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1.1 Investigation of metal silos structures to determine the cause of their destruction

The silos to be inspected are located on the territory of the complex of the grain-receiving enterprise in the Khmelnytskyi region. Nine silos are located in a cascade and are connected to each other in a common technological process by galleries above the silos (Fig. 1, 2, 3). Each silo is 27,4 m in diameter, the wall height is 18,7 m, the total height with the dome cover is 27 m.

At the time of the survey, five of the nine silos were destroyed (Figs. 2, 3). Their numbers in order of destruction: #9, #7, #5, #3, #4.

From the time of completion of the construction of the metal silos to their inspection, about five years have passed. More than half of this period has passed since the beginning of the gradual and successive destruction of the structures of their conical coatings.

Figure 1. Aerial photography of the territory of the enterprise in the Khmelnytskyi region, before the destruction of the silos (photo from Google maps)

Figure 2. View of the silos from the southeast, after the destruction of the silos

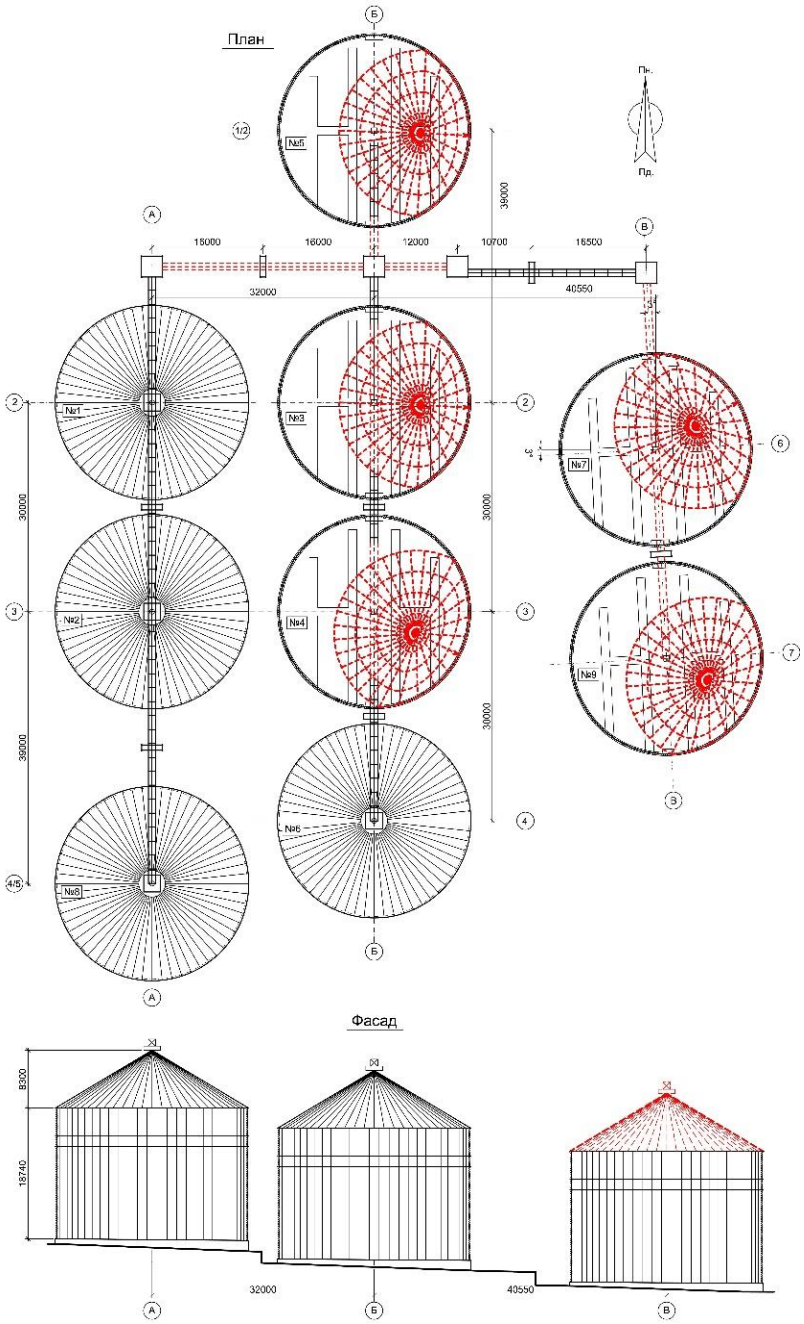


Figure 3. Layout of silos

The technical survey was carried out with the aim of recording the actual nature and directions of destruction of the structures of the conical coverings of the silos, the technical condition of individual structures of the silos, and recording the discovered imperfect technical and design solutions that led to the destruction of the silos.

The expected result of the survey is an assessment of the influence of the slopes of the foundations, the depth of their laying, engineering and geological conditions, territory planning, structural features of the elements of the galleries above the silos and their intermediate vertical supports connected with the silos in one general technological process, on the actual technical condition existing silo facilities.

The results of the examination are necessary to determine the causes of the destruction of the conical coverings of silos and their elements, and to prevent the identified imperfections in the development of design solutions for structures of this type.

The analysis of the available archival documentation made it possible to determine and assess the state of the silo facilities in their pre-emergency period. This analysis included:

- constructive decisions on silos of models 85-09022 and 85-09024 [1] and data on their operational loads;

- schemes of technological combinations of silo structures;

- constructions of foundations of silos;

- design solutions for the location of silo foundations on engineering-geological sections;

- the actual location of silo foundations on engineering and geological sections, taking into account the natural topography of the territory;

- determination and analysis of the directions and values of the maximum slopes of the foundations of all silos;

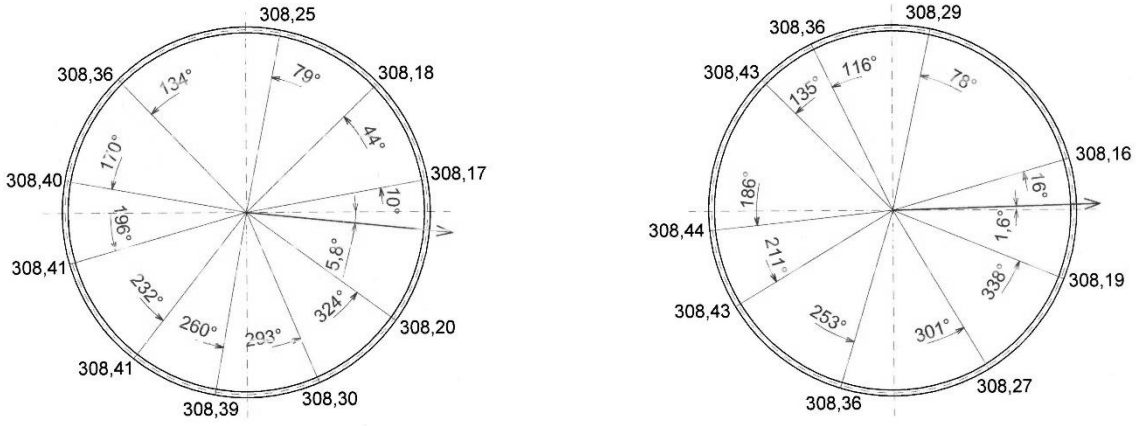
- determination of the maximum differences in the marks of the opposite sides of the foundations according to the directions of their maximum tilts;

- determination of the maximum and minimum depths for laying the soles of silo foundations in the directions of their maximum slopes.

Analysis of the vertical movements of the edges of the reinforced concrete ring foundations of nine silos by marking fixed points along the perimeter of their edges to determine the directions of the maximum tilts of the foundations.

Markings at fixed points along the perimeter of the edges of the reinforced concrete ring foundations of nine silos, to determine the directions of maximum tilts and foundations *i*, were taken according to measurements before the destruction of the roofs of the silos (provided by the owner of the enterprise).

The angles of attachment of the beams from the center of the foundation to the marks along their perimeters β are determined. For example, the markings on the perimeters of the foundations for silo #1 and silo #2 are shown in Fig. 4.



а б

Figure 4. The angle of direction of the maximum inclination of the bank and foundations of the silos: a – #1; b – #2

The values of the angles of the directions of the maximum inclinations (tilts *i*) of the foundations of the silos were determined by the values of the vertical movements of the edges of the foundations of the silos # 1-9 at fixed points located on the rays with angles from the origin of the coordinates in the center of the silos.

The angles of the directions of the maximum slopes of the foundations of the silos were determined according to the method [2] for calculating the values of φ_{11}, c_{11}, γ_{11} at the confidence probability α, which is accepted for calculations according to the second limit state, which is equal to 0,85. Then, using this formula, we determined the

weighted average value of the angle of the directions of the maximum slopes of the foundations:

$$\beta = \sum_{i=1}^{n} \beta_i \cdot h_i \Big/ \left(\sum_{i=1}^{n} h_i \right);$$

where:

β_I is the value of the angles to the ith value of the vertical movements of the fixed points;

h_i – marks of vertical movements of the fixed points along the perimeters of the edges of the ring foundations.

Depths of laying the foundations according to the maximum directions of the slopes of the foundations.

The calculation of the foundation laying depth is performed according to the norms [2] and taking into account the standard [3]. The normative depth of seasonal soil freezing for silos is d_{fn} =0,77 m, the estimated depth is d_f =0,847 m.

The design of the bases and foundations must include measures that prevent the soil of the base from becoming wet, as well as freezing during the construction period. At the same time, the level of groundwater should be taken taking into account its forecast for the period of operation of the structure and the impact of water-reducing measures on it, if they are foreseen by the project.

The foundations of the structure or its compartment must be laid on the same level. If it is necessary to lay adjacent foundations at different marks, their permissible difference Δh is determined based on the condition:

$$\Delta h \le a \cdot \left(tg\varphi_I + \frac{c_I}{p} \right),$$

where:

a is the distance between the inner faces of the foundations;

φ_I and c_I are calculated values of the angle of internal friction and specific soil adhesion, respectively;

p is the average pressure under the sole of the foundation located above from the calculated loads (for calculating the foundation based on its bearing capacity).

As you can see, requirement of norms [2] is not taken into account in the territory planning project, and the depths of the foundations of silos #2 (d=0,745 m) on the eastern side and #3 (d=0,4 m) on the northern side are smaller for the depth of freezing.

An analysis of the provision of the actual horizon of foundation cuts on all silos based on the root-mean-square deviations from the straight (conditional design plane) values of the absolute marks by straight-line approximation was performed. The approximation line shows the weighted average slope of each silo.

We determined the minimum and maximum depth of foundation laying *d* (from the opposite sides of the silos). The actual differences in the ΔS_{ϕ} marks were determined in the direction of the maximum slope of the foundations. Limit slopes of the foundations were taken as i_u =0,004.

Determination of the technical condition of structures.

The assessment of the technical condition of the silo structures was carried out based on a set of data: analysis of available archival documentation, measurements of the structures, results of visual and instrumental inspection, photos of the condition of the silo structures after their construction and during the period of gradual destruction of their coatings, determination of concrete strength characteristics, assessment of the impact of defects on the condition of structures and their corresponding assessment and classification at the time of inspection by categories of technical conditions [4].

The general technical condition of silo foundations can be attributed to "3" category of technical condition.

The general technical condition of the bottoms of the silos can be attributed to the "3" category of technical condition.

Metal cone coverings of silos #9, 7, 5, 3, 4 are in the "4" category of technical condition, emergency.

Part of the metal trusses of the galleries above the silos are in the "4" category of technical condition, emergency, and some are in the "3" category.

Part of the metal structural and load-bearing elements of the intermediate

supports of the galleries above the silos, which are standing separately, have structural and strength defects in the nodes of fastening of braces and braces to the racks, as well as the absence of braces and braces since installation. They are in the "3" category of technical condition.

The walls of silos #9, 7, 5, 3, 4 are in the "3" category of technical condition.

During the survey, the rigid attachment of the spatial lattice trusses above the silo conveyor galleries to the central ring of the conical coverings (Fig. 5) was recorded through a "chair", which is a faulty technical solution.

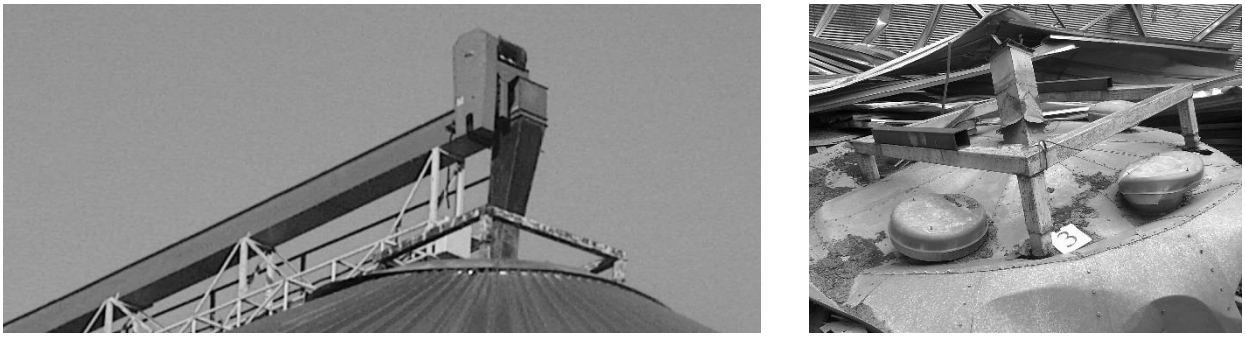


Figure 5. Rigid fastening of the lattice trusses of the conveyor galleries above the silos through the "chair" to the central ring of the conical cover

The foundations of the intermediate vertical supports of the galleries above the silos, which are connected to the foundations of the silos with different stiffness, with significant and different directions of the foundations of individual silos connected by inseparable galleries, affected the destruction of the coatings.

Some structures of intermediate supports are overloaded or have significant defects, damage, unreliable execution, which indicates an unconditional decrease in their bearing capacity and the need for repair. Part of the load-bearing elements of the intermediate supports above the silo galleries are in the 3rd category of technical condition (Fig. 6). This is due to the fact that the lattice structures of the intermediate vertical supports of the galleries have structural and strength defects in the nodes of fastening of braces and braces to the posts, as well as the absence of braces and braces since installation.

Photofixation of structural and load-bearing elements of silos was carried out,

which helped to assess the impact of defects and damage on the sequence of destruction of silo coatings (Fig. 7) and the silos themselves.

Figure 6. Lattice vertical rack between silos #4 and #6 and continuous lattice truss of the conveyor gallery

Figure 7. Hanging of the destroyed elements of the load-bearing structures of the conical coverings of silo #5 on the contour of its wall

Conclusions.

Based on the analysis of archival data and taking into account the data of the survey, it was established that the soles of the eastern side of the foundations of the silos rest on layers of soil that can be classified as bulk, since their physical and mechanical characteristics are not identified and specified in the engineering and geological report.

The lack of drainage from the inner sides of the retaining walls and the absence of drainage trays along the retaining walls were established. The actual planning of the site showed that the conditions of the closed areas around the silos contribute to the accumulation of water in the soils under the foundations of the silos, taking into account the slope of the soil layers and their reduced filtration coefficient. At the time of the survey, the actual planning of the territory around the silos does not correspond

to the design decisions.

Analysis of the calculations showed that the lower the silos are located in the cascade, the greater their tilt, even with a greater depth of foundation laying on the eastern side of the silos. The smaller the depth of foundation laying on the eastern side of the silos, the greater the increase in deformations of the base and tilting of the foundations of silos located at the level of one cascade, regardless of the condition of the silos themselves.

Based on the above data, we came to the conclusion that the cause of the beginning of the destruction of all silos is a significant inclination of the foundations of silos #9 and #7 towards each other, which caused significant forces from the movements of the tops of the conical coverings of silos #7 and #9, which are directed toward each other to the second.

The reason for the destruction of silo #9 in the first place is its falling component of the slope towards silo #7 and the elastic support of the gallery truss above the silos on the first intermediate corner support. An intermediate corner support is located on the northern side of silo #7, to which one end of the gallery's continuous truss is fixed. The continuous truss of the gallery along its length has three more supports: the top of the cover of silo #7; intermediate support between silos #7 and #9; top of silo cover #9. The continuous truss of the gallery was rigidly fixed to the tops of the conical structure of silo covers #7, 9 and had sufficient longitudinal rigidity to transmit and redistribute forces from the total horizontal movement of the tops of silo covers #7 and #9 towards each other. The total horizontal movement is: $\Sigma U_x = U_{7x} + U_{9x} = 89{,}13 + 104{,}89 = 194{,}02$ mm.

The directions of horizontal movements of the tops of the conical covers of silos #7 and #9, which are directed toward each other, are components of the recorded maximum tilts of the foundations of these silos.

Vertical movements (directed downwards) of the tops of the conical coverings: silo #7 – ($-U_{7z}$)=45,8 mm; of silo #9 – ($-U_{9z}$)=54 mm.

The destruction of the cover of silo #9 caused a chain horizontal reaction through the trusses of the galleries above the silos, fixed on intermediate supports, which

successively led to the deformation of the supporting elements of the conical covers and their gradual successive destruction under the influence of the accumulation of a complex of factors: inconsistencies in the slopes of the foundations of various silos with the horizontal movement of the trusses of the conveyor galleries; differences in the average vertical movements of silo foundations at the level of one terrace and different terraces; uneven snow loads and ice loads on deformed roofs of silos.