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TƏBİƏT ELMLƏRİ

NATURAL SCİENCE

Investigation of the Causes of Deformation Processes at Industrial Construction Sites and Methods of Geotechnical Rehabilitation

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Abstract. This paper investigates the causes of intensive structural deformations and differential *settlements recorded at the construction site of an insulation board manufacturing plant. Based on comprehensive visual-geotechnical monitoring, diagnostic engineering-geological surveys, and a rigorous retrospective analysis of previously obtained laboratory data, it was established that the lithology of the underlying soils is represented by moisture-sensitive, poorly compacted loessial silty clay soils. Retrospective verification calculations showed that 14 out of 21 sampled soil specimens exhibit pronounced collapsible properties upon wetting, which allows classifying the site's ground conditions as Type II collapsible soil conditions. The primary catalysts for the developing structural damages were recognized as technological violations during backfill compaction operations, insufficient hydraulic slopes of protective concrete aprons, and the complete absence of functional stormwater drainage networks, which led to total surface water infiltration. To eliminate the developing geodynamic hazards and ensure the long-term operational reliability of the enterprise specialized geotechnical rehabilitation strategies are proposed and evaluated from structural, hydraulic, and economic perspectives. Special emphasis is placed on the application of advanced Jet Grouting technology to construct load-bearing soil-cement columns, along with creating reliable hydroisolation barriers and transitioning to deep pile foundations.*

Keywords: *geotechnics, differential settlement, Jet Grouting, loessial soils, deformation, engineering geology, geodynamics*

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Sənaye tikinti sahələrində deformasiya proseslərinin səbəblərinin tədqiqi və geotexniki reabilitasiya üsulları

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Xülasə. *Bu məqalədə izolyasiya lövhələri istehsalı zavodunun tikinti sahəsində qeydə alınmış intensiv konstruktiv deformasiyaların və diferensial çökmələrin yaranma səbəbləri araşdırılmışdır. Kompleks vizual-geotexniki monitorinq, diaqnostik mühəndis-geoloji tədqiqatlar və əvvəllər əldə edilmiş laboratoriya nəticələrinin hərtərəfli retrospektiv təhlili əsasında müəyyən edilmişdir ki, ərazinin əsasını nəmliyə həssas, kifayət qədər sıxlaşdırılmamış lösşəkilli gilli-tozlu qruntlar təşkil edir. Retrospektiv yoxlama hesablamaları göstərmişdir ki, götürülmüş 21 qrunt nümunəsindən 14-ü islanma zamanı nəzərəçarpacaq çökmə xüsusiyyətləri nümayiş etdirir ki, bu da tikinti sahəsinin qrunt şəraitini II tip çökməyə meyilli qruntlar kateqoriyasına aid etməyə əsas verir. İnkişaf edən konstruktiv zədələnmələrin əsas səbəbləri kimi geri doldurma işləri zamanı texnoloji tələblərin pozulması, mühafizəedici beton örtüklərin kifayət qədər maililiyə malik olmaması və yağış sularının kənarlaşdırılması üçün funksional drenaj sisteminin tamamilə olmaması müəyyən edilmişdir. Bu amillər səth sularının tam həcmdə qrunt qatlarına sızmasına və geodinamik proseslərin inkişafına səbəb olmuşdur. Yaranmış geodinamik təhlükələrin aradan qaldırılması və müəssisənin uzunmüddətli istismar etibarlılığının təmin edilməsi məqsədilə konstruktiv, hidrotexniki və iqtisadi baxımdan qiymətləndirilmiş xüsusi geotexniki reabilitasiya tədbirləri təklif olunmuşdur. Tədqiqatda daşıyıcı qrunt-sement sütunlarının yaradılması üçün müasir Jet Grouting texnologiyasının tətbiqinə, etibarlı hidroizolyasiya baryerlərinin qurulmasına və dərin svay bünövrələrinə keçidin məqsədəuyğunluğuna xüsusi diqqət yetirilmişdir.*

Açar sözlər: *geotexnika, diferensial çökmə, Jet Grouting, lösşəkilli qruntlar, deformasiya, mühəndis-geologiyası, geodinamika*

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Introduction

Determining the true causes of the deformation processes observed at the construction site of the insulation board manufacturing plant is of paramount importance for assessing the current state of the geotechnical environment and developing well-founded engineering protection recommendations. To this end, detailed visual-geotechnical and visual-geological field observations were carried out on January 25, 2025, within the territory of the industrial facility (Fig. 1). Furthermore, archival engineering-geological survey data and laboratory testing records reflecting the regional geological and hydrogeological conditions of the site were subjected to an exhaustive retrospective engineering analysis.

Figure 1
Location map of the industrial facility territory

Source. Authors.

To provide the initial stages of construction and installation design with the necessary baseline geological parameters, a specialized subcontractor, «Azgeotechnoservice» Limited Liability Company, carried out engineering-geological surveys in December 2020. During these investigations, 22 exploratory boreholes were drilled across the entire development area to a uniform depth of 6.0 meters. A total of 21 undisturbed soil core samples (monoliths) were collected from various lithological layers and depth intervals and sent to the laboratory to determine the physical and mechanical properties of the soils.

Methods

Local geotechnical monitoring, engineering-geological diagnostics, and technical safety assessments performed along the plant's perimeter revealed several critical lithological anomalies and structural defects. Within the soil strata underlying the foundation beds of the industrial complex, signs of active vertical displacement deformations (Figure 2) were clearly recorded, namely intensive settlements and differential collapse profiles (An et al., 2022).

Figure 2
Foundation deformation

Source. Authors.

Following the completion of the main structural construction works, site preparation and backfilling activities (specifically, the compaction of excavation trench and foundation pits adjacent to reinforced concrete foundations) were executed without proper geotechnical engineering supervision.

The backfill materials were not compacted to the required maximum dry density values, creating an artificial, highly porous medium that catalyzed active infiltration (Figure 3) of industrial and stormwater runoff into the primary underlying soil mass.

Figure 3
Infiltration of industrial and stormwater

Source. Authors.

The production areas of the insulation board workshops and auxiliary elements in direct contact with the underlying soil matrix, as well as the isolated foundations of the steel frame columns, lacked sufficient engineering protection against exogenous, anthropogenically induced hydrogeological hazards. Perimeter protective concrete aprons (waterproof pavements) lacked the standard hydraulic slopes necessary to divert surface runoff away from load-bearing elements, resulting in localized water ponding (Figure 4).

Post-construction engineering solutions designed to isolate the highly moisture-sensitive loess formations from atmospheric precipitation (particularly heavy rainfalls) lacked structural-functional justification and completely ignored the internal hydrostructural instability inherent in the foundation substrate.Many historical failures in loess regions occurred because standard surface water-defense measures (like concrete aprons or drainage ditches) were designed as isolated superficial solutions. Designers failed to account for the internal microstructural collapse triggering mechanism when continuous rainwater infiltration bypasses these barriers (Li et al., 2016).

Figure 4
Localized water ponding

Source. Authors.

Major macro-fissures and multi-directional structural cracks with varying aperture widths were mapped across load-bearing structural elements, reinforced concrete partition walls, and concrete drainage channels (Figure 5). Monolithic reinforced concrete floor slabs serving as foundations for heavy industrial equipment demonstrated significant differential settlements accompanied by micro-cracking.

Figure 5

Major macro-fissures and multi-directional structural cracks

Source. Authors.

Due to malfunctioning downspouts, atmospheric precipitation collected from extensive roofing systems was systematically discharged directly into these open cracks in the concrete, causing total vertical infiltration into the underlying collapsible loess layers (Li et al., 2016). The existing subsurface drainage system and the stormwater collection network were quantitatively and volumetrically inadequate for the catchment area of this facility. The only operational drainage outlet on site was found to be completely decommissioned due to severe internal siltation (clogging) and a total loss of the design hydraulic slope.

Field diagnostics included a visual inspection of an excavation approximately 10 meters deep located close to the facility site. Wetting tests performed on selected soil samples demonstrated an extreme degree of hydrophilicity, rapid structural collapse upon soaking, and complete loss of internal cohesive bonds. Visual descriptions of the walls of the 10-meter deep utility trench, excavated in immediate proximity to the plant boundary, confirmed that the upper geological profile (in the depth interval of 0.0–4.0 m) is entirely composed of structurally unstable, macro-porous loess and loessial loams (Smalley et al., 2001).

A methodical analysis of the engineering-geological report previously compiled by "Azgeotechnoservice" LLC showed that the classification and delineation of engineering-geological units (EGUs) across the construction site were performed without strict adherence to the mandatory requirements of interstate standards GOST 25100-2011 (Soils. Classification) and GOST 20522-2012 (Soils. Methods of Statistical Processing of Test Results) (Standartinform, 2011, 2012). Despite drilling 22 exploratory boreholes to a depth of 6.0 meters, a critically low volume of monoliths was sampled—only 21 specimens from 7 boreholes. Moreover, standard odometer compression tests to determine the primary soil compressibility and settlement modules were conducted on only 1 (maximum 2) samples. Such a limited sample size completely precludes statistical representativeness and scientific validity of the obtained design parameters (Table 1).

Table 1
Physico-mechanical properties of soils

№№	BH №	Depth,м, m	Particle-size distribution,% fractions				Water content, %	Soil density, gr/sm³		Solid particles density, gr/sm³	Porosity , %	Void ratio	Total moisture capacity, %	Degree of saturation	Liquidity index, %			Consistency index	Soil name in accordance with GOST 25100-2011
			2-0,05 mm	0.05-0.01 мм	0.01-0.005 mm	< 0,005 mm		At natural moisture	At natural moisture						Liquid limit	Plastic limit	Plasticity index		
			Sand	Silt		Clay	W	P	$P_д$	P_s	n	e	W_{sat}	S_r	W_L	W_p	I_p	I_L	
1	1	1,0-1,5					0,16	1,77	1,53	2,73	44,0	0,784	0,29	0,56	0,36	0,19	0,17	-0,18	Clay, very stiff
2		3,0-3,5	19,50	53,0		27,50	0,10	1,79	1,63	2,74	40,5	0,681	0,25	0,40	0,38	0,21	0,17	-0,65	Clay, very stiff
3		5,0-5,5					0,13	1,94	1,72	2,72	36,8	0,581	0,21	0,61	0,37	0,22	0,15	-0,60	Loam , very stiff
4	4	1,0-1,5	31,00	47,0		22,00	0,15	1,86	1,62	2,74	40,9	0,691	0,25	0,59	0,36	0,19	0,17	-0,24	Clay , stiff
5		3,5-4,0					0,10	1,85	1,68	2,72	38,2	0,619	0,23	0,44	0,34	0,19	0,15	-0,60	Loam , very stiff
6		5,5-6,0					0,14	1,94	1,70	2,72	37,5	0,600	0,22	0,63	0,34	0,21	0,13	-0,54	Loam , very stiff
7	10	1,0-1,5					0,06	1,82	1,72	2,71	36,5	0,576	0,21	0,28	0,28	0,16	0,12	-0,83	Loam , very stiff
8		3,5-4,0					0,13	1,92	1,70	2,72	37,5	0,600	0,22	0,59	0,31	0,17	0,14	-0,29	Loam , very stiff
9		5,5-6,0					0,11	1,85	1,67	2,73	38,8	0,635	0,23	0,47	0,33	0,16	0,17	-0,29	Clay, very stiff
10	13	1,0-1,5					0,14	1,93	1,69	2,73	38,1	0,615	0,23	0,62	0,33	0,16	0,17	-0,12	Clay, very stiff
11		3,0-3,5	17,00	45,00		38,00	0,14	1,86	1,63	2,74	40,5	0,681	0,25	0,56	0,42	0,25	0,17	-0,65	Clay, very stiff
12		5,0-5,5					0,12	1,90	1,70	2,72	37,5	0,600	0,22	0,54	0,31	0,18	0,13	-0,46	Loam , very stiff
13	15	1,0-1,5					0,17	1,91	1,63	2,73	40,3	0,675	0,25	0,69	0,37	0,20	0,17	-0,18	Clay, very stiff
14		3,0-3,5	23,50	49,00		27,50	0,24	2,02	1,63	2,73	40,3	0,675	0,25	0,97	0,38	0,21	0,17	0,18	Clay, stiff
15		5,5-6,0					0,17	1,95	1,67	2,72	38,6	0,629	0,23	0,74	0,33	0,20	0,13	-0,23	Loam , very stiff
16	18	1,0-1,5					0,16	1,95	1,68	2,72	38,2	0,619	0,23	0,70	0,35	0,19	0,16	-0,19	Loam , very stiff
17		3,5-4,0					0,21	2,02	1,67	2,72	38,6	0,629	0,23	0,91	0,34	0,19	0,15	0,13	Loam , stiff
18		5,5-6,0					0,15	1,94	1,69	2,72	37,9	0,609	0,22	0,67	0,34	0,21	0,13	-0,46	Loam , stiff
19	21	1,0-1,5					0,13	1,90	1,68	2,71	38,0	0,613	0,23	0,57	0,30	0,17	0,13	-0,31	Loam , very stiff
20		3,5-4,0	19,00	47,50		33,50	0,19	1,96	1,65	2,74	39,8	0,661	0,24	0,79	0,36	0,18	0,18	0,06	Clay, stiff
21		5,5-6,0					0,12	1,88	1,68	2,71	38,0	0,613	0,23	0,53	0,29	0,15	0,14	-0,21	Loam , very stiff

Furthermore, the final report completely lacked a comprehensive mathematical-statistical analysis of laboratory data. Consequently, the normative and design geotechnical values required for limit state design calculations—both for bearing capacity (first limit state) and deformations (second limit state)—were not established. While the initial laboratory conclusion paradoxically stated that the soil sample tested in the compression apparatus exhibited high resistance, high deformation modules, and swelling properties, independent verification calculations performed by our working group using standardized methods from official regulatory documents—namely, the *Manual for Designing Foundations of Buildings and Structures*—yielded deeply contradictory results (State Committee for Urban Planning and Architecture of the Republic of Azerbaijan, 2015; State Committee for Construction of the USSR, 1984). Out of the 21 silty clay samples subjected to physical testing, exactly 14 monoliths mathematically proved their classification as highly collapsible, macro-porous loessial loams undergoing sharp volume reduction upon wetting (Table 2).

Table 2

Determination of collapsibility characteristics of soils

№/№	BH №	Depth,м, m	Water content, %	Soil density, gr/sm³		Solid particles density, gr/sm³	Void ratio	Liquidity index, %			Consistency index	Void ratio at liquid limit	Collapse index	Criteria for collapse index	Collapsibility-related soil properties	Soil name in accordance with GOST 25100-2011
				At natural moisture	At natural moisture			Liquid limit	Plastic limit	Plasticity index						
			W	P	$P_{д}$	P_s	e	W_L	W_p	I_p	I_L	e_L	I_{ss}	I_{ss}<		
1		1,0-1,5	0,16	1,77	1,53	2,73	0,784	0,36	0,19	0,17	-0,18	0,98	0,11	0,24	Collapsible	Clay, very stiff
2	1	3,0-3,5	0,10	1,79	1,63	2,74	0,681	0,38	0,21	0,17	-0,65	1,04	0,21	0,24	Collapsible	Clay, very stiff
3		5,0-5,5	0,13	1,94	1,72	2,72	0,581	0,37	0,22	0,15	-0,60	1,01	0,27	0,24	Non-collapsible	Loam , very stiff
4		1,0-1,5	0,15	1,86	1,62	2,74	0,691	0,36	0,19	0,17	-0,24	0,99	0,17	0,24	Collapsible	Clay , stiff
5	4	3,5-4,0	0,10	1,85	1,68	2,72	0,619	0,34	0,19	0,15	-0,60	0,92	0,19	0,24	Collapsible	Loam , very stiff
6		5,5-6,0	0,14	1,94	1,70	2,72	0,600	0,34	0,21	0,13	-0,54	0,92	0,20	0,17	Non-collapsible	Loam , very stiff
7		1,0-1,5	0,06	1,82	1,72	2,71	0,576	0,28	0,16	0,12	-0,83	0,76	0,12	0,17	Collapsible	Loam , very stiff
8	10	3,5-4,0	0,13	1,92	1,70	2,72	0,600	0,31	0,17	0,14	-0,29	0,84	0,15	0,24	Collapsible	Loam , very stiff
9		5,5-6,0	0,11	1,85	1,67	2,73	0,635	0,33	0,16	0,17	-0,29	0,90	0,16	0,24	Collapsible	Clay, very stiff
10		1,0-1,5	0,14	1,93	1,69	2,73	0,615	0,33	0,16	0,17	-0,12	0,90	0,18	0,24		Clay, very stiff
11	13	3,0-3,5	0,14	1,86	1,63	2,74	0,681	0,42	0,25	0,17	-0,65	1,15	0,28	0,24	Non-collapsible	Clay, very stiff
12		5,0-5,5	0,12	1,90	1,70	2,72	0,600	0,31	0,18	0,13	-0,46	0,84	0,15	0,17	Collapsible	Loam , very stiff
13		1,0-1,5	0,17	1,91	1,63	2,73	0,675	0,37	0,20	0,17	-0,18	1,01	0,20	0,24	Collapsible	Clay, very stiff
14	15	3,0-3,5	0,24	2,02	1,63	2,73	0,675	0,38	0,21	0,17	0,18					Clay, stiff
15		5,5-6,0	0,17	1,95	1,67	2,72	0,629	0,33	0,20	0,13	-0,23	0,90	0,17	0,17		Loam , very stiff
16		1,0-1,5	0,16	1,95	1,68	2,72	0,619	0,35	0,19	0,16	-0,19	0,95	0,21	0,24	Collapsible	Loam , very stiff
17	18	3,5-4,0	0,21	2,02	1,67	2,72	0,629	0,34	0,19	0,15	0,13					Loam , stiff
18		5,5-6,0	0,15	1,94	1,69	2,72	0,609	0,34	0,21	0,13	-0,46	0,92	0,20	0,17	Non-collapsible	Loam , stiff
19		1,0-1,5	0,13	1,90	1,68	2,71	0,613	0,30	0,17	0,13	-0,31	0,81	0,12	0,17	Collapsible	Loam , very stiff
20	21	3,5-4,0	0,19	1,96	1,65	2,74	0,661	0,36	0,18	0,18	0,06	0,99	0,20	0,24	Collapsible	Clay, stiff
21		5,5-6,0	0,12	1,88	1,68	2,71	0,613	0,29	0,15	0,14	-0,21	0,79	0,11	0,24	Collapsible	Loam , very stiff

Source. Authors.

Results

The baseline engineering-geological surveys of the site, which served as the foundation for the structural design of the plant, violated key provisions of regional and international regulatory codes. The recorded geological parameters do not reflect the actual foundation conditions, rendering the initial geotechnical report internally inconsistent and methodologically invalid. Independent geotechnical verification calculations verified that the primary subfoundation zone is composed of weak, undercompacted, and structurally unstable silty loam strata, posing a specific geotechnical hazard. The loam layers forming the soil foundation are characterized by high spatial variability in depth and thickness both horizontally and vertically. These formations possess a tendency for sudden collapsible failure upon moisture saturation. Based on the calculated values of relative collapsibility coefficients under design loads, the site's ground conditions are officially classified as Type II Collapsible Ground Conditions, meaning that the soil profile is capable of undergoing massive collapsible deformations under the combined action of external structural loads and its own self-weight upon wetting (Lim & Kim, 2021).

Consequently, the initial geological assumptions used for designing the building's foundations were fundamentally flawed. The width, embedment depth, and configuration parameters of the existing shallow foundations were erroneously determined, rendering them incapable of safely absorbing and redistributing the combined static and dynamic operational loads of the structure under saturated foundation conditions. The complete absence of operational surface stormwater management systems left the facility vulnerable to unregulated flooding, inducing intensive moisture accumulation within the sub-foundation matrix. Engineering measures to isolate the foundation zones were missing; the lack of monolithic concrete aprons at critical junctions where reinforced concrete walls meet the ground permitted unhindered gravitational infiltration of surface runoff directly into the collapsible loess strata. Currently, the processes of intensive vertical and differential structural settlements within the sub-foundation soil mass are in an active phase of development. As unorganized stormwater discharge from the roofing system continues to saturate the loess profile, differential settlement gradients will inevitably increase over time.

The principal trigger for the observed distressed state of the structures is the complete lack of design and implementation of proper hydro-isolation barriers and waterproof pavements. Prolonged wetting of the loess mass caused a catastrophic degradation of its shear strength parameters, namely a sharp drop in the internal friction angle (φ) and cohesion (c), alongside a drastic reduction in the deformation modulus (E) (Cheng et al., 2024). Simultaneously, moisture saturation significantly increased the unit weight of the soil, introducing a severe additional gravitational load that accelerates foundation failure.

Discussion and Conclusion

To ensure the long-term operational safety of the industrial plant under conditions of developing geodynamic hazards, a comprehensive implementation of modern geotechnical and hydrotechnical solutions is required. First, when designing and reconstructing structures located on unsaturated silt-clay formations ($Sr < 0.80$), engineering models must take into account the sharp decrease in bearing capacity and shear strength as the moisture content increases until it reaches full saturation (Vanapalli & Mohamed, 2013). Second, the integration of moisture barriers into foundation structures and the execution of verification engineering-geological and geophysical surveys are required to eliminate lithological uncertainties. Special attention should be devoted to controlling the microclimate of the subsurface environment and preventing further wetting of the collapsible horizons. As methods for soil mass rehabilitation, both traditional solutions (soil replacement, soil cushions) and advanced technologies can be applied, including Jet Grouting (Modoni et al., 2019; Shiraliyev et al., 2024), which ensures the formation of high-strength soil-cement columns and blocks water infiltration.

The final selection of the remediation scheme must be based on rigorous numerical modeling that accounts for predicted settlement, moisture migration pathways, and structure-utility interactions. Additionally, alternative stabilization methods can be considered—dynamic compaction, controlled collapse, chemical grouting, or thermal treatment. An integral part of the strategy is the reconstruction of the surface water management system, including the design of a closed high-capacity stormwater network and the construction of protective concrete aprons at least 2.0 m wide. These measures must be accompanied by replacing the wet backfill soils with compacted clayey materials and constructing drainage channels directing runoff away from the site.

To eliminate foundation deformations of heavy processing equipment, various scenarios are possible: mechanical foundation reconstruction, stabilization via Jet Grouting (Shen et al., 2020), pile foundation upgrading, or precision equipment alignment. Thus, the proposed complex of measures combines engineering-geological diagnostics, advanced soil remediation methods, and hydrotechnical protection, ensuring risk reduction and enhancing the resilience of the industrial infrastructure.

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