure.

The volume weight of the samples changes due to the fill-in method which has a great impact on 45° filling with the lowest volume weight (Table 3.). Similar results were described in the works of Molenda et al. [11] and Tong et al. [14].

Conclusion

1. Volume weight of the composite mixture depends on the fill in method, which affects the horizontal silage pressures

2. For the given content of flat particles (30% of plane particles) filling at 0° and 45° is slightly different from Jansen's theory (max 19%) which can be neglectable

3. Horizontal silage pressures are functionally dependent on the filling method (up to 44%), which should be definitely taken into account

Analysis of experimental research showed that the fill-in methods substantially impact the value of horizontal silage pressure. Therefore, the method of material fill-in should be considered and used for economic benefit using the optimal fill technology.

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Эксперименттік деректер негізінде толтыру әдісімен көлденең сүрлем қысымының таралуын талдау

Андатпа. Бұл жұмыста толтырылған күйдегі бөлшектердің көлбеу силостың көлденең қысымына әсер ету нәтижелерін талдау ұсынылған. Талданған деректер әр түрлі толтыру жағдайларында қатты қабырғасы бар тікбұрышты сүрлем моделіндегі тәжірибелер нәтижесінде алынды. Агрегат құм мен тегіс қабық бөлшектерінің 2:1 қатынасты композициялық қоспасы болды. Нәтижелерді талдау композиттік қоспаның көлемдік салмағы силостың көлденең қысымына әсер ететін толтыру әдісіне байланысты деп қорытынды жасауға мүмкіндік берді. 0° және 45° толған кезде қысым Янсен теориясынан біршама ерекшеленеді (максимум 19%), оны елемеуге болады. Силостың көлденең қысымы функционалды түрде толтыру әдісіне байланысты (44% дейін), оны ескеру қажет.

Кілт сөздер: Сүрлемнің бүйірлік қысымы, шектеулі қабырғалар, байланыссыз материал, бөлшектердің бағыты, толтыру әдісі.

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Анализ распределения давления горизонтального силоса методом засыпки на основе экспериментальных данных

Аннотация. В этой работе представлен анализ результатов влияния наклона частиц в состоянии заполненности на горизонтальное давление силоса. Анализируемые данные были получены в результате экспериментов на модели прямоугольного силоса с жесткой стенкой в различных условиях заполнения. Заполнителем служила композитная смесь песка и частиц плоской оболочки в соотношении 2:1. Анализ результатов позволил сделать вывод, о том, что объемный вес композитной смеси зависит от способа заполнения, что влияет на горизонтальное давление силоса. При заполнении 0° и 45° давление незначительно отличается от теории Янсена (максимум на 19%), чем можно пренебречь. Горизонтальное давление силоса функционально зависит от метода заполнения (до 44%), что обязательно следует принять во внимание.

Ключевые слова: боковое давление силоса, ограниченные стенки, несвязный материал, ориентация частиц, метод заполнения.

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