Some Aspects of the Work of Silos as Cellular Structures with Static and Temperature Effects

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Abstract. This work is devoted to studying the behavior of silos as cellular structures during their work on static and temperature effects. The paper presents the characteristic differences in the operation of metal and concrete silos, identifies their advantages and disadvantages, and considers the conditions of their work connected with the difficulty of storing “living” material backfill. The reasons for the destruction of metal silos are given. The work also evaluated the effect of surface tension of the moisture in the backfill at natural humidity and a backfill humidity higher than honest. The nature of the backfill behavior is shown depending on its moisture content. Information is given on the temperature distribution in the silo type cellular structure for seasonal and ten-day fluctuations in outdoor temperatures. It is proposed to consider the influence of these parameters in further research and design of cellular structures, including silos. It is also recommended to use the data given in the development of regulatory materials.

Keywords: Cellular structure · Silo, Backfill · Janssen’s formula · Backfill pressure · Surface tension · Poisson’s ratio · Static · Thermal

1. Introduction

Today, while ensuring food security in Russia, the increased production of grain products is noted. In contrast, with a highly competitive grain market globally, it is a matter of production and high-quality storage for the excellent quality of Russian grain. High-quality storage of grain is essentially its second birth, the second crop. However, at the same time, this issue affects many aspects of the storage process at once. These include conditions of grain drying, processing, and the multifactor method of direct storage of grain in a silo, the success of which is ensured by observing the temperature and humidity conditions, the quality characteristics of the grain itself, as well as the characteristics that affect the joint work of the grain and silo (cellular structure), which are expressed through the following parameters: the angle of repose of the backfill material, its volumetric weight when filling the silo, its moisture and thermophysical characteristics.

Many of these factors are associated, among other things, with intricate modern grain storage designs – silos and bins. Let us open the veil of physical processes that occur in the silo to monitor the granary's proper operation, understanding how it works.

2. Materials and Methods

Grain storages in Russia are mainly divided into two types, depending on the silage frame (cell) material: concrete or metal structures. In the Soviet Union, most elevators were square monolithic concrete structures; they were distinguished by sufficient reliability and an extended warranty work duration. At
the same time, high-quality grain storage was ensured with a significant volume. The first Soviet silos date to 1938. And these silos have not yet lost their operational quality. This is especially noticeable where their viability is maintained at an acceptable level. These elevators have official land allocation and reliable official communications. Serious operators and researchers predict a long-life span for such concrete structures (silos) with a severe attitude. They will work and continue to make a profit [5].

However, today, with insufficient funding for the need for quick solutions with minimal investment, very often switch to the use of metal elevators in the form of metal “bulbs”. The analysis of accidents of metal silos shows that they are associated with a lack of experience in design and construction, as well as inappropriate operations. Many customers do not want to finance engineering surveys and design work, but use ready-made solutions of factory-made steel silos, leading to major accidents and, accordingly, grain losses.

3. Results
According to the literature [1], the following causes of accidents can be distinguished based on statistical data, which are presented in Figure 1. As can be seen from the figure, almost 50% of accidents are caused by defects in the direct manufacture and installation of metal silos. The second main reason is unreasonable design decisions; the third place is the lack of proper monitoring and proper operation.

![Figure 1. Statistics of accidents of silos [1].](image_url)

In this regard, it should be noted that metal silos for grain storage are new constructions from their application in various regions of Russia. Their application should be carried out using the following procedures: analysis of construction conditions (natural – climatic, geological, and hydrogeological conditions), a wide range of engineering surveys, design work, analysis of the materials used, manufacturing technology and installation of structures, the correct determination of loads and impacts, continuous monitoring and compliance with the operating rules of this particular structure.

The data obtained during monitoring should be processed online and immediately received by the customer. According to the results of the analysis of the operation of metal silos, it is fashionable to attribute them to hazardous production facilities that require increased attention and responsibility at all stages of the production cycle.

When taking into account and observing the above requirements, the question of the interaction of the silo (honeycomb frame) and backfill (grain storage) remains essential, since the pressure of the grain on the walls of the silo when filling the silo, storage (static state of the grain) and unloading are sharply different and are one of the main roads leading to damage.

According to [4, 7-8], a mathematical explanation of grain pressure law in a silo was outlined in the 19th century by a German engineer Janssen: and is still used. Therefore, the processes of grain pressure in silos have been studied for a long time.

Why are silos damaged more often during unloading?
During these studies, it was found that there are two main types of loads:

- **Static**: occurs when filling and storing the product.
- **Dynamics**: occur when emptying – unloading the tank.

Since the horizontal pressure on the silo walls increases significantly when unloading the grain, damage to the silos occurs more often during the silo's emptying. The walls of a cylindrical silo are designed based on an analysis of the distribution of ring stresses and vertical compression stresses, based on the assumption that these internal force factors are distributed axisymmetrically. The same hypothesis is the main one in the implementation of the silo loading-unloading process. This type of operation is called the “central flow” (figure 2).

![Figure 2](image-url)  
**Figure 2.** Standard grain silos are designed for central discharge—source: [4].

“Central flow” is the grain that has come into motion in the center of the silo because of the opening of the valve in the bottom along the axis of the structure. Subject to the system's symmetry and the grain backfill movement in the zone between the central flow and the walls, the grain remains at rest until the flow channel begins to contact the vertical wall of the silo. Furthermore, increasingly new layers of the grain are involved in the movement.

Significant non-uniformity of the process occurs whenever the stored grain enters the funnel formed inside the stationary backfill material, and this funnel touches the wall of the skeleton – silo. Such irregularities are observed in all silos with the product's expiration in the form of a “central flow”. The pressure in the cylindrical silo due to these irregularities causes a bending force group (instead of the membrane). It leads to skew-symmetric deformation, which causes a local loss of stability of the thin-walled silo shell.

![Figure 3](image-url)  
**Figure 3.** Active deformation of the silo. **Source**: [4].

According to our computational studies of the backfill pressure in the cell using the STADIO program [6-9], the influence of the external friction angle of the backfill, deg. On the value of the vertical and horizontal backfill pressures on the cell ($\sigma_z$ and $\sigma_x$), results are obtained close in values 10% to the results determined by the Jansen formula when the angle of external friction in the calculations varies from 0 to 15 degrees since the Jansen solution does not take into account the possibility of deformation walls of the silo. Numerical studies made it possible to take into account the deformation of the honeycomb frame and reveal a change in the lateral pressure coefficient with height by increasing it from the top of the cell to the bottom of the silo by about 10% relative to the average value adopted in the Jansen
formula. Thus, the deformability of the silo is essential and should be taken into account in the calculations. The angle of external friction at values greater than 15 degrees also affects the stress-strain state of the system “the silo – backfill – base” and, with the deformability of the walls of the silo, the horizontal displacements of the walls increase cells significantly and backfill in the lower zone of the silo.

Moreover, computational studies have revealed a significant effect of a change in the value of the Poisson’s ratio \( \mu \), which can be associated with the cell frame’s deformative properties – silo. It was found that, with an increase in \( \mu \) from 0.05 to 0.4, \( \sigma_z \) increases approximately 2.0 times, and \( \sigma_x \) approximately 8–9 times.

The performed computational studies have revealed a significant relationship between the stress-strain state of the silo-backfill complex depending on the ratio of their deformation and elasticity moduli \( - \frac{E_k}{E_z} \): an increase in the backfill elasticity modulus by a factor of 10 relative to the initial \( E_z = 29 \) MPa causes an increase in compressive stresses 1.9 times, and lateral backfill pressure 1.6 times.

Considering the properties of the silo base will make its adjustments to this problem's solution and complicate it. This once again emphasizes the importance of considering hydrogeological data when selecting a silo for specific conditions.

The conducted experimental studies revealed another feature of the behavior of the frame (silo) – filling (grain) system. In courses of the action of the wet backfill of cells, one can observe the relationship between the surface tension of the liquid contained in the damp backfill of the section with the vertical \( \sigma_z \), lateral \( \sigma_x \), and the tangential \( \tau \) stresses of the pressure of the wet backfill in the cell [8].

Figures 4a and 4b show the study of freezing of the backfill material on the cell walls. The backfill of natural humidity hangs on the backfill walls during the movement of the cell frame, and part of the weight of the backfill is transferred to the edge, as can be seen from Figure 4b - at a specific moisture content of the cell backfill. Thus, we can talk about a certain stress \( \sigma_{st} \), which can be called the surface tension stress for wet filling and determined by the formula (2) that we propose.

The force of “surface tension” acting on the backfill and holding its shape following the shape of the cell frame (silo), we denote

\[
P_{s.t.} = \frac{F}{u} \cdot \sigma_z = R \cdot \sigma_{st} \frac{N}{m} \tag{1}
\]

where \( F \) is the cross-section of the material of the cell backfill (the cross-sectional area of the cell frame in the light), \( u \) is the perimeter of the cell cross-section (in the morning), \( \sigma_z \) is the vertical pressure in the cell at a depth \( Z \) from the action of gravity [8].

Thus, the behavior of the backfill in the section is therefore affected by the ratio of the hydraulic radius of the cross-section of the backfill of the cell \( R = \frac{F}{u} \) and the wetted perimeter \( u \), as well as the cross-sectional area \( F \) - their ratio and soil moisture will or will not allow the formation of the required surface tension in filling material to keep it in equilibrium (when there is practically no freezing of the filling on the cell walls) and almost the entire weight of the filling material is transferred to the bottom of the cell.

Substituting in the formula (1) the value of \( \sigma_z \) according to the procedure H. A. Janssen, we get:

\[
P_{s.t.} = R \cdot \sigma_z = R \cdot \frac{\gamma}{\xi \eta \delta} \cdot R \cdot \left( 1 - e^{\frac{-\xi \eta \delta Z}{R}} \right) = R^2 \cdot \frac{\gamma}{\xi \eta \delta} \cdot \left( 1 - e^{\frac{-\xi \eta \delta}{R} Z} \right) \cdot N/m \tag{2}
\]

Qualitatively, the effect of the surface tension of the moisture contained in the backfill is shown in figure 4b, where the cell backfill material has a moisture content of about 5% by weight. It is necessary to evaluate this process's effect for silos, especially when the grain is released from the silo, specifying the values of the new coefficients given in the formula.
Figure 4. The interaction of the frame and backfill cell: a – with the natural moisture content of the material filling the section; b – when the moisture content of the filling is higher than natural (humidity 5% by weight). Source: [8].

When conducting numerical studies using the “Kvazis” program [2], we studied the distribution of temperature fields for a ring structure of concrete with a thickness of 0.6 m on temperature effects in the presence of backfill and without it [8].

As shown by the results of numerical studies, the presence of backfill significantly reduces the seasonal temperature fluctuations in January and April compared to a design that works without filling the cells with backfill material and reduces the depth of their penetration into the cell. This circumstance allows us to talk about the possibility of regulating the temperature in the section with an appropriate selection of design parameters. It is also necessary to check the operation of structures for the effects of ten-day fluctuations in outdoor temperatures. For metal silos in conditions of a significant temperature difference, a heat shield can be provided on the silo's surface.

All conducted studies indicate the need for further experimental and theoretical studies of the distribution of the load on the walls of the cellular structure, including taking into account the variability of limitations and the spatial work of the walls of the cellular frame using modern computer modeling systems [3, 7].

4. Conclusion
The work of the cellular structure as a complex “frame-backfill-base” is still a challenging task. It can be solved only with the help of a combination of volumetric computational and model studies. And the data presented in work can be used in the design and development of regulatory documents.

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