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THE INFLUENCE OF ATMOSPHERIC PRECIPITATION, SURFACE WATER AND LEVELING EMBANKMENTS ON THE SETTLEMENT OF STRUCTURES

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Abstract. The article provides an analysis of the results and causes of increased settlements of cement plant structures and the negative impact of leveling embankments, atmospheric precipitation and surface water on settlements of structures. Many design firms for the design of civil, industrial and infrastructure construction projects, often ignoring the requirements of the relevant building codes and regulations, design buildings and structures only based on the bearing capacity of soils and the deformation characteristics of the soils of the foundation of buildings and structures are not taken into account. In some cases, when designing buildings and structures, even for two limit states, the weight of the embankment is not taken into account, which will lead to additional compression of the underlying soils. In addition, when designing foundations and bases of a structure, the physical and mechanical properties are not taken into account, including the composition of the soils of the planning embankment, which often create additional negative impacts on the reliability of the structure during the operation of construction projects. One example of the noted processes is the experience of designing and constructing a cement plant in the administrative territory of the Gazakh region of the Republic of Azerbaijan.

Keywords: *Man-made soil, embankment, pile, foundation, settlements, water.*

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1. Introduction

As shown by 14 years of experience in monitoring deformation processes in the soils of the geological environment of the territory under consideration, carried out on the main technological structures, additional all from man-made (fill soil) soil often leads to very significant and unacceptable subsidence of foundations, including pile foundations in the bases of structures that are buried in relatively low-compressible soils.

Technogenic soils, also called bulk soils, are natural soils that have been altered and moved as a result of human production and economic activities (Sazonova & Ponomarev, 2013).

The fill layer was formed as a result of artificial changes in the relief for the purpose of engineering preparation (planning, leveling) of the territory for construction and is

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characterized by a heterogeneous composition and structure, uneven density and compressibility, as well as a high content of organic matter and soluble salts.

The thickness of the technogenic formation has a natural increase in the direction from south to north and from southeast to northwest and is associated with the surface of the natural relief, which has a noticeable slope (about 3o) to the north and northwest.

Construction on bulk soils is one of the most important and complex problems caused by the widespread occurrence of these soils. One of the main technological processes of construction on bulk soils is their compaction. The reliability, quality and durability of the structure depend on how the compaction works are designed and implemented. At the same time, the cost of compaction is only a relatively small part of the total construction costs (about 5%). Correctly performed compaction allows to significantly increase the bearing capacity and stability of the bulk foundation (Seskov, 2013).

According to the information provided, compaction work was carried out during the formation of the fill layer at the construction site of the cement plant. But the information obtained during engineering-geological surveys and the results of geotechnical monitoring lead to the conclusion that the compaction of bulk soil was carried out in violation of the compaction process, as a result of which self-compaction of bulk soils occurred for a long time (Figure 1).

Figure 1. Self-compacting of bulk soil at a construction site

The self-compaction of man-made soils in combination with the self-compaction of highly compressible dusty-clayey soils that formed the soil massif of the construction site can last for decades accompanied by dangerous physical and geological processes and other negative phenomena for the safety of the production cycle.

2. Research object and research methodology

Research into the influence of a leveling embankment from soils of technogenic origin was carried out at the main technological structures of the Gazakh cement plant (Figure 2), which were, are and are currently exposed to deformation processes, in accordance with the requirements of regulatory documents:

1. Guide to monitoring deformations of foundations and foundations of buildings and structures. Moscow. 1975.
2. GOST 24846-2019 Soils. Methods for measuring deformations of foundations of buildings and structures.

The territory of the cement plant is included in the southern side of the Kura depression and from the west directly borders with the north-eastern slopes of the Lesser Caucasus with the towering peaks of Mount Avey (889.7 m), Mount Rizachal (605.8 m), from the west it borders with the foothills of the Lesser Caucasus. On other sides the site has no natural boundaries, but is a single flat area, the surface of which is slightly hilly-ridged, with small negative forms (suffusion funnels), slightly dissected by shallow and gently sloping sides, gullies and ravines.

Figure 2. Research object

The geological structure of these mountains includes (directly adjacent to the study area) Upper Cretaceous deposits of the Maastricht, Campanian and Upper Santonian. The Maastrichtian stage mainly fills the troughs of anticlinal folds of lower orders. The deposits unconformably lie on the Campanian rocks and are unconformably overlain by the Data and Paleocene deposits. Lithologically, they are represented by sandy, silty-clayey, organogenic-clastic limestones with layers of clays, clayey limestones, bentonite clays. Their thickness is about 100-150 meters (Verdiyev & Shiraliyev, 2023).

In the geological structure of the study area, a complex of continental deposits of the Holocene system was formed, represented by modern technogenic (fill soils of the planning embankment), deluvial-proluvial (silty-clayey soils), alluvial-deluvial-proluvial (coarse-grained soils) and deluvial-proluvial deposits (hard clays, argillite-like) of the Upper Pleistocene, which by genesis and material composition are technogenic dispersed weakly cohesive, natural dispersed non-cohesive soils and soils with variable physical and physicochemical structural bonds (weakly cohesive and cohesive).

All varieties of the noted sediments belong to a single lithological (geological) formation and according to the physical and geographical conditions of sedimentation, are characterized by a variable facies.

A geological formation is a natural association of rocks and associated mineral formations, the individual members of which (rocks, layers, strata) are closely related to each other as a result of paragenetic relationships both spatially and in age (interbedding and other types of alternation) (Izosov, 2011).

Facies is a regular synthesis of sediments that can express their lithological and paleontological features (Feng, 2019).

Anthropogenic man-made formations (anQ4), widespread on the construction site are represented everywhere by bulk soils of predominantly clay composition with inclusions of coarse-grained soil of various types (from rubble to boulders) and frequently encountered construction waste (pieces of concrete). Moreover, in the area of foundations of structures, the bulk layer is represented mainly by coarse-grained soils with clay fillers, being a source of soaking and additional reasons for vertical displacement of the soil base of the foundations of structures and buildings. The thickness of the bulk soil is 0.1-6.7 m.

Holocene deluvial-proluvial (dpQ4) deposits are widespread in the deep intervals of the geological environment from a depth of 0.10-6.7 m to 63.70 meters, are represented by silty-clayey soils (clays, loams and sandy loams) of varying consistency and are the main soils that form the geological structure of the study area.

Quaternary deluvial-proluvial deposits, lithologically represented by clays, loams and sandy loams, have a specific character, anisotropy, mainly loess, naturally uncompacted or weakly compacted and highly compressible.

Plastic sandy loams were formed in horizons with a depth of 11.5-12.10 m and 49.0-54.0 m and are characterized by those characteristics that are characteristic only of these soils - sandy loams located at great depths are closer to fluid sandy loams in terms of water saturation and consistency and sandy loams formed in the upper part of the geological environment are close to solid sandy loams in terms of the same characteristics.

Hard sandy loams were formed in horizons with a depth of 12.4-16.90 m and 53.9-61.6 m and regardless of the depth of occurrence, the sandy loams of both horizons have the same physical and mechanical characteristics.

Alluvial-deluvial-proluvial (adpQ4) deposits are represented by coarse-grained soils with lithological compositions of boulders, pebbles, gravel and debris with fillers of dispersed cohesive (silty-clayey) and rarely non-cohesive (sandy) soils.

They are distributed throughout the studied strata and are characterized by a unique formation. In the peripheries of the studied area, coarse-grained soils are represented by several layers, lying in different horizons of the soil massif. In the central part of the site, coarse-grained soils, forming one (in some cases two layers) layer of small thickness, lie at great depths of the soil massif (from 36.0 meters).

The layers of coarse-grained soils that took part in the lower horizons (above the layers of argillite-like clays) of the geological environment are cemented by clay materials, have the properties of a conglomerate and are characterized as a layer with reliable bearing capacity.

Deluvial-proluvial (dpQ3) deposits were formed in the depth range of 63.7-81.60 meters and are represented by argillite-like hard clays, which are the bedrock of the study area. Argillite-like clay is characterized as a substantially transformed clay rock, belongs to the same facies as clay soils participating in the formation of the geological structure of the construction site. Their formation is associated with compression and partial (weak) recrystallization of clay particles.

Groundwater is located at a depth of more than 28.0 mm. During the research it was established that, over the course of two years (from 2011 to 2013) the groundwater level dropped by 2.1-2.8 meters.

3. Research results, an analysis and a discussion

The main structures of the cement plant are: Limestone Silo, Corrective Silos, Raw Mill, Cooling Tower, Homogenization Silos, Preheater, Rotary Kiln Supports, Clinker Cooling, Clinker Silos, Gypsum Silos, Cement Mill, Cement Silos and Cement Packing.

For all structures, pile foundations (d=600.0 mm, h=16.0 m) were designed and constructed and the cement silos were erected on a solid monolithic reinforced concrete foundation slab without piles with a soil base of tight and soft plastic natural loams.

Despite the fact that "Design of foundations is an integral part of the design of structures as a whole. Foundations are calculated according to two groups of limit states: according to the first group - according to the bearing capacity; according to the second group - according to deformations (by settlements, deflections, etc.) (Marinichev *et al*., 2017), the design of pile foundations for the cement plant structures was carried out only according to the bearing capacity of the soils.

During the final stages of construction and after completion, unacceptable deformations, such as foundation settlement, tilting, cracks, etc., occurred in the structures of some structures (Preheater and Rotary Kiln Supports).

In this regard, in 2010, based on the requirements of regulatory documents and taking into account the fact that, "Engineering and geodetic surveys are a set of works carried out to obtain information about the relief. Work on engineering and geodetic surveys may include observations of vertical and horizontal displacements of buildings and structures. Shifts and settlements can occur both during construction and during the operation of individual buildings and structures, so they require full control of attention in order to avoid further capital investments or human tragedies (Sukmanyuk *et al*., 2016)", a "network of geodetic measurements for deformation processes" was created and engineering and geodetic studies were started, consisting in monitoring the settlement of structures, which continue to this day and experimental work was also carried out.

Observations show that, despite the fact that all structures were erected 3-5 years after the completion of the filling of the planning embankment, the settlement of the foundations of these structures continued and continues to increase with a practically constant intensity and dynamics equal to 0.8-7.3 mm/month (Figures 3 and 4).

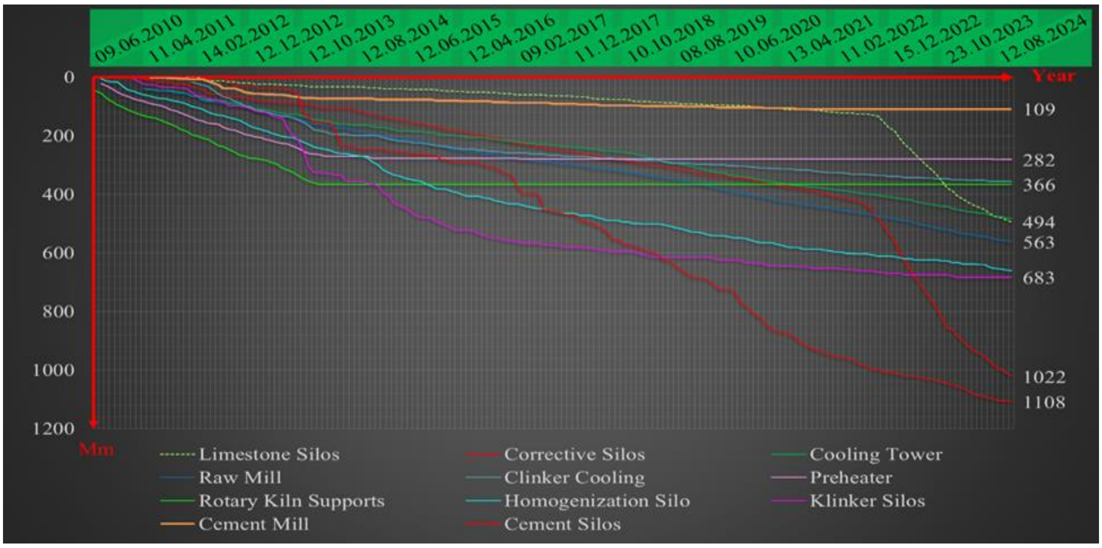

Figure 3. Development of foundation settlement over time, mm

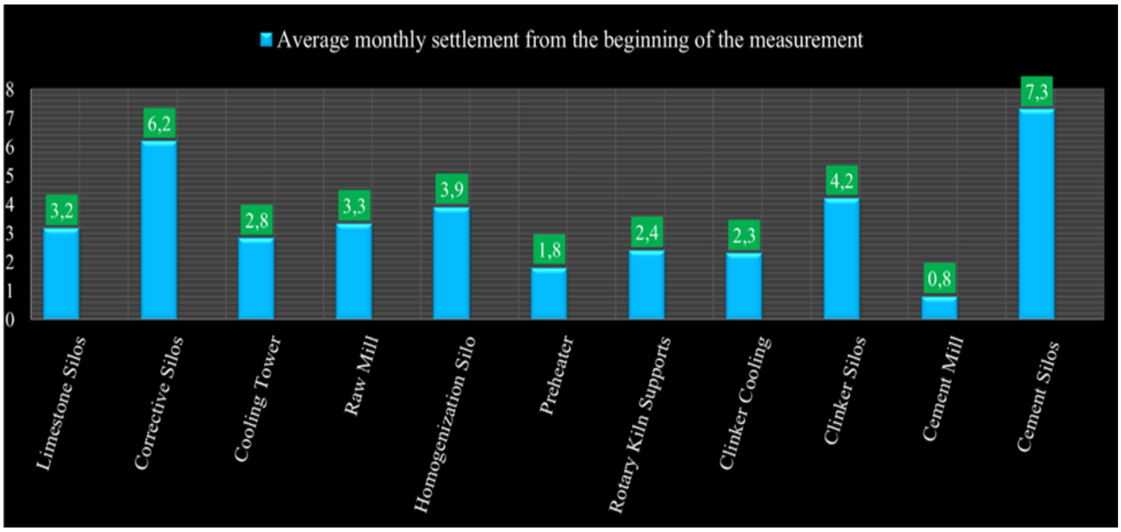

Figure 4. Monthly dynamics of settlement processes, mm

Analysis of design documentation and statistical processing of the results of observations of settlement showed that the main reasons for the constantly increasing settlement of structures are: additional loading of the soil massif by the weight of the planning embankment; reduction of deformation and strength characteristics as a result of increased moisture content of the soils underlying the embankment, caused by development of the territory and infiltration of rainwater through the embankment soils;

To study the effect of the planning embankment on the compression of the underlying soils in the area where the existing Rotary Kiln Supports foundations are located, partial unloading of the soil massif was carried out by up to 6 t/m^2 by digging a test pit measuring 43x55 m and 3 m deep (Figures 5 and 6).

Surface marks were installed in and around the pit (Figure 7), two bushes of deep marks with a depth of embedment hд=10, 20, 30, 40 and 50 m were made inside and at the edge and three experimental cast-in-place piles (Figure 5) with a diameter of 0.8 m and a depth of 31.5-32 m were made.

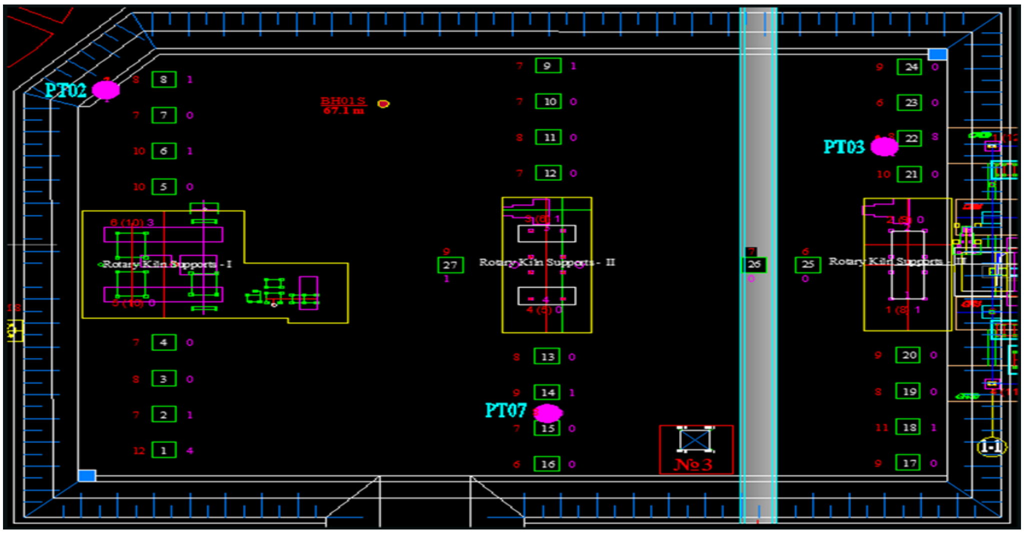

Figure 5. Scheme of unloading the soil mass from the embankment and placement of test piles

Figure 6. The area of unloading of the soil mass from the embankment

Figure 7. Surface geodetic marks

Geodetic observations over three months of the pit's existence have shown that due to the unloading of the soil massif:

- The intensity of the increase in settlement of Rotary Kiln Supports foundations located in the pit decreases by 2-3.5 times from 8.3-11.6 to 2.5-4 mm/month and after backfilling the pit after 3-4 months it gradually returns to almost the previous values;
- The intensity of the increase in the sediments of the deep marks, after excavation of the pit, in bush No. 1 decreases from 5.5-6 to 3-2.5 mm/month, i.e. by 1.5-2.7 times;
- The increase in settlement of surface marks located in the pit and beyond it amounted to 2-1.5 mm/month and mainly depended on the thickness of the embankment (Figure 8);
- The settlements of 3 experimental piles over 3 months were 16-22 mm (Figure 9) and of deep marks with a depth of 10, 20, 30 m by 10 mm, i.e. an average of 3 mm/month.

Figure 8. Graph of settlement in the experimental pit, mm

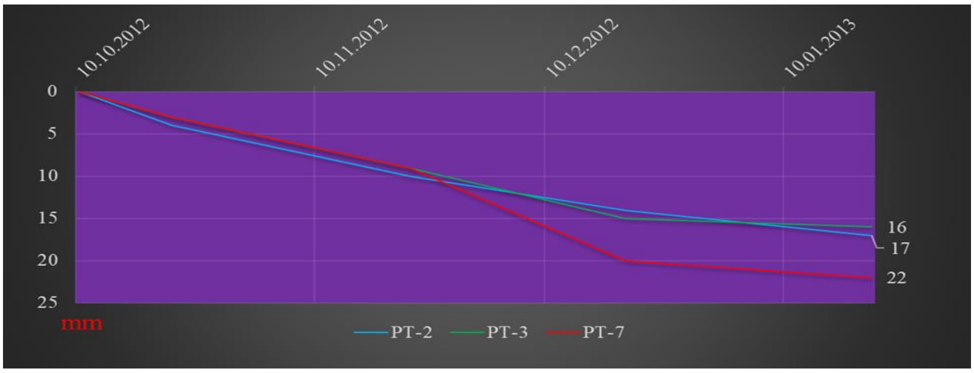

Figure 9. Graph of settlement of test piles

The results of the experimental work show that the partial unloading of the soil mass, although it significantly reduces the intensity of the development of subsidence of the underlying natural soils, is insufficient to completely stop it in this case.

Figure 10. Location of depth marks

According to the results of observations of the subsidence of deep marks (Figure 10), it follows that the compression of the underlying natural soils under the weight of the planning embankment occurs within their thickness exceeding 50 m and over 12 years of observations amounted to about 200 mm. The compression of the soil layers below 20 m, i.e. below the depth of the piles of the foundations of the plant structures, amounted to 144 mm, below a depth of 50 m - 93 mm (Figure 11).

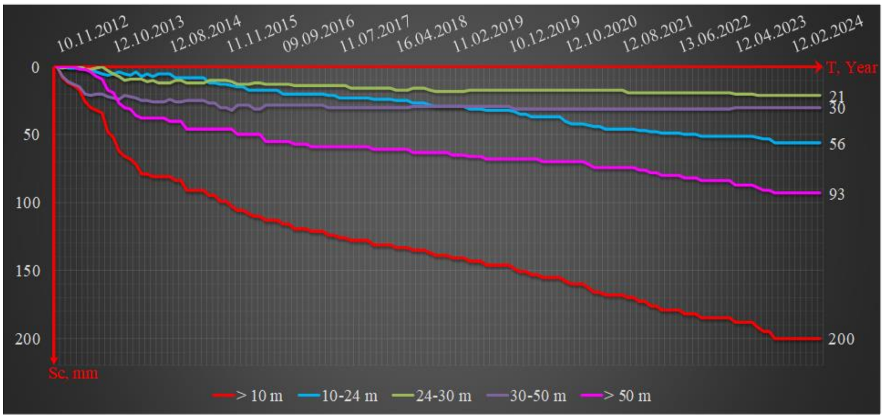

Figure 11. Graph of settlement in a soil massif by depth marks over time

Based on the characteristics of the development of settlement of structures over time, their main characteristics, as well as their loading with useful load, it is advisable to divide the structures of a cement plant into 3 groups.

Group 1 – heavy structures with a rigid structural design, made of monolithic reinforced concrete and as a rule, with an increased total load on the base soils (Pc = 18-40 t/m^2), which include Clinker Silos; Cement Silos; Limestone Silos, Homogenization Silos, Rotary Kiln Supports, as well as Preheater and similar ones.

With increased dimensions in the plan, the stress-strain state of the foundation of these structures increases significantly: due to the summation of the loads from the dead weight of the structures, the useful loads and the weight of the planning embankment: the depth of the compressible layer increases and as a rule, extends to the roof of slightly compressible soils.

At the same time, there is a decrease in the deformation modulus of clay soils due to the inevitable increase in humidity during the development of the territory and due to the infiltration of surface waters of various origins through bulk soils of gravel-pebble and coarse-grained composition.

To prevent settlement processes of existing foundations made of shallow piles (h=16.0 m), modern foundation construction methods should be used.

Pile foundations are currently widely used in construction.

This is facilitated by:

a) A significant reduction in the volume of excavation work, reduction in construction time, etc.;

b) High mechanical equipment of construction allows driving piles of considerable length into the ground, reaching denser soil layers and transferring heavy loads to them;

c) Long piles, taking up relatively large loads, give relatively small settlements;

d) Foundations made of driven piles are highly industrial;

e) In difficult engineering and geological conditions, the pile option is often the only possible type of foundation (Kalachuk, 2015).

Taking into account the above and in order to completely prevent ongoing settlement under the foundations of heavy structures, employees of NIIOSP (Moscow), based on the requirements of regulatory documents and methodological recommendations, designed additional deep piles with a diameter of 1.5 m and a depth of 80.0 m under the foundations of Preheater and Rotary Kiln Supports (Krutov *et al*., 2015; SP 24.13330, 2016).

After the installation of pile foundations, deformation processes in the soil massif under the Preheater and Rotary Kiln Supports structures have completely ceased since February 2014.

Group 2 - light structures, usually with a flexible structural scheme of the frame structure on free-standing or strip pile foundations made of bored piles. Specific loads on the base soils are often 5.5-12 t/m^2. The main representatives of this group are one- or two-story, less often high-rise structures: Clinker Cooling; Raw Mill; Cement Packing, etc.

Group 3 - heavy structures with increased cyclic useful load, often exceeding the load on the foundation soils from the structure's own weight by 1.5-2.0 times. With cyclic application of load caused by loading and unloading, stabilization of the compression of the foundation soils is not achieved, as a result of which the intensity of the increase in silo settlements decreases and the time of their stabilization increases significantly compared to other structures of the 1st group.

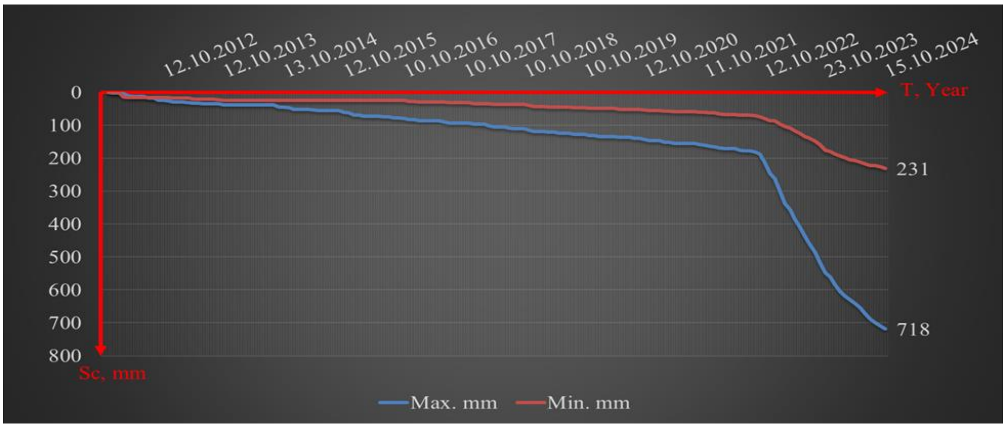

Figure 12. Limestone Silos foundation settlement graph over time

Analysis and comparison of the presented data on the settlements of the foundations of Limestone Silos, Corrective Silos and Cement Silos (Figures 12, 13 and 14) allows us to note, first of all, that the construction of the above pile foundations (d=600.0 mm, h=18.0 m) under Limestone Silos and Corrective Silos, as well as other structures of the plant, did not lead to a significant reduction in the settlement processes in the soil massif of the geological environment at the base of the structure.

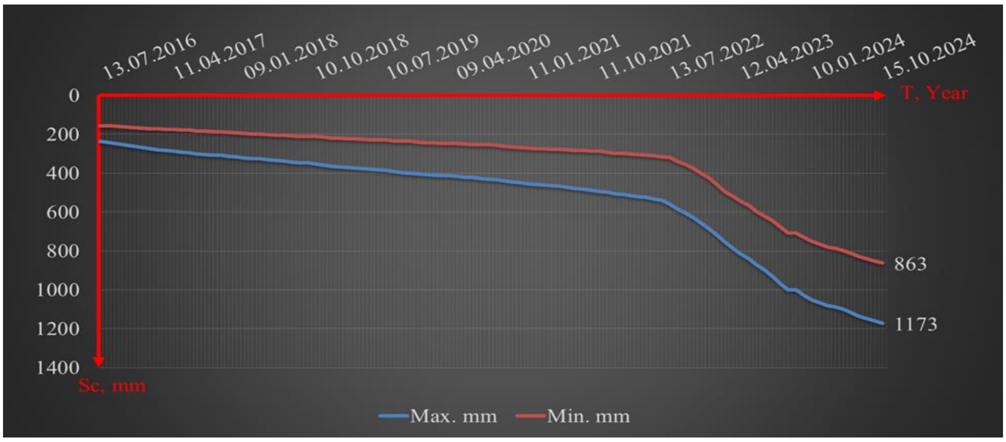

Figure 13. Graph of Corrective Silos foundation settlement over time

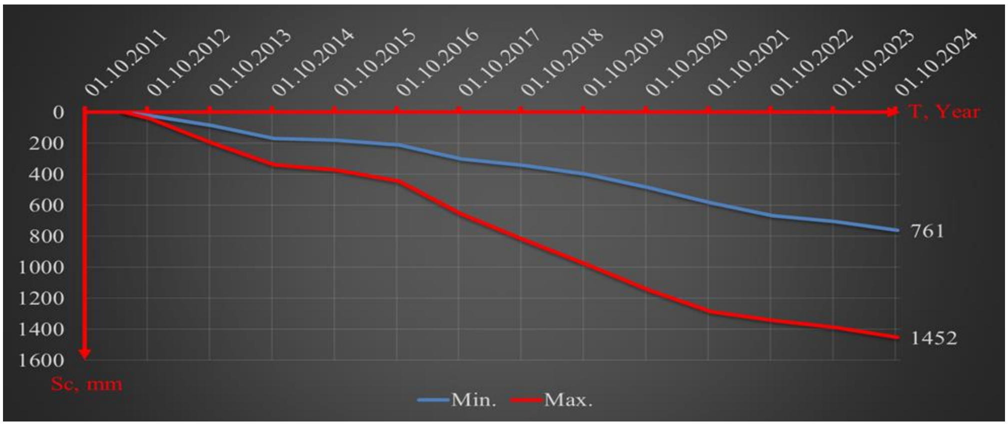

Figure 14. Graph of Cement Silos foundation settlement over time

The data provided on the settlement of structures allow us to note that the settlement of the foundations of structures and the unevenness of their development depend mainly on:

a) Engineering and geological composition of the soil base and their main characteristics. Before the start of operation, higher values of settlement were observed in the foundations of Rotary Kiln Supports, Preheater, Clinker Silos, Raw Mill, at the base of which subsidence and semi-solid and fluid loams lie on top, below clay of semi-solid and fluid consistency with separate layers and interlayers up to 1 m thick of gravel-pebble soils. The smallest values of settlement were in the locations of Limestone Silos, Corrective Silos, Cement Mill, at the base of which semi-solid clays and gravel-pebble soils predominate.

b) Violation of the structure, density and other physical and mechanical characteristics of self-compacting bulk soils as a result of anthropogenic impacts. These factors will lead to the creation of conditions for the infiltration of waters of various origins (mainly rain and snow water) into the soil massif of the geological environment under the foundations of structures.

Due to the fact that the silty-clayey soils at the base of these structures have a loess and loess-like nature, soil subsidence occurred accompanied by an increase in foundation settlement several times at the Limestone Silos and Corrective Silos structures, where in a certain period the dynamics of the average monthly foundation settlement reached 26.0 mm and 37.0 mm and the maximum average monthly settlement was 40.0 mm and 43.0 mm, respectively (Figures 15 and 16).

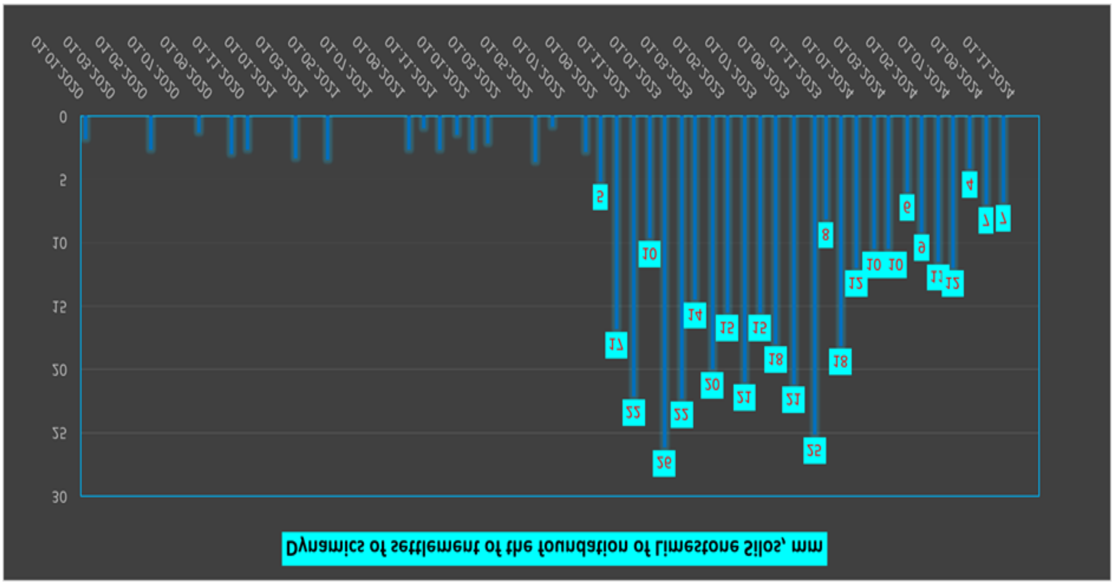

Figure 15. Dynamics of foundation settlements of Limestone Silos

a) The choice of the type of foundations and bases and their structures must comply with the requirements of SP 50-101-2004 and SP 50-102-2003 and the design of foundations must be carried out with their calculation according to two limit states, according to the bearing capacity and according to soil deformations.

The completed verification settlements according to SP 50-101-2004 show that the actual settlements of the foundations of the structures under consideration exceed the limit values by 2-3.5 times.

Therefore, it was necessary to use foundations for structures with deep piles, taking into account the engineering and geological conditions of the construction site, including the characteristics of the soils, in particular the subsidence of clay soils and with their calculation not only by bearing capacity, but also by deformations taking into account the additional load from the weight of the planning embankment and to make a slab grillage with its cutting by settlement joints for each silo (Krutov *et al*., 2016; SP 22.13330, 2016).

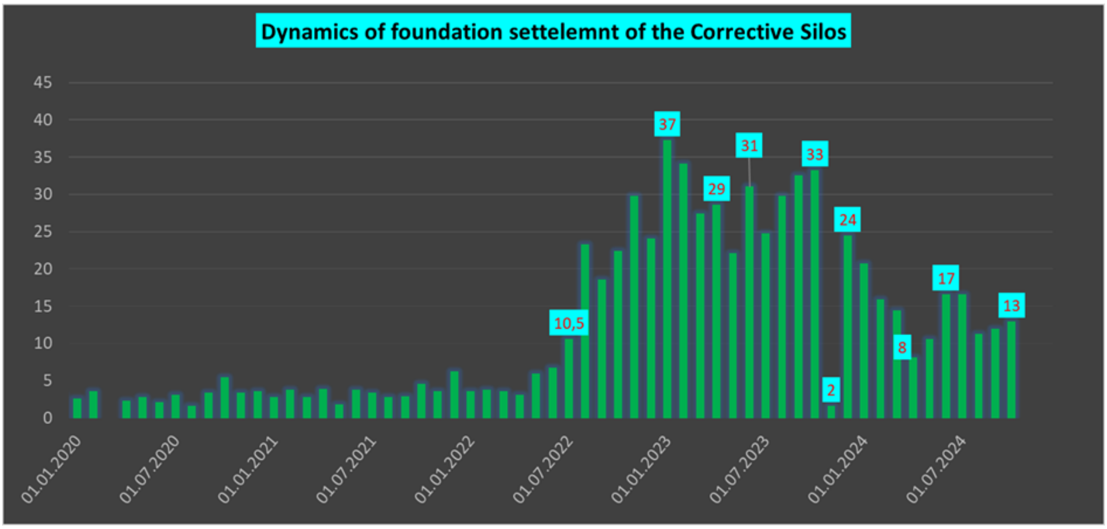

Figure 16. Dynamics of foundation settlement Corrective Silos

3. Conclusion

Analysis of the results of observations of the settlements of structures allows us to conclude that when designing pile foundations for all structures of the plant, the features of the stress-strain state of soils caused by the construction of a newly erected leveling embankment and the unfavorable composition of the bulk layer from technogenic formations with inclusions of coarse soils that created the conditions were not taken into account for the infiltration of atmospheric precipitation and surface water into the geological environment of the territory characterized by significant increases:

- Vertical stresses from the weight of the planning embankment and from additional soaking without significantly reducing them along the depth of the soil layer;
- The depth of the compressible layer to the roof of the bearing layer of slightly compressible soils, which in this case are the bedrock argillite-like clay.
- Transfer of additional loads to the piles from negative friction forces.
- Loads from the weight of the planning embankment and from an increase in the density of the soils of the geological environment due to an increase in humidity;
- The dead weight of structures, including foundations of process equipment;
- A decrease in the physical and mechanical properties of soils under the influence of additional soaking as a result of infiltration of atmospheric precipitation and surface water through a fill layer consisting mainly of coarse-grained, non-cohesive soils.

The engineering-geological properties of silty-clayey (loess) soils of the soil massif of the study area are greatly influenced by anthropogenic phenomena (formation of an embankment, creation of conditions for infiltration of precipitation and surface water, dynamic loads not provided for by the design, etc.) and modern physics -geographical conditions, in particular temperature fluctuations, amount and nature of precipitation.

Formed as a result of unjustified engineering and economic activity of man, the embankment is the main reason for a strong and unpredictable change in the engineering and geological conditions of the construction site, leading to negative engineering and geological and geotechnical phenomena. The embankment of gravel and pebble composition filled around the foundations of all structures is not only an additional load on the soil base of the structures, but also a source of soaking or moistening of loess and loess soils of the foundation base.

The influence of the above conditions (infiltration of precipitation and surface water, soaking and increase in soil moisture, moisture migration, etc.) on soil properties results in a violation of structural connections, which leads to an additional settlement process in the soil massif of the geological environment under the foundations of buildings.

Of the factors listed, water has the primary effect on the strength of loess rocks. An increase in the moisture content of loess soils as a result of water infiltration through the planning embankment causes softening of crystallization bonds, dissolution and movement of easily soluble salts in the thickness contributes to the disruption of structural bonds, the deformation characteristics of soils decrease and as a result, additional foundation settlements occur.

Despite the presence of very significant, both in absolute value and in terms of the degree of unevenness of the settlement of the main structures, the plant has been operated without interruption since 2013 on the basis of the monthly updated recommendations presented by the authors of this article on minimizing the degree of risk of safe operation of individual structures and other proposals for the non-stop operation of the production cycle.

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