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Assessment of the Mutual Influence of Prefabricated Steel Silo Foundations Under Staged Loading

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Abstract: *A three-dimensional numerical model of a cast-in-situ raft foundation interacting with elastic subsoil was developed using the Finite Element Method (FEM) in the LIRA-FEM software environment, incorporating the GRUNT module for subsoil modelling. The analysis considered both isolated and two-row grouped configurations under three sequential loading stages. Key parameters, including vertical displacements and tilt, were assessed to determine the impact of mutual interaction. The results indicate that adjacent structures significantly intensify subsoil deformations. In particular, the maximum settlement increased from 115.2 mm for an isolated structure to 177.25 mm under grouped conditions, representing a 1.54-fold increase. The corresponding structural tilt reached 0.0024, exceeding the allowable limit of 0.002, while the settlement surpassed the normative maximum permissible of 150 mm. The findings demonstrate that neglecting the mutual geotechnical influence of closely spaced storage facilities may lead to exceeding ultimate limit states. Therefore, comprehensive spatial numerical modelling is essential for the safe and reliable design of modern agricultural infrastructure.*

Key words: *steel silo foundations; finite element method; geotechnical mutual influence; subsoil settlement; structural tilt*

1. INTRODUCTION

Steel silos are a cost-effective solution for grain storage due to the automation of grain handling processes, which results in low operating costs in the long-term perspective. Their economic efficiency and large storage capacity stimulate the development of the global grain storage silo market. The global average annual growth rate of silo construction is projected to reach 4.2% by 2030.

In 2024-2025, the grain storage construction market n Ukraine generally demonstrated growth, most notably in the western regions and to a lesser extent in the central ones. The structure of orders has changed compared to the pre-war period: approximately 80% of projects involve the expansion, modernisation, and restoration of elevator capacities, whilst only 20% involve the construction of new elevators [1, 2].

During the full-scale war, the elevator infrastructure of Ukraine suffered significant losses (amounting to USD 1.1 billion). A substantial proportion of the facilities (equivalent to ≈ 10 million tonnes of grain capacity) has been successfully restored. Consequently, the current elevator capacities are 3.7 million tonnes lower than in 2021, totalling 52.9 million tonnes. It is noted that a critical capacity deficit does not currently arise, as the production of grain and oilseed crops has decreased during the war years from 106 million tonnes in 2021 to 76 million tonnes in 2025. The reduction in the production of these crops has partially balanced the ratio between the available grain volumes and the storage capabilities [1, 2].

It should be noted that prefabricated steel silos have become widespread in Ukraine over the last 25–30 years. Prior to this, reinforced concrete silo structures were built, which remain in operation to date [3]. In the structure of grain storage facilities, 18% of capacities comprise reinforced concrete elevators, 35% are floor-type storage facilities, and 47% are steel elevators [4]. Furthermore, a trend has emerged towards mobile grain storage facilities constructed from hopper-bottomed steel silos. These silos have a small volume and, if necessary, can be rapidly dismantled and reassembled in a different location. Mobile grain storage facilities are primarily utilised by farming enterprises [1, 2].

The widespread application of steel silos, particularly in the reconstruction and restoration of war-damaged elevators, is highly promising due to both the speed and simplicity of installation, especially in constrained site conditions. At the same time, the steel silos of elevator complexes are more sensitive to operational conditions than reinforced concrete ones [4, 5].

The primary feature of cylindrical silos is their thin-walled metal shell, which is highly sensitive to non-uniform loads and settlements [5–8]. A significant proportion of complications and emergency situations are caused by static and dynamic impacts on the shell structures and foundations during the loading and unloading of the silos [8–12].

For steel silos, raft foundations are the most widely used [3, 13, 14, 15]. To increase the stiffness of the silo subgrade, vertical soil-cement elements are employed [16]. When designing foundations, particular attention must be paid to the mutual influence of adjacent silos on the subsoil settlement [17], which can lead to foundation displacements that may exceed the normative values [18, 19].

In this regard, the aim of the present work is to investigate the influence of the gradual loading of a row of grain storage silos on the assessment of the subsoil settlement of adjacent buildings.

2. RESEARCH METHODOLOGY

2.1. Foundation structural solutions

For the steel silo utilised for grain storage, a circular cast-in-situ raft foundation is adopted. An under-silo gallery and a ring wall rest upon the raft foundation, transferring the loads from the silo structure to the foundation. The entire weight of the grain is transferred to the foundation via a cast-in-situ slab constructed over a backfill of a crushed stone and sand mixture, compacted to a factor of no less than 0.95. The cast-in-situ concrete structures of the foundation are executed using concrete of strength class C20/25. The foundation depth (from the design datum) is 3.45 m. The thickness of the raft foundation is 500 mm, the foundation thickness along the perimeter is 550 mm, the floor slab thickness is 200 mm (and 400 mm in the gallery area), the gallery wall thickness is 300 mm, and the thickness of the cast-in-situ aeration slab is 450 mm. The diameter of the raft foundation is 28.7 m, and the diameter of the foundation walls (along the outer face) is 28.3 m (Fig. 1).

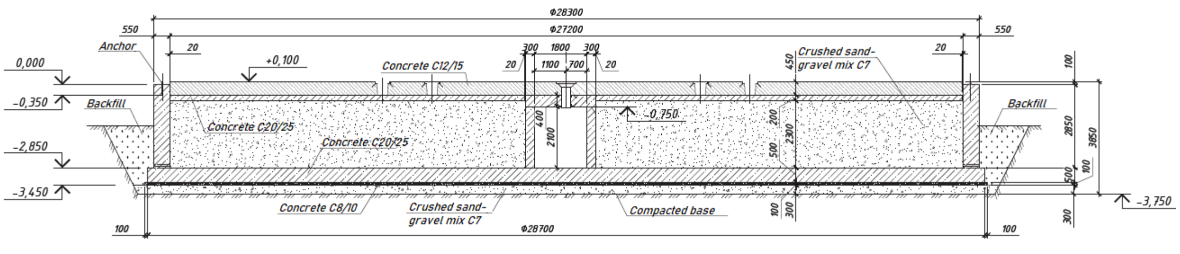


Figure 1. Cross-section of the silo foundation.

Embedded items (cast-in inserts) emerge from the foundation wall (ring) and are connected to the steel silo structure. Due to these embedded items, the loads acting upon the silo (snow, wind, operational loads, etc.) are transferred directly to the walls and foundation themselves, thereby ensuring their structural interaction.

The investigated steel silos are arranged in a group comprising two rows with three silos in each row (Fig. 2). The silo spacing within a row is 30.3 m, and the clearance between the edges of their foundations is 1.6 m, whilst the row spacing is 30.0 m, and the clearance between the foundations of adjacent rows is 1.3 m. Such a design solution regarding the compact layout of the silos significantly reduces technological costs during grain conveyance and facilitates the placement of structures in the vicinity of other grain-processing facilities.

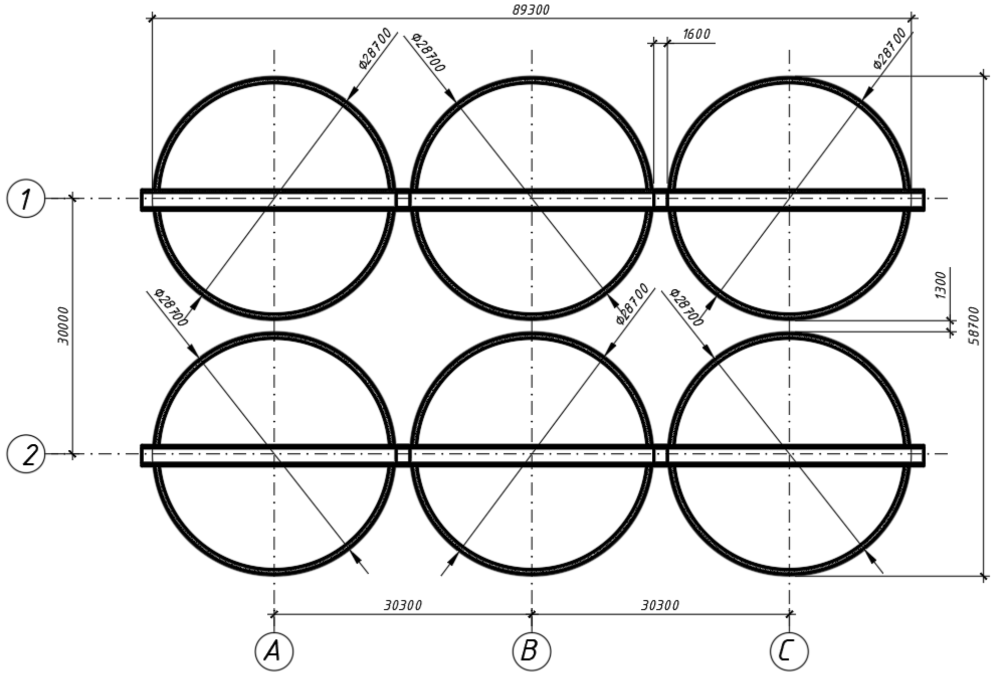


Figure 2. Arrangement scheme of foundation rows for the silo

2.2. Loads on the silo foundation

During normal operation, various types of loads act upon the silo foundations: permanent loads (from the self-weight of the silo structure and foundations), long-term loads (from the weight of the grain and process equipment), and short-term loads (from snow cover and wind pressure).

As stated previously, the loads acting upon the silo structure are transferred to the foundations via the embedded items.

The following load values were adopted for the calculation: self-weight of the steel silo: vertical component – 39 150 kN, horizontal component – 517.5 kN; the weight of the concrete structures is determined automatically assuming a unit weight of 25 kN/m³ with a partial load factor of 1.1; the load from the technological floor layer – 12.4 kPa; the load from the backfill on the raft foundation – 43.5 kPa (the vertical component of the earth pressure is not considered, as the wall is situated within the soil on both sides); the weight of the grain on the floor slab at full silo capacity – 170 kPa; snow load – 880 kN; wind load in the X or Y direction – 6 000 kNm; and the maximum force acting on a single embedded item during uplift – -17.5 kN.

The load from the grain is transferred to the floor slab and subsequently through the compacted backfill to the raft foundation, whereas the loads from the backfill are transferred directly to the raft foundation. The self-weight of the silo, alongside snow and wind loads, are transferred via the embedded items.

2.3. Boundary conditions and geological conditions

The structural stability of the silos is ensured by the composite action of the «silo-foundation-subsoil» system. In the vertical direction, the stability of the system is provided by a rigid subsoil comprising three engineering geological elements (EGE), whilst stability in the horizontal direction is ensured by the friction between the raft foundation and the subsoil, as well as the passive earth pressure.

As noted above, three engineering geological elements serve as the subsoil for the silos: EGE 1 – made ground with layers of construction debris and loam, dark grey; EGE 2 – stiff loam, brownish-yellow; EGE 3 – semi-solid clay, ferruginous, pale yellow. The principal physical and mechanical properties of the subsoil layers are presented in Table 1.

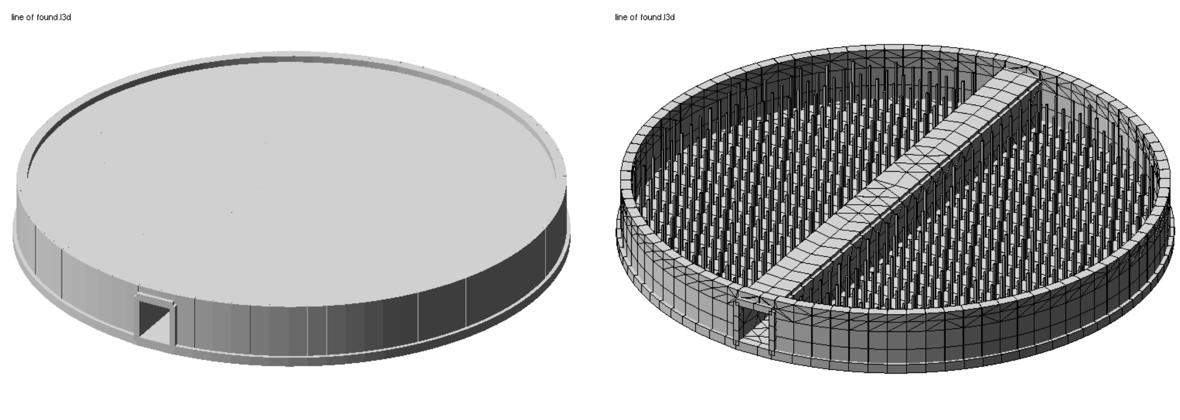
Table 1. Principal physical and mechanical properties of the subsoil layers

№ EGE	Soil Name	Natural Moisture Content (fraction)	Liquidity Index	Unit Weight (kN/m³)	Porosity Ratio	Deformation Modulus (MN/m²)	Cohesion (kN/m²)	Internal Friction Angle (°)
1	Fill soil	0.05	0.20	17.0	0.70	10.3	-	-
2	Stiff loam	0.20	0.26	18.6	0.72	15.5	24.5	18.6
3	Semi-solid clay	0.25	0.13	19.9	0.70	22.5	61.1	19.9

2.4. Modelling and research methodology

For the investigation of the foundations and subsoil for the prefabricated steel grain storage silos, the LIRA-FEM software package (formerly LIRA-SAPR) was utilised, incorporating the GRUNT module for subsoil modelling.

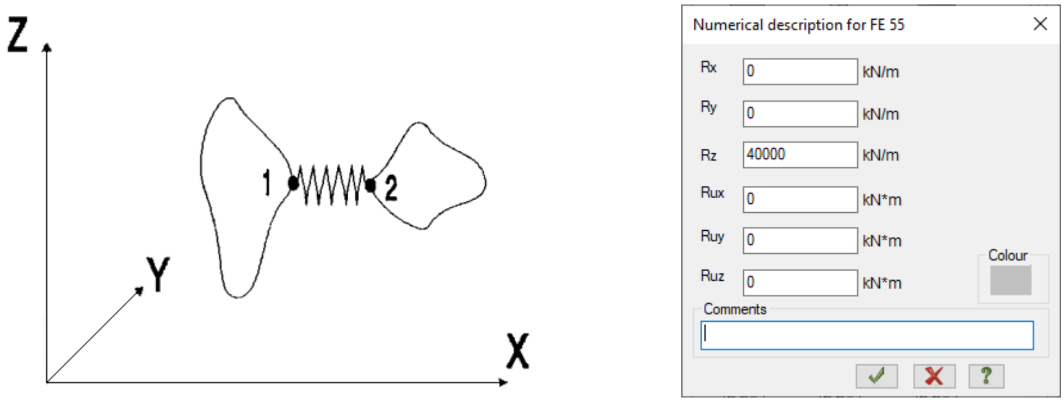
To model the foundation elements, plate finite elements (FE) were employed, assigned with their respective characteristics (thickness, modulus of deformation, unit weight, etc.). To ensure the accurate transfer of forces from the silos to the foundations, the FE mesh of the ring was coordinated with the number of embedded items (90 units). Consequently, the average size of the finite element in the model is 1 m (Fig. 3).



a) b)

Figure 3. Finite element model of the foundation: without the FE mesh displayed (a) and with the FE mesh and elastic backfill elements displayed (b).

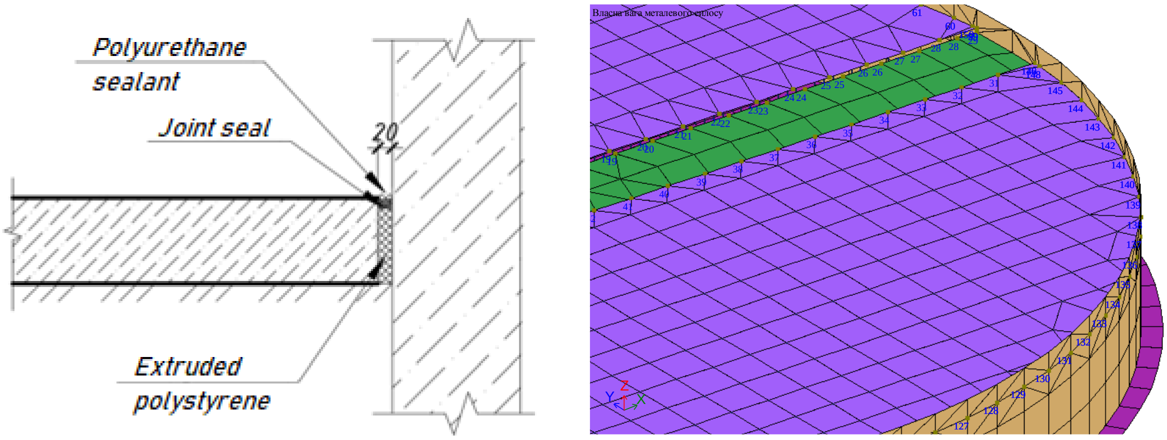
To model the elastic backfill (comprising a crushed stone and sand mixture – CSSM) between the floor and the raft foundation (see Fig. 1), with a compaction factor of 0.95, the bar finite element FE 55 was utilised – a two-node FE of elastic links between nodes, which accounts for the compliance between the element nodes (Fig. 4 (a)). Knowing the elastic parameters of the backfill, specifically the coefficient of subgrade reaction, which for CSSM is 40 000 kN/m³, the vertical stiffness parameter for FE 55 was determined (Fig. 4(b)), given that the average finite element size was set to 1 m, as it is modelled by a bar analogue. Establishing horizontal and torsional stiffness values is impractical, as the floor slab is situated between the foundation and gallery walls, which restrict its movement in these directions.



a) b)

Figure 4. Schematic representation of the operation of the finite element FE 55 between nodes (LIRA-FEM) (a) and its design values (b).

For the foundation, correct connection nodes between the elements were modelled. Thus, the foundation wall and slab are connected absolutely rigidly, which in practice is achieved by installing appropriate reinforcement; the gallery structure is pin-jointed to the foundation structure, and the floor slab has a movement joint between the foundation wall and the gallery. In practice, the movement joint is executed by installing a rigid filler (typically extruded polystyrene), a backer rod, and a polyurethane sealant (Fig. 5(a)). During modelling, such a movement joint solution signifies the absence of shared vertical displacements and the non-transfer of torsional forces, whilst ensuring composite horizontal action. This structural solution was modelled using the coupling of displacements with the release of nodes in the corresponding directions (Fig. 5(b)).



a) b)

Figure 5. Execution of the movement joint (a) and the design solution of its analogue during modelling (b).

Consequently, the modelling of the silo foundation rows was executed in this manner to investigate the mutual influence during their gradual loading (Fig. 6).

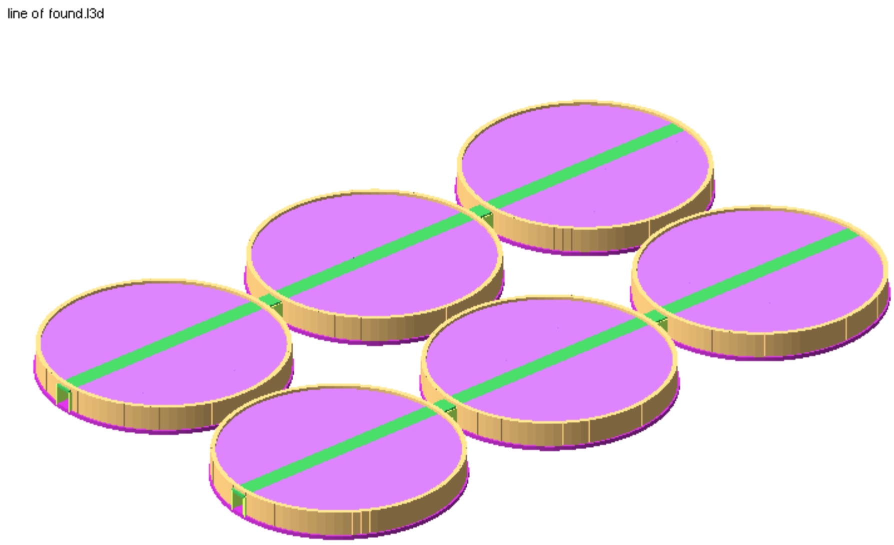
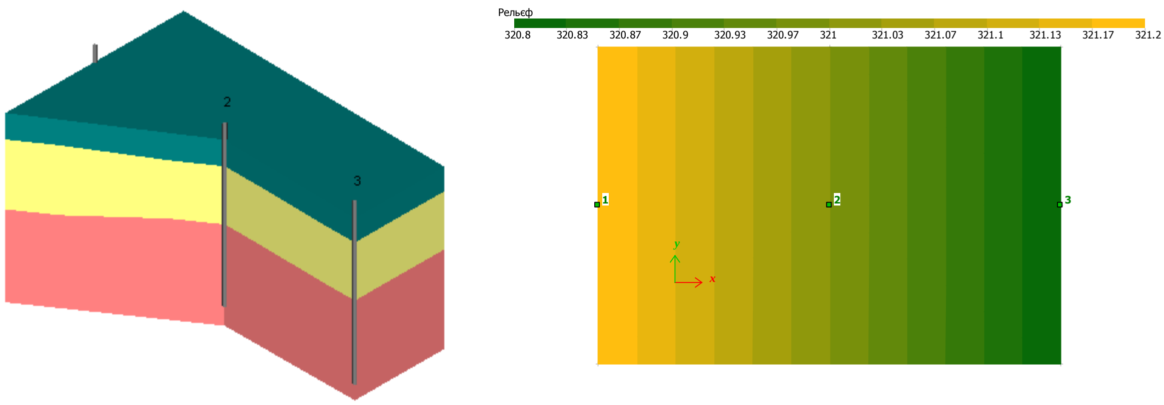


Figure 6. Model of the silo foundations.

To model the elastic subsoil, the GRUNT module within the LIRA-FEM software was utilised. Employing the previously defined soil types and their thicknesses, a 3D model of the soil mass was generated (Fig. 7(a)) with the corresponding surface topography (Fig. 7(b)).



a) b)

Figure 7. 3D model of the soil mass (a) and its surface topography (b).

The raft foundations of all silos have an identical absolute elevation of 319.0 m (Fig. 8). The subsoil calculation was performed in accordance with DBN V.2.1-10-2018 and DBN V.2.1-10-2009. The depth factor of the compressible stratum was set at 0.5, the minimum depth of the compressible stratum is 6.9 m, and the load triangulation step is 1 m, which aligns with the size of the foundation FEs. For calculating the deformation and stiffness of the subsoil, the Winkler-Fuss method (Method 2 in the GRUNT system) was employed, as it is based on models consistent with current foundation design codes [17, 20]. The design bearing capacity of the subsoil, the settlement, and its stiffness were determined using an approximate calculation method with five iterative approximations, yielding sufficiently accurate research results.

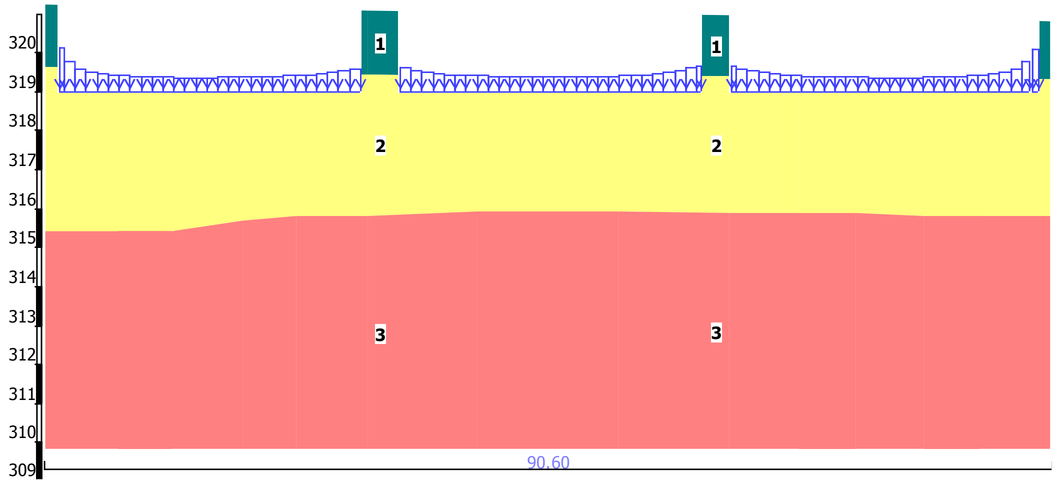


Figure 8. Engineering geological cross-section of the subsoil beneath the foundations.

3. ANALYSIS OF RESULTS AND DISCUSSION

Modelling was performed taking into account the gradual loading of the silos. The filling of the silo occurs in three stages, where 1/3 of the total grain mass is loaded per stage. A sequence for loading the silos within a row was also established. Fig. 9 presents the models of: empty silos – a); filled to one-third of the volume – b); two-thirds of the volume – c); and completely filled – d).

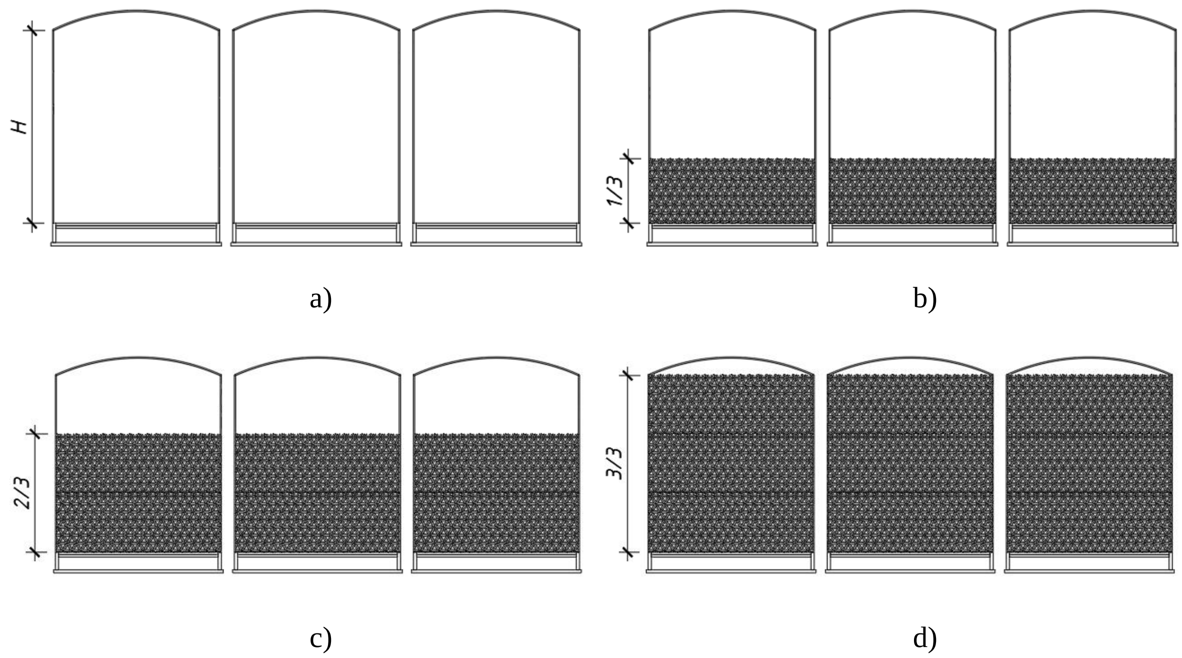


Figure 9. Stages of filling a row of silos: a) empty row 0/3; b) 1/3 filling; c) 2/3 filling; d) completely filled with grain 3/3.

Figs. 10 and 11 present the contour plots of displacements (settlements) of the raft foundations during the staged grain filling of a single silo and silos in a two-row layout, respectively.

Tables 2 and 3 present the settlement values for specific points of a single silo and silos in a two-row layout, respectively. The data were obtained during the staged loading of the silos (Fig. 9).

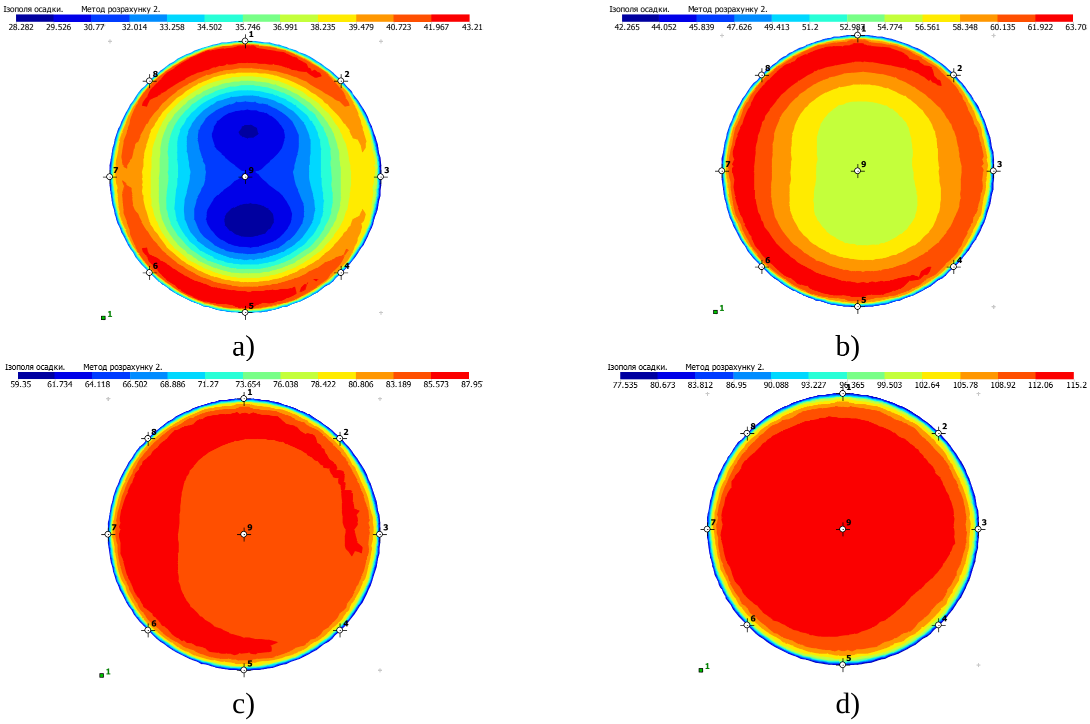


Figure 10. Subsoil settlement beneath a single foundation: a) without grain, b) with 1/3 filling, c) with 2/3 filling, d) with full silo loading.

Table 2. Settlement values of corresponding subsoil points depending on the single silo loading

Silo fill level	Settlement of the base at the relevant points, mm									Maximum settlement, mm
	1	2	3	4	5	6	7	8	9	
0/3	34.47	33.26	31.11	33.14	34.34	34.11	32.43	34.13	30.72	43.2
1/3	48.61	47.88	46.69	47.67	48.33	48.8	48.26	48.93	55.21	63.7
2/3	65.41	65.17	64.96	64.86	65.01	66.18	66.81	66.43	83.64	87.9
3/3	83.14	83.63	84.28	83.23	82.9	84.68	86.34	85.05	114.19	115.2

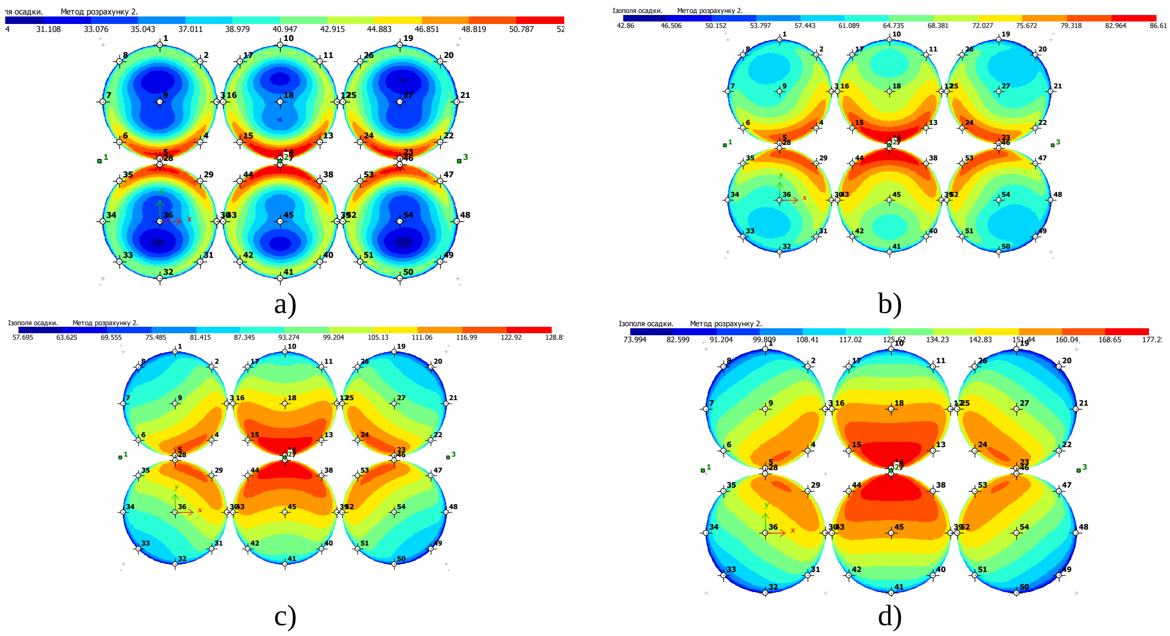


Figure 11. Subsoil settlement beneath the rows of silo foundations: a) without grain, b) with 1/3 filling, c) with 2/3 filling, d) with full silo loading.

Table 3. Settlement values of corresponding subsoil points beneath the foundations of a silo row during their staged loading

Silos fill level	Silo position	Settlement of the base at the relevant points, mm									Maximum settlement, mm
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	
		10	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	
		19	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	
		28	**29**	**30**	**31**	**32**	**33**	**34**	**35**	**36**	
		37	**38**	**39**	**40**	**41**	**42**	**43**	**44**	**45**	
		46	**47**	**48**	**49**	**50**	**51**	**52**	**53**	**54**	
silo row 0/3	1-A	34.00	34.09	37.43	38.30	46.38	37.51	33.29	33.58	34.14	52.75
	1-B	33.93	34.00	37.85	39.04	47.74	38.88	37.55	33.96	36.13	
	1-C	33.47	32.64	32.27	36.76	46.36	38.83	37.78	34.04	33.94	
	2-A	46.31	38.22	37.60	34.39	34.19	33.67	33.28	37.38	34.18	
	2-B	47.62	38.86	37.92	34.37	34.48	34.50	37.73	38.74	36.26	
	2-C	46.25	36.62	32.28	32.76	33.65	34.26	37.84	38.67	33.95	
silo row 1/3	1-A	47.77	52.58	64.58	65.07	73.64	57.97	49.54	46.81	63.08	86.61
	1-B	49.41	52.62	65.12	66.59	78.78	66.48	64.79	52.52	68.39	
	1-C	47.42	46.03	48.64	57.30	73.64	65.46	64.96	52.68	62.89	
	2-A	73.59	65.06	64.81	52.93	47.97	46.87	49.54	57.86	63.14	
	2-B	78.69	66.44	65.22	53.03	50.07	53.07	65.03	66.40	68.56	
	2-C	73.55	57.18	48.67	46.12	47.61	52.90	65.06	65.34	62.90	
silo row 2/3	1-A	64.46	73.91	97.18	95.00	107.06	80.91	68.66	62.70	97.94	128.85
	1-B	68.05	74.12	97.91	98.32	117.96	98.19	97.59	74.00	108.38	
	1-C	63.91	61.63	67.48	80.16	106.98	95.44	97.56	73.97	97.69	
	2-A	107.02	95.04	97.47	74.32	64.67	62.71	68.67	80.82	98.04	
	2-B	117.88	98.20	98.05	74.56	68.78	74.62	97.88	98.15	108.57	
	2-C	106.89	80.05	67.52	61.69	64.10	74.22	97.68	95.33	97.71	
silo row 3/3	1-A	82.77	97.77	134.07	129.98	144.96	106.67	89.32	79.87	136.72	177.25
	1-B	89.09	98.49	135.06	135.74	163.00	135.59	134.75	98.35	153.41	
	1-C	82.11	78.67	87.97	105.82	144.75	130.49	134.43	97.79	136.35	
	2-A	144.93	130.05	134.41	98.26	83.00	79.84	89.33	106.58	136.84	
	2-B	162.92	135.64	135.22	98.96	89.89	99.06	135.09	135.57	153.61	
	2-C	144.67	105.71	88.03	78.69	82.31	98.08	134.58	130.38	136.38	

The analysis of the settlements of a single silo during its gradual loading indicates a relatively uniform vertical displacement of the silo raft, with the maximum settlement occurring in its central part. For an unloaded single silo, the maximum settlement of the raft is observed along its perimeter, which is subjected to the maximum loads from the metal shell of the silo. In the two-row layout of empty silos, the greatest settlements are observed at the closest situated points of the foundation raft perimeters. Furthermore, during the gradual loading of the silos (in their two-row layout), the maximum settlements increase and become localised in the zones of the rafts closest to one another (Fig. 12).

As can be seen, upon the full loading of all silos, the maximum settlement is 177.25 mm, which is greater than that of a single silo, which is 115.2 mm. It should also be noted that the maximum settlements are localised in the central part of the construction site (Fig. 11), leading to the tilting of the foundations (Fig. 13).

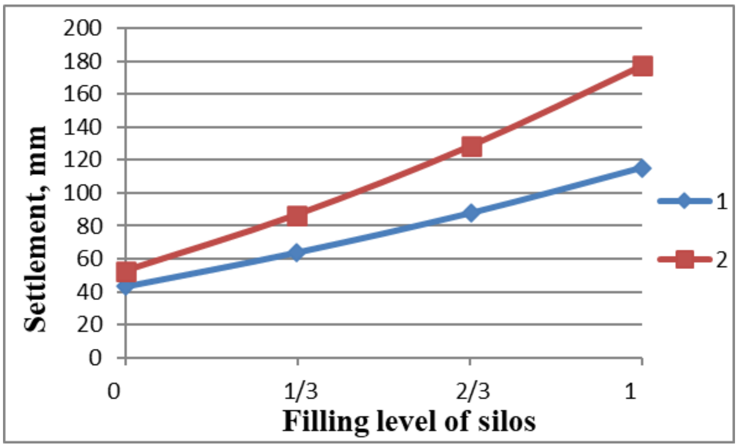


Figure 12. Maximum subsoil settlements during the staged grain loading of a single silo (1) and for a two-row layout of silos (2)

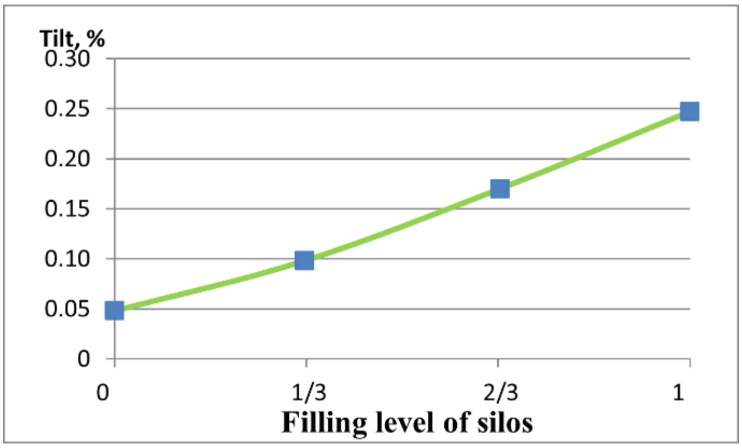


Figure 13. Tilt of the raft foundations during the staged loading of silos and their two-row layout

An analysis of the data presented in Tables 2 and 3, and in Figs. 12 and 13, demonstrates that accounting for the mutual influence of the silo foundations via FEM modelling leads to an increase in the maximum subsoil settlement value (177.25 mm) by a factor of 1.54 compared to the subsoil settlement beneath the foundation of a single silo. Even greater settlement values when evaluating the mutual influence of silo foundations designed on weak soils were obtained in [18]. As the calculations show (Figs. 12 and 13), the maximum settlements and tilts for individual silos do not exceed the maximum permissible values for the subsoils of steel silos, which are $S_{max,u}$ = 150 mm and i_u = 0.002 (0.2%), respectively [17, 20]. At the same time, when modelling the subsoils taking into account the mutual influence of the loaded silos, results were obtained that exceed the specified maximum permissible values: the maximum settlement is 177.25 mm and the tilt is 0.0024 (0.24%).

The obtained results indicate that the mutual influence of steel silo foundations on their subsoils is an important factor that must be considered when designing new and expanding existing capacities.

4. CONCLUSIONS

Based on a modelling experiment, the peculiarities of settlement of slab foundations of metal silos arranged in two rows under conditions of staged loading of structures were investigated. It was shown that the mutual influence of metal silos on foundation slabs and subsoils is an important factor that must be taken into account when designing new and expanding existing elevator complexes.

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Data Availability Statement: The data that support the findings of this study are available from the corresponding author upon reasonable request.

Declaration of Generative AI and AI-assisted technologies in the writing process: The authors declare that no generative AI or AI-assisted technologies were used in the writing of this manuscript.

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