FACTA UNIVERSITATIS
Series: Architecture and Civil Engineering Vol. 22, Nº 3, 2024, pp. 277-291
https://doi.org/10.2298/FUACE231111004M

Original Scientific Paper

GROUND IMPROVEMENT AND FOUNDATION DESIGN OF INDUSTRIAL FACILITIES ON LOESS SOIL

UDC 624.15:624.954(497.2)

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Abstract. *This study addresses the exploration of two interchangeable foundation strategies for an industrial site (silo base) located in Silistra, Bulgaria. The geological conditions at the site present significant challenges due to the presence of local loess soil, which has been classified as "collapsible – Type II" in accordance with the Bulgarian Shallow Foundations Code, extending to a depth of 12 meters. To adhere to the code requirements and meet the stringent operational limitations imposed on the silos, including restrictions on foundation settlement and tilt, two potential approaches are considered. These options involve either mitigating the collapsibility of the soil or navigating through the collapsible soil using deep foundation techniques like piles, slurry walls, and similar methods. Following an initial technical analysis and cost estimation, this study favors the utilization of shallow foundation methods combined with local soil improvement practices. The first approach entails the construction of a dual mat foundation, which is placed atop a relatively thick base layer comprising a soil-cement mixture and soil that has been enhanced through rapid impact compaction (RIC). The second approach involves a mat foundation positioned on a relatively thinner base layer of soil-cement mixture, supplemented by strategically placed deep soil mix (DSM) columns. Both of these strategies ensure the structural reliability of the silos, advocate for the implementation of soil improvement methods readily accessible within the Bulgarian market, and offer a swift and cost-efficient execution.*

Key words: *loess, collapsible soil, shallow foundation, soil improvement, silo, rapid impact compaction, cement-soil mixing, deep soil mixing*

Received November 11, 2023 / Revised February 2, 2024 / Accepted March 5, 2024

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1. INTRODUCTION

Collapsible soils present significant challenges in geotechnical and structural engineering worldwide. They can occur naturally or due to human activities, involving unstable structures with various bonding mechanisms. Bonds may form through capillary forces or cementing materials, and collapse happens when applied stresses exceed the yield strength of these bonds. Collapsibility is often triggered by water inundation, which varies in impact. Effective management of collapsible soils requires accurate identification, based on geological and geomorphological data, along with wetting-loading tests. Spatial distribution and wetting extent are crucial considerations. Soil improvement techniques can mitigate collapse potential. Common features of collapsible soils include unstable open structure, high voids ratio, high porosity, recent deposits, high sensitivity, and weak interparticle bonding.

Collapsible loess soils, composed of fine quartz particles, are widespread in various regions globally, posing collapse risks. Understanding soil particle Provenance, Transportation, and Deposition sequences is vital in developing a collapsible structure. Wind direction and climate fluctuations influence collapsibility zones, water infiltration, and ground improvement effectiveness.

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Loess soils, covering approximately 9800 km^2 in Northern Bulgaria, vary in thickness from 1 m in the Balkan Mountains to over 100 m along the Danube River. These soils have aeolian origins, transported mainly from the north-northeast winds during the late Pliocene and early Quaternary periods. Sources include the Paleodanube floodplains, shaped by glacial denudation of the Eastern Carpathians slopes. Bulgarian loess is characterized by high silt content, ample pores, macropores, low dry density, and relatively low moisture levels. Buried soil horizons form during periods of reduced dust deposition, resulting in six distinct loess varieties. In the northern Danube Plain of Bulgaria, construction-related challenges arise due to loess subsidence upon saturation, primarily in typical loess, sandy loess, and clayey loess.

Due to the diverse geomorphological processes contributing to loess formation, loess deposits typically exhibit three distinct zones of relative collapsibility:

- Zone 1: This zone is situated at a depth where material collapses due to overburden pressure.
- Zone 2: Known as the collapsible zone, this layer is susceptible to collapse.
- Zone 3: The surface crust, requiring additional load to induce collapse.

Countries with extensive loess deposits, such as Eastern Europe and the former Soviet Union, have developed classification systems related to foundation collapse under loading. These schemes categorize collapsibility into two types:

- Type I: Mainly associated with loaded collapsibility, where collapse deformation occurs under an overburden pressure of less than 5 cm.
- Type II: Primarily linked to unloaded collapsibility, characterized by collapse induced deformation more than 5 cm.

Type I loess is typically of limited thickness and contains one or two palaeosols (PS) along with an associated carbonate zone (Cz). Collapse in Type I loess occurs once the foundation stress surpasses a critical stress threshold, determinable through laboratory or field tests.

The focus of this report is a planned industrial base in Northern Bulgaria, specifically in Silistra municipality. The investment intentions revolve around a silo farm, comprising 44 silos, each with a volume of 12 500 m^3, organized into 11 groups of 4 each, resulting in a total volume of up to 50 000 m^3. Additionally, there are 11 truck unloading stations, two truck scales with a capacity of 60 t and a length of 18 m, a checkpoint, and related facilities.

The development involves the foundation of the aforementioned silos, each consisting of a cylindrical body and a conical roof, both constructed from galvanized trapezoidal sheet metal. These facilities are designed for the storage of various types of grain, with a focus on wheat storage in this case. The dimensions of the silos are as follows: a diameter of 25.47 m, a height of the cylinder to the roof of 22.92 m, and a height of the conical roof of approximately 7.2 m.

The maximum load capacity is approximately 15 t, and comprehensive calculations have been conducted, considering two primary load scenarios from a technological perspective: SYM (symmetric silo emptying) and SD (one-sided silo emptying). The accepted absolute elevation for the site is ±0.00, with a reference point at 120.00 m.

The permissible settlement limit, according to [1] and [2] (National Annex – NA), is 15 cm, and that of permissible rotation is 4‰. Additional technological requirements for the facilities provide stricter values, specifically 5 cm for settlement and 2‰ for rotation. To ensure the optimal operation of the facilities and achieve the best technical and economic solution, the following final limit values have been adopted:

- Densification settlement should not exceed 5 cm.
- The combined settlement from densification and collapse shall not exceed 15 cm.
- Rotation due to subsidence from compaction should not exceed 2‰.
- Rotation resulting from densification settlement and collapse induced settlement should not exceed 4‰.

The current development examines the foundation structure of the silo base and the measures for improving soil’s physical and mechanical, taking into account the specific geological conditions and the loads imposed by the structures. Two alternative and interchangeable foundation options, from a technical perspective, are proposed.

2. GEOLOGICAL CONDITIONS

Geological surveys of the construction site, located at an altitude of 117.00 to 122.0 m, were conducted by a team of engineering geologists in April 2022. Fifteen boreholes (from BH1 to BH15) were drilled (plan view of the borehole locations and a geological section are on Fig. 1 and Fig. 2, respectively). Due to the uneven terrain, BH1 to BH9 and BH13 to BH14 are situated in the higher part, while boreholes BH10 to BH12 and BH15 are in the lower part. These boreholes reached a total depth of 191 m, and 191 soil samples, both disturbed and undisturbed, were collected and examined.

The site's ground base primarily consists of loess deposits, which extend to a depth of over 20 m. These deposits consist of alternating loess horizons and buried soils. The thickness of the first and second loess horizons, separated by a buried soil layer, ranges from 12.00 to 12.50 m.

Below the second loess horizon, additional layers include a second buried soil, a third loess horizon, and basic loess clays. Notably, the loess horizons are thicker than the buried soils. The geological section concludes with a young soil layer, which has a limited thickness compared to flat terrain due to erosion processes, particularly pronounced in sloping areas. It is important to note that shallow groundwater is absent in the area.

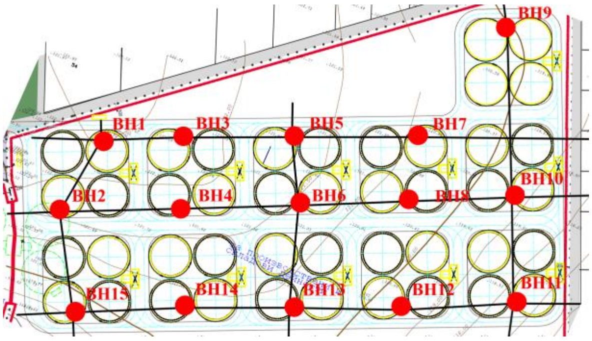


Fig. 1 Plan view of the locations of the boreholes

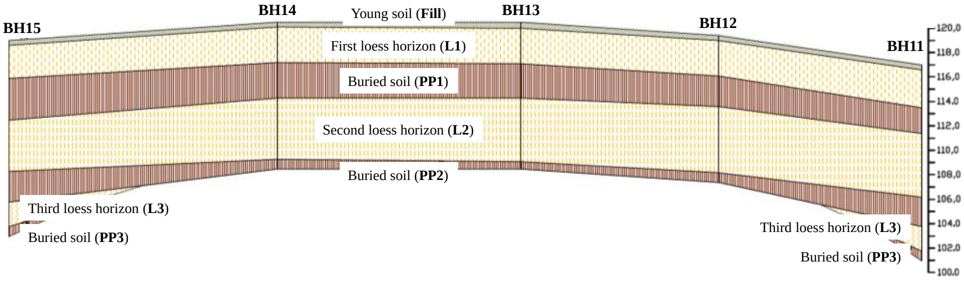


Fig. 2 Geological section through BH11, BH12, BH13, BH14 and BH15

The loess deposits comprising the site's ground base are prone to collapsing. Research has revealed that the first and second loess horizons, the intervening buried soil, and the upper half of the second buried soil layer all experience collapse when wet and subjected to geological and additional loads. The thickness of the collapse layer can reach up to 12 m, and the relative collapse coefficient (δ_p) at a stress of 300 kPa varies, falling within the range of 0.016 to 0.080.

Table 1 Elevation and depth of the boreholes

Level +/- 0.00	Layer No.	Soil Type	G.W.T.	Collapse	BH1, BH2, BH3, BH4, BH5, BH6, BH7, BH8, BH9, BH13 & BH14				BH10, BH11, BH12 & BH15			
					Top level Bot. level [m]	Top Bottom [m]	Height [m]	Total height [m]	Top level Bot. level [m]	Top Bottom [m]	Height [m]	Total height [m]
120.00	**-**	**FILL**	**NONE**	**NO**	-	-	-	-	120.00 118.30	0.00 -1.70	1.70	16.80
	1	**YOUNG SOIL**			-	-	-	-				
	2	**LOESS - L1**		**YES**	120.00 117.60	0.00 -2.40	2.40	13.70	118.30 115.30	-1.70 -4.70	3.00	
	3	**BURIED SOIL - PP1**		**YES**	117.60 114.80	-2.40 -5.20	2.80		115.30 112.70	-4.70 -7.30	2.60	
	4	**LOESS - L2**		**YES**	114.80 109.60	-5.20 -10.40	5.20		112.70 107.60	-7.30 -12.40	5.10	
	5	**BURIED SOIL - PP2**		**YES**	109.60 108.80	-10.40 -11.20	0.80		107.60 106.00	-12.40 -14.00	1.60	
	6	**LOESS - L3**		**NO**	108.80 107.10	-11.20 -12.90	1.70		106.00 104.00	-14.00 -16.00	2.00	
	7	**BURIED SOIL - PP3**		**NO**	107.10 106.30	-12.90 -13.70	0.80		104.00 103.20	-16.00 -16.80	0.80	

Table 2 Physical parameters of the soils

Level +/- 0.00	Layer No.	Soil Type	G.W.T.	Collapse	Physical Parameters									
					γ_n	γ_s	γ_d	γ'	γ_r	e	n	w_n	w_r	S_r
					[kN/m^3]	[kN/m^3]	[kN/m^3]	[kN/m^3]	[kN/m^3]	[-]	[-]	[%]	[%]	[-]
120.00	-	**FILL**	**NONE**	**NO**	18.50	26.00	16.00	10.00	20.00	0.60	0.38	-	23.08	-
	1	**YOUNG SOIL**												
	2	**LOESS - L1**		**YES**	16.19	26.49	13.73	8.33	18.33	0.980	0.495	16.10	37.00	0.44
	3	**BURIED SOIL - PP1**		**YES**	16.78	26.49	13.83	8.37	18.37	0.969	0.492	21.30	36.57	0.58
	4	**LOESS - L2**		**YES**	17.27	26.49	14.81	8.54	18.54	0.931	0.482	18.40	35.15	0.52
	5	**BURIED SOIL - PP2**		**YES**	18.54	26.49	15.21	8.74	18.74	0.887	0.470	22.00	33.48	0.66
	6	**LOESS - L3**		**NO**	18.15	26.49	15.01	8.24	18.24	1.000	0.500	21.00	37.75	0.56
	7	**BURIED SOIL - PP3**		**NO**	19.42	26.49	15.70	8.24	18.24	1.000	0.500	23.80	37.75	0.63

Table 3 Deformation parameters of the soils

Level +/- 0.00	Layer No.	Soil Type	G.W.T.	Collapse	Deformation Parameters							
					ν	$\delta_{pr,300kPa}$	p_0	E	E_d	$E_{oed,0.1MPa}$	$E_{oed,0.2MPa}$	$E_{oed,0.3MPa}$
					[-]	[%]	[kPa]	[kPa]	[kPa]	[kPa]	[kPa]	[kPa]
120.00	-	**FILL**	**NONE**	**NO**	0.300	-	-	10000	30000	10000	15000	20000
	1	**YOUNG SOIL**										
	2	**LOESS - L1**		**YES**	0.325	4.8	62	10250	9500	4100	4400	3500
	3	**BURIED SOIL - PP1**		**YES**	0.325	2.3	128	11000	10000	4400	5600	7800
	4	**LOESS - L2**		**YES**	0.325	4.5	66	15250	12000	6100	8000	9500
	5	**BURIED SOIL - PP2**		**YES**	0.325	1.0	300	14000	18000	5600	7700	10800
	6	**LOESS - L3**		**NO**	0.325	-	-	14000	18000	5600	7700	10800
	7	**BURIED SOIL - PP3**		**NO**	0.325	-	-	23335	30000	9334	12834	18000

Table 4 Strength parameters of the soils

Level +/- 0.00	Layer No.	Soil Type	G.W.T.	Collapse	Strength Parameters			
					φ	c	c_u	R_0
					[°]	[kPa]	[kPa]	[kPa]
120.00	-	**FILL**	**NONE**	**NO**	35.00	0.00	0.00	250
	1	**YOUNG SOIL**						
	2	**LOESS - L1**		**YES**	23.00	5.00	50.0	160
	3	**BURIED SOIL - PP1**		**YES**	21.00	7.00	70.0	160
	4	**LOESS - L2**		**YES**	25.00	7.00	70.0	170
	5	**BURIED SOIL - PP2**		**YES**	20.00	15.00	150.0	200
	6	**LOESS - L3**		**NO**	22.00	20.00	200.0	200
	7	**BURIED SOIL - PP3**		**NO**	19.00	35.0	350.0	250

Overall, research in the area classifies the ground base as a pronounced Type II, following [3] criteria. This means that it is expected to undergo collapse upon wetting, but only when subjected to geological loads of approximately 15 to 25 cm, surpassing the 5 cm threshold. Visible humidity anisotropy is observed up to a depth of 9 to 10 meters, with the underground water level extending to a depth of 16.00 meters. Unfavorable geological phenomena and processes were not identified, except for the collapsibility of the loess and high seismic activity.

The results of the geological survey and additional data, as assessed by the author, are organized as depicted in Tables 1, 2, 3, and 4. To determine the initial collapse stress (p_0), the relative collapse coefficient (δ_p) at 300 kPa for each failure layer in the "stress-relative collapse coefficient" relationship was used. The initial collapse stress (p_0) is graphically defined for δ_p=1% (see Figure 3). The most significant geological feature is that layers of the first loess horizon (L1), the first buried soil (PP1), the second loess horizon (L2), and the second buried soil (PP2) exhibit collapsibility (with a volume of macropores, n_m, exceeding 1%). They are classified as Type II according to [8], indicating that the collapse due to the soil's own weight exceeds 5 cm. The depth of subsidence reaches approximately 11.20 meters below the established site elevation of ±0.00, which is referenced to a relative elevation of 120.00 meters, or roughly 109.30 meters.

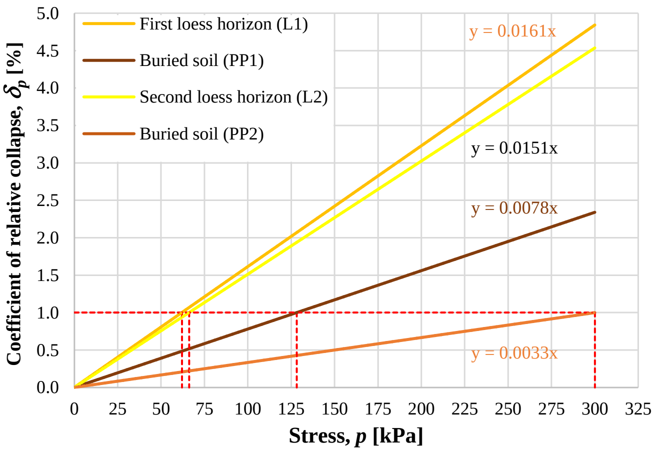


Fig. 3 Procedure for evaluation coefficient of relative collapse

Designing foundation structures on Type II soil foundations, as per [3], requires determining the following:

1. The maximum collapse induced settlement ($s_{collapse}$) occurring when the entire subsidence zone becomes fully saturated with water ($h_{collapse}$) due to extensive flooding or a rise in the water level.
2. The potential failure that occurs in the event of localized wetting of an area narrower than the failure zone's width.

Total settlement is calculated as the sum of vertical deformation from soil densification and subsidence from loess collapse when wetted. Design considerations must account for the possibilities of soil moisture increase due to:

1. Localized (partial) inundation of the soil foundation by emergency water, leading to collapse in a limited area.
2. Extensive inundation of the soil foundation across a substantial area, covering the entire failure zone height.
3. Rising groundwater levels.
4. Gradual increase in water content in problematic layers caused due to alterations in natural hydrogeological conditions.

3. SETTLEMENT EVALUATION PROCEDURE

An analysis of settlements was conducted using three independent methods, incorporating classical computational approaches such as the method of layer-by-layer summation and stress distribution based on the Westergaard method (see Fig. 4), along with the finite element method (FEM – Mohr-Coloumb constitutive model) in geotechnics, known for its high precision (see Fig. 5 and Fig. 6).

In the context of shallow foundations in geotechnical engineering, the Mohr-Coulomb constitutive model is particularly valuable. It helps assess the stability and load-bearing capacity of these foundations by considering soil properties like cohesion and internal friction angle.

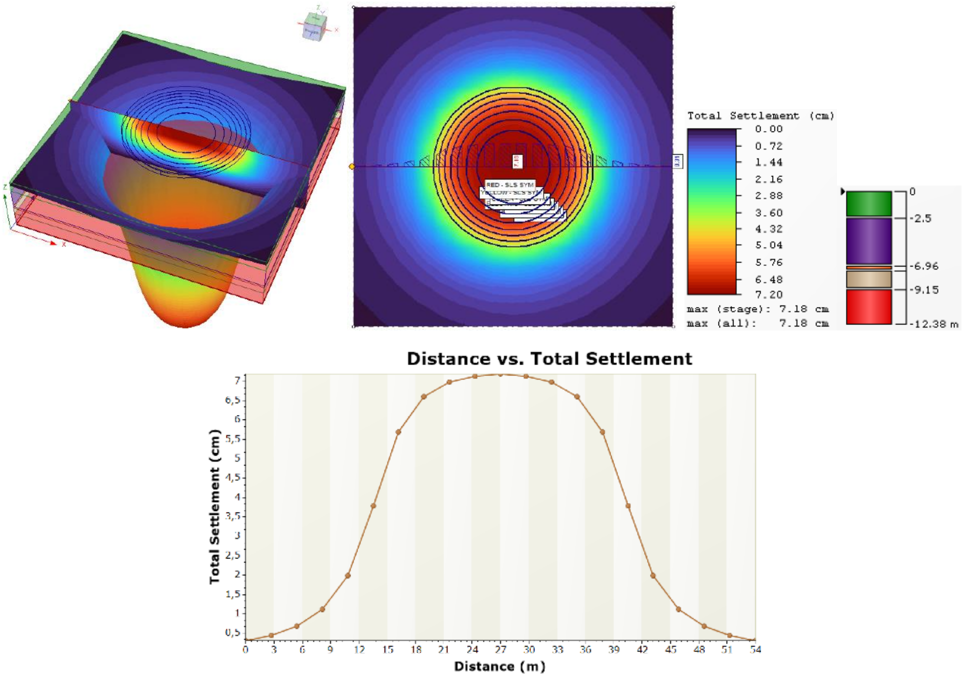


Fig. 4 Westergaard stress distribution (analytical solution) results: foundation base at +116.35 – mean settlement for SLS-SYM combination

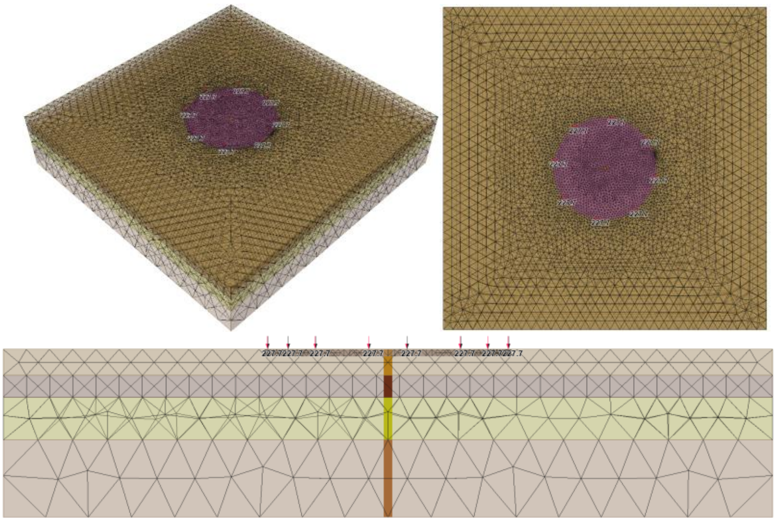


Fig. 5 Overview of the FEM model

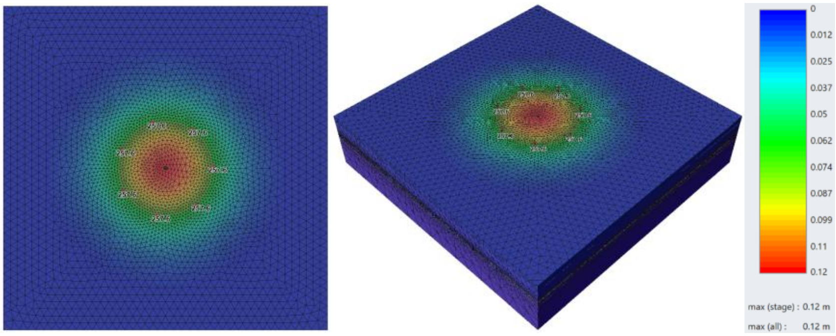


Fig. 6 FEM (Mohr-Coloumb constitutive model) results: foundation base at +116.35 – mean settlement for SLS-SYM combination

Shallow foundations, which include footings and mats, rely on the soil directly beneath them to support the structure's loads. The Mohr-Coulomb model allows engineers to analyze how different soil types and conditions will behave under the applied loads, helping ensure the safety and longevity of structures resting on shallow foundations. By understanding the soil's shear strength characteristics through this model, engineers can make informed decisions about foundation design, soil improvement, and construction techniques to prevent settlement, tilting, or failure. In the design of shallow foundations, several key aspects must be considered, including bearing capacity (both structural and geotechnical) and settlement, as outlined in [1] and [2]. In the presented practical case, the aspect related to settlement is particularly critical. The active subsidence zone has been determined to be at a depth of 12.50 meters, in accordance with the recommendations of [3] for wide-area (mat) foundations.

4. SOIL IMPROVEMENT AND FOUNDATION CONCEPT

The study presents two interchangeable foundation construction concepts as follows:

1. A double reinforced concrete slab with connecting vertical structural elements (columns) with a height of 4.15 meters - the foundation base is at elevation +116.35.
2. A single reinforced concrete slab (F-type) with a height of 2.10 meters – the mat base falls at elevation +116.35.

Both solutions provide functionality, with technological installations (pipes) placed between the two slabs in one version and within channels formed in the structure in the other. They also ensure reliable broad-area load transmission from the superstructure to the ground base, preventing stress concentration and ensuring even settlements.

In the first iteration, options were considered without improving the soil parameters by placing the foundation structures directly on the virgin ground – Table 5. The stress distribution in depth for the two foundation cases is shown in Fig. 7.

Table 5 Evaluated settlement for a case without soil improvement

Foundation concept	**Location according to the geological survey**	**Without soil simprovement**						
		Densification				Collapse	**Total**	
		Layer-by-layer Sum	Westergaard Method	FEM		Layer-by-layer Sum	Layer-by-layer Sum	Layer-by-layer Sum
				Mohr-Coloumb	HSM			
		[cm]	[cm]	[cm]	[cm]	[cm]	[cm]	[cm]
Double mat foundation at +116.35	BH1, BH2, BH3, BH4, BH5, BH6, BH7, BH8, BH9, BH13 & BH14	13.98	14.40	19.00	**0.18**	31.89	**45.87**	**46.29**
	BH10, BH11, BH12 & BH15	16.52	16.70	21.00	**0.18**	35.90	**52.42**	**52.60**
Single mat foundation at +118.40	BH1, BH2, BH3, BH4, BH5, BH6, BH7, BH8, BH9, BH13 & BH14	14.46	14.20	19.00	**0.16**	34.13	**48.59**	**48.33**
	BH10, BH11, BH12 & BH15	16.20	15.60	22.00	**0.16**	44.85	**61.05**	**60.45**

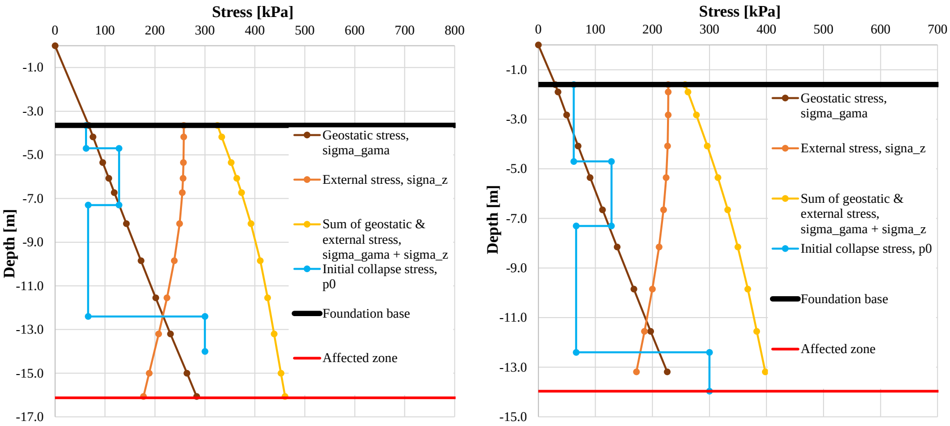


Fig. 7 In-depth stress distribution for the two types of foundations at different elevation of the base – without soil improvement

The results clearly demonstrate that the settlements exceed the accepted limit values, with subsidence being the dominant contributor, reaching values of approximately 50 to 60 cm. Therefore, treating the entire failure zone up to an elevation of 109.30 m (-11.20) is essential for the conceptual foundation decisions. An exception is the finite element method solution (Hardening Soil constitutive model), which, although it usually yields realistic results, should not be definitively adopted due to the lack of reliably determined parameter values in geological survey. It is provided for informational purposes, while the other three independent methods described above were used for calculations.

In accordance with [3], three types of measures to reduce the effect of soil subsidence are given:

1. Removal of soil collapsible properties through compaction or strengthening: surface compaction, laying compacted soil or cement-soil cushions, silicification, cementation, heat treatment, etc.
2. Protection of the ground base from flooding: proper placement of the structures, constructing watertight screens under buildings, laying pipelines in troughs and casings, implementing leak detection systems, etc.
3. Structural measures (Fig. 8): using structural systems that are insensitive to uneven settlements, increasing the stiffness of the underground part of the buildings (facilities), increasing foundation depth, passing the failure layer with a deep foundation, etc.

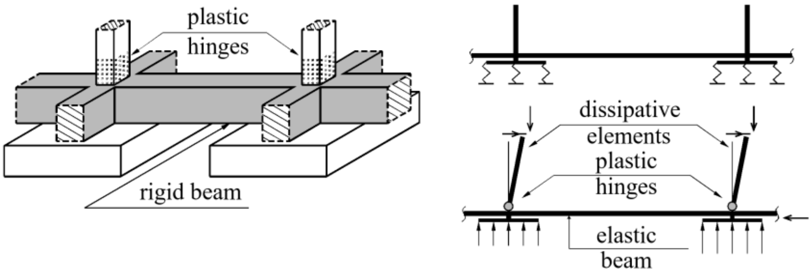


Fig. 8 Continuous footing design for collapsible soils

Additionally, with a Type II soil (loess) type, a screen should be created under the entire building or facility – [4]. Considering the above, two final foundation options have been proposed – Fig. 9 and Fig. 10.

1. Option 1: A foundation structure with a double bottom (4.15 m high), a 2.5 m cement-soil cushion, and rapid impact compacted soil, as described in references [5] and [6], with dimensions of approximately 4.55 m. In total: 4.15 m (foundation height) + 2.5 m (cement-soil cushion – CSC) + 4.55 m (compacted soil) = 11.20 m, which should effectively address the issue of the collapsible zone. Rapid Impact Compaction (RIC) is a dynamic soil improvement technique appreciated for its efficiency and cost-effectiveness. RIC is a method that involves the utilization of heavy machinery equipped with a specialized compaction hammer. This powerful equipment delivers a sequence of impactful blows to the ground surface, inducing soil densification and bolstering its load-bearing capacity. Renowned for its swift and budget-friendly approach, RIC has emerged as a favored choice in the realm of construction and infrastructure development. Its

primary role is to swiftly fortify weak or loose soils, mitigating the likelihood of settlement-related challenges and ensuring a stable foundation for various structures. Option 1 includes increasing the embedment depth, a robust reinforced concrete box beneath elevation ±0.00 and the elimination of soil collapsibility. Additionally, measures for waterproofing will be implemented, as mandated for Type II soil conditions according to [3]. Before commencing ground improvement activities, an experimental section should be provided to demonstrate the applicability of rapid impact compaction. Compaction using rammers is applied to soils with a degree of water saturation (S_r) less than 0.7 and a density not exceeding 1.6 g/cm^3. While the degree of water saturation condition is met in this specific case, the bulk density requirement of less than 1.6 g/cm^3 is not satisfied. Nevertheless, based on prior experience, the author remains confident in the positive results achievable through this compaction technique. Historical evidence from similar previous projects using this method suggests that "impulse compaction" effectively enhances soil layers with thicknesses ranging from 3.5 to 8 m. Settlement data is organized in Table 6 for reference.

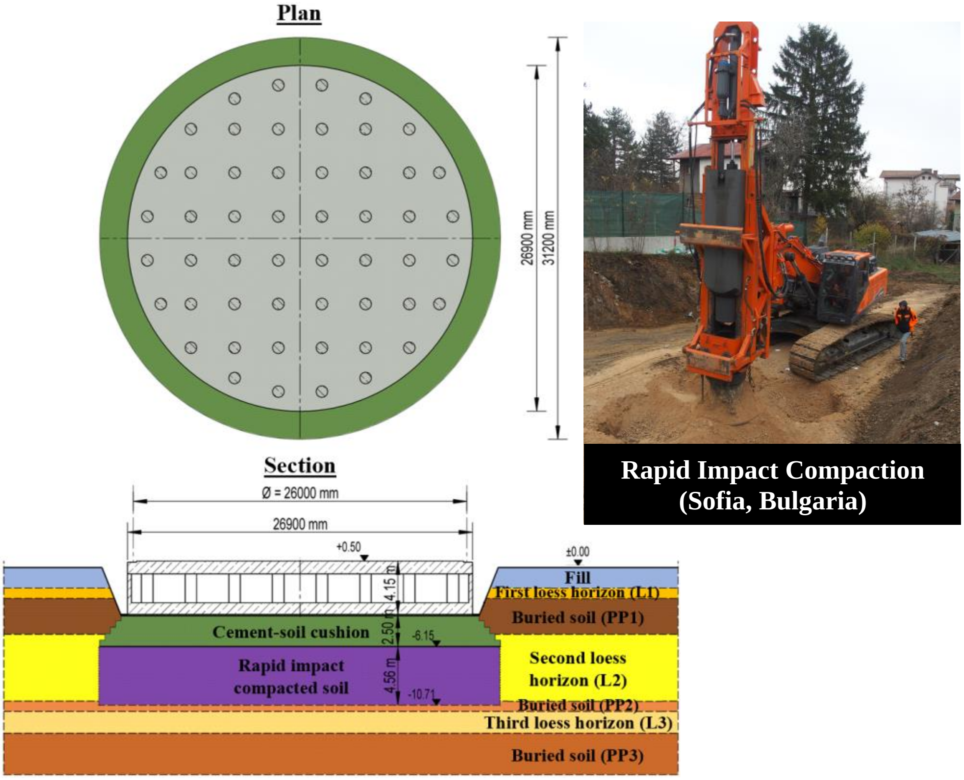
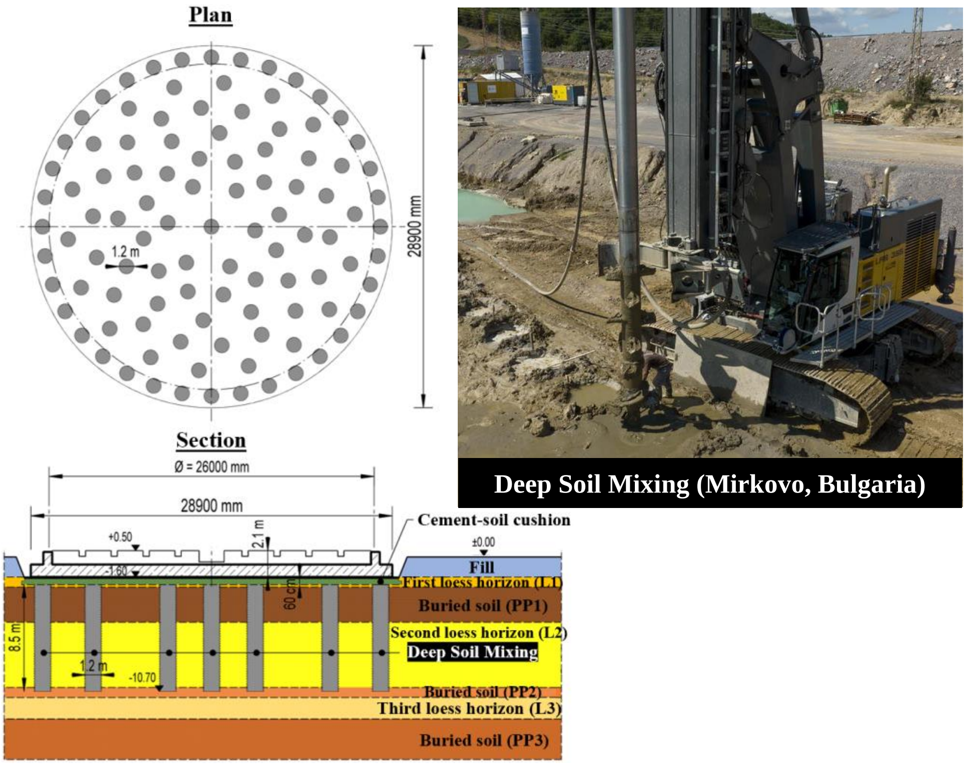


Fig. 9 *Option 1*: double foundation mat, thick cement-soil cushion and rapid impact compaction

2. Option 2: The foundation structure, F-type, consists of a single bottom (2.10 m high), a 0.6 m cement-soil cushion (CSC), and deep soil mixing columns – [7] and [8]. There are a total of 103 columns with a diameter of D=1.20 m and a length of 8.50 m for all the silos, accounting for 17.5% of the collapsible zone. The overall treatment depth is calculated as follows: 2.10 m + 0.6 m + 8.50 m = 11.20 m, which is sufficient to overcome the collapsible zone. Deep Soil Mixing (DSM) is a construction technique that strengthens weak or unstable soils by mechanically blending them with cementitious materials. Specialized equipment injects the binder as it penetrates the ground, creating soil-cement columns with improved strength and durability. DSM is versatile, suitable for various soil types, and environmentally friendly as it reduces the need for soil disposal. It is a preferred choice for geotechnical challenges in construction. Option 2 assumes the removal of any unfavorable soil properties. The cement-soil cushion (CSC) serves not only as a waterproof screen but also activates the deep soil mixing columns evenly within the zone. Furthermore, water protection measures will be implemented, in accordance with the requirements for a Type II soil conditions as specified in [3]. Prior to applying the technology for the execution of the deep soil mixing columns, an experimental section will be designated. The settlements are presented in Table. 7.



Deep Soil Mixing (Mirkovo, Bulgaria)

Fig. 10 *Option 2*: single mat foundation, thin cement-soil cushion and deep soil mixing columns

Both types of loading conditions, SYM (symmetric silo discharge) and SD (single-sided silo discharge), lead to further subdivisions of foundation types. All the ground improvement measures described above remain valid. SD condition leads to tensile stresses in the main plane of the foundations, which can be resolved in two ways:

- For *Option 1*: Tension is eliminated by joining adjacent silos in a common foundation mat, while all other ground improvement measures remain in effect.
- For *Option 2*: Tension is eliminated by uniting adjacent silos in a common foundation mat or embedding steel profiles in the outer two rings of DSM columns (the profiles are anchored to the foundation mat). Once again, all other ground improvement measures remain in effect.

Based on the author's previous experience and that of the geotechnical community in Bulgaria, the estimated amount of cement for forming the cement-soil cushions is 6% to 8% of the solid phase of the soil – [9] and [10]. It is advisable to use sulfate-resistant cement. The amount of water to be added should be determined based on the optimum water content obtained from Proctor tests.

Table 6 Evaluated settlement for *Option 1*: double foundation mat, thick cement-soil cushion and rapid impact compaction

Foundation concept	**Location according to the geological survey**	**Thick cement-soil cushion (CSC) & rapid impact compaction**						
		Densification				Collapse	**Total**	
		Layer-by-layer Sum	Westergaard Method	FEM		Layer-by-layer Sum	Layer-by-layer Sum	Layer-by-layer Sum
				Mohr-Coloumb	HSM			
		[cm]	[cm]	[cm]	[cm]	[cm]	[cm]	[cm]
Double mat foundation at +116.35	BH1, BH2, BH3, BH4, BH5, BH6, BH7, BH8, BH9, BH13 & BH14	6.01	7.18	12.00	-	0.49	**6.50**	**7.67**
	BH10, BH11, BH12 & BH15	7.69	8.24	13.00	-	9.31	**17.00**	**17.55**
Single mat foundation at +118.40	BH1, BH2, BH3, BH4, BH5, BH6, BH7, BH8, BH9, BH13 & BH14	-	-	-	-	-	-	-
	BH10, BH11, BH12 & BH15	-	-	-	-	-	-	-

Table 7 Evaluated settlement for *Option 2*: single mat foundation, thin cement-soil cushion and deep soil mixing columns

Foundation concept	**Location according to the geological survey**	**Thin cement-soil cushion & deep soil mixing (DSM)**						
		Densification				Collapse	**Total**	
		Layer-by-layer Sum	Westergaard Method	FEM		Layer-by-layer Sum	Layer-by-layer Sum	Layer-by-layer Sum
				Mohr-Coloumb	HSM			
		[cm]	[cm]	[cm]	[cm]	[cm]	[cm]	[cm]
Double mat foundation at +116.35	BH1, BH2, BH3, BH4, BH5, BH6, BH7, BH8, BH9, BH13 & BH14	-	-	-	-	-	-	-
	BH10, BH11, BH12 & BH15	-	-	-	-	-	-	-
Single mat foundation at +118.40	BH1, BH2, BH3, BH4, BH5, BH6, BH7, BH8, BH9, BH13 & BH14	2.71	3.31	7.40	-	0.50	**3.21**	**3.81**
	BH10, BH11, BH12 & BH15	3.61	3.54	8.80	-	9.28	**12.89**	**12.82**

5. COMPARISON OF FOUNDATION CONCEPTS

The advantages and disadvantages of the two proposed foundation options have been meticulously evaluated, drawing upon the author's previous experience and a comprehensive technical-economic analysis is demonstrated on Table 8. Preliminary evaluation suggests Option 1 as more suitable technique for the particular project.

Table 8 Benefits and drawbacks of the two suggested soil improvement methods

Criteria / Foundation concept	**Option 1: Thick cement-soil cushion (CSC) & rapid impact compaction (RIC)**	**Option 2: Thin cement-soil cushion (CSC) & deep soil mixing (DSM)**	**Comment**
Bearing capacity check	○	○	-
Mean settlement check	○	○	After proving the applicability of rapid impact compaction.
Applicability	△	○	Applicability of rapid impact compaction shall be proved.
Foolproofness	○	X	-
Price	△	△	Cheaper solution has to be chosen on the basis of offers.
Duration	X	○	-

6. CONCLUSION

The presented paper delves into the exploration of two interchangeable foundation strategies for an industrial site in Silistra, Bulgaria, confronted with challenging geological conditions, mainly due to 'collapsible – Type II' loess soil. The study considers options to mitigate soil collapsibility and enable efficient foundation construction for silos. After a thorough technical analysis and cost assessment, the study favors shallow foundation methods combined with local soil improvement practices. Two approaches are presented: a double mat foundation on a thick soil-cement cushion (CSC) and a single mat foundation on a thinner soil-cement cushion (CSC) with DSM columns below. Both ensure structural integrity, utilize readily available soil improvement techniques, and offer cost-effective execution. The research highlights the dominance of collapse subsidence over densification settlement, with advanced computational methods confirming realistic densification vertical displacements. However, adhering to safety and responsibility, addressing soil failure properties up to an elevation of 109.30 m is crucial to mitigate potential catastrophic consequences.

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UNAPREĐENJE TLA I PROJEKTOVANJE TEMELJA INDUSTRIJSKIH OBJEKATA U LESNOM ZEMLJIŠTU

Ovaj istraživački rad bavi se ispitivanjem dve međusobno zamenljive strategije za fundiranje industrijske lokacije (osnove silosa) koja se nalazi u Silistri, Bugarska. Geološki uslovi na ovoj lokaciji predstavljaju značajne izazove zbog prisustva lokalnog lesnog zemljišta, koje je klasifikovano kao 'sklopivo - tip II' u skladu sa bugarskim kodeksom o plitkim temeljima i prostire se do dubine od 12 metara. Da bi se odgovorilo na zahteve kodeksa i ispunila stroga operativna ograničenja koja važe za silose, uključujući ograničenja na sleganje i nagib temelja, razmatraju se dva potencijalna pristupa. Ove opcije uključuju ili ublažavanje sklopivosti tla ili navigaciju kroz sklopivo tlo koristeći tehnike dubokih fundamenata kao što su šipovi, zidovi od gline i slični metodi. Nakon početne tehničke analize i procene troškova, ova istraživanja se zalažu za korišćenje metoda plitkih fundamenata u kombinaciji sa lokalnim praksama unapređenja zemljišta. Prvi pristup uključuje izgradnju dvostrukih mat fundamenata, koji se nalaze na relativno debelom osnovnom sloju koji se sastoji od mešavine zemljišta i cementa i zemljišta koje je podložno brzom sabijanju. Drugi pristup podrazumeva mat fundamente postavljene na relativno tankom osnovnom sloju mešavine zemljišta i cementa, koji je dopunjen strateški postavljenim dubokim stubovima sa mešavinom zemljišta. Oba ova pristupa obezbeđuju strukturnu pouzdanost silosa, zalažu se za primenu metoda unapređenja zemljišta koji su lako dostupni na bugarskom tržištu i nude brzo i efikasno izvođenje.

Ključne reči: *les, sklopivo tlo, plitki temelj, poboljšanje tla, silos, brzo sabijanje, mešanje cementa i tla, duboko mešanje tla*