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Restoration measures for foundations of metal silos on degraded loess soils

Abstract. This paper examines the restoration of the serviceability of foundations of steel silos located on wetted and degraded loess soils. Based on the survey results and the analysis of the recorded deformations, a sequence of engineering measures is presented, including local repair of the ring foundation, restoration of the underground gallery, strengthening of the anchor connections and replacement of the pavement. It is shown that the applied set of repair measures ensures the stabilisation of the foundation structures and allows continued operation of the silos without a complete shutdown. The effectiveness of the implemented measures is confirmed by the results of geotechnical and geodetic monitoring conducted after the completion of the repair works.

Keywords: silo, collapsible soils, crack, restoration, foundation.

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Introduction.

The full-scale armed aggression of the Russian Federation has led to significant losses in the infrastructure of Ukraine's agricultural sector, including grain-storage facilities, some of which were destroyed or located in temporarily occupied territories. Under these conditions, preserving and extending the service life of existing structures becomes particularly important, especially for corrugated-wall metal silos, which represent the most widespread type of storage for long-term grain preservation.

Most metal silos constructed in Ukraine during the 2000s–2010s are now approaching the midpoint of their design life or have already surpassed it. A considerable number of such structures exhibit typical operational deficiencies: differential settlements of foundations, tilting, cracking in underground galleries and in the above-ground part of the ring foundation, wetting of the soil foundation, excessive deflections of floor slabs, and similar issues. These defects are typical of silos founded on collapsible loess soils that have experienced prolonged and uneven wetting leading to degradation.

When such deviations are present, it is necessary to assess whether the silos can continue to operate without a complete shutdown of storage processes. This requires documenting the actual condition of structural elements, analysing the deformation behaviour of the soil base, and determining the conditions under which repair measures can be performed safely. In these cases, the primary objective is not only to eliminate local defects but also to restore the ability of the foundation system to function within its already deformed configuration.

Review of the latest research sources and publications.

The restoration of foundations of metal silos after the development of differential settlements remains insufficiently studied. For silos with corrugated walls, where the structural behaviour depends on the interaction between the shell, the floor slab, the ring foundation, and the underground gallery, existing publications provide little practical guidance on repairing foundation systems once significant deformations of the soil base have formed, particularly under wetting of collapsible loess soils.

Modern inspection practices, in addition to traditional visual and instrumental methods, include the use of laser 3D scanning to capture the actual geometry of structural elements [1]. This technology enables engineers to assess the structure using its real spatial configuration, account for geometric deviations, and combine the scanned data of the silo's exterior surfaces and underground galleries into a single coherent model.

Differential deformations of the soil base generate additional internal forces in the foundation elements of silos. These effects often lead to cracking, local concrete damage, and a reduction in structural stiffness. Restoring the stiffness of reinforced-concrete components in such cases may involve external strengthening with carbon-fiber reinforcement [2, 3] or injection of cracks using polymer strengthening systems [4].

In parallel with addressing the effects of deformation, an approach aimed at eliminating its root causes may be implemented, particularly by improving the properties of the soil foundation through deep soil mixing to form soil-cement columns [5]. As a separate method, or as a supplement to these measures, the spatial position of foundation blocks can be corrected using horizontal drilling techniques [6].

As noted in [7], restoring the operational performance of foundations requires accounting for actual technological and structural constraints rather than applying superficial repair measures.

Repair measures for this type of structure should be supported by systematic geotechnical and geodetic monitoring. Such monitoring makes it possible to track changes in the stress-strain state (SSS) of the soil-foundation-structure system (SFSS), evaluate the effectiveness of the implemented measures, and respond in time to any emerging deviations [8, 9].

At the same time, most solutions described in the literature focus on repairing individual structural components. The link between local damage and the spatial behaviour of the entire SFSS is rarely analysed, which makes it more difficult to choose an appropriate restoration strategy.

Problem statement.

The aim of this work is to demonstrate the relationship between the survey results, the deformation patterns of the foundation structures, and the repair measures adopted, showing how these measures allow the silos to continue operating without a complete shutdown.

Main material and results. In December 2022, a technical survey was carried out for a group of six silos at the Kononivskyi elevator facility in Pomynnyk, Mankivka district, Cherkasy region (Fig. 1).

Each silo has a capacity of 7,760 m³ and a diameter of 23.78 m. Structurally, the foundations consist of a ring foundation combined with a floor slab and an underground gallery.

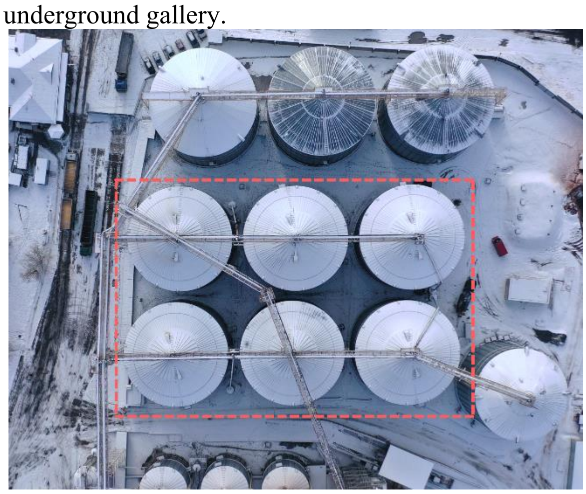


Figure 1 – The group of silos under study (aerial view)

The geological profile of the site to a depth of 20 m consists of Quaternary heavy and light loams, overlain by fill soils to depths of 1.6–1.9 m and underlain by light silty clays from approximately 16 m. The soil layers are laterally continuous and show consistent thickness across the site.

The site is affected by several unfavourable engineering-geological processes, including the presence of anthropogenic fill, the occurrence of loess soils, and their progressive degradation.

According to the results of the engineering-geological investigation, the collapsible loess layer is already degraded to a depth of 7.6 m.

At the same time, archival survey data from 2014 indicate that the loess layer between the foundation base and the groundwater level still retained its collapsible properties at that time. This means that over the course of nearly ten years the collapsible loess became fully wetted, both from "below" due to rising groundwater levels and from "above" as a result of repeated non-uniform wetting caused by damaged surface drainage and failures in local utility networks.

During the survey, the following defects and damages were identified:

- extensive freeze–thaw damage to concrete in the above-ground part of the ring foundation;;
- detachment of the applied waterproofing on the above-ground part of the foundation;
- numerous vertical and inclined cracks in the floor and walls of the underground gallery;
- significant height differences (up to 7 cm) between adjacent blocks at the vertical expansion joints of the underground galleries;
- continuous cracks in the floor slab along the interface with the underground gallery, as well as branching cracks near openings for equipment and service channels;
- recurrent flooding of the underground gallery due to poorly executed expansion joints;
- design errors related to the site's drainage system;
- extensive damage to the concrete pavement around the group of six silos, including settlements, cracking, and voids beneath the pavement;
- failures in water supply and sewer networks that contributed to wetting of the soil foundation.

To determine the actual SSS of the elements within the SFSS, a step-by-step procedure was applied, based on the survey results and numerical modelling. The first stage involved collecting and systematising the design documentation and archival materials, which made it possible to reconstruct the foundation design and the main stages of its operational history [10].

Subsequently, visual and instrumental inspections were carried out to document structural defects, along with geodetic measurements of settlements of the ring foundation, floor slab, and underground gallery. The collected data served as input for the initial analytical checks, which were used to assess the initial deformation pattern, possible stress redistribution scenarios, and approximate contact pressures in the foundation-soil interaction zone.

Based on the initial assessments and the presence of significant non-uniform deformation, the loading sequence was refined and scenarios for numerical analysis were developed. The next stage involved finite-element modelling (FEM) of the spatial behaviour of the SFSS in PLAXIS 3D, using the measured settlements and the settlement profile as input data, along with soil parameters adjusted in accordance with previous studies [10, 11].

Calibration of the stiffness parameters of the foundation soil and the backfill was performed based on the convergence between the numerical and measured deflections and tilts. Once an acceptable level of agreement was achieved, the model was used to identify the structural behaviour of the foundation elements and to assess the influence of non-uniform deformation on their load-bearing capacity.

At the final stage, the obtained diagnostic indicators were compared with the current classification limits for technical condition. This made it possible to justify the assigned condition category and to formulate further recommendations regarding the operating regime and the need for repair measures.

The analytical and numerical analyses showed that some of the deficiencies in the foundation performance can be traced back to the design stage, in particular due to an underestimation of the interaction between the floor slab, the ring foundation, and the underground gallery.

At the time of the survey, the actual load levels in several sections exceeded the load-bearing capacity of certain foundation elements, primarily the gallery structures. Combined with the existing defects and long-term wetting, this resulted in a significant reduction of their performance.

At the same time, the modelling results showed that further operation of the structures is possible if the loading is reduced to 80% for silos No. 13 and No. 16, and if a set of repair measures is implemented to restore their performance and prevent further wetting of the foundation soils. These findings formed the basis for developing and executing the corresponding structural and technological measures, which are presented below.

The repair and restoration works on the silo foundations were carried out under a restricted operating regime, accompanied by regular monitoring of changes in the performance characteristics and technical condition of the silos [12].

In particular, a geodetic monitoring system was installed, which included permanent benchmarks and fixed observation points on the bearing plates of the silos' vertical stiffeners for deformation tracking.

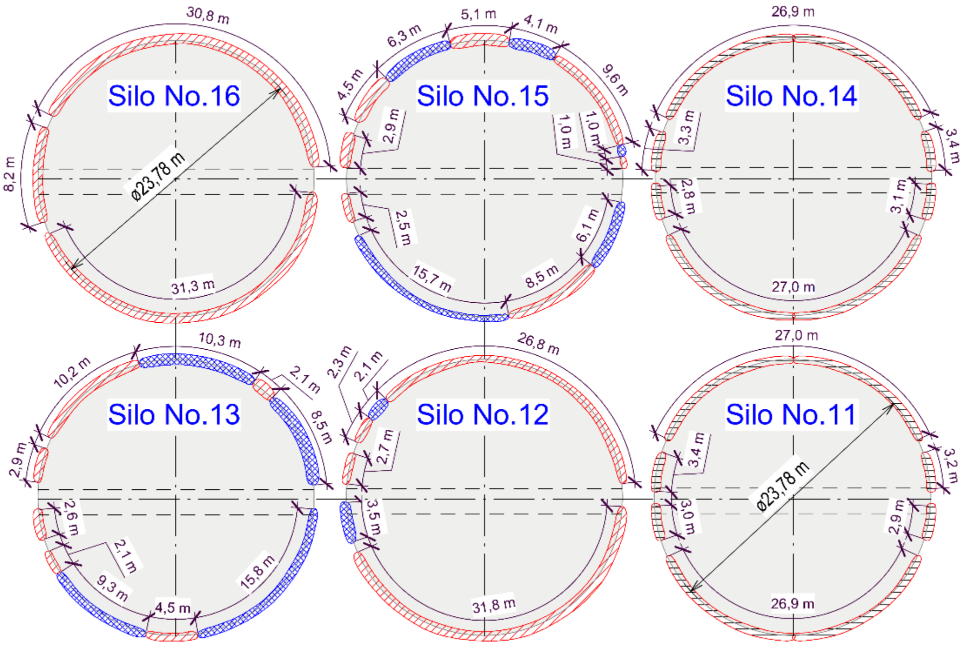
For silos No. 13 and No. 16, loading was prohibited until the repair works were completed. For the adjacent silos, No. 12 and No. 15, unloading was recommended for the duration of the works.

The restoration of the foundations was carried out in several stages:

1. Repair of the ring foundation damaged as a result of freeze-thaw deterioration of the concrete.
2. Treatment of cracks in the walls and floor of the underground gallery and restoration of the expansion joints.
3. Replacement of the concrete pavement around the silos and regrading of the surface drainage system.

Before repairing the above-ground part of the ring foundation, the damaged concrete was removed to the depth of intact material, and any exposed reinforcement was cleaned of corrosion.

The concrete damage was conventionally classified into two types according to its extent and depth. The scheme of the identified defects in the ring foundation, classified by type, is presented in Fig. 2.

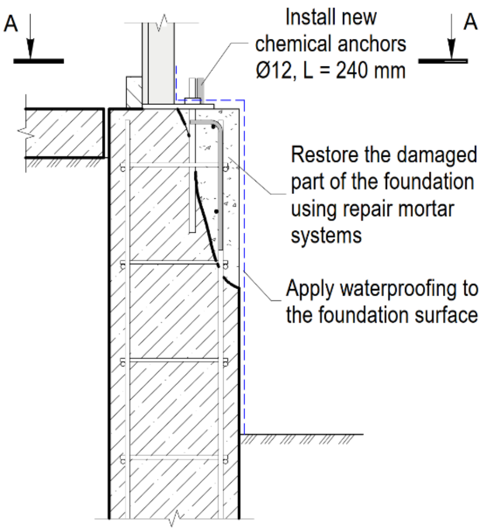


Type 1 repair zones of the above-ground part of the ring foundation **Type 2 repair zones of the above-ground part of the ring foundation**

Figure 2 – Diagram of the identified defects in the ring foundation

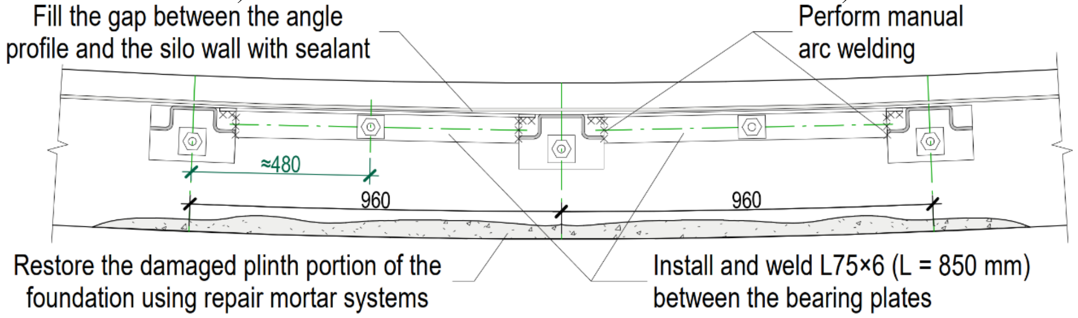
Type 1 damage is characterised by extensive (deep) concrete deterioration which, after removal of the damaged material, resulted in full exposure of the outer reinforcement layer along large portions of the foundation, as well as partial exposure of the anchor bolts. This represents deep structural damage. In cases of significant concrete loss and complete exposure of the bars, additional reinforcement was installed, with the new bars connected by spot welding (Fig. 3).

Type 2 damage is characterised by a relatively limited depth of concrete removal, which involves partial exposure of the foundation reinforcement and may include isolated areas of full exposure (Fig. 4). Most of the deterioration is confined to the concrete cover zone.



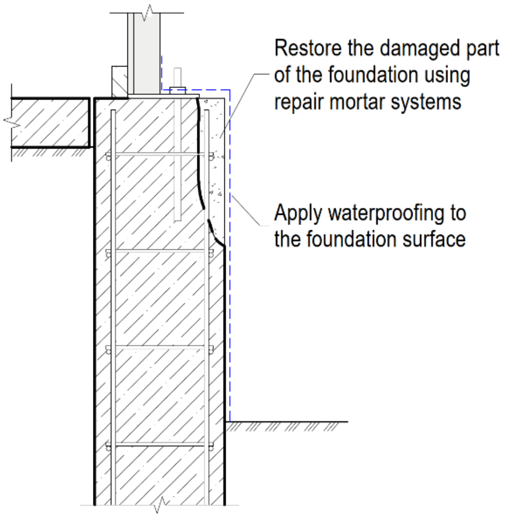
a)

b)



c)

Figure 3 – Above-ground part of the ring foundation after removal of Type 1 damaged concrete: a) design solution for restoring the damaged foundation segment; b) photograph of the foundation after removal of damaged concrete; c) design solution with increased number of anchor bolts



a)

b)

Figure 4 – Above-ground part of the ring foundation after removal of Type 2 damaged concrete: a) design solution for restoring the damaged foundation segment; b) photograph of the foundation after removal of damaged concrete

a) b)

Figure 5 – Waterproofing of the above-ground part of the silo foundation: a) before repair; b) after repair

Given the identified level of damage in the connection points between the steel silo and the foundation, as well as the results of the SSI analysis, particular attention was paid to verifying the performance of the anchor connections under wind loading. The horizontal component of grain pressure at the level of the floor slab is resisted by the walls of the steel bin; therefore, the primary role of the anchor bolts is to carry tensile forces that develop during periods when the silo is fully or partially unloaded.

The connection between the silo and the foundation is provided by vertical stiffeners bearing on 78 base plates anchored with M24 bolts. To evaluate their load-bearing capacity, a calculation of wind action on the fully unloaded silo was performed in accordance with [13, 14] for a nominal service life of 30 years. The analysis was carried out under the assumption of an isolated (stand-alone) structure, which slightly increases the design forces but is appropriate given that the objective was to assess the performance of the anchor connections.

The results showed that most of the base plates remain in compression, meaning that the anchor bolts do not experience tensile forces. At the same time, several zones form along the silo perimeter where groups of adjacent anchors are in tension. The average tensile force in these zones is $P = 45$ кН. According to the procedure in [15], a single M24 anchor bolt can resist a design tensile force of $N_{\mathrm{M24}} = 48.6$ кН., which formally satisfies the strength requirement ($P/N_{\mathrm{M24}} = 0.925 < 1$). However, this check does not account for the reduced load-bearing capacity of the reinforced-concrete ring foundation due to the Type 1 damage previously identified.

In view of this, for the areas with deep concrete damage (Fig. 3c), it was decided to install additional M12 anchor bolts on chemical anchors, arranged at half spacing (480 mm). The design tensile capacity of a single M12 anchor is $N_{\mathrm{M12}} = 11.6$ кН, which increases the total load-bearing capacity of the connection to $\sum N = N_{\mathrm{M24}} + N_{\mathrm{M12}} = 60.2$ кН. As a result, the load-to-capacity ratio decreases to $P/\sum N = 0{,}748$.

The adopted repair solutions for the anchor connection nodes are shown in Fig. 3 and Fig. 4.

At the final stage, local restoration of the reinforced-concrete elements in the damaged zones was carried out. Exposed reinforcement was cleaned and treated with the anti-corrosion coating ARCAN RM-510. After surface preparation, all exposed concrete and reinforcement were covered with the bonding agent Cembond 956 to ensure reliable adhesion between the repair layer and the existing structure. The removed concrete fragments were rebuilt using the polymer-cement mixtures ARCAN RM-500, whose strength exceeds that of the C20/25 structural concrete used in the ring foundation.

The use of high-strength repair compounds provided a denser protective layer, improved adhesion to the reinforcement, and reduced the risk of renewed detachment or local damage caused by moisture and freeze-thaw effects.

After the local restoration of the reinforced-concrete elements, a horizontal and vertical coating system was applied to the above-ground part of the foundation using bitumen-based waterproofing (Fig. 5). The protective barrier is intended to limit moisture ingress into the concrete substrate and the reinforcement, thereby reducing the likelihood of renewed freeze–thaw deterioration and mitigating the risk of corrosion at the support interface of the steel silo structure.

The restoration works on the underground gallery were preceded by the development of a crack-mapping scheme based on the visual and instrumental surveys, documenting the transverse and inclined cracks in the walls and floor of the galleries for all silos. Figure 6 presents the crack layout for the galleries of silos No. 13 and No. 16. The crack pattern and orientation indicate that the primary causes are poorly compacted backfill beneath the floor slab, which leads to stress redistribution and overloading of the underground gallery [10], as well as uneven local wetting of the collapsible soil foundation.

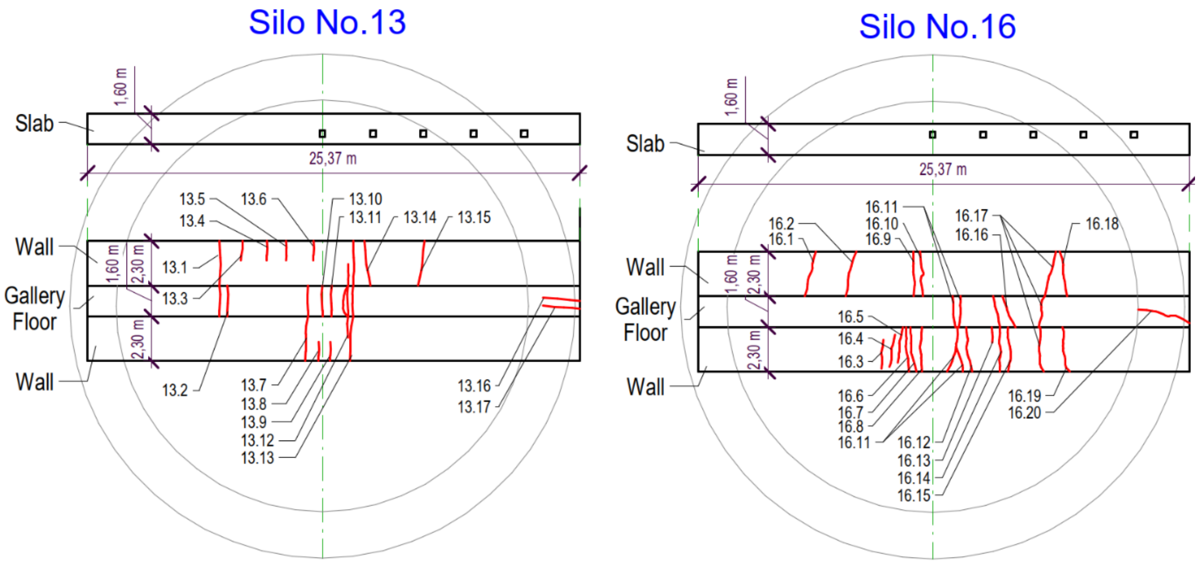


Figure 6 – Crack layout of the underground gallery for silos No. 13 and No. 16

a) *b)* *c)*

Figure 7 – Condition of the underground galleries: a) floor cracks as recorded during the survey; b) wall cracks as recorded during the survey; c) walls and floor after completion of the repair works

To restore the serviceability of the structure, including its stiffness, integrity and watertightness, the cracks were injected with the polymer resins HydroBloc PU 500 and HydroBloc Rapid 570. These materials provide strong adhesion to the mineral substrate and sufficient mechanical performance to operate under the existing non-uniform deformations. The injection was carried out in the actual deformed state of the structure, which was taken as the baseline condition for the repair works. The repair did not include modifying the geometry or re-levelling the gallery. Restoration was achieved through crack sealing, local stiffness enhancement in weakened zones and re-establishing the continuity of the structural section (Fig. 7).

This approach made it possible to stabilise the gallery in its existing SSS and to ensure its continued compatible behaviour with the other foundation elements. The effectiveness of the applied measures was confirmed by subsequent geodetic observations within the geotechnical monitoring programme [12].

The final stage of the restoration and service-life extension measures for the silos was the complete replacement of the existing concrete pavement with a new one. This included forming the required slopes and regrading the pavement to ensure effective surface drainage within the silo area.

a) b)

Figure 8 – Pavement around the silos: a) removal of the old pavement; b) new pavement

Conclusions.

Thus, using the example of a group of six silos, it has been demonstrated that restoring the serviceability of the foundation structures and extending the service life of silos operating under a restricted loading regime is achievable through a combination of controlled loading conditions and a set of targeted rehabilitation measures. These measures included local restoration of the above-ground part of the ring foundation, strengthening of the anchor connections, repair of cracks in the underground gallery, installation of waterproofing and complete replacement of the pavement with the required slopes for effective surface drainage.

The implementation of these measures made it possible to restore the stiffness and integrity of the structures while taking into account their actual deformed state, and to eliminate the main factors that had caused non-uniform wetting of the collapsible soil foundation. The combined effect of the applied measures ensured the stabilisation of the SSS of the SFSS elements, which was confirmed by the results of geodetic monitoring conducted after the completion of the repair works [12].

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Комплекс відновлювальних заходів для фундаментів металевих силосів на деградованих лесових ґрунтах

Аннотація. У роботі наведено результати обстеження та відновлення фундаментів групи металевих силосів, що експлуатуються на замоклій просадочній лесовій основі та зазнали нерівномірних деформацій. Встановлено, що тривале замокання ґрунтів і неякісне виконання зворотної засипки під плитою днища призвели до розвитку крену, появи тріщин у підсилосних галереях та локального пошкодження цокольних елементів кільцевої фундаментної стрічки. Для визначення фактичного напружено-деформованого стану споруд виконано комплекс робіт, що включав технічне обстеження, геодезичні вимірювання та аналіз просторової роботи елементів фундаменту з урахуванням результатів попередніх досліджень. Отримані дані стали основою для формування послідовності відновлювальних заходів, реалізованих без повної зупинки експлуатації силосів. Запропонований комплекс включав ремонт пошкоджених ділянок фундаментної стрічки, відновлення тріщин у підсилосних галереях методом ін'єктування полімерними смолами, перевірку та підсилення анкерних вузлів з урахуванням вітрового навантаження, а також повну заміну вимощення для усунення причин подальшого замокання основи. Паралельне проведення геотехнічного та геодезичного моніторингу дозволило оцінити ефективність виконаних робіт та підтвердило стабілізацію напружено-деформованого стану системи «основа–фундамент–споруда». Результати показують, що застосований підхід дозволяє забезпечити подальшу безпечну експлуатацію силосів навіть за умов наявних деформацій, за рахунок поєднання цілеспрямованих ремонтних рішень, контрольованого режиму роботи та систематичного моніторингу.

Ключові слова: силос, замокла лесова просадочна основа, тріщина, ремонт та підсилення, фундамент.

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