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EXPERIMENTAL STUDY OF HORIZONTAL PRESSURE DISTRIBUTION ON CORRUGATED STEEL SILO WALLS

Purpose. The paper aims: 1) qualitative assessment of the nature of the container corrugated wall deformation caused by the load from bulk materials. 2) determination of the horizontal pressure redistribution scheme for each individual corrugation plate and the calculation method that is closer to the real situation. 3) obtaining the quantitative deformation indicators to compare them with the calculated ones produced by means of mathematical model simulation. **Methodology.** To achieve this purpose the different types of capacitive structure profiles were investigated and the values of total vertical displacement under load were obtained. The computational experiment used the design computer system Structure CAD for Windows. In addition, the laboratory experiment was conducted, the analysis of which is important to confirm the correctness of pre-made computer models. **Findings.** The conducted experiment allowed receiving the confirmation of the FEM calculated data, namely qualitatively and quantitatively the deformation direction and nature completely repeated the design situation in SCAD. The work of corrugated profile was analysed for different theoretically possible load schemes and different calculation methods. Also the work contains the recommendations for the real calculation using computer simulation. During a joint study the authors obtained the data that allow for more accurate assessment of the corrugated profile performance under the pressure from bulk materials. **Originality.** The conducted research and experimental tests explain and clarify the ways for possible redistribution of bulk material pressure on each corrugation plate, while there is no such information in the existing recommendation literature and regulatory framework concerning the capacitive structure design. **Practical value.** The use of the proposed solutions is useful for correct design of containers with corrugated walls during further calculations and search of new directions for future research.

Keywords: silo; capacitive structure; silo wall; corrugated profile; experimental studies; deformations; computer simulation

Introduction

In Ukraine, the major portion of grain is stored in state bulk reinforced concrete silos whose equipment is morally and physically obsolete, that results in reduced grain quality and throughput efficiency of elevators. At the same time the silos are remote from grain manufacturers, while the grain storage costs are very high and are about 25% of the stored grain cost.

One of the most important ways to reduce losses and improve product quality is to provide each household with an own modern grain elevator. Thus, in the agro developed countries up to 80% of the crop is kept at its producer. Herewith the storage towers are the most preferred in the world. The technology of storing grain in the storage towers equipped with active ventilation is widely used in

the USA and Canada and in this decade in Europe [13].

Metal ventilated silos are deservedly considered as the most profitable for storage of grain crops [10]. Prefabricated metal silos have the following advantages: they reduce the capital costs during installation in two or three times and the complexity of installation – in four-five times; allow mounting silos closer to the place of collection and use of grain; make it possible to implement a complete mechanization and automation of the storage process [13]. Their construction and maintenance is cheaper, and the self-warming process that occurs in the grain can be influenced through effective aeration, ventilation and thermometry systems. Abroad, the half of all granaries is metal silos. Their number is slowly but surely growing in Ukraine as well [4].

The best containers in terms of design and subsequent operation are rigid vertical capacities. Mostly they consist of two parts: the top one with vertical walls, designed to accumulate the necessary stored supply of bulk material and the bottom one with sloping walls designed to discharge the material by gravity [1]. This type of silo is realized in two versions of walls: profiled or smooth. Most overseas silos are manufactured and operated with corrugated steel wall plates [16]. For optimal storage of bulk materials the best containers are those with smooth walls in the bottom part and profiled walls in the top part. This reduces the pressure at the bottom of the silo and facilitates the discharge flow due to the smooth wall section at the bottom part. To the extent that the profiled wall itself is very durable, it requires less steel, which also makes this solution economic [15].

Purpose

To design a silo an engineer must determine all loads that can affect it. These loads include the whole range, namely, wind, seismic, snow load, as well as the load on the silo inner surface caused by pressure from the bulk material that is stored. Numerous Eurocodes and national standards [6, 7] determine the methods to calculate the latter load [14]. However, the regular recurrence of silo structure accidents and damages indicate that the existing methods of calculation and design of such structures do not include all the features of their operation [3]. Still, one of the challenges to creating reliable and economic structures of this type is the interaction of bulk material with corrugated wall elements of the capacitive structure [8]. Unfortunately, the enacted DSTU-N B EN 1991-4:2012 [6] has no information on how to properly set the horizontal component of the pressure on the profiled wall. And meanwhile the operating experience of these structures demonstrates the need for improved methods of bulk material pressure determination [2].

To solve this problem the authors created multiple mathematical models in the program complex SCAD [11] and investigated the capacity behaviour at different ways of transferring the load onto the corrugated wall elements [8]. However, the obtained results were multivalued by direction and character of deformations and required clarification.

Thus, it was necessary to formulate and conduct more sophisticated experimental research that will determine fundamentally the nature of corrugated wall deformation under the load from bulk materials and help to understand how the horizontal pressure is distributed on each individual corrugated plate [9]. In addition, it was necessary to get quantitative deformation values to compare them with the calculated ones obtained during mathematical modelling.

Methodology

The researches in this field were performed by means of the searching laboratory model experiment because it was not possible to examine the object itself, given its large size [5]. Therefore, the model of the studied object was examined.

Preparation and planning of the experiment contained a lot of tasks, including the following: previous theoretical analysis and mathematical modelling of the experiment-predicted situation; selection of a common form of the experimental capacity and the material from which it must be manufactured; accurate selection of parameters to characterize the bulk materials to be used and the created experimental capacitive structure; determination of the total number of these parameters and their linkage to each other; defining the number of variables, etc. In addition, the scope of the research was limited by the dimensions of the used premises (outdoors had a high probability of influence of the hard-predictable adverse factors), the scope of physical work (loading and unloading of capacities was performed manually), the estimated cost of the planned research. More details concerning the experiment planning and preparation can be found in the previous publication of the authors [9].

In the final study, the experimental design was adopted as symmetrical single-stage capacity of prismatic type with three flat and one replaceable corrugated walls.

The material for prismatic capacity was chosen as follows: for two sides and the bottom – 8 mm MDF sheets, for the third side – glass of the same thickness. The corrugated wall was made of the technical paper with 0.27 mm sheet thickness and 220 g/m² density that is equivalent to 0.815 g/cm³. The strength factor and Poisson coefficient according to A.H. Yahofarov's thesis [12] were adopted as 10000 MPa and 0.5, respectively.

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The main parameters that characterized the experimental bulk material – millet – included the following of its physical and mechanical characteristics: grain diameter, bulk density, specific weight, angle of friction, angle of external friction and friction coefficient. They were determined experimentally during the special relevant additional research and had the following values respectively:

- $d_{gr} = 2.25$ mm;
- $\rho_b = 707.33$ kg/m³;
- $\gamma = 707.56$ kgf/m³;
- $\psi_{gr} = 24.8^\circ$;
- $\varphi_{ext}^{gr} = 15^\circ$;
- $f = 0.27$.

As the variable design parameters were taken the corrugation form type and size – crinkle height and length.

The corrugation profile for the panel was made in three versions: square profile with smaller plate oriented to bulk material, square profile with bigger plate oriented to bulk material and triangular profile (or zigzag), which was a simplified version of the wavy one (see Fig. 1). Herewith the crinkle length, depending on the profile type and experiment stage, ranged from 22 to 78 mm and the crinkle height was researched in two versions: 19 and 25 mm.

To solve the experimentally set task the corrugated wall deformations were measured. For this purpose the construction was equipped with a watch-type indicator of 0.01 mm-accuracy to obtain the values of total vertical displacements of the corrugated panel top point. Also the 1 mm-scale rule was attached to the grooves along the entire corrugated wall on both sides, in order to fix the vertical deformations of each crinkle while the capacity is filled with bulk materials. Material filling was carried out at the wall the most remote from the corrugated panel in order to transmit the bulk load gradually, by gravity, without bumps.

The experiment was conducted twice. The aim of the first one was qualitative determination of the nature and direction of the deformations of various corrugation types, since the previous mathematical modelling of experimental situations provided the results with different directions of vertical displacements and they needed experimental confirmation. Loading of capacity took place for the

three above mentioned corrugation types, whose dimensions (see. Fig. 2) were selected from the conditions of proportionality of plate sizes to bulk material fraction and compliance with profile groove sizes.

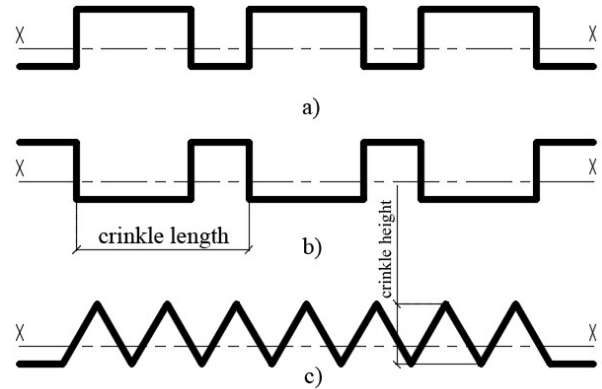


Fig. 1. The studied corrugation profile types:
a – square profile with smaller plate oriented to bulk material;
b – square profile with bigger plate oriented to bulk material;
c – triangular profile

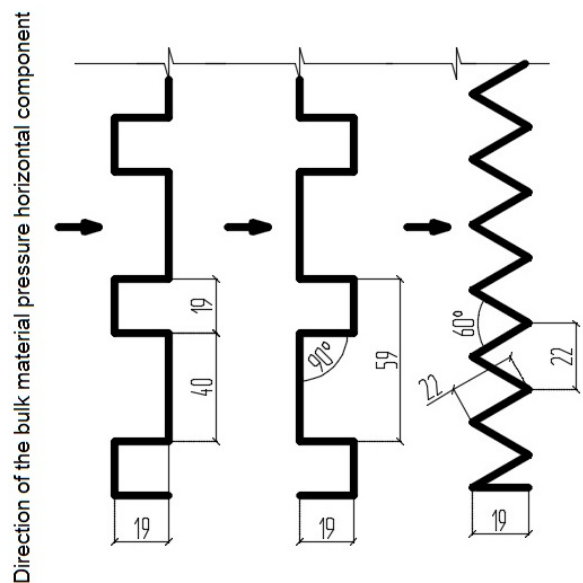


Fig. 2. Sizes of some corrugation plates of each section type for production of capacity corrugated wall

The aim of the second experiment was to obtain quantitative indicators of displacements for clarifying the scheme of load on each individual corrugation plate as well as selection of a calculation method to analyse the future mathematical models in FEM (finite element method).

This version tested only square profiles with smaller and bigger plates oriented to bulk material. Theoretically, the model evaluation included con-

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sideration of 7 load charts with different versions of the pressure distribution on each individual plate. These charts and sizes for square profile with smaller plate oriented to bulk material are shown in Fig. 3.

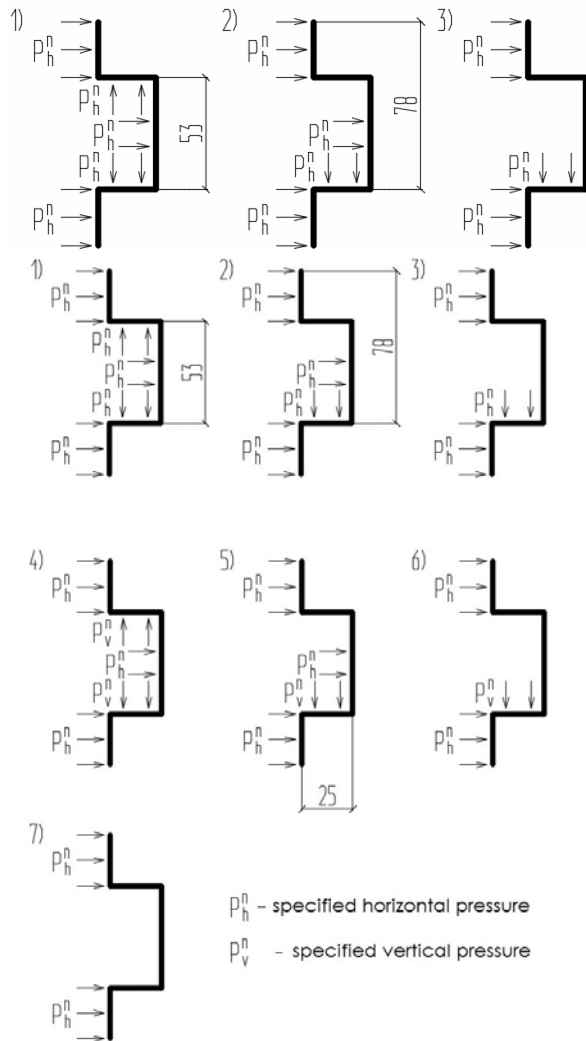


Fig. 3. Theoretically probable load charts

The load values for SCAD simulation were determined in accordance with DBN [6] by Jansen theory with consideration of local pressure rise coefficient a_1 , taken in accordance with the requirements of par. 4.11. The calculation was performed using linear and nonlinear methods.

Findings

During computer simulation of the first experiment by non-linear calculation method each type of profile sections was deformed differently

and quite specifically. Direction of total vertical displacements of the square profile with smaller plate oriented to bulk material was downward and had a value of 4.34 mm, and that of the square profile with bigger plate oriented to bulk material – upward (coincided with the direction of z-axis in SCAD model) by 5.79 mm. For triangular profile the vertical deformation values were significantly lower and made 1.76 mm downward, but the profile was quite significantly deformed in plane, which was not observed in the previous two versions.

The conducted experiment confirmed the data obtained by FEM calculation, namely – in essence the direction and character of the deformations completely repeated the SCAD design situation. In addition, the quantitative values of vertical deformations of the corrugation plate top reference point for each section type under full load were very close to the pre-calculated ones and differed in value by less than 1 mm.

Photos of full loading of the experimental capacity to 48 cm height are shown in Fig. 4.



Fig. 4. Experimental capacity with the square profile with smaller plate oriented to bulk material under full load

For more accurate monitoring of deformation nature the samples were taken evenly along the entire height of the corrugated panel for pre-defined control points at different levels of capacity load. The results for each type of profile in the form of charts are presented in Fig. 5.

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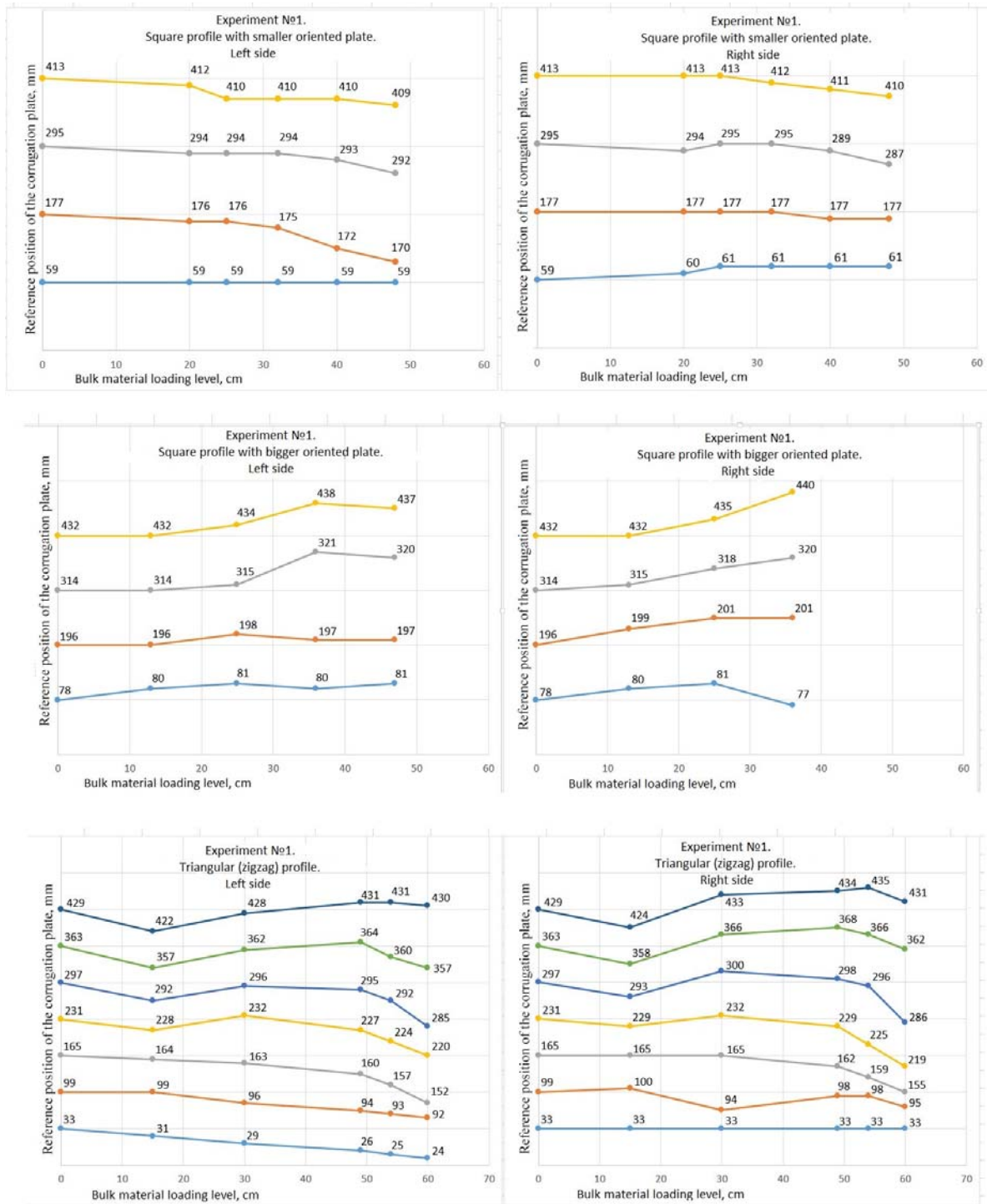


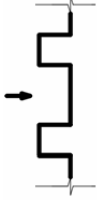
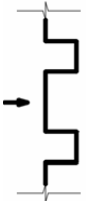
Fig. 5. Charts of displacement of corrugated panel control points when capacity is loaded with bulk material

The comparative results of computer calculation for square profiles in design and computing complex SCAD at different load patterns, which

were analysed during the second experiment, are given for full load of the capacity in the Table 1.

Table 1

The calculation results for total vertical displacement of corrugated panels

Profile type	Calculation method	Values of total vertical deformations at the appropriate load patterns, mm						
		1	2	3	4	5	6	7
	Linear	-28.39	-187.57	-164.94	-58.53	-324.83	-302.37	+5.12
	Non-linear	-10.74	-24.21	-22.38	-15.86	-27.93	-25.90	+1.4
	Linear	+39.72	-147.12	-123.04	+56.92	-346.41	-341.55	+32.47
	Non-linear	+11.02	-20.23	-17.81	+13.58	-28.41	-28.52	+8.76

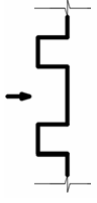
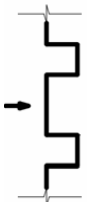
Note: The sign of deformations indicates their direction with regard to the set z-axis direction in SCAD; “+” – corrugated panel is deformed upward; “-” – corrugated panel is deformed downward.

After analysing the figures, the load patterns 2, 3, 5, 6, 7 were immediately rejected as the sign indicating the deformation direction does not comply with the real operation scheme of corrugated panel, which was observed during both experiments.

To choose the calculation method and the final load pattern the results of the left patterns 1 and 4 required the comparison with quantitative indicators obtained after the second experiment. However, if in case of the first experiment all types of profiles withstood the full load, then in case of the second one the last samples which managed to be taken before destruction of corrugated panels were at the capacity load levels of 25 and 20 cm for the square profile with smaller and bigger plates oriented to bulk material respectively. This flow of experiment occurred because the dimensions of crinkle length and height in the latter case were increased by 30%, and therefore the area of material of the corrugated panel perceiving the pressure from the bulk material decreased. Therefore, the need to compare the quantitative deformation indicators led to another simulated load situation for appropriate experimental level, as well as to additional calculations, the results of which are summarized in the Table 2.

Table 2

Values of total vertical displacements of corrugated panels under partial load

Profile type	Method of result generation	Values of total vertical deformations at the appropriate load patterns, mm	
		1	4
 $h = 25$	Linear calculation	-12.62	-26.16
	Non-linear calculation	-4.78	-7.09
	Experiment	-5.25	
 $h = 20$	Linear calculation	+8.11	+10.44
	Non-linear calculation	+2.25	+2.49
	Experiment	+2.45	

Note: h – experimental capacity load level, cm.

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It should be noted that almost all destructions of the square profile panels occurred due to loss of local stability of separate corrugation flanges at the bottom and the most loaded part of the panel (the second or third crinkle), which is shown in Figure 6, while the triangular (zigzag) profile was losing the crinkle stability almost simultaneously throughout the height (Fig. 7). The exceptions of the above information were the cases when the initial corrugation deformations (workshop faults, inadequate angle between the plates under their own weight, etc.) resulted in crinkle jamming in grooves.



Fig. 6. Panel destruction due to loss of local stability of bottom plates of the second and the third corrugations



Fig. 7. Panel destruction due to loss of local stability of corrugation plates throughout the height

Originality and practical value

Since the existing recommendation literature and regulatory framework concerning the capacitive structure design contain no information about

the features of modelling bulk material pressure on the corrugated steel elements, the conducted research and experimental tests explain and clarify the ways for possible redistribution of bulk material pressure on each corrugation plate, that is useful for correct design of containers with such walls during further calculations and search of new directions for future research.

Conclusion

Summarizing all the above, we can make the following conclusions:

1. The experimental studies resulted in qualitative determination of the corrugated wall deformation character under the load from bulk materials and obtaining of quantitative indicators of total vertical displacements for the three types of corrugation section with variable output parameters.

2. Experimental data confirmed the analysis correctness of pre-made mathematical models, in addition the numerical results obtained from mathematical modelling and laboratory experiments have very similar values.

3. Also, it is fair to say that when the diameter of the bulk material is more than ten times smaller than the size of the smallest corrugation plate, the load pattern is as close as possible to the hydrostatic one.

4. For further mathematical modelling of capacitive structures it is recommended to use non-linear calculation method and the proposed 1 and 4 load patterns, selecting the worst option for real calculation.

5. The results obtained during the experiment show promise for further development of scientific research to discover new research areas.

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ЕКСПЕРИМЕНТАЛЬНЕ ДОСЛІДЖЕННЯ РОЗПОДІЛУ ГОРИЗОНТАЛЬНОГО ТИСКУ НА ГОФРОВАНІ СТАЛІВІ СТИНКИ СИЛОСУ

Мета. У дослідженні потрібно зробити: 1) якісну оцінку характеру деформацій гофрованої стінки ємності при дії навантаження від сипучих матеріалів; 2) визначити схеми перерозподілу горизонтального тиску на кожну окрему пластину гофра та методи розрахунку, що ближчі до дійсної ситуації; 3) отримати кількісні показники деформацій для співставлення їх із розрахунковими, отриманими при моделюванні математичної моделі. **Методика.** Для досягнення поставленої мети були досліджені різні типи профілів ємнісних конструкцій та отримані значення вертикальних сумарних переміщень при дії навантаження. Для обчислювального експерименту був використаний проектно-обчислювальний комплекс Structure CAD для Windows. Крім того, проведено лабораторний експеримент, аналіз результатів якого важливий для підтвердження вірності

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ТРАНСПОРТНЕ БУДІВНИЦТВО

попередньо виконаних комп'ютерних моделей. **Результати.** В роботі, внаслідок проведеного експерименту, було знайдено підтвердження отриманих при розрахунку методом скінченних елементів (МСЕ) даних, а саме – напрямок та характер деформацій повністю (якісно та кількісно) повторював розрахункову ситуацію в SCAD. Було виконано аналіз роботи гофрованого профіля при різних теоретично ймовірних схемах навантаження та різних методах розрахунку. Також викладені рекомендації для реального розрахунку за допомогою комп'ютерного моделювання. У процесі спільного дослідження авторів були отримані дані, що дозволяють більш точно та коректно оцінити роботу гофрованих профілів при дії тиску від сипучих матеріалів. **Наукова новизна.** Проведені дослідження та експериментальні випробовування пояснюють та уточнюють способи можливого перерозподілу тиску сипучого матеріалу на кожні окремі пластини гофра, про що відсутня інформація в наявній рекомендованій літературі та нормативній базі в сфері проектування ємнісних споруд. **Практична значимість.** Застосування запропонованих рішень є корисним для коректного моделювання ємностей із гофрованими стінками при наступних розрахунках та пошуку нових напрямків подальшого дослідження.

Ключові слова: силос; ємнісна споруда; стінка силосу; гофрований профіль; експериментальне дослідження; деформації; комп'ютерне моделювання

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ЭКСПЕРИМЕНТАЛЬНОЕ ИССЛЕДОВАНИЕ РАСПРЕДЕЛЕНИЯ ГОРИЗОНТАЛЬНОГО ДАВЛЕНИЯ НА ГОФРИРОВАННЫЕ СТАЛЬНЫЕ СТЕНКИ СИЛОСА

Цель. В исследовании необходимо установить: 1) качественную оценку характера деформаций гофрированной стенки емкости при воздействии нагрузки от сыпучих материалов; 2) определить схемы перераспределения горизонтального давления на каждую отдельную пластину гофра и методы расчета, что ближе к действительной ситуации; 3) получить количественные показатели деформаций для сопоставления их с расчетными, полученными при моделировании математической модели. **Методика.** Для достижения поставленной цели были исследованы различные типы профилей емкостных конструкций и получены значения вертикальных суммарных перемещений при воздействии нагрузки. Для вычислительного эксперимента был использован проектно-вычислительный комплекс Structure CAD для Windows. Кроме того, проведено лабораторный эксперимент, анализ результатов которого важен для подтверждения достоверности предварительно выполненных компьютерных моделей. **Результаты.** В работе, в результате проведенного эксперимента, было найдено подтверждение полученных при расчете методом конечных элементов (МКЭ) данных, а именно – направление и характер деформаций полностью (качественно и количественно) повторял расчетную ситуацию в SCAD. Был выполнен анализ работы гофрированного профиля при различных теоретически возможных схемах нагрузки и различных методах расчета. Также изложены рекомендации для реального расчета с помощью компьютерного моделирования. В процессе совместного исследования авторов были получены данные, позволяющие более точно и корректно оценить работу гофрированных профилей при воздействии давления от сыпучих материалов. **Научная новизна.** Проведенные исследования и экспериментальные испытания объясняют и уточняют способы возможного перераспределения давления сыпучего материала на каждые отдельные пластины гофра, про что отсутствует информация в имеющейся рекомендованной литературе и нормативной базе в области проектирования емкостных сооружений. **Практическая значимость.** Применение предложенных решений является полезным для корректного моделирования емкостей с гофрированными стенками при последующих расчетах и поиска новых направлений дальнейшего исследования.

Ключевые слова: силос; емкостное сооружение; стенка силоса; гофрированный профиль; экспериментальное исследование; деформации; компьютерное моделирование

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