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METIN ÖZLEKLI[1*], KURBAN ÖNTÜRK[1],
SEDAT SERT[2], EMINE AYDIN[1]

EVALUATION OF THE EFFECT OF DEEP SOIL MIXTURE AND EXPANSION JOINT ON ALLUVIAL SOILS USING THE FINITE ELEMENT METHOD

This study analyses building foundation models with and without expansion joints, investigating the effects of deep soil mixing (DSM) on settlement and the effect of expansion joints on stress distribution. Numerical models were developed to evaluate the impact of DSM parameters, including diameter, length, and spacing, as well as the influence of mini-piles and anchorage systems on the support structure, and showed that increasing the diameter and length of DSM columns significantly reduced settlements, achieving reductions of 81-94% in models with expansion joints and 77-94% in models without expansion joints. In models with expansion joints and without joints, closely spaced DSM applications (1.3 m) have significantly reduced settlement and also prevented non-uniform settlement. Expansion joints limit stress interaction between blocks, interrupt stress continuity, and thus prevent the propagation of secondary stresses arising from non-uniform settlement, temperature effects, and stiffness differences. The relationship between DSM length and settlement is similar to the relationship between DSM diameter and settlement. For this study, a DSM length of 12 meters and a DSM diameter of 0.4 meters were determined as the ideal DSM parameters. DSM configuration with 12 meter length, 0.4 m diameter, and 1.3 m spacing was identified as the most efficient solution in terms of both performance and cost for this project. These findings indicate that expansion joints are a secondary parameter in settlement control under DSM-improved soil conditions, that soil improvement properties should be prioritised in design evaluations, and that expansion joints are an important criterion in terms of stress distribution.

Keywords: Settlement; soil improvement; deep mixing; expansion joint; finite element method

1. Introduction

Alluvial soils generally refer to soil types formed by the accumulation of materials transported by water through rivers, streams, or sea waves. These soils are considered young, as they have

[1] SAKARYA UNIVERSITY OF APPLIED SCIENCES, TURKEY
[2] SAKARYA UNIVERSITY, TURKEY

* Corresponding author: metinozlekli@subu.edu.tr

not yet completed their full geomorphological formation [1-3]. Alluvial soils typically exhibit low bearing capacity and shear strength, along with high compressibility potential, due to their organic matter content and high void ratio [4-5]. To address these challenges, it is essential to investigate the geotechnical behaviour of alluvial soils and, if necessary, implement suitable soil improvement techniques [6]. In this study, settlement, which is one of the most significant geotechnical problems, was addressed.

Settlement problems occurring in soils play a critical role in geotechnical applications as they can affect the safety and serviceability of infrastructures. [7]. Therefore, for soils that are likely to settle, it is necessary to implement the necessary improvement measures in a way that will increase the safety of the structures and obtain maximum benefit from the soil. In addition to the application process, all geotechnical parameters of the soil in question and data of the structure to be implemented can be used to analyse all results of geotechnical problems that may occur in the soil with the finite element method. Thanks to the finite element method, all settlements that may occur in the parcel in question due to the structure can be analysed, and solutions can be produced accordingly. Real examples of damage caused by settlement problems in structures are shown in Fig. 1.

Fig. 1. Examples of structural damage caused by settlement [8]

DSM is the process of improving the soil in situ using various binders. The aim of the DSM method is to increase the strength and reduce the compressibility of the soil [9]. When concerns arise due to weak soil and groundwater, the DSM method is used as an additional measure to reduce structural settlement under service loads [10]. In the DSM process, a binder is injected with the help of a mixing tool while the soil is mixed in situ. After hardening, a soil mixture is formed with improved mechanical and hydraulic properties. Initially developed in the 1960s for soil improvement works, this technology has seen significant growth in the past few decades. Today, the deep mixing method is used for a wide range of engineering projects, such as soil reinforcement, slope stabilisation, embankment support, and liquefaction reduction. In addition, soil mixture elements are increasingly used as structural components in the construction of soil-water retaining walls, cut-off walls, and even as an alternative to conventional foundation solutions. Geo-environmental applications are also carried out by trapping or treating contaminants directly in the soil with soil mixing improvement technology [11]. Modern applications have shown that the DSM method is a suitable and effective technique for land structures and fill foundations, yielding reasonable settlement values under structural foundations [12]. The DSM application is shown in Fig. 2.

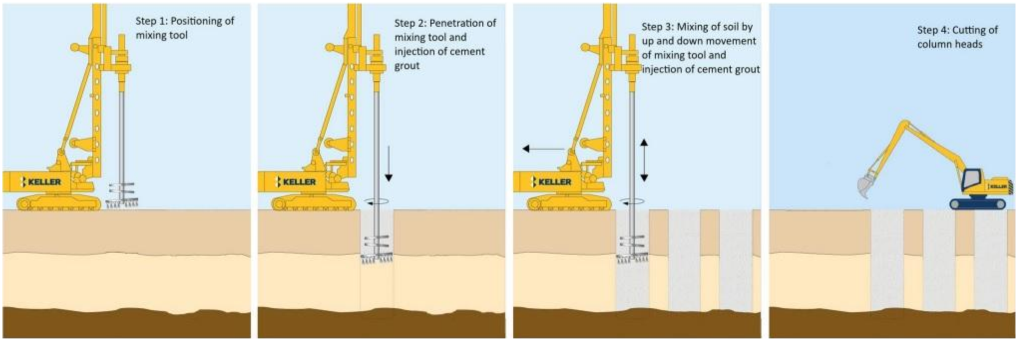


Fig. 2. DSM process steps [13]

Numerical modelling tools are widely used today to simulate soil behaviour and analyse engineering properties such as bearing capacity. In this study, Plaxis 2D software was used as a numerical analysis method to determine the bearing capacity of alluvial soils. In this study, 2D analysis was preferred. Although the three-dimensional interactions between columns (group effect) cannot be fully analysed, the soil profile, retaining system, and loading conditions do not show significant changes in the longitudinal direction along the examined section. Therefore, the additional geometric details obtained with 3D modelling will not make a significant difference in understanding the fundamental mechanisms of the problem. Furthermore, because 3D analyses require a much higher computational load, conducting a 2D analysis on a representative typical section is a common and accepted approach in the literature for most similar geotechnical cases. In this context, 2D analysis was considered the optimal choice in terms of both computational efficiency and sufficiently accurate representation of field conditions.

Archeewa et al. [12] conducted a study to eliminate the settlement problem by applying DSM to a highway subgrade. In their study, the model was simulated using finite element software. The data obtained showed that the DSM method reduced settlement and was consistent with field data. Melentijevic and Arcos [14] presented a case study where the DSM method was applied to the soil of a collapsed industrial structure. They stated that the analyses performed using Plaxis software and the design procedures were consistent with each other. Madhyannapu et al. [15] analysed a geotextile-reinforced backfill model constructed on DSM columns using the finite element software Plaxis. The soil model used was Mohr-Coulomb. The data obtained were consistent with analytical procedures and settlement prediction models found in the literature. Rashid et al. [16] conducted a series of laboratory experiments and analyses using ABAQUS software to investigate the effect of DSM columns on settlement problems. It was shown that the settlement effect of the soil increased with the number of DSM columns. Kavandi et al. [17] analysed the effect of the DSM method on improving soil properties, specifically its impact on the bearing capacity and settlement amount of soils using the finite element method. Their analyses confirmed that the DSM method increased soil bearing capacity and decreased settlement amounts. In the study, increasing the DSM length from 8 meters to 15 meters resulted in an approximate 40% reduction in settlements at the foundation corners and a 20% decrease in the total settlement at the midpoint. Makararotrit and Youwai [18] presented the DSM application used in a river wall foundation. Mohr-Coulomb was selected as the soil model, and finite element analysis was performed with GTS NX 3D software. DSM columns were modelled separately using Mohr-Coulomb, UBCSand, and Hardening Soil models. The analyses showed that Mohr-Coulomb was the best model for this study, and predictions about the behaviour of the river wall could be made using three-dimensional finite element software. Zakaria et al. [19] investigated the effect of DSM columns in clay soils through finite element analysis, considering different depths, cement dosages, diameters, and spacing configurations. The results revealed that the DSM application reduced settlement by 21% to 74% compared to the unimproved soil condition. Esmaeili et al. [20] improved the influence of DSM columns with diameters of 0.9 m and 1.2 m at various spacings on settlement, and reported a reduction of approximately 18% to 70% relative to the unimproved condition. Shah and Gandhi [21] constructed DSM columns to stabilise soils with varying degrees of saturation, and their findings indicated that settlement decreased by about 80% compared to unimproved soil. Lai et al. [22] studied the performance of DSM columns constructed beneath a 6-meter-high embankment and determined that the columns reduced settlement by up to 70%. Many researchers have studied the usability of soil improvement methods, such as DSM or other methods, by analysing them with finite element analysis methods [23-31]. It clearly indicates that the increase in the diameter and length of DSM columns leads to a reduction in settlements. This is because a higher proportion of rigid columns allows a larger share of the structural load to be transferred to the columns, thereby reducing the stress transmitted to the soil.

Although various ground improvement methods are commonly applied to mitigate settlements, certain modifications in the superstructure can also contribute to addressing this issue. One of the most effective approaches is to divide the structure into blocks and construct each block independently from the foundation in cases where non-uniform settlements are anticipated. In the literature, this practice is referred to as an expansion joint, dilation joint, or settlement joint; in the present study, the term ‘expansion joint’ is adopted. Moreover, the use of expansion joints is also advantageous in terms of cost, as it prevents potential structural damage and subsequent maintenance expenses arising from non-uniform settlements, thereby offering significant economic benefits.

Structures may be separated by expansion joints in order to prevent structural cracks and deformations that can result from non-uniform settlements in the foundation. The proper construction of these joints has a significant effect on the overall strength and durability of buildings. Expansion joints should be provided in soils where uneven settlement of the foundation is expected. They are particularly required at the junctions of structural components located on different soil conditions or constructed at different times, when a new building is constructed adjacent to an existing one, when the height difference between separate parts of a building exceeds 10 m, when there is a considerable difference in foundation width or embedment depth between adjacent walls, and similarly when the foundation types beneath various sections of a building differ, such as strip footings, pile foundations, raft slabs, isolated footings, etc. [32].

While an expansion joint is a physical separation created within the foundation, it also presents a geotechnical mechanism that significantly alters the soil-structure interaction. By disrupting the stress continuity between adjacent blocks, the joint alters the geometry of the foundation load distribution. Consequently, the presence of the joint reduces net stress in certain critical areas. Therefore, the expansion joint should be considered not merely a structural detail but a crucial geotechnical parameter that directly affects the soil's load-bearing behaviour and settlement mechanism.

This study demonstrates the influence of deep soil mixing column parameters and the use of expansion joints on the settlement behaviour of a building foundation located in the Tuzla district of Istanbul. Although case studies on ground settlements are frequently found in the literature, factors such as structural and foundation geometry, improvement methods, structure-soil interactions, or the presence of expansion joints in foundations are rarely emphasised. The lack of finite element analysis studies specifically addressing the relationship between expansion joints and settlement highlights the novelty of this study. Furthermore, the selection of DSM as the improvement method in this field demonstrates the impact of expansion joints and DSM column parameters on ground settlement in this study.

2. Material and methods

2.1. Soil Properties and Improvement Method

The study area is located in the Tuzla district of Istanbul province. A total of four boreholes were drilled: two reaching a depth of 17 meters, one reaching 18 meters, and one reaching 19 meters. During the drilling operations, both the Standard Penetration Test (SPT) and the pressuremeter test were conducted within the boreholes. Drilling data indicate that the first meter consists of fill and vegetative soil, followed by 15 meters of sandy silty clay (alluvial soil). The borehole data revealed that the upper 1 m consists of fill and topsoil, underlain by approximately 15 m of silty clay with sand (alluvial soil), followed by claystone. The groundwater level was determined to be at a depth of 4.5 meters during the drilling studies. The physical and engineering parameters of the soil used in the geotechnical analyses are presented in TABLE 1 below. The parameters presented below were obtained from the geotechnical data report as well as from field and laboratory tests.

TABLE 1

Engineering parameters of the soil

Soil Layers	Parameter	Value
Alluvial Soil (1-15 m)	Undrained Cohesion Value (c_u)	30 kPa
	Drained Internal Friction Angle (Φ')	25°
	Drained Cohesion (c')	5 kPa
	Unit Volume Weight (γ)	17 kN/m^3
	Modulus of Elasticity (E_s)	10 MPa
Claystone (15 m – End of the drilling)	Drained Internal Friction Angle (Φ')	35°
	Drained Cohesion (c')	15 kPa
	Unit Volume Weight (γ)	22 kN/m^3
	Modulus of Elasticity (E_s)	100 MPa

The site plan of the boreholes conducted in the study area is presented in Fig. 3, and the corresponding soil profile encompassing these boreholes is illustrated in Fig. 4.

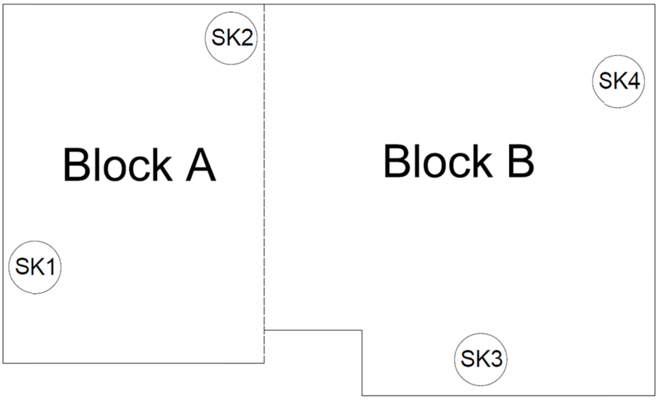


Fig. 3. Study area

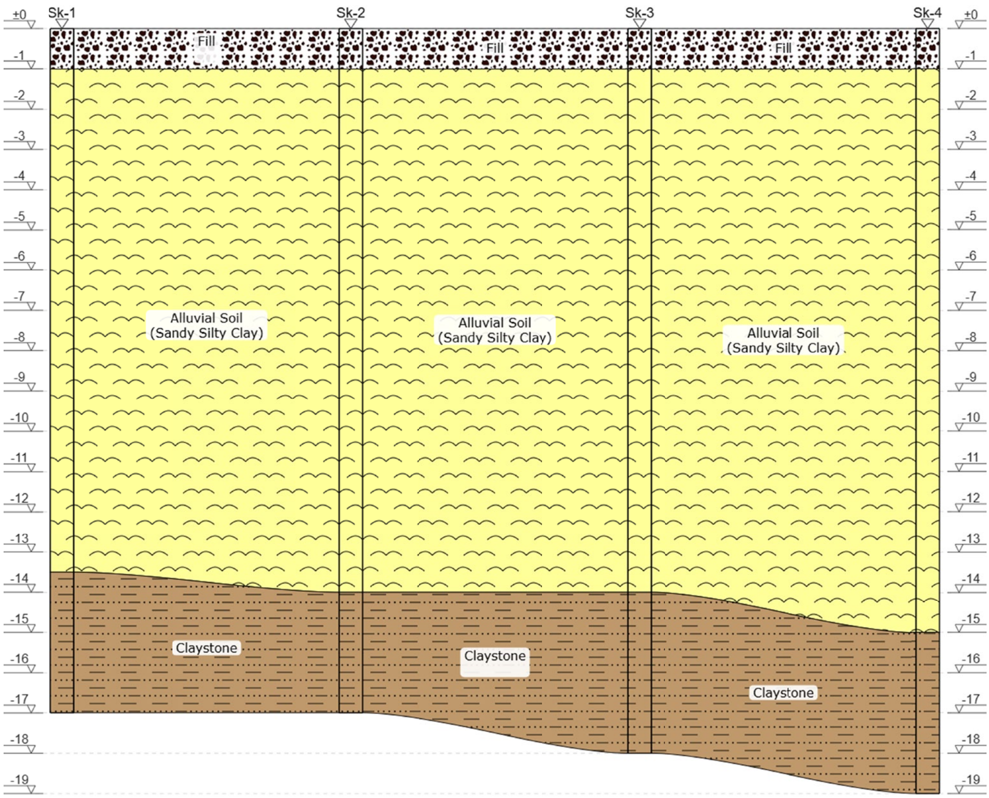


Fig. 4. Soil profile section

A 0.8 m-thick raft foundation is constructed on the soil, supporting a B+Z+5 storey residential building. The structure is separated by an expansion joint at the foundation level, forming two blocks: A and B. The total stress exerted by Block A on the soil is 159 kPa, while Block B applies a total stress of 132 kPa. In the Plaxis 2D software, the structural loads were modelled as linear loads. To assess the effect of the expansion joint, the same model was analysed in two scenarios: with and without the expansion joint.

The soil in the study area was reported to have settlements beneath the structure that exceeded allowable limits. To enhance soil stability before construction, Deep Soil Mixing (DSM) columns with a diameter of 0.4 m and a length of 12 m were installed, each with a bearing capacity of 25 tons. These columns were designed with a 7.4% area replacement ratio and arranged in a 1.3 m × 1.3 m grid pattern, extending 0.5 m into the fractured claystone. Under static conditions, the load transferred from the superstructure to each DSM column was 21 tons. A 0.8 m-thick raft foundation was constructed on top of the DSM columns.

2.2. Creating Models

Sample soil profiles were generated, and numerical models were developed by deriving the necessary model parameters for Plaxis 2D software, which utilises the finite element method for analysis. The stresses and settlements before and after the soil improvement were examined based on the obtained results. Details of the soil models used in Plaxis 2D are provided in TABLE 2 below.

TABLE 2

Soil parameters

	Alluvial Soil	Claystone
Material Model	Hardening Soil	Hardening Soil
Drainage Type	Drained	Drained
γ_{unsat} (kN/m^3)	17	22
γ_{sat} (kN/m^3)	17	22
E_{50ref} (kN/m^2)	10000	100000
E_{oedref} (kN/m^2)	10000	100000
E_{urref} (kN/m^2)	30000	300000
Power (m)	0,5	0,5
c_{ref} (kN/m^2)	5	15
φ (phi)	25	35
ψ (psi)	0	5
V_{ur}	0.2	0.2
p_{ref} (kN/m^2)	100	100
K_{0nc}	0.5774	0.4264
R_f	0.9	0.9
Tension cut-off	Yes	Yes
R_{inter}	0.8	0.8
OCR	1	4

The soil parameters were derived from the geotechnical data report, field tests conducted during borehole investigations, and laboratory experiments. Parameters such as E_{ur}, which are not included in the study's geotechnical data report, were determined using the Plaxis 2D manual

[33]. The OCR value was obtained from consolidation tests conducted on soil samples. Other parameters were obtained from test reports conducted in accordance with ASTM standards. The Hardening Soil model was selected because it provides a more realistic representation of soil behaviour during excavation and backfilling, taking into account the variability in soil stiffness under different loading conditions [18,23,26].

The Plaxis mesh model of the field production is shown in Fig. 5.

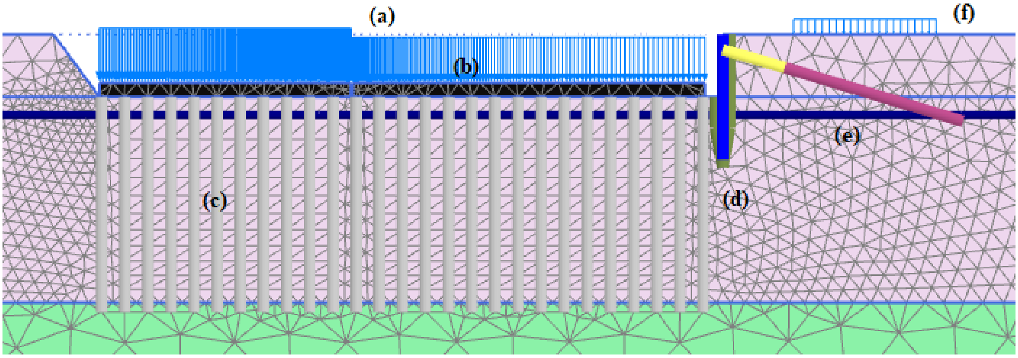


Fig. 5. Mesh Model (a) Structure load (b) Foundation (c) DSM Columns (d) Mini- Piles (e) Anchor (f) Other Structure Load

In the field application, a 7 m long mini-pile and a 10 m long anchor were employed to support the 3.5 m deep basement and foundation excavation. Since these elements were implemented in the actual construction to ensure excavation safety and structural stability, they were also incorporated into the numerical model in accordance with the original application. Detailed information on the mini-pile, anchor, tendon, and anchor root is provided in TABLE 3.

TABLE 3

Information on mini-pile, anchor rope and anchor root

	Mini-Pile	**Anchor Rope**	**Anchor Root**	**DSM**	**Basis**
Material Type	Elastic	Elastic	Elastic	Elastic	Linear Elastic
$L_{spacing}$ (m)	—	2	2	1.3/2.6	—
EA (kN)	—	42000	—	—	—
γ (kN/m^3)	—	—	8	24	24
d (m)	—	—	0.3	0.4	—
v	—	—	—	—	0.2
E (kN/m^2)	—	—	2000000	2000000	30000000
$T_{skin,\,start,\,\max}$ (kN/m)	—	—	100	Layer Dependent	—
$T_{skin,\,end,\,\max}$ (kN/m)	—	—	100	Layer Dependent	—
w (kN/m/m)	4	—	—	—	—
Isotropic	Yes	—	—	—	—
EA$_1$ (kN/m)	4524000	—	—	—	—

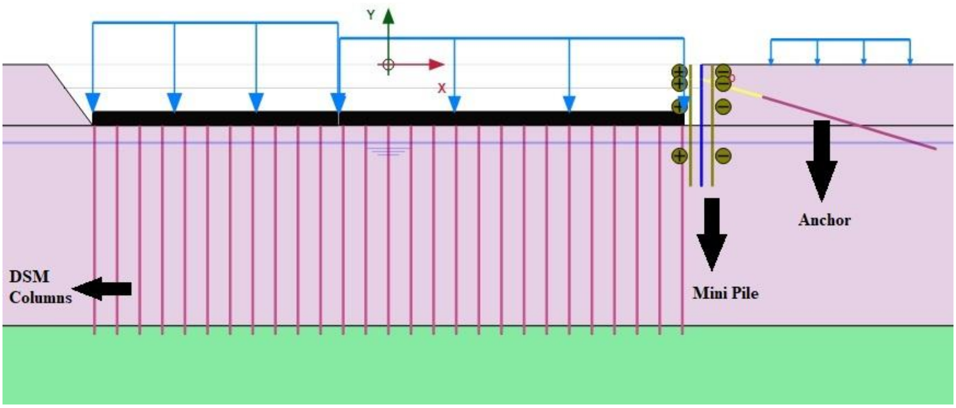
* For DSM, γ is taken as 7 kN/m^3 to show the excavation-filling difference in the calculations.

In the case of modelling, 20 different models were developed based on variations in DSM length, DSM diameter, mini-pile length, and anchor length. Details of the created models are provided in TABLE 4. Model 6 used in this study represents the actual construction arrangement implemented in the field. This configuration was constructed with DSM columns of 0.4 m

TABLE 4

Model specifications table

	DSM Length (m)			DSM Diameter (m)					Mini-Pile Length (m)			Anchor Length (m)		
	7	10	12	0.2	0.4	0.6	0.8	1	5	7	12	5	10	15
Model 0										x			x	
Model 1	x			x						x			x	
Model 2		x		x						x			x	
Model 3			x	x						x			x	
Model 4	x				x					x			x	
Model 5		x			x					x			x	
Model 6*			x		x					x			x	
Model 7	x					x				x			x	
Model 8		x				x				x			x	
Model 9			x			x				x			x	
Model 10	x						x			x			x	
Model 11		x					x			x			x	
Model 12			x				x			x			x	
Model 13	x							x		x			x	
Model 14		x						x		x			x	
Model 15			x					x		x			x	
Model 16			x		x					x				
Model 17			x		x				x				x	
Model 18			x		x						x		x	
Model 19			x		x					x		x		
Model 20			x		x					x				x



* Model 6 was applied in the study area.

in diameter and 12 m in length, spaced at 1.3 m intervals. Although post-construction settlement measurements were not recorded, no evidence of non-uniform settlements or structural problems was reported during the service period of the structure. This observation supports the reliability of the numerical modelling results. The selection of Model 6 was based on the fulfilment of engineering design criteria (meeting the settlement limits reported in the literature) as well as its consideration as the most appropriate solution from a technical perspective.

For DSM length, 7 m, 10 m and 12 m were selected. DSM diameters of 0.2 m, 0.4 m, 0.6 m, 0.8 m, and 1 m were considered. Although a 0.2 m DSM diameter is impractically small for field application, it was included for comparative purposes.

To evaluate the influence of mini-piles and anchor lengths in preventing basement excavation collapse, additional analyses were conducted with mini-piles of 5 m, 7 m, and 12 m, and anchors of 5 m, 10 m, and 15 m.

For each model, settlement analyses were performed under three conditions:

1. Without DSM,
2. With DSM at 2.6 m (sparse) intervals,
3. With DSM at 1.3 m (dense) intervals.

Additionally, an analysis without DSM was conducted to compare settlement values with those observed in Model 6, which was implemented in the field. Model 0 is the situation where there is no ground improvement application, but there are anchors and mini-piles due to deep excavation. In graphical representations, the models are labelled in the format S13L12D40 (where s = 1.3 m spacing, L = 12 m DSM length, D = 0.4 m DSM diameter) or M6L12D40 (where M6 = Model 6, L = 12 m DSM length, D = 0.4 m DSM diameter).

In addition to the main DSM models, Models 16-20 were developed to evaluate the effect of retaining wall and anchor lengths on settlement. In these models, different wall and anchor lengths were defined in order to investigate the influence of lateral support systems on ground settlement.

The soil model showing the critical points of the created model is shown in Fig. 6. The critical points were selected to represent the edges and central locations of the building foundation. In this way, the settlement values both between the blocks and along the edges could be monitored. To define the critical points indicated in Fig. 6: Point A represents the lower left corner of Block A's foundation base; Point B represents the midpoint between Block A and Block B; Point C represents the lower right corner of Block B's foundation base.

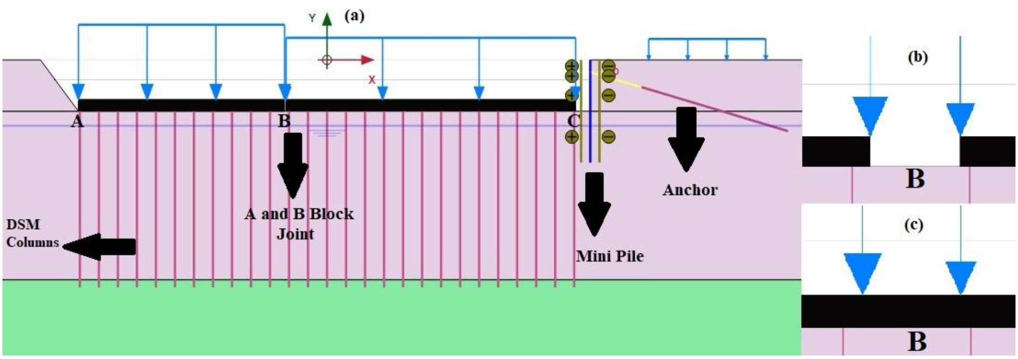


Fig. 6. (a) Model geometry (b) Joint point of model with joint (c) Joint point of model without joint

3. Findings

3.1. Model with Expansion Joint

The foundation and structural model on the soil were analysed with the inclusion of an expansion joint, and settlement values were obtained for each critical point. To evaluate the effect of DSM column spacing on settlement, the models were analysed separately with DSM spacings of 1.3 m and 2.6 m. The analysis results are presented in TABLE 5.

TABLE 5

Model settlement data with expansion joint

	Settlement (mm)					
	A		B		C	
	S = 2.6	S = 1.3	S = 2.6	S = 1.3	S = 2.6	S = 1.3
Model 0	95		110.93		60.22	
Model 1	75.94	44.72	96.43	64.71	44.18	28.83
Model 2	60.37	30.84	81.35	41.28	36.44	20.50
Model 3	48.93	20.82	62.73	23.96	31.59	13.33
Model 4	49.77	33.58	77.52	50.39	29.44	21.95
Model 5	32.61	17.15	48.31	23.71	20.21	10.87
Model 6	17.93	5.54	24.84	6.00	9.96	7.78
Model 7	39.77	30.93	62.47	48.13	24.93	20.55
Model 8	22.69	13.56	33.66	18.78	13.67	9.20
Model 9	7.20	2.51	9.53	2.96	10.60	5.04
Model 10	36.92	28.73	58.46	47.52	23.20	19.13
Model 11	19.06	13.46	28.36	18.75	11.22	8.70
Model 12	3.33	1.67	3.55	2.09	7.61	4.22
Model 13	35.71	25.67	56.66	46.77	22.56	16.58
Model 14	17.44	12.17	25.74	16.80	10.25	7.65
Model 15	1.85	1.57	1.28	1.09	6.16	4.14
Model 16	17.83	5.44	24.69	5.88	8.09	7.86
Model 17	17.91	5.54	24.80	6.03	9.65	7.64
Model 18	17.91	5.53	24.77	5.99	10.08	7.98
Model 19	17.94	5.50	24.85	5.93	10.11	7.88
Model 20	17.90	5.53	24.82	6.00	9.71	7.82

Representative settlements of the model with expansion joints are shown in Fig. 7.

A representative visual of the settlement analysis of models with expansion joints within the scope of the study is shown in Fig. 8. The primary reason why DSM columns reduce settlements is that they possess significantly higher stiffness and lower compressibility compared to the surrounding weak soil. During load transfer, a substantial portion of the structural load is carried by the columns, thereby reducing the stresses transmitted to the alluvial soil. As the superstructure load is mainly supported by the columns, the surrounding soil is subjected to lower deformation, which in turn decreases the overall settlement.

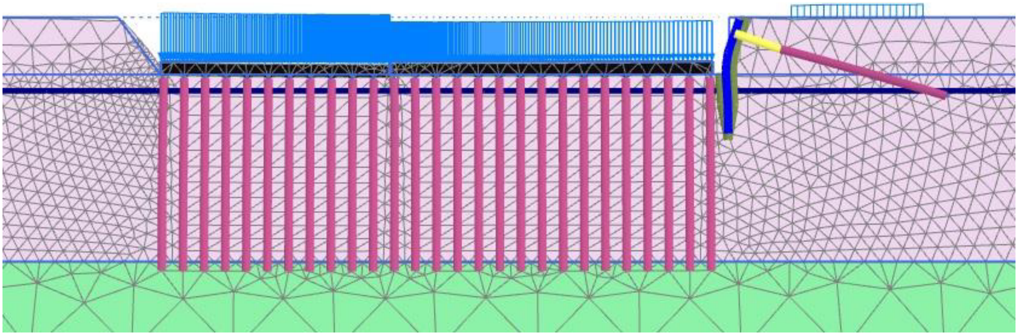


Fig. 7. Representative settlement in expansion joint model (Scale: ×50)

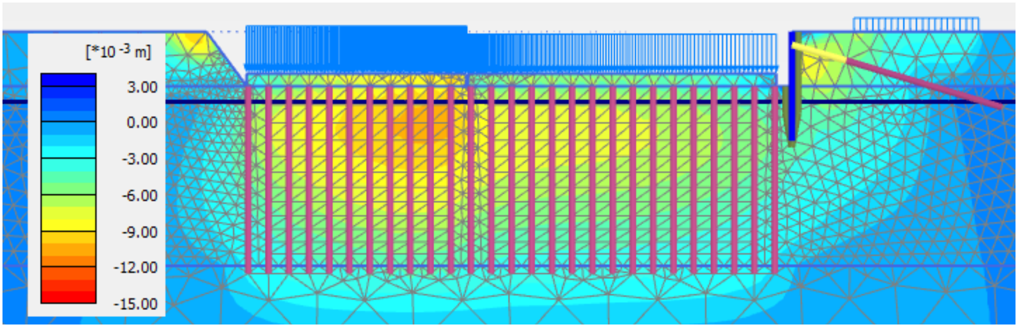


Fig. 8. Settlement image for representative analysis

The data showing the settlement amounts of the variations in TABLE 5 and the percentage decrease in the settlement amounts compared to Model 0 are presented in TABLE 6.

TABLE 6

Percentage of Decrease in Settlement Amount (%)

	Settlement (mm)					
	A		**B**		**C**	
	S = 2.6	**S = 1.3**	**S = 2.6**	**S = 1.3**	**S = 2.6**	**S = 1.3**
1	**2**	**3**	**4**	**5**	**6**	**7**
Model 0	95.079		110.93		60.22	
Model 1	20.12	52.96	13.07	41.67	26.64	52.13
Model 2	36.50	67.56	26.67	62.79	39.49	65.96
Model 3	48.53	78.10	43.45	78.40	47.54	77.86
Model 4	47.65	64.68	30.12	54.57	51.11	63.55
Model 5	65.70	81.96	56.45	78.63	66.44	81.95
Model 6	81.14	94.17	77.61	94.59	83.46	87.08
Model 7	58.17	67.47	43.69	56.61	58.60	65.88
Model 8	76.13	85.74	69.66	83.07	77.30	84.72

TABLE 6. Continued

1	2	3	4	5	6	7
Model 9	92.43	97.36	91.41	97.33	82.40	91.63
Model 10	61.17	69.78	47.30	57.16	61.47	68.23
Model 11	79.95	85.84	74.43	83.10	81.37	85.55
Model 12	96.50	98.24	96.80	98.12	87.36	92.99
Model 13	62.44	73.00	48.92	57.84	62.54	72.47
Model 14	81.66	87.20	76.80	84.86	82.98	87.30
Model 15	98.05	98.35	98.85	99.02	89.77	93.13
Model 16	81.25	94.28	77.74	94.70	86.57	86.95
Model 17	81.16	94.17	77.64	94.56	83.98	87.31
Model 18	81.16	94.18	77.67	94.60	83.26	86.75
Model 19	81.13	94.21	77.60	94.65	83.21	86.91
Model 20	81.17	94.18	77.63	94.59	83.88	87.01

These findings confirm that both increasing DSM length and reducing DSM spacing contribute significantly to settlement reduction, with the DSM diameter playing a crucial role in improving ground stability. Fig. 9 shows the graphs illustrating the effect of DSM diameter on the amount of settlement at points A, B, and C.

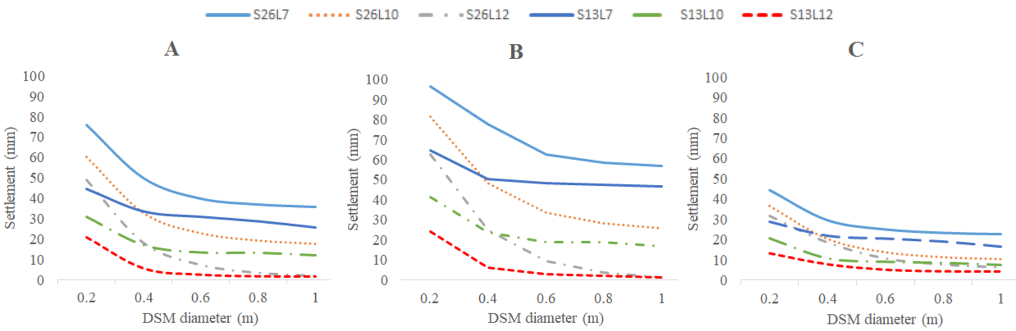


Fig. 9. Model settlement graphs with expansion joint (A point (A); B point (B); C point (C)

Fig. 9 shows the effect of increasing the DSM diameter on total settlement under different model variations, based on data obtained from TABLE 5. In all configurations, it is observed that settlement values decrease significantly with increasing DSM diameter. The settlement reduction is particularly sharp in the 0.2-0.4 m diameter range, indicating that smaller diameters, shorter DSM lengths, and shorter DSM spacing may have a limited effect on soil rigidity and load sharing. At larger diameters (0.6 m and above), the flattening of the settlement curves clearly demonstrates the DSM diameter effect. The results show that increasing the DSM diameter alone is not sufficient to limit settlement; DSM length and DSM spacing are also important parameters.

Fig. 10, obtained from data in TABLE 5, shows the effect of DSM lengths on settlement amounts. In all models, settlement values show an approximately linear decrease trend with increasing DSM length, indicating that load transfer is directed to deeper and more rigid layers

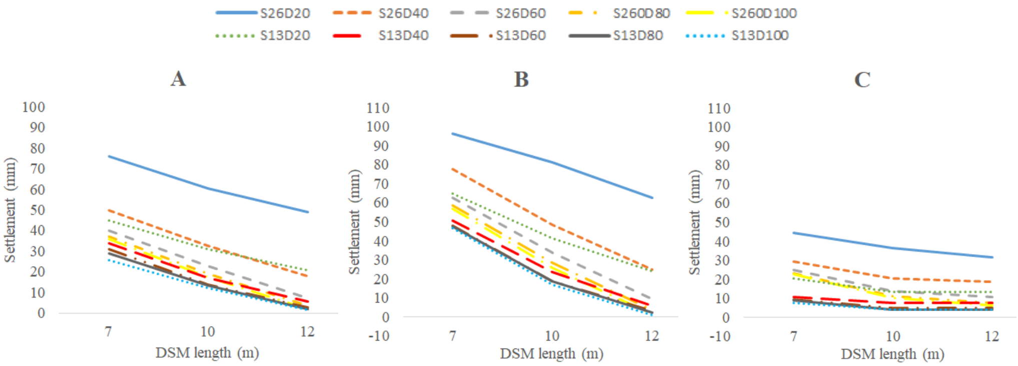


Fig. 10. Model settlement graphs with expansion joint (A point (A); B point (B); C point (C))

as column length increases. At the same DSM length, S13 models with denser column spacing systematically produce lower settlement values compared to S26 models with wider spacing. Furthermore, increasing column diameter significantly supports settlement reduction; however, the decrease in the slope of the curves at longer column lengths shows that DSM length achieves maximum efficiency in settlement control and is the optimum length. The results reveal that considering column length, column spacing, and diameter together in DSM design is critical for effectively improving settlement performance.

3.2. Model without Expansion Joint

The foundation and structural model on the soil was also analysed without expansion joints, and settlement values were obtained for each critical point. To assess the impact of DSM column spacing on settlement, models were analysed separately with 1.3 m and 2.6 m DSM spacing. The resulting settlement values are presented in TABLE 7, allowing for a comparison between different DSM configurations and their effectiveness in reducing settlement in the absence of expansion joints.

TABLE 7

Model settlement data without expansion joint

	Settlement (mm)					
	A		**B**		**C**	
	S = 2.6 m	**S = 1.3 m**	**S = 2.6 m**	**S = 1.3 m**	**S = 2.6 m**	**S = 1.3 m**
1	**2**	**3**	**4**	**5**	**6**	**7**
Model 0	103.81		109.08		61.02	
Model 1	85.23	52.46	94.07	62.37	45.75	30.62
Model 2	68.25	33.87	78.69	40.18	37.85	21.30
Model 3	52.63	22.45	25.56	26.08	32.21	13.43
Model 4	58.44	38.46	73.30	47.07	31.70	23.50
Model 5	36.14	18.78	45.77	23.57	21.57	11.43
Model 6	19.27	5.94	24.23	6.82	10.45	7.91

TABLE 7. Continued

1	2	3	4	5	6	7
Model 8	25.01	14.63	31.62	18.27	14.67	8.90
Model 9	7.75	2.68	9.09	3.40	10.60	5.04
Model 10	42.08	32.13	54.93	42.67	25.21	20.58
Model 11	20.89	14.39	26.49	18.20	12.02	8.24
Model 12	3.63	1.78	3.29	2.43	7.70	4.27
Model 13	40.60	30.56	52.99	40.06	24.43	20.31
Model 14	19.02	13.75	24.15	17.34	10.94	7.88
Model 15	2.01	1.66	2.29	0.67	6.27	4.18
Model 16	19.16	5.84	24.05	6.64	8.27	7.98
Model 17	19.26	5.94	24.20	6.82	10.14	7.75
Model 18	19.22	5.93	24.21	6.86	10.56	8.10
Model 19	19.29	5.89	24.22	6.64	10.59	7.99
Model 20	19.24	5.92	24.05	6.80	10.19	7.94

Sample settlements of the model without expansion joints are shown in Fig. 11.

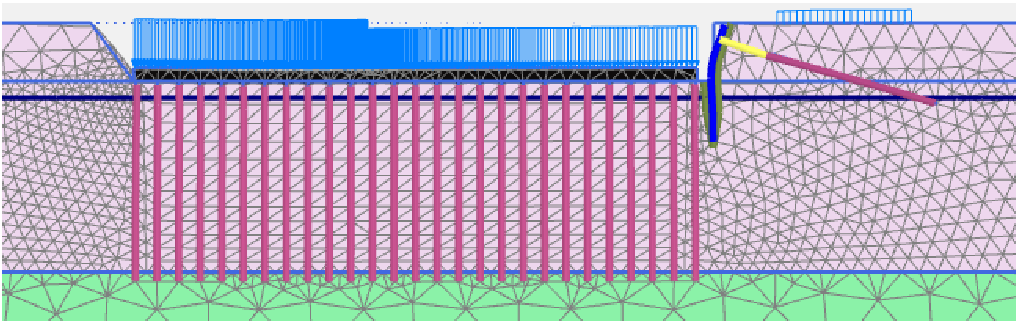


Fig. 11. Sample settlement in expansion joint model (Scale: ×50)

A representative visual of the settlement analysis of models without expansion joints within the scope of the study is shown in Fig. 8.

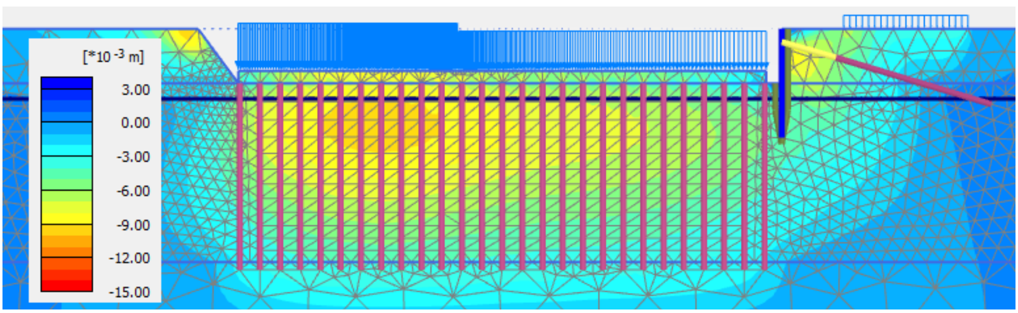


Fig. 12. Settlement image for representative analysis

The data showing the settlement amounts of the variations in TABLE 7 and the percentage decrease in the settlement amounts compared to Model 0 are presented in TABLE 8.

TABLE 8

Percentage of Decrease in Settlement Amount (%)

	Settlement (mm)					
	A		B		C	
	S = 2.6 m	S = 1.3 m	S = 2.6 m	S = 1.3 m	S = 2.6 m	S = 1.3 m
Model 0	103.81		109.08		61.02	
Model 1	17.90	49.47	13.76	42.82	25.02	49.82
Model 2	34.25	67.37	27.86	63.16	37.97	65.09
Model 3	49.30	78.37	76.57	76.09	47.21	77.99
Model 4	43.70	62.95	32.80	56.85	48.05	61.49
Model 5	65.19	81.91	58.04	78.39	64.65	81.27
Model 6	81.44	94.28	77.79	93.75	82.87	87.04
Model 7	56.52	66.32	46.30	59.53	55.85	63.98
Model 8	75.91	85.91	71.01	83.25	75.96	85.41
Model 9	92.53	97.42	91.67	96.88	82.63	91.74
Model 10	59.46	69.05	49.64	60.88	58.69	66.27
Model 11	79.88	86.14	75.72	83.31	80.30	86.50
Model 12	96.50	98.29	96.98	97.77	87.38	93.00
Model 13	60.89	70.56	51.42	63.27	59.96	66.72
Model 14	81.68	86.75	77.86	84.10	82.07	87.09
Model 15	98.06	98.40	97.90	99.39	89.72	93.15
Model 16	81.54	94.37	77.95	93.91	86.45	86.92
Model 17	81.45	94.28	77.81	93.75	83.38	87.30
Model 18	81.49	94.29	77.81	93.71	82.69	86.73
Model 19	81.42	94.33	77.80	93.91	82.65	86.91
Model 20	81.47	94.30	77.95	93.77	83.30	86.99

These findings confirm that both increasing DSM length and reducing DSM spacing contribute significantly to settlement reduction, with the DSM diameter playing a crucial role in improving ground stability. Fig. 13 shows the graphs illustrating the effect of DSM diameter on the amount of settlement at points A, B, and C.

Fig. 13 shows the effect of increasing the DSM diameter on total settlement under different model variations, based on data obtained from TABLE 7. In all configurations, it is observed that settlement values decrease significantly with increasing DSM diameter. The settlement reduction is particularly sharp in the 0.2-0.4 m diameter range, indicating that smaller diameters, shorter DSM lengths, and shorter DSM spacing may have a limited effect on soil rigidity and load sharing. At larger diameters (0.6 m and above), the flattening of the settlement curves clearly demonstrates the DSM diameter effect. The results show that increasing the DSM diameter alone is not sufficient to limit settlement; DSM length and DSM spacing are also important parameters.

Fig. 14, obtained from data in TABLE 7, shows the effect of DSM lengths on settlement amounts. In all models, settlement values show an approximately linear decrease trend with increasing DSM length, indicating that load transfer is directed to deeper and more rigid layers as column length increases. At the same DSM length, S13 models with denser column spacing

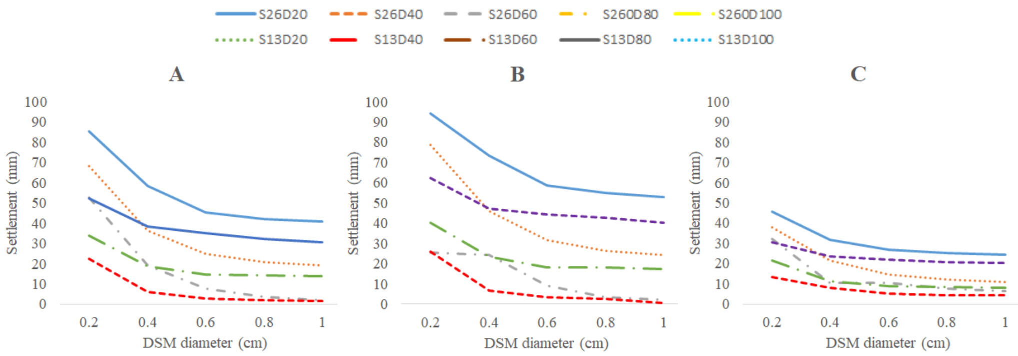


Fig. 13. Model settlement graphs without expansion joint (A point (a); B point (B); C point (c))

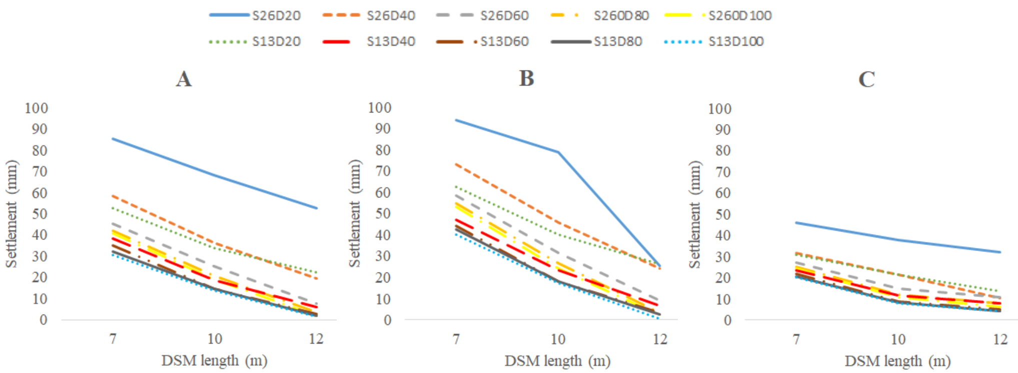


Fig. 14. Model settlement graphs without expansion joint (A point (a); B point (B); C point (c))

systematically produce lower settlement values compared to S26 models with wider spacing. Furthermore, increasing column diameter significantly supports settlement reduction; however, the decrease in the slope of the curves at longer column lengths shows that DSM length achieves maximum efficiency in settlement control and is the optimum length. The results reveal that considering column length, column spacing, and diameter together in DSM design is critical for effectively improving settlement performance.

3.3. Expansion Joint Effect on the Field-Manufactured Case (Model 6)

In order to see the effect of the expansion joint on Model 6 applied in the field, the displacement values obtained from the analysis of the model with and without expansion joints are given in TABLE 9.

In Model 6, which is a model with expansion joints applied in the field, the settlement value at point A from the critical points was obtained as 5.54 mm, at point B as 6 mm, and at point C as 7.78 mm. These results show that when soil improvement is applied, the settlement amounts

TABLE 9

Comparison Settlement of Field Model with and without Expansion Joint

	Settlement (mm)					
	A		B		C	
	S = 2.6 m	S = 1.3 m	S = 2.6 m	S = 1.3 m	S = 2.6 m	S = 1.3 m
Model 6 without expansion joint	19.27	5.94	24.23	6.82	10.45	7.91
Model 6 with expansion joint	17.93	5.54	24.84	6.00	9.96	7.78

are significantly reduced. The effect of the expansion joint at critical points is shown in Fig. 15 by drawing a graph for each point.

The fundamental technically explainable reason for these results is that in the analysed models, soil-structure interaction is predominantly controlled by soil rigidity and DSM improvement, and the expansion joint cannot create stress redistribution on a scale that would provide significant freedom in this loading and settlement mechanism. Since settlement in the soil environment improved with DSM columns, which are largely limited by the column-soil composite behaviour, the expansion joint defined in the superstructure does not significantly alter the vertical load transfer path or effective load distribution area. Furthermore, the fact that the joint width

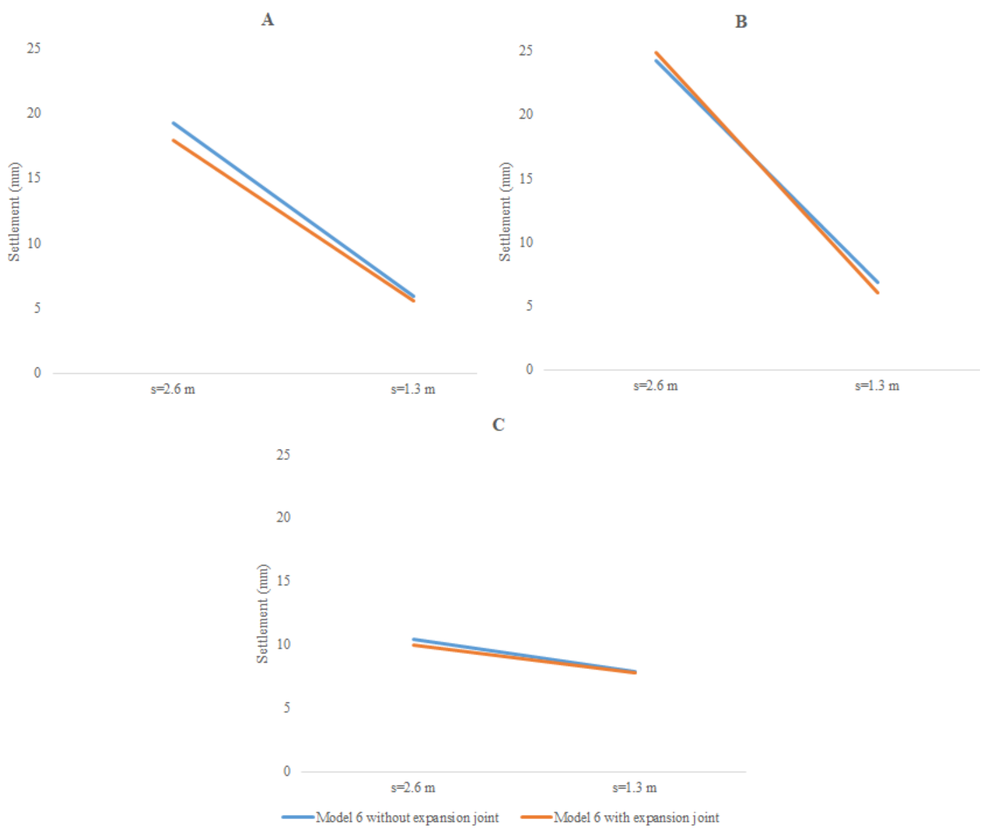


Fig. 15. Model 6 settlement with expansion joint and without expansion joint

remains small compared to the foundation dimensions and column spacing causes loads to still be transmitted to the soil through similar areas of influence; this prevents a significant difference in settlement between the jointed and unjointed cases. In this context, the observed results show that the expansion joint does not become a parameter controlling the settlement mechanism.

Fig. 16 shows the total vertical stresses in the model with and without expansion joints.

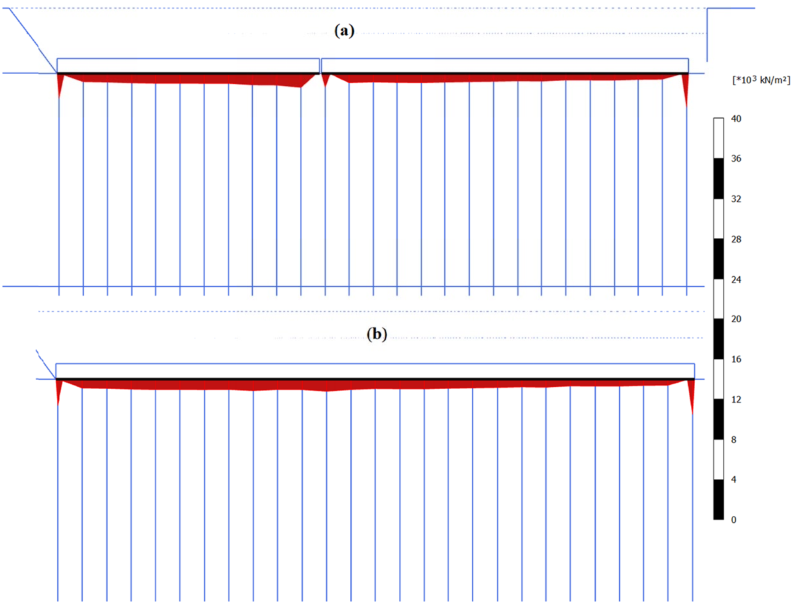


Fig. 16. Total Vertical Stress ((a) with expansion joint, (b) without expansion joint)

The use of expansion joints offers a significant advantage in controlling load transfer in the soil-structure system by limiting stress interaction. Expansion joints interrupt the stress continuity between adjacent building blocks, preventing the propagation of secondary stresses caused by non-uniform settlement, temperature effects, and stiffness differences. This, especially in long and rigid foundations, prevents the transfer of local stress concentrations to neighbouring areas, contributing to both safer soil behaviour and a reduced risk of crack formation in the superstructure. In this respect, expansion joints are an effective design element that increases serviceability and long-term performance as well as structural strength.

3.4. Mini-Pile and Anchor Effect

To ensure excavation safety in the study area, mini-piles and anchorage systems were implemented. To analyse the impact of these structural elements on settlement, Models 16-17-18-19, and 20 were created. Model 16 does not include an anchorage system, while Model 17 features mini-piles with a length of 5 meters, and Model 18 extends the mini-pile length to 12 meters. In Model 19, the anchorage length was reduced to 5 meters, whereas in Model 20, it was increased to 15 meters.

The settlement values obtained for the expansion models (Models 16-17-18-19-20) and Model 6, which were applied in the field, are presented in TABLE 10. When settlement values were compared, it was observed that changes made only to the mini-pile and anchor models for deep excavation support in the area where the structure is located had no effect on the critical points of the structure, but did have effects on the settlements of the structure in the adjacent plot. Looking at Fig. 17, it can be interpreted that the close spacing of the DSM significantly reduced settlements at the point where the expansion joint is located, and also reduced the probability of the structure being subjected to non uniform settlements.

The settlement curves for these models are illustrated in Fig. 17, a representative image is displayed in Fig. 18.

TABLE 10

Model mini-pile anchor effect with expansion joint

	Settlement (mm)					
	A		B		C	
	S = 2.6	S = 1.3	S = 2.6	S = 1.3	S = 2.6	S = 1.3
Model 6	17.93	5.54	24.84	6.00	9.96	7.78
Model 16	17.83	5.44	24.69	5.88	8.09	7.86
Model 17	17.91	5.54	24.80	6.03	9.65	7.64
Model 18	17.91	5.53	24.77	5.99	10.08	7.98
Model 19	17.94	5.50	24.85	5.93	10.11	7.88
Model 20	17.90	5.53	24.82	6.00	9.71	7.82

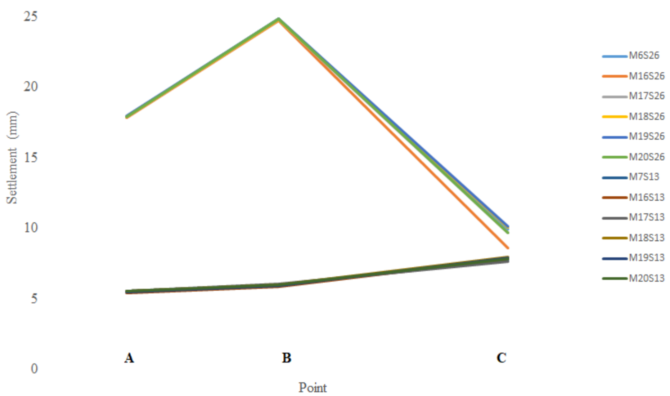


Fig. 17. Settlement graph of expansion joint mini-pile-anchor models

Fig. 17 is intended to illustrate the settlement amounts at selected critical points, and the portions outside the critical point represent the potential settlement amounts.

The settlement values obtained for Models 16-17-18-19-20 in the models without expansion joints, along with Model 6 applied in the field, are presented in TABLE 11. When comparing the settlement amounts, it was observed that the mini-pile or anchorage length did not lead to significant changes in the settlement values at points A, B, and C in the model without an expansion joint.

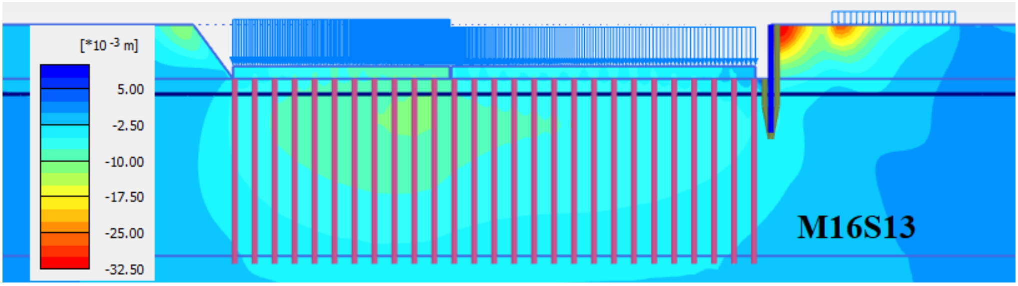


Fig. 18. Mini-pile Anchor models with expansion joints representative image

The settlement curves for these models are illustrated in Fig. 19, and the corresponding settlement images are displayed in Fig. 20.

TABLE 11

Model mini-pile-anchor effect without expansion joint

	Settlement (mm)					
	A		B		C	
	S = 2.6	S = 1.3	S = 2.6	S = 1.3	S = 2.6	S = 1.3
Model 6	19.27	5.94	24.23	6.82	10.45	7.91
Model 16	19.16	5.84	24.05	6.64	8.27	7.98
Model 17	19.26	5.94	24.20	6.82	10.14	7.75
Model 18	19.22	5.93	24.21	6.86	10.56	8.10
Model 19	19.29	5.89	24.22	6.64	10.59	7.99
Model 20	19.24	5.92	24.05	6.80	10.19	7.94

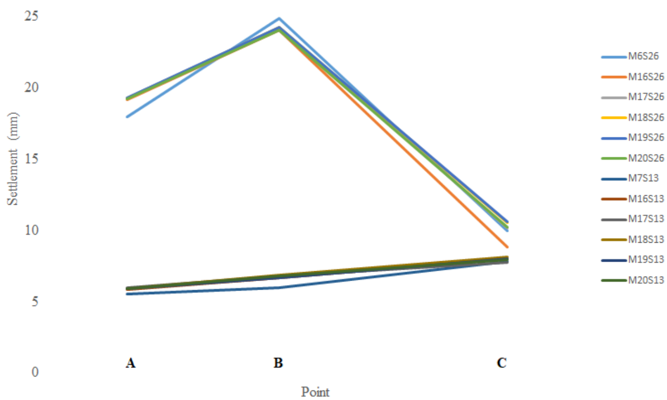


Fig. 19. Settlement graph of mini-pile anchor models without an expansion joint

Fig. 19 is intended to illustrate the settlement amounts at selected critical points, and the portions outside the critical point represent the potential settlement amounts. Looking at Fig. 18, it can be interpreted that the close spacing of the DSM significantly reduces settlements at the point where the expansion joint is located, and also decreases the likelihood of the structure being subjected to non-uniform settlements.

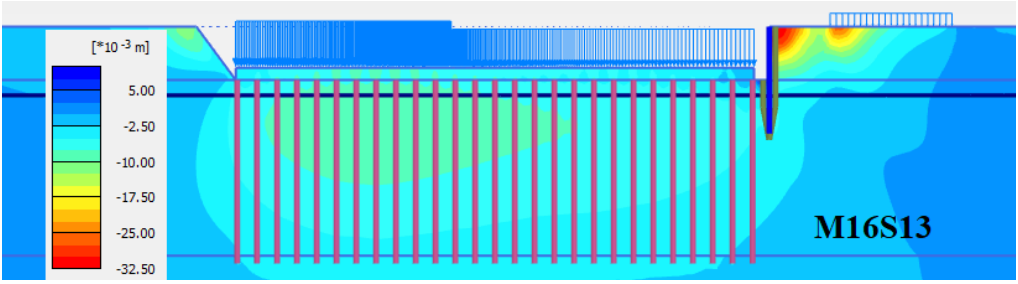


Fig. 20. Mini-pile Anchor models without expansion joint representative image

4. Conclusions and recommendations

- An increase in DSM column parameters (length and diameter) and a reduction in column spacing can decrease soil settlements induced by structural loads by up to 95%.
- DSM application provided a reduction of 94,17% at point A, 94,59% at point B, 87,08% at point C, according to the results obtained in the expansion joint model applied in the study area (Model 6). These results confirm that DSM effectively reduces settlement.
- In the model without an expansion joint, DSM reduced settlement amounts by 94,28% at point A, 93,75% at point B, 87,04% at point C. The expansion joint models did not show a particularly effective decrease at the expansion point.
- In the models, increasing the diameter and length of the closely spaced (1.3 m) DSMs significantly reduced settlement, effectively decreasing the settlement at point B compared to the sparsely spaced (2.6 m) layout and preventing non-uniform settlements in the structure.
- In the model with an expansion joint, anchor and excavation curtain length did not significantly affect settlement values at points A, B and C due to the expansion joint.
- In the model without an expansion joint, anchor and excavation curtain length did not significantly affect settlement values at points A, B and C due to the expansion joint.
- When the relationship between DSM length and settlement is examined, it is observed that there is a linear slope and a significant decrease in settlements at DSM lengths between 7 and 12 meters. However, it was seen that non-uniform settlements were less when the DSM spacing was 1.3 m compared to when it was 2.6 m, and the amount of settlement decreased significantly when the DSM diameter was 0.4 m or more. These results indicate that DSM diameter, length, and grid are important parameters that should be evaluated together.
- In the soil-structure interaction, the stresses are predominantly borne by the DSM columns, and the expansion joint defined in the superstructure did not create a significant change in the vertical load distribution. The fact that the joint width remained small compared to the foundation dimensions and column spacing resulted in the loads being transmitted to the soil through similar areas of influence, and this prevented a significant difference in settlement between the jointed and non-jointed cases.

- Expansion joints interrupt the stress continuity between adjacent building blocks, preventing the propagation of secondary stresses caused by non-uniform settlement, temperature effects, and stiffness differences.
- The results emphasise the critical role of DSM spacing and design parameters in settlement control. For this case study, the most cost-effective and efficient application is a 12-meter DSM length, 0.4 m DSM diameter, and 1.3 m DSM spacing using an expansion joint structure model.

This study has demonstrated the effectiveness of DSM columns in reducing settlements through both numerical modelling and field application. Based on the results obtained, it is recommended that practitioners consider parameters such as column diameter, length, and spacing not only in terms of bearing capacity but also with respect to settlement criteria during the design stage. In addition, in areas with non-uniform settlement potential, the incorporation of expansion joints should not be overlooked, as they are crucial for structural safety and serviceability. Future studies should also investigate the effects of expansion joints on bearing capacity, seismic behaviour, and long-term consolidation settlements. Moreover, optimising the dimensions of DSM columns and the arrangement of expansion joints can lead to both safe and economical designs, thereby providing the most effective engineering solutions.

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