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DIAGNOSTICS OF STRESS STRAIN STATE OF SOIL FOUNDATION SILO SYSTEM AND ITS IMPACT ON STRUCTURAL CONDITION OF FACILITIES

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Abstract- The article considers a comprehensive approach to assessing the technical condition of the Soil-Foundation-Silo System (SFSS). The absence of standardized diagnostic methods for silo foundations complicates the prediction of residual service life and the assurance of safe operation. The proposed two-level methodology combines analytical checks, finite element modeling in Praxis 3D, and field geodetic monitoring. The scientific contribution of the study lies in developing an integrated diagnostic procedure with quantitative threshold values of key indicators (settlement, tilt, crack opening), which provides an algorithmic classification of silos by technical condition categories. The practical effectiveness of the methodology was confirmed by a case study of a group of metal silos with a diameter of 23.78 m on collapsible soils, where the decisive influence of the compacted backfill condition on stress distribution and deformation irregularity was established. The results provide a basis for further development of semi-empirical models for silo groups that account for mutual interaction and loading scenarios, which would reduce the dependence of engineering practice on complex 3D modeling.

Keywords: Stress-Strain State, Steel Silo, Soil-Foundation-Silo System, Structural Condition, Uneven Deformations, Settlement, Geodetic Monitoring, Geotechnical Monitoring, Foundation Diagnostics, Finite Element Method.

1. INTRODUCTION

Corrugated steel grain silos are among the most widespread structures for storing agricultural products. Their massive size, substantial loads from bulk materials, and cyclic loading-unloading processes form a complex stress-strain state (SSS) within the Soil-Foundation-Silo System (SFSS) [1]. Reliable prediction of this state is essential for improving structural reliability and ensuring the safe operation of silos.

Modern studies confirm that the distribution of grain pressures on silo walls and bottom slabs is highly non-uniform and varies with operating conditions. Full-scale experiments have been carried out to investigate the loading characteristics on the bottom and walls during cyclic filling and emptying processes [2, 3]. These data make it possible to improve silo load models that account for both spatial and temporal variability.

In parallel, research is progressing toward improving the reliability of evaluating the performance of silo foundations and subsoil. In particular, experiments with circular slab foundations on sandy [4], clayey [5], and layered [6] soils demonstrate that classical simplified approaches do not always adequately capture the stress distribution and settlements, especially for large-diameter structures. These findings stimulate the development of analytical modeling approaches for the "slab-soil" system, including the use of classical Winkler and Pasternak foundation models, which allow for consideration of the spatial variability of subsoil stiffness [7]. In this context, modern refinements of classical solutions are also important, particularly the generalization of Bossiness's problem for the case of a non-homogeneous half-space where deformation moduli vary with depth [8].

A key focus of current research is the integrated consideration of geotechnical [9] and structural parameters [10, 11]. For example, the analysis of an industrial coal silo demonstrated that neglecting the interdependence between wall stiffness and subsoil behavior leads to significant errors in predicting the SSS of the SFSS, confirming the need for an integrated modeling approach [12]. Operational experience and failure cases of silo complexes further emphasize the critical importance of foundation design. Full-scale experiments have confirmed that incorrect assumptions regarding the joint performance of ring and slab foundation elements can lead to failure scenarios [13]. In addition, analyses of silo construction practices on loess soils have revealed the risk of excessive settlements caused by moisture-induced softening and loss of structural

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strength of the subsoil at the early stages of operation [14]. Notably, there is also an example of probabilistic analysis of the deformation behavior of soil-cement foundations for metal grain silos [15].

The assessment of the technical condition of existing foundations is becoming increasingly important. Recent publications focus on combining inspection (monitoring) data with computational models to refine the bearing capacity and residual service life of circular reinforced concrete silo foundations [16]. This integrated approach improves the reliability of evaluations and enables the timely identification of the need for strengthening elements of the SFSS. In the search for effective structural solutions for complex geotechnical conditions, including collapsible and weak soils, both numerical and full-scale studies have demonstrated the advantages of piled raft foundations [17], various types of rigid subsoil reinforcement [18], and artificially compacted or stabilized ground bases [19]. It has also been found that under prolonged cyclic loading, residual deformations accumulate in pile systems, which must be considered in the design process [20].

In parallel with the improvement of foundation solutions, there is growing interest in the use of lightweight and high-strength structures for the above-ground part of silos. A promising direction is the application of composite cylindrical shells, which, due to their high specific strength and corrosion resistance, may outperform traditional steel counterparts while reducing loads on the foundation. Their low weight allows for the use of designs both with and without stiffening ribs. However, the friction of bulk materials against the walls requires assessing the shell's resistance to localized stresses [21] and evaluating the necessity of structural reinforcement [22]. This opens prospects for the development of a new generation of energy-efficient and reliable silos.

This paper aims to define and justify the sequence of procedures necessary for evaluating the SSS of the SFSS in order to determine the structural condition and forecast the remaining service life of the structures. The main scientific contribution of this study lies in establishing a two-level approach to assessing the technical condition of the SFSS under complex geotechnical conditions. The proposed methodology integrates analytical checks and FEM modeling into a unified diagnostic procedure, with quantitative threshold values of key indicators (differential settlements, tilt, crack opening) for classifying structures by technical condition categories. This provides an algorithmic classification scheme that ensures a reproducible transition from field data to engineering interpretation. The practical effectiveness of the approach was confirmed by a field case of a group of metal silos on a collapsible subsoil.

2. ANALYSIS OF KEY FEATURES OF SFSS

Steel silos are vertical cylindrical containers constructed from corrugated steel sheets and installed on various types of foundations. In most cases, they are arranged in groups connected by underground unloading and overhead loading technological galleries, conveyors, and transport systems. Such a spatially integrated arrangement imposes increased requirements for the uniformity of foundation settlements for each silo. Structural solutions for steel silo foundations, depending on subsoil conditions and technological requirements, are most commonly implemented in the following configurations:
- monolithic reinforced concrete slab;
- ring foundation combined with a separate bottom slab and a sub-silo gallery (classic scheme);
- slab-and-raft systems designed with consideration of gallery layouts and the need for subsoil reinforcement;
- combined foundations with the use of soil-cement elements (SCE) on weak or collapsible soils.

In particular, the most widespread in Ukraine are classical design solutions that were extensively implemented during the period of intensive construction of silo complexes approximately 20 years ago. This structural scheme includes a ring foundation supporting the silo walls and a separate bottom slab connected to the sub-silo gallery. The geometric parameters and structural design of the ring foundation are determined by the calculated loads on the silo walls and the properties of the subsoil.

The bottom slab and gallery are generally designed in accordance with technological requirements (aeration systems, conveyors, central grain discharge). A compacted sand fill is typically arranged beneath the bottom slab. In some cases, an expansion joint is provided between the ring foundation and the bottom slab, although there are also solutions with rigid or hinged connections [23]. Underestimating the interaction between the bottom slab and the ring foundation can lead to operational issues, localized deformations, and even failure scenarios [13]. From a structural perspective, the silo foundation consists of 3 interconnected elements: the bottom slab, the sub-silo gallery, and the ring foundation strip (Figure 1).

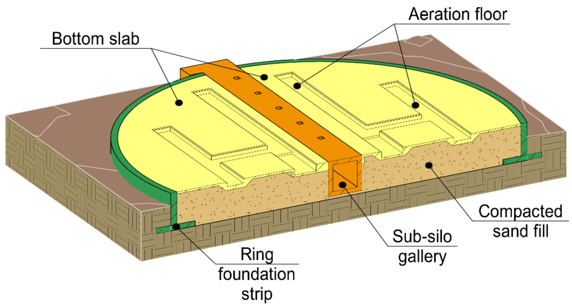

Figure 1. Layout of the silo foundation considered in this study

The bottom slab, divided by the gallery into two parts, rests on the gallery on one side and is either rigidly connected to the ring foundation strip along the perimeter or separated from it by an expansion joint, bearing on the inner ledge of the footing through a layer of compacted backfill. The slab behaves as a two-way bending element while additionally resisting tensile forces in the radial direction (similar calculations are provided in the Australian standard AS 3774 (1996) but are absent in the current EN 1991-4). Transverse compressive forces are not considered due to their negligible effect on the slab's performance.

The sub-silo gallery is located beneath the bottom slab and is usually connected to it either rigidly or by a hinged joint, while being separated from the ring foundation strip by an expansion joint. The gallery serves as a stiffness element, carrying part of the forces from the slab and creating asymmetry in the foundation's behavior. Its high longitudinal bending stiffness enables the transfer of effects from adjacent silos connected by technological lines. In the transverse direction, the combined stiffness of the gallery and the slab is lower, which leads to tilting of slab sections relative to the gallery when silos in neighboring rows experience settlement. Under such conditions, the gallery behaves as a beam-like element subjected to biaxial bending and transverse torsion.

The ring foundation strip is the main element of the foundation that resists vertical forces from grain friction against the silo wall, active horizontal pressure from the compacted backfill beneath the bottom slab, and vertical pressure from the bottom slab. External horizontal actions are partly balanced by the passive earth pressure beneath the footing, which makes the embedment depth a decisive parameter. Insufficient embedment depth causes the predominance of tensile forces in the strip and creates a risk of rupture.

The interaction between the ring foundation strip and the gallery causes uneven deformations along its perimeter even without additional settlements from adjacent silos or subsoil heterogeneity. The ring strip also resists non-uniform loads from wind action. Overall, it behaves as a beam element on a soil foundation with vertical bending, tension, and torsion induced by the unbalanced pressure of the backfill. These structural and performance features of silo foundations demonstrate the need for a thorough assessment of their condition.

3. DIAGNOSTIC CHALLENGES OF THE STRESS-STRAIN STATE IN EXISTING SILOS

Diagnostics of the SSS of the SFSS in structures already in operation remains a challenging task. In most cases, there are no standardized methodologies or algorithms capable of providing an objective assessment of the structural condition. Existing inspection practices are typically limited to visual surveys and various types of instrumental measurements, which do not always provide a complete picture of the interaction between the elements of the SFSS. In addition, there is a lack of studies on the redistribution of loads between the wall and bottom slab in cases of uneven bottom deformations and silo tilting.

In the absence of validated analytical solutions, engineers rely on simplified assumptions or resource-intensive numerical models that require considerable expertise. Diagnostics should include not only the identification of defects but also the determination of their causes and mechanisms of development, which necessitates analyzing the operational history of the structure, including loading and unloading regimes, accidental events, and changes in the performance of the subsoil and foundations.

A significant problem is the unknown initial conditions: the actual state of the subsoil and the quality of foundation construction at the time of building are often undocumented. It is also difficult to account for the repetitiveness and loading rates characteristic of silo cyclic operation, which cause the accumulation of residual deformations. Combined with the lack of comprehensive methodologies, systematic monitoring, and effective analytical tools, this reduces the accuracy of assessing the SSS of the SFSS and complicates reliable prediction of the residual service life of the structure.

4. METHODS AND APPROACHES FOR SSS ANALYSIS OF THE SFSS

The analysis of the SSS of the SFSS in existing silos requires a combination of analytical methods, numerical modeling, and monitoring. The main tool remains the Plaxis 2D/3D software package, which makes it possible to construct spatial models of structure-soil interaction considering the nonlinear behavior of soils. At the same time, difficulties persist in the joint modeling of the SSS of reinforced concrete elements with the soil foundation.

Despite the broad capabilities of FEM, its application to silo foundations is associated with several challenges. The sub-silo gallery introduces asymmetry in the stress distribution, making it impossible to use simplified axisymmetric 2D models. To accurately capture the behavior of the SFSS, full-scale 3D modeling is required, which demands substantial computational resources and detailed data on both the soil and the structural components.

The absence of clear approaches for determining the depth of the compressible zone for circular foundations with a combined structure (ring foundation strip, bottom slab, and gallery) also introduces additional uncertainty. Classical criteria (e.g., the 20% condition between stresses from self-weight and additional applied pressure) require further refinement when applied to foundations of this type.

In Plaxis, soils are mainly described using the Mohr-Coulomb and Hardening Soil models. The MC model is characterized by simple parameterization (E, φ, c) and fast computations, which makes it suitable for preliminary assessments and scenario analysis. The HSM provides a more accurate representation of soil behavior under repeated complex loading, as it accounts for compaction and the stress-dependent stiffness moduli (E_{50}, E_{oed}, E_{ur}). Its use requires broader input data and calibration, and the calculations take longer. When the necessary data are available, however, the HSM ensures a more reliable evaluation of the SSS in complex conditions and for predicting residual deformations.

Monitoring is the primary source for validating models. Geodetic measurements of tilts, settlements, and crack openings record deformations and their dynamics. Systematic observations make it possible to timely identify critical areas and adjust computational schemes [23]. For practical diagnostics, it is advisable to develop simplified analytical and semi-empirical methods that estimate forces in foundation elements without detailed soil modeling. The approach presented by the authors [24] analyzes ring foundations and bottom slabs as planar elements using analytical relationships and provides rapid preliminary values of internal forces and deflections, with subsequent refinement based on monitoring data and FEM.

5. RESEARCH RESULTS

Field studies were conducted on a group of 6 silos, each with a diameter of 23.78 m and a capacity of 7.760 m³. The structural scheme corresponds to that described earlier (Figure 1). The bottom slab rests on a compacted layer of backfills soil. At the center of each silo there is a box-shaped underground gallery (2.2 × 2.6 m) with 300 mm thick walls, which is connected to the bottom slab and supported by the ring foundation strip. The embedment depth of the foundation footing from the ground level is 1.8 m. The engineering-geological cross-section of the site with reference to the foundations is shown in Figure 2, and the soil properties are presented in Table 1.

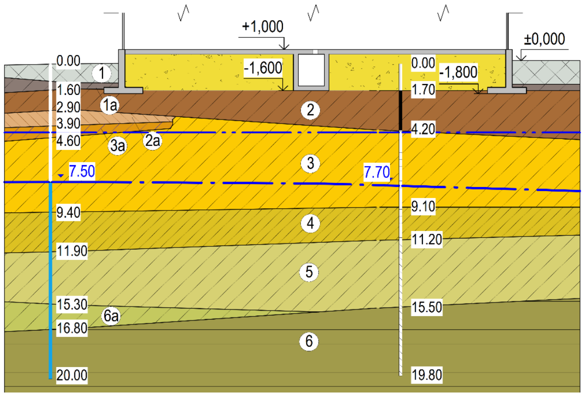

Figure 2. Engineering-geological cross-section of the site and silo foundations: 1) fill; 1a) humus-bearing loam; 2, 2a) heavy silty loams, stiff-plastic; 3a, 3) light silty loams, soft-plastic; 4) heavy silty loam, stiff-plastic; 5) light silty loam, soft-plastic; 6a) heavy silty loam, stiff-plastic; 6) light silty clay, semi-solid.

Table 1. Physical and mechanical properties of the natural foundation soils of the silos

EGE No.	Physical and mechanical properties of soils				
	γ, kN/m³	e	c, kPa	φ, deg	E, MPa
1	18.0	-	-	-	-
1a	17.5	-	-	-	-
2	18.0	0.83	16.2	18	6.0
2a	18.0	0.82	15.9	18	5.0
3a	18.1	0.82	12.2	18	4.0
3	18.2	0.8	13.6	18	5.0
4	18.8	0.77	27.7	16	10.0
5	18.3	0.77	13.0	17	7.0
6a	18.9	0.76	19.6	20	12.0
6	19.2	0.72	32.1	16	18.0

The geological structure of the site to a depth of 20 m is composed of Quaternary heavy and light silty loess-like loams, specifically engineering-geological elements EGE-2, EGE-2a, EGE-3, EGE-3a, EGE-4, EGE-5, and EGE-6a, underlain at approximately 15 m by light silty clays (EGE-6). Loess loams exhibit subsidence potential down to a depth of 7.2 m. Due to groundwater influence, loess elements EGE-2, EGE-2a, EGE-3, and EGE-3a are in a degraded state. At a depth of 1.7-2.2 m, the loess deposits are overlain by fill soils (EGE-1).

In 2022, as part of a technical inspection, a comprehensive set of investigations was carried out, including engineering-geological surveys, visual examination of structures with defect documentation, determination of relative settlement irregularities along the silo perimeter by leveling the ring foundation strip, as well as the construction of settlement profiles for the bottom slab and the ceiling of the sub-silo gallery based on geodetic surveying results (Appendix 2).

Visual inspections and bottom slab leveling revealed significant tilting, indicating insufficient compaction quality of the backfill during construction. An additional adverse factor was inadequate drainage: damage to the paving and failures in underground utilities led to prolonged localized wetting of the loess collapsible foundation soils, which intensified uneven settlements. As a result, load redistribution occurred within the "collapsible subsoil - foundation - steel silo" system, causing transverse cracking in the structures of the sub-silo gallery and along the perimeter of the ring foundation strip. The inspection established that, according to formal criteria, the technical condition of the silos was on the boundary between Categories 3 and 4 (Table 2).

Table 2. Mapping of technical condition categories between DBN and ISO 13822:2010

Ukrainian standard (DSTU 9273:2024)		ISO 13822:2010 (verbal condition scale)
Technical condition category	Description	
«1» - Serviceable (normal)	Structure without defects or damage, ensures design load-bearing capacity and reliability; no repair required.	None
«2» - Satisfactory	Minor defects or damage (micro-cracks, local damage to protective layers) that do not affect load-bearing capacity or safe operation.	Minor
«3» - Limited serviceability	Defects reducing load-bearing capacity or durability, requiring repair or strengthening; operation is possible with restrictions.	Moderate.
«4» - Critical	Structure in a dangerous condition, risk of failure; operation is unacceptable without immediate strengthening or repair.	Severe / Destructive

The classification of the technical condition of building structures in Ukraine is regulated by DSTU 9273:2024, which defines four categories ranging from serviceable to critical. Unlike this approach, ISO 13822 does not use a numerical scale but apply a verbal classification (None-Destructive) that reflects the level of damage and structural reliability. Table 2 provides an approximate alignment between the categories of DSTU 9273:2024 and their counterparts according to ISO 13822:2010. It should be noted that this alignment is relative, as the referenced standards employ different classification logics. However, certain correlations can be traced between the categories based on key indicators such as damage level and conditional serviceability of the structures.

The methodology for assessing the technical condition of silos is based on the classification of DSTU 9273:2024, which is harmonized with the verbal scale of ISO 13822:2010.

Before analyzing the SSS of the SFSS, the main operational stages of the investigated structures were identified based on archival data and interviews with technical personnel. A two-level approach was applied to assess the performance of the structural elements. At the first level, calculations were carried out using simplified analytical methods [24], which describe the system behavior under the assumption of no local soil wetting and no uneven deformations. This approach made it possible to obtain a basic picture of the force distribution between the bottom slab, the ring foundation strip, and the gallery under the condition of correct implementation of the design solutions.

At the second level, FEM modeling of the foundations was carried out using inspection data. The reinforced concrete elements (slab, ring strip, gallery) were modeled as plates with corresponding geometry and stiffness; local damage to the gallery was taken into account by reducing the stiffness of the plate elements in the crack zones (see Appendix 1). The foundation soils (Table 1) were determined from field and laboratory tests. Particular attention was given to the backfill, which governs the joint performance of the foundation elements and has a significant effect on the uniformity of deformations in the SFSS. The backfill parameters for both scenarios are presented in Table 3.

- Scenario 1 - compacted backfill in accordance with the design requirements (baseline case).
- Scenario 2 - insufficient compaction confirmed by inspection results, accounted for by reducing the stiffness of the backfill and by stiffness reduction of the elements in the gallery zone ($n_{cr} = 0.3 \ldots 0.5$).

Table 3. Physical and mechanical properties of the sand backfill under the silos

Backfill compaction scenario	Physical and mechanical properties of soils				
	γ, kN/m³	e	φ, deg	ψ, deg	E, MPa
Properly compacted	20.0	0.465	39	9	45.0
Poorly compacted	16.0	0.65	25	0	10.0

To refine the analysis of the SFSS behavior, a 3D model was created in Plaxis 3D and calibrated using geodetic monitoring data according to the procedure described in Appendix 1, with residual settlements Z^* determined following the methodology in Appendix 2.

Load collection was performed for wheat using the typical characteristics of EN 1991-4:2012, Annex *E*. Along the perimeter of the ring strip, vertical compressive forces on the wall per unit perimeter were applied as n_{zSk} = 260 kN/m, while the vertical load on the bottom slab was p_{vsq} = 156 kPa. Grain loads were assumed to act during unloading and were applied in both scenarios. Quasi-static effects caused by wind loads, mutual influence of silos, and local subsoil wetting were not introduced as separate load actions, since their integral effect was reflected in the measured group tilt, which was excluded at the data preparation stage (Appendix 2).

The criteria for assessing the technical condition of structures (crack opening, tilt, differential settlements, etc.) are systematized in Section 6, where their limiting values for different condition categories are provided in accordance with the current national standards (Table 2).

In the case of poor sand fill compaction, significant additional deflections of the bottom slab are observed toward the periphery: for the most heavily loaded section (Point A), the vertical deformation of the ring foundation strip is 131 mm, the bottom slab 158 mm, and the maximum slab deflection (Point B) reaches 172 mm (Figure 3). In this scenario, the bottom slab additionally loads the sub-silo gallery, with its settlement reaching about 142 mm at the center.

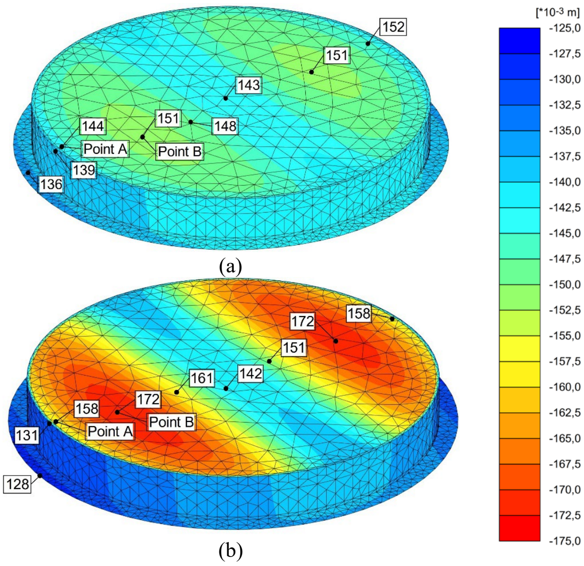

Figure 3. Vertical deformation contours of silo foundation elements for: (a) properly compacted backfill (Scenario 1); (b) poorly compacted backfill (Scenario 2), mm

Figures 4 and 5 present the FEM-calculated settlements at Points A and B for both scenarios. Figure 6 shows the settlement of the ring strip without and with consideration of the additional load from the grain weight on the bottom slab. For the scenario with properly compacted backfill, the deformations of all foundation components are similar in magnitude: in the considered section, they are 139 mm for the ring foundation strip, 144 mm for the bottom slab, and 143 mm for the gallery settlement at the center. This indicates the joint performance of the gallery and bottom slab without excessive mutual effects that could cause cracking or uneven deformations. The obtained results are in good agreement with field observations and the crack patterns recorded during inspections.

To enable the continued operation of the silo, restrictions were imposed on the maximum filling level to 80% of capacity. The damaged structures (the ring strip and the sub-silo gallery, with cracks injected using repair mixtures) were repaired, and the drainage system around the foundations was replaced to prevent further wetting of the collapsible subsoil [24].

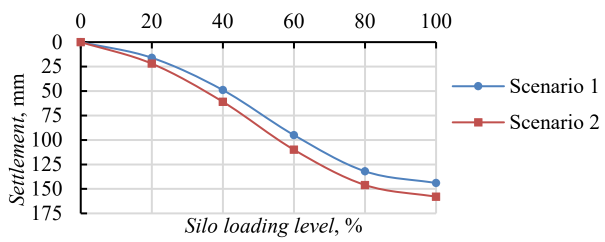

Figure 4. Settlement of the bottom slab in the most heavily loaded section (Point A)

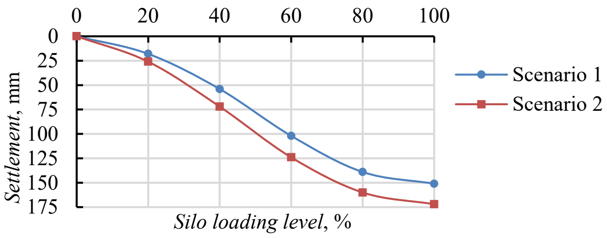

Figure 5. Settlement of the bottom slab at the point of maximum deflection (Point B)

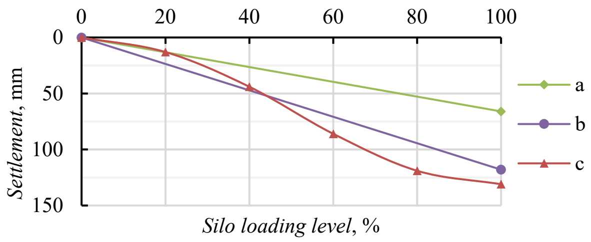

Figure 6. Settlement of the ring foundation strip: (a) without consideration of the additional load from the grain weight on the bottom slab; (b) with consideration of the additional load from the grain weight on the bottom slab and the collapsible properties of the subsoil; (c) according to FEM results for Scenario 2

Subsequent regular monitoring of the structure's deformations showed that the settlement dynamics at the observation points were minor ($\Delta S / \Delta t < 0.0002$ mm/year, $\Delta i / \Delta t < 0.0002$ year^{-1}) and did not cause the formation of new cracks or the development of repaired ones. If unfavorable deformation trends are detected, it is necessary to reduce the loading level and perform recalibration of the computational model. Future work will use the results of long-term settlement monitoring of the silo group to determine the interaction patterns between adjacent structures under different loading levels.

6. NEW ALGORITHM FOR EVALUATING THE CURRENT SSS OF THE SFSS

The new methodology for assessing the SSS of the SFSS is based on a two-level approach that combines simplified analytical methods with numerical modeling (Figure 7). The choice of analysis tools is determined by the actual condition of the structure and the presence of defects or abnormal deformations. The key diagnostic indicators are summarized in Table 4.

The algorithm for assessing the technical condition of the SFSS is presented in Table 5. Its flexible structure makes it possible to avoid excessively complex computations when no visible damage or defects are observed and to apply the full range of methods for analyzing problematic structures. Thus, the application of the algorithm enables an objective assessment of the condition of metal silos depending on the level of deformations and existing damage. This provides a basis for making well-founded decisions regarding further operation, determining residual service life, and identifying the need for strengthening or repair of structures.

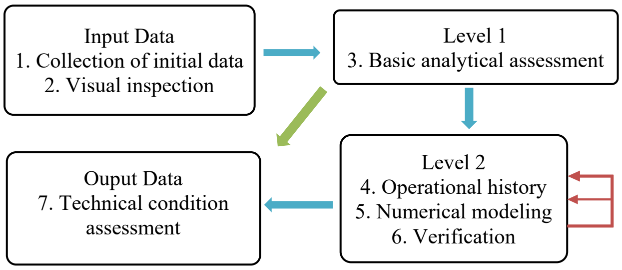

Figure 7. Block diagram of the algorithm for assessing the technical condition of the "soil - foundation - grain silo" system

Table 4. Classification criteria for assessing the technical condition of grain silo foundation structures

Technical condition	Bottom slab	Sub-silo gallery	Ring foundation strip
1	$W_{cr} \le 0.1$ mm and/or $S \ll 150$ mm and/or $\Delta S/L \ll 0.002$ *** and/or $i \ll 0.002$		
2	Longitudinal cracks along the joint with the sub-silo gallery $0.1\text{ mm} < W_{cr} \le 1\text{ mm}$ *	Single flexural cracks in the span section $0.1\text{ mm} < W_{cr} \le 1\text{ mm}$ *	Single vertical cracks $0.1\text{ mm} < W_{cr} \le 0.5\text{ mm}$ *
	$S < 150$ mm and/or $\Delta S/L < 0.002$ *** and/or $i < 0.002$		
3	Propagation of branched cracks, irregular cracks in the areas of aeration floor installation $0.5\text{ mm}^* < W_{cr} \le 5\text{ mm}^{**}$	Inclined and flexural structural cracks in span and support zones $0.5\text{ mm}^* < W_{cr} \le 5\text{ mm}^{**}$	Irregular vertical through cracks (including in the underground part of the strip) $0.5\text{ mm}^* < W_{cr} \le 1\text{ mm}^{**}$
	$S \ge 150$ mm and/or $\Delta S/L \ge 0.002$ *** and/or $i \ge 0.002$ and/or $\Delta S/\Delta t \le 0.0002$ mm/year *** and/or $\Delta i/\Delta t \le 0.0002$		
4	Regular cracks across the entire surface, converging and intersecting $W_{cr} > 5$ mm **	Regular flexural and inclined cracks, converging and intersecting $W_{cr} > 1$ mm **	regular vertical through cracks (including in the underground part of the strip) $W_{cr} > 1$ mm **
	$S \gg 150$ mm and/or $\Delta S/L \gg 0.002$ *** and/or $i \gg 0.002$ and/or $\Delta S/\Delta t > 0.0002$ mm/year *** and/or $\Delta i/\Delta t > 0.0002$ year^{-1}		
* The limit depends on the restrictions of the exposure class ** The permissible upper limit of crack opening is determined by calculation *** For the bottom slab, it is necessary to account for the local deflections of each section relative to the gallery			

Table 5. Algorithm for assessing the technical condition of the SFSS

Stage	Input data	Method	Indicators	Decision
1. Collection of input data	Design documentation, operational archives	Systematization, completeness check	-	A baseline set of parameters is formed; if data are missing, further analysis is based on actual field observations with the corresponding accuracy limitations.

Stage	Input data	Method	Indicators	Decision
2. Visual inspection and diagnostics	Visual observations, damage recording, results of geodetic measurements and monitoring, non-destructive testing of structures, laboratory soil investigations	Documentation of defects, construction of settlement and tilt schemes	W_{cr}, S , $\Delta S/L$, i	A set of diagnostic indicators was formed (Table 5) and a preliminary assessment of the technical condition was carried out (initial classification into one of Categories "1"- "4"). The data and conclusions are forwarded for the basic analytical assessment (Step 3).
3. Basic analytical assessment	Geometry and results of investigations (Step 1), set of diagnostic indicators (Step 2), structural loads according to EN 1991-4	Simplified analytical calculations of forces and deformations; verification of the interaction between the bottom slab and the ring strip	Predicted settlement of the entire structure and average contact pressure under the ring foundation strip	Based on the preliminary calculations, in the case of Categories "1"- "2" the condition of the structures is confirmed as acceptable and a transition to the final assessment (Step 7) is possible. In the case of Categories "3"- "4", the obtained values are taken as input data for extended diagnostics and modeling (Steps 4-6).
4. Analysis of construction and operation stages	Archival data on construction sequence, loading regimes, repairs, accidents, etc. (if available)	Systematization of operational events and development of computational scenarios for reproduction in the model	Logical consistency of the reconstructed stages with facts confirmed by archival or field data	If data are available, a load chronology is formed and used as input information for modeling (Step 5); if data are absent, modeling is carried out using typical loading scenarios.
5. Numerical modeling	Geometric characteristics of the structure and foundation soils (Table 1, Table 3), loads adopted at previous stages or scenarios developed in Step 4, damage map of the structures	Modeling in Plaxis using appropriate soil behavior models (HSM); accounting for collapsibility and uneven wetting; local stiffness reduction of gallery elements	Modeling results: absolute settlements, or relative settlements (according to Appendix 2), tilt, differential settlement, slab deflection shape (location and maximum deflection)	Proceed to verification (Step 6) if consistent with field data: characteristic damage near the gallery, location of maximum bottom settlement, etc. If consistency is not achieved, refine the scenarios in Step 4 and stiffness values and repeat Step 5.
6. Verification	Results of numerical modeling (Step 5) and field observations (geodetic measurements, visual inspection)	Quantitative verification of model-to-measurement consistency; evaluation of errors and similarity of deformations	Convergence between modeling results and field data: quantitative (RMSE, MAE) and qualitative (similarity of the deformation surface shape)	Acceptable convergence is defined by the RMSE and MAE criteria. If these conditions are met, the model is considered verified and passed to the stage of technical condition assessment (Step 7). If the conditions are not satisfied, parameter or scenario adjustments are made and the modeling step (Step 5) is repeated.
7. Technical condition assessment	Generalized results of the previous steps (2-6)	Comparison of diagnostic indicator values with classification thresholds (Table 7); determination of the technical condition category of the structures	Key indicators: position, length, and width of crack openings; tilt of the structure; differential settlements; time-dependent deformation trends; result of the calibrated FEM model	A technical condition category is assigned in accordance with Table 7. For Categories "1"- "2", the possibility of normal operation is confirmed; for Categories "3"- "4", recommendations are formulated regarding the operating regime, monitoring frequency, or the need for structural strengthening.

7. CONCLUSIONS

The study implemented a two-level approach to assessing the SSS of the SFSS, combining simplified analytical calculations with numerical 3D modeling calibrated using field data (Table 5). This sequence makes it possible to adapt the depth of analysis to the actual technical condition of the structure. Key diagnostic indicators were systematized and their quantitative threshold values were determined (Table 4), ensuring a transparent transition from inspection results to technical condition categories and further decisions regarding the operation of grain silos. A particular role in shaping the SSS of SFSS is played by quality of backfill compaction.

Simplified analytical methods are appropriate at the stage of initial diagnostics for the rapid evaluation of settlements and contact pressures. A detailed analysis of the behavior of the complex system should be performed through modeling with the use of proper soil models, which allows its spatial performance and the influence of real operational conditions to be considered. In the future, it is advisable to develop semi-empirical models for evaluating the performance of silo groups that take into account the mutual influence of adjacent structures, load cyclicity, and the characteristics of the soil foundation. Such models will reduce dependence on resource-intensive numerical calculations and improve the efficiency of diagnostics.

APPENDICES

Appendix 1. Model Setup and Calibration

A Plaxis 3D model was developed for a single silo to reproduce the local interaction of the "slab-ring-gallery" system under different backfill compaction scenarios (Table 3). Adjacent structures and conveyor galleries were not directly modeled. Reproducibility was ensured at the level of current (2022) relative deformations (see Appendix 2), since the complete history of loads and operational events was unavailable. For consistency with leveling data, residual settlements Z^* were obtained by removing the rigid tilt component from the measured settlement field (methodology presented in Appendix 2). These data were used for model calibration.

The computational domain measured 100×100×22 m (plan dimensions ≈5d and depth ≈d of the silo, corresponding to the compressible stratum); the lateral boundaries were fixed in the horizontal direction, and the bottom boundary was fixed in the vertical direction. A 10-node tetrahedral mesh (~1.2×10^5 elements) was used. Reinforced concrete elements were modeled as plates with elastic properties and interfaces (R_{inter} = 0.7). The local effect of cracks in the gallery zone was accounted for in Scenario 2 by reducing the stiffness of the plates n_{cr} = 0.3 … 0.5. Loading was applied in five stages corresponding to the filling process.

The foundation soils were modeled using the Hardening Soil Model (HSM) with parameters from Table 1, while the properties of the sand backfill were taken from Table 3. Calibration was performed by varying the deformation modulus E within the scenario ranges to match the shape and level of residual settlements with the 2022 geodetic data. Convergence metrics (RMSE/MAE) were calculated at control points; the calibration criterion was set as RMSE ≤ 15 mm (Appendix 2).

In the considered cases, the change in RMSE (MAE) is insignificant, and all values remain below the threshold, which allows its use for local deformation assessment.

Table A1. Comparison of residual settlements ΔS^* and errors

Element	Field measurement, mm	Scenario 1, mm	Scenario 2, mm
ΔS^*	19.9	5.1	21.0
RMSE	-	13.23	13.75
MAE	-	9.93	9.26

Appendix 2. Description of the monitoring program and data preparation

This appendix formalizes the field data used for calibration and scenario comparison. Geodetic measurements were carried out by geometric leveling in the local coordinate system, with the root mean square error of height measurements at a station not exceeding 2 mm. The monitoring scheme included six evenly distributed points on the ring strip of each silo, points on the bottom slab area and its perimeter, as well as separate control points in the gallery zone (Figure B1). For comparison with the model, the rigid tilt component (group tilt), approximated by a plane using the least squares method, was removed from the measured settlement field. The analysis was carried out using ΔS^*, which is an indicator of non-uniformity equal to the difference between the maximum and minimum values of residual settlements Z^* within the selected group of points. Here, Z^* is defined as the residual settlements obtained after removing the rigid tilt component. The model displacements in the corresponding coordinates were also adjusted to the same plane.

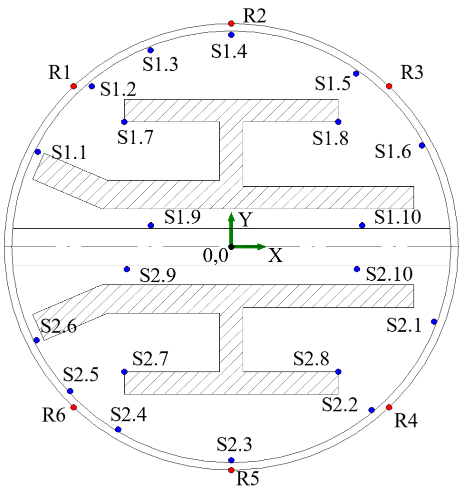

Figure B1. Layout of control points: R1…R6 - ring, SX.X - bottom slab and gallery

It was also established that the settlement pattern has a complex shape: the ring strip and the slab exhibit a common tilt in the direction of the group tilt, but the slab additionally undergoes a local "break" relative to the gallery, with maximum deflection occurring between the gallery and the ring strip. Therefore, the ring strip and the slab were considered separately. This approach made it possible to more accurately assess the local non-uniformity of deformations in each subsystem. The complete list of reference points from the 2022 baseline survey with relative elevations is provided in Table B1 and in the supplementary materials. This dataset was used to calculate the convergence metrics (RMSE/MAE) and to compare the scenarios in Section 5.

Table B1. Control points of the 2022 baseline survey (relative elevations)

ID	X (mm)	Y (mm)	Z (mm)	ID	X (mm)	Y (mm)	Z (mm)
R1	-8250	8550	-34	R4	8250	-8550	-52
R2	0	12000	-72	R5	0	-12000	0
R3	8250	8550	-99	R6	-8250	-8550	-25
S1.1	-10460	5325	-98	S2.1	10940	-4250	-130
S1.2	-7555	8985	-103	S2.2	7500	-9000	-91
S1.3	-4385	10890	-145	S2.3	0	-11740	-75
S1.4	0	11740	-165	S2.4	-6050	-10060	-55
S1.5	6730	9620	-165	S2.5	-8620	-7975	-73
S1.6	10270	5690	-195	S2.6	-10420	-5200	-95
S1.7	-5720	6790	-155	S2.7	-5690	-6790	-95
S1.8	5720	6790	-193	S2.8	5720	-6790	-111
S1.9	7000	1030	-170	S2.9	-5590	-1650	-111
S1.10	-4300	1030	-125	S2.10	6710	-1650	-153

NOMENCLATURES

1. Acronyms

SFSS Soil-Foundation-Silo System
SSS Stress-Strain State
FEM Finite Element Method
HSM Hardening Soil Model
MC Mohr-Coulomb Model
EGE Engineering-Geological Element
SP Software Package
SCE Soil-Cement Element

2. Symbols / Parameters

γ : unit weight of the soil
e : void ratio
c : soil cohesion
E : deformation modulus of the soil
φ : angle of internal friction
ψ : dilatancy angle
S : settlement of the structure
i : tilt of the structure
$\Delta S/L$: relative differential settlement
$\Delta S/\Delta t$: rate of settlement increase
$\Delta i/\Delta t$: rate of tilt increase

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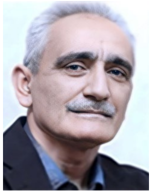

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