International Journal of GEOMATE, March, 2025 Vol.28, Issue 127, pp.12-19
ISSN: 2186-2982 (P), 2186-2990 (O), Japan, DOI: https://doi.org/10.21660/2025.127.4548
Geotechnique, Construction Materials and Environment

METHOD FOR INCREASING LOAD-BEARING CAPACITY OF SOIL-CEMENT COLUMNS ON SOFT SOILS IN KAZAKHSTAN

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ABSTRACT: The historically developed geological conditions of Kazakhstan are characterized by the diversity of the composition of the geological profile. In most of the developed territory, conditions are represented by deposits of macroporous, loess soils of different moisture conditions. Construction on these soils requires a set of measures to strengthen and improve mechanical properties. The article discusses the application of the deep mixing method for strengthening compressible soils. However, the method is still limited in application. The main reason for the weak spread of the method is the quality of the soil-cement column material obtained by mixing and the effect of seismic action on its load-bearing capacity. Strengthening elements in the form of soil-cement columns are the main element that increases the bearing capacity of foundation soils. The article presents the results of a study of the physical and mechanical properties of column material obtained in the field by wet deep mixing. The results of studies of the DSM soil-cement column model, performed on a scale of 1:100, are presented. The models are strengthened by reinforcement with metal profiles or a frame of reinforcing bars. The reliability of the results obtained was verified by analytical calculations in a real geological profile.

Keywords: Deep mixing, Strengthening elements, Bearing capacity, Soft soil.

1. INTRODUCTION

A feature of the geological structure of the intensively developed regions of Kazakhstan is the widespread occurrence of loess macroporous soils. Such soils are found both in the north and south of Kazakhstan. Most often, they form mountain counters and piedmont surface deposits, which are extended up to tens of meters. By origin, such soils belong to alluvial deposits of middle-Quaternary age and are represented by sandy loams or loams. Such deposits are classified as structurally unstable soils, especially in the case of active moisture and seismic loads. Both reasons are relevant for the regions of Kazakhstan since, in the foothill areas, groundwater has both deep and surface distribution [1,2]. In this regard, simultaneous soaking of both deep and surface layers of soil occurs. This leads to subsidence phenomena due to an increase in the specific gravity of loess deposits and an increase in the actual total deformation of buildings and structures under construction [3].

The building codes of Kazakhstan prohibit the use of subsidence soils as foundations for structures without special measures to strengthen and increase the bearing capacity. Traditionally used strengthening methods include the use of reinforced concrete piles [3,4]. But this is not always effective and possible, especially in densely built cities.

The main importance of these studies is to improve the method of strengthening weak soils and increase their bearing capacity by using soil cement elements. The mixing conditions in loess macroporous soils of Kazakhstan and the use of additional reinforcement of soil-cement columns to increase the load-bearing capacity are analyzed. This article presents some results of research on increasing the bearing capacity of soil cement elements and expanding the possibilities of using deep mixing technology in Kazakhstan.

DSM technology is actively used in many countries around the world [5-9, 11, 12]. In Kazakhstan, DSM technology is just beginning to be used.

Research into the operation of DSM soil-cement columns is actively carried out in many countries around the world [12-20]. Research results confirm that the use of reinforcement for weak foundations leads to an increase in their bearing capacity [6, 8, 9], as well as to the formation of soil masses with higher mechanical properties.

The results of tests of soil-cement columns in the field and models in the laboratory showed [7-9] that the main zones where the destruction of DSM columns occurs are located closer to the ground surface or the destruction occurs in places where poorly mixed local material and cement are concentrated.

There are several directions for increasing the mechanical properties of soil-cement materials. These areas include increasing the amount of cement, using various technical and chemical additives [15-20] and increasing rigidity by introducing a more durable element into DSM. The main goal of our research is to study the possibility of additional strengthening of DSM soil cement with elements of high rigidity and increasing the bearing capacity of DSM.

2. RESEARCH SIGNIFICANCE

The primary focus of this research is to investigate the feasibility of applying a method to stabilize weak soils by enhancing their bearing capacity through the use of soil-cement elements in the conditions of Kazakhstan. The structural characteristics and petrographic composition of the most common loess clay soils in the southern regions of Kazakhstan were studied and identified. The preparation of experimental columns and testing of control samples revealed the conditions influencing the quality of mixing and the formation of a homogeneous soil-cement column. Innovative approaches were explored to improve bearing capacity by incorporating additional reinforcement with high-stiffness structural elements.

3. GEOLOGICAL CONDITIONS

The lithological structure of the southernmost regions of the country is represented by a thick layer of Upper Quaternary sediments of alluvial-proluvial origin. On the surface, there are loams, which are underlain by a thick layer of pebble soils. These rocks were previously carried out by water flows from the mountains and formed the area of the alluvial cone of the Trans-Ili Alatau ridge and the foothill plain. The thickness of the loam layer is variable and varies from a few meters to 20 meter [1, 2, 4]. According to the data of drilling deep wells in the thickness of pebble soils, ranging from 300 to 400 m, layers of sandy-loamy material up to 10 meter were identified [3].

Geological research has identified the following engineering-geological elements: IGE-1. The soil-vegetative layer is loam. Layer thickness 0.10 m; IGE 2 - collapsible loam, light and sandy, hard consistency, macroporous with inclusions of carbonate salt deposits and broken shells [4]. Ground conditions for subsidence are of the second type. Layer thickness 14.90 m; IGE 3 - non-subsiding loam, light and sandy, semi-solid consistency with thin layers of sand; when saturated with water, it easily gets wet and washed away. The maximum exposed thickness of the layer is 5.00 meters.

The seismic hazard of the area on the MSK-64 (K) scale, in accordance with the seismic zoning map of Kazakhstan, will be equal to 9 (nine) points. However, data from engineering geological surveys have established that the soils that make up the natural base of the foundations have type III soil conditions in terms of seismic properties [1,3]. This increases the seismic hazard of the construction site.

Table 1 Physical and mechanical properties of soils

№ layer	W,	γ	γ_d,	e	PI	ϕ	C	E
1	6	14.1	1.33	1.0	8	-	-	-
2	8	15.5	14.2	0,98	9	21/16	23/15	11,9/2,7
3	18	18.4	15.9	0.69	10	23/18	30/20	14.8/11.8

Here, W – Moisture conture, %, γ – Moist weight volume, kH/ m^3, γ_d – Dry unit weight, kN/m^3, e – Porosity coefficient, PI – Plasticity index, ϕ – Friction angle, degree, C – Cohesion, kPa, E – Deformation modulus, MPa

4. SELECTION OF MEASURES FOR STRENGTHENING SOIL

Analyzing the geological structure, we can say that the foundation soils are homogeneous. However, their physical and mechanical parameters show that some parameters change with depth. A decrease in the porosity coefficient *e* and an increase in the deformation modulus E is particularly noticeable. This indicates a slight increase in the bearing capacity of the soil. However, the soil is macroporous and weak, and therefore measures are required to strengthen the surface layer located in the zone of effective stress. When installing reinforcement in the form of reinforced concrete piles, the natural soil is completely replaced, and the piles are filled, which greatly increases the cost of this method. When constructing soil-cement columns, the main material is cement.

As strengthening measures, one can consider the use of driven piles and reinforcing elements performed by rolling out or installing DSM soil-cement columns. This article discusses only the latter method. The underlying layer IGE 3 is classified as non-subsidence. It can be used as a load-bearing support layer. To strengthen the soil, we use soil-cement columns with a diameter of 0.8-1.0 meters, deepening them into the load-bearing structure at IGE 3 at least 3.0 meters. The total length of the column will be more than 10 meters. At the same time, when forming the design diagram of the foundation, we believe that the soil-cement columns with the surrounding IGE 2 soil work together, forming a strengthened mass.

The final design solution for the foundation of the buildings was taken in the form of a soil cushion up to 1.5 meters thick made of undrained soil. The pillow rests on an array reinforced with DSM elements. The elements have a diameter of 1.0 meters and are made to a depth of up to 10 meters. The elements are buried in IGE 3. Studies of the physical and mechanical properties of an array, a soil-cement column made using the technology Deep Soil Mixing (DSM) are given below.

5. FIELD AND LABORATORY STUDIES OF DSM STRENGTH

The main methods for studying the properties of soil-cement columns are field tests of the bearing capacity of experimental columns for vertical load. Laboratory studies are carried out in uniaxial and triaxial compression devices. Research is carried out on samples obtained from experimental columns. In Kazakhstan, such studies were carried out using soils from the southern regions. The main parameters of the strength and deformation properties of soil-cement columns made to strengthen weak foundations were investigated. Experimental soil-cement columns were made in the field and were cured for 28 days. After gaining strength, test columns were excavated to a depth of 3 meters.

Fig. 1. General view of soil-cement columns

Fig. 2. Locations of horizontal drilling and core sampling

According to the testing program, to determine the physical and mechanical properties and the manifestation of anisotropy of the column material, cores in Fig. 1 were examined.

Cylindrical samples were cut with a diameter of 100 mm, 50 mm in the vertical and horizontal direction Fig. 2, relative to the longitudinal axis of the column.

The main goal of the research is to determine the ultimate strength of the column material in uniaxial compression, the total deformation modulus and Poisson's ratio.

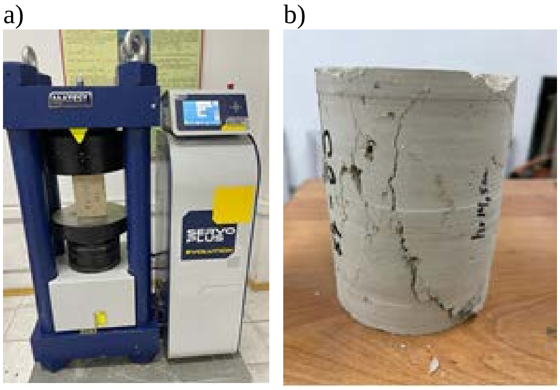


Fig. 3. General view of the uniaxial compression device (a), tested sample (b).

For uniaxial compression testing, a MATEST brand press was used; samples with a diameter of 100 mm and a height of 200 mm were tested. Samples of 50 mm and a height of at least 2d were tested in a three-stage compression device.

The tests were carried out in accordance with the requirements of GOST 12248-2010, Soils, “Methods for laboratory determination of strength and deformability characteristics”.

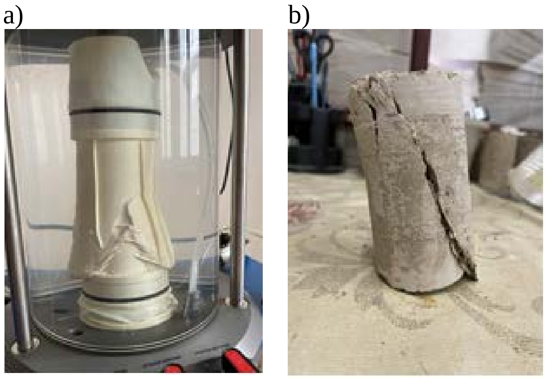


Fig. 4. General view of the sample in a triaxial compression test (a), sample after testing (b).

The tests were carried out in the «Base and Foundations» laboratory of JSC KazRICA. For testing, uniaxial compression devices and a triaxial compression test we used Fig. 3, Fig. 4.

The studies were carried out for samples in natural and soaked states. The samples were soaked and kept for two weeks before testing.

Table 2 Physical and mechanical parameters of soil-cement columns

№	State	Coring direction	Density, kg/m^3	Rc,		Eo	ν
				Design	Characteristic		
1	Natural	Horizontal	1721	6,36	6,04	424,3	0,29
		Vertical	1725	4,68	4,36		
2	Soaked	Horizontal	1921	3,7	3,53	381,5	0,32
		Vertical	1908	3,14	2,97		

Here, Rc - niaxial compressive strength, MPa, ν - Poisson's ratio, Eo - Deformation modulus, MPa

6. MODELING OF SOIL-CEMENT ELEMENTS

The effectiveness of this approach has been tested in laboratory conditions using physical models. The obtained results were compared with the results of analytical calculations of reinforced DSM in soil using the PLAXIS 3D.

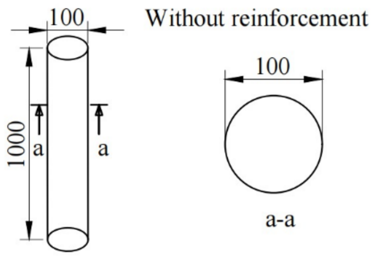
The laboratory testing program for models of four variants of soil-cement columns is shown in Fig. 5.

For reinforcement, the following were used: steel I-beam, steel pipe, reinforcing steel assembled in the form of a wire spatial frame. The models are made on a scale of 1:10, with sample sizes of 10 cm in diameter and 100 cm in length. The material of the samples is loess-like loam - 85% and cement - 15%.

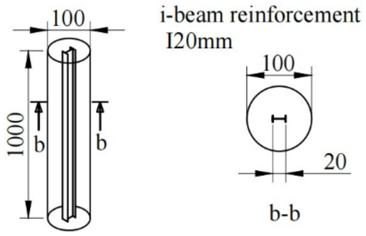
When preparing the samples, loam and cement were weighed in a ratio of 85/15 and mixed with the addition of water to a plastic state.

Then the mixture was poured into a mold made of PVC pipe with an internal diameter of 100 mm.

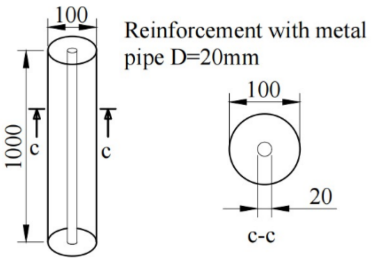
The reinforcing elements were immersed into the sample immediately after pouring the mixture. The prepared samples were kept in a plastic container with wet sawdust for at least 28 days and stored at a temperature of 20ºC.



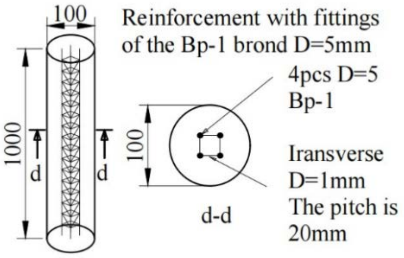
a) Model 1



b) Model 2



c) Model 3



d) Model 4

Fig. 5 Testing program for DSM models 1 to 4

The tests carried out in a special load-bearing frame, the structural diagram are presented in Fig. 6 and general view are presented in Fig. 7. The upper part of sample 4 rested against the upper transverse beam of frame 1, and the lower part rested against the lower transverse beam. The longitudinal force was created by a hydraulic jack 2, with a lifting capacity of 10 tons. The longitudinal force was measured with an electronic dynamometer type 3 DSM 10 kN. To measure the deformations of a column sample, an electronic deflectometer 5 type PSK MG-4 is used. The deflection meter division value is 0.01 mm.

The tests were carried out according to the following method. The test sample is installed in a thrust frame and a preliminary vertical force of 0.5 kN is created. Then the force is reduced to 0.1kN and the deflexometers are set to zero. In the experiment, a vertical force is applied to the sample in steps of 0.1Rc. Here Rc is the uniaxial compressive strength, previously obtained from the results of laboratory tests in Table 2. Loading continues until the sample fails.

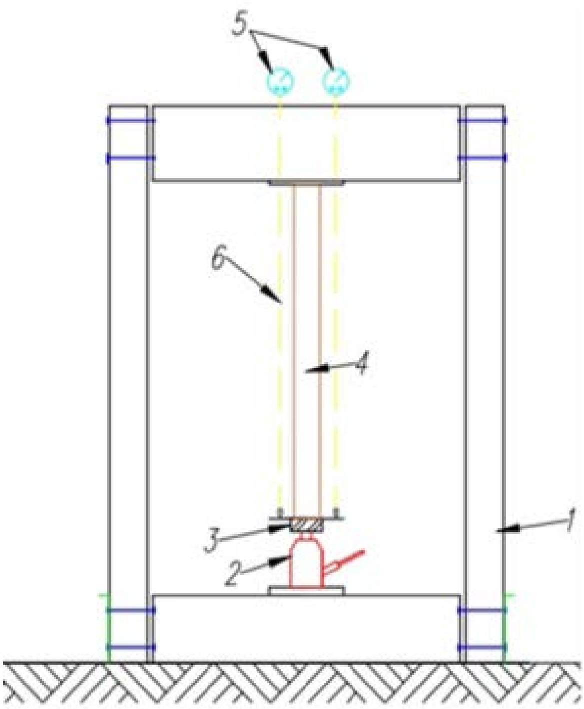


Fig. 6. Design scheme of the DSM test setup; 1-test frame; 2-jack; 3-dynamometer; 4-test sample; 5-displacement deflectometers; 6-steel thread with counterweight.

6.1 Main results of laboratory tests of DSM models

Tests of four variants of DSM models without reinforcement and with reinforcement with a metal profile in the form of a steel I-beam, a steel pipe and a spatial wire frame were carried out according to two schemes for the formation of a stress-strain state.

According to the first scheme, lateral pressure was not taken into account and was equal to zero. According to the second scheme, lateral compression by soil was modeled with high-density foam rubber. In this case, the value of the lateral pressure changed along the height of the sample in proportion to the change in natural pressure along the height of the sample. The test results showed a significant influence of the type of internal reinforcement on the strength and stability of the DSM element. Table 3 shows the results of determining the mechanical parameters of the models. Fig.8 shows the results for compression without taking into account lateral pressure. The results taking into account lateral pressure are not presented in the article.

Fig. 7. General view of the experimental laboratory setup.

Analyzing the results obtained, it should be argued that the most effective is the use of an I-beam and a pipe. The presence of a spatial reinforcement frame is also effective. However, the experienced element is more pliable when compressed. In general, the research results showed that the presence of reinforcement in the material of soil-cement columns leads to an increase in the load-bearing capacity of the material of soil-cement elements by approximately 2.0-2.5 times and a decrease in its deformations by more than 2 times.

The results obtained should be verified by DSM field tests. In general, the results provide grounds for using such reinforcement methods to increase the load-bearing capacity of DSM columns when used to strengthen weak soils.

Table 3 Basic parameters during destruction

Model No	No. Experience	Force, kN	Load, kPa	Deformation, mm	Relative deformation	Modulus of elasticit, MPa
Model 1	1	8,7	1108,2	36,1	0,036	48,3
	2	9,0	1146,5	13,2	0,0132	49,9
	3	10,0	1273,8	9,04	0,009	55,5
	Average meaning	9,2	1176,2	38,3	0,0038	51,2
Moc 2	1	21,8	2777,1	7,1	0,0071	325,8
	2	18,8	2394,9	5,5	0,0055	280,9
	3	20,2	2573,2	6,9	0,0069	301,8
	Average meaning	20,2	2581,6	6,5	0,0065	302,8
Model 3	1	17,6	2242,0	15,3	0,0153	176,4
	2	12,8	1630,5	12,7	0,0138	172,61
	3	21,1	2687,9	20,5	0,0205	179,8
	Average meaning	17,16	2186,8	16,1	0,0165	176,27
Model 4	1	14,0	1783,4	10,0	0,0099	210,73
	2	18,5	2356,7	13,2	0,0132	277,15
	3	16,0	2038,2	11,4	0,0114	240,8
	Average meaning	16,16	2059,4	11,5	0,0115	220,56

6.2 Results of analytical calculations of DSM models

Analytical calculations were performed on the actual geological profile, which consists of layers of hard subsidence loam, semi-solid non-subsidence loam and medium-sized sand. The properties of the DSM material corresponded to the parameters in Table 1. In the calculation model, the length of the DSM element was 10.0 meters. The diameter of the element was assumed to be 1.0 m. Loads were applied to the sample in steps of 0.5 MPa. The initial load is 0.5 MPa, the maximum load is 3.0 MPa. At each loading stage, the values of vertical deformations and stress changes along the length of the DSM are determined. In the analytical calculation, only three models from those given in the test program in Table 4 were considered. Model 3 with reinforcement in the form of a pipe was not considered.

Analyzing the results obtained, they show that the presence of reinforcement significantly increases the load-bearing capacity and reduces the deformation of the column. For comparison, Table 4 and Fig. 9, shows data on the accumulation of deformations under stepwise loading. The mosaic of tension changes along the length of the element is not presented due to the large volume of illustrative material. It was found that the total settlement of the sample without reinforcement is 87 mm.

The specimen with I-beam reinforcement has a total draft of 28 mm. The sample with a reinforcement cage has a draft of 45 mm.

At the same time, analyzing the change in deformations along the height of the sample, it should be noted that in the upper part of the non-reinforced sample at 1/3 of its length, settlement occurs especially intensively.

With depth, sediment accumulation decreases. The change in deformations in a column reinforced with a reinforcement cage occurs in approximately the same way. Tests with a column reinforced with an I-beam element showed a more uniform distribution of deformations along the length of the column.

The maximum accumulation of deformations appears only in the upper part, equal to one eighth of the column length. Along the main length of the column, deformations appear evenly. In the analytical calculation, the model with reinforcement in the form of a pipe was not considered.

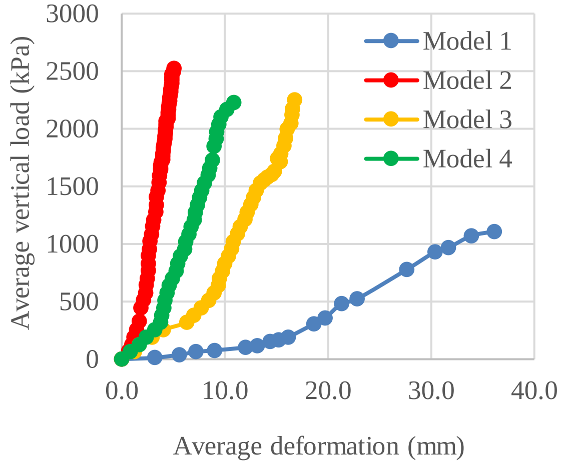


Fig. 8. Test results for DSM. Model 1 - models without reinforcement; Model 2 - I beam reinforcement; Model 3 - pipe reinforcement; Model 4 – reinforcement with reinforcement cage.

Table 4 Results of analytical calculations

Models	Load, kPa	Model 1	Model 2	Model 4
Axial force, kN	500	69,57/ 232,3	23,14/ 165,1	35,1 / 178
Deformation, mm		13,7	6,5	7,5
Axial force, kN	1000	123,2/ 466,2	29,36/ 331,5	60,56/ 356.3
Deformation, mm		27	9	14,5
Axial force, kN	1500	177,6/ 703,4	34,03/ 498	86,04/ 534,1
Deformation, mm		41	14,4	22
Axial force, kN	2000	208,4/ 944,1	38,7/ 664,8	111,6/ 712,6
Deformation, mm		55	18,9	29
Axial force, kN	2500	235,9/ 1184	43,37/ 831,6	134,9/ 891,5
Deformation, mm		70	23	37
Axial force, kN	3000	266/ 1428	48,05/ 998,6	140,6/ 1070
Deformation, mm		87	28	45

An analysis of the distribution of longitudinal maximum and minimum forces along the height of columns with stepwise application of load is given in Table 4.

The actual stress values can be determined taking into account the cross-sectional area of the column. The general pattern of development of deformations under stepwise loading is shown in Fig. 9.

The above results confirm that reinforcing columns with more rigid materials leads to an improvement in their performance and an increase in load-bearing capacity.

It can be seen that the reinforcement of soil-cement elements increases their strength and reduces deformability.

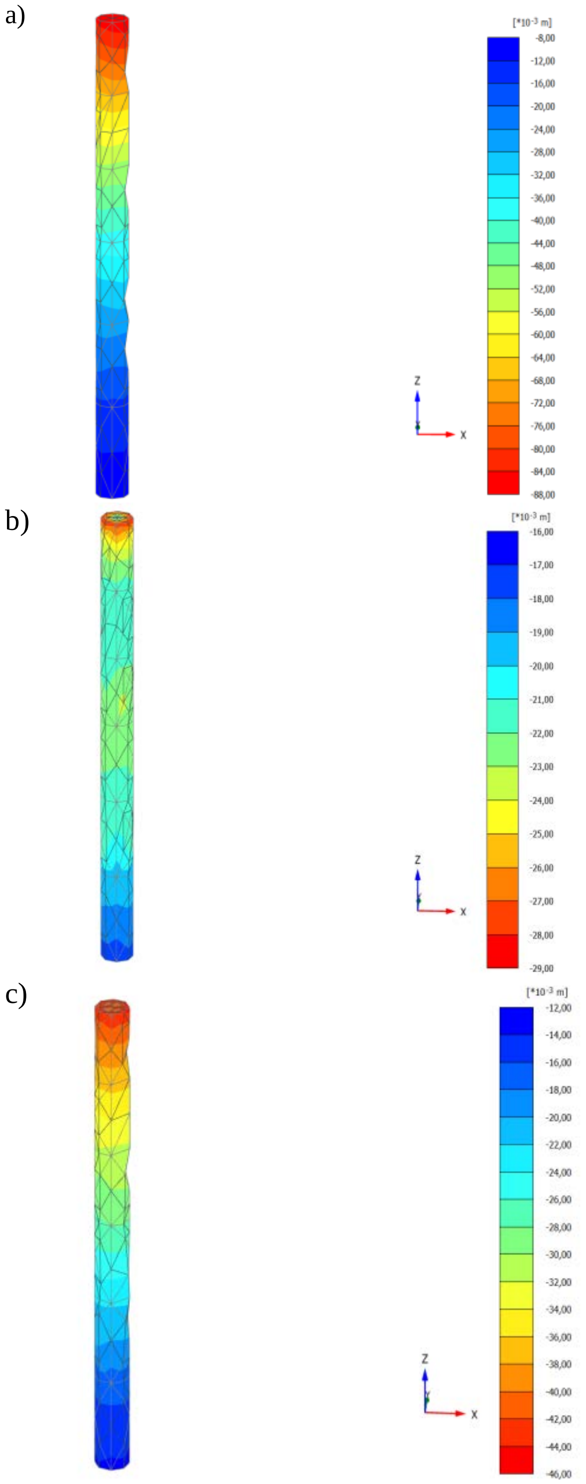


Fig. 9. Results of column deformations along the u_z axis at a load of 3000 kN/m^2: a) Model 1 – without reinforcement 87mm; b) Model 2 - model with I-beam 28mm; c) Model 4 - with reinforcement - 45mm.

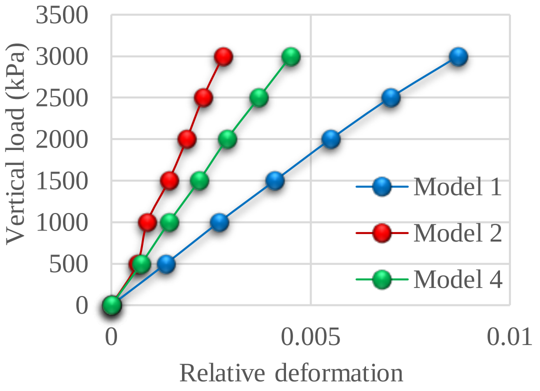


Fig. 10. Test results for DSM. Model 1 - without reinforcement; Model 2 – I- beam reinforcement; Model 4 – reinforcement with reinforcement cage.

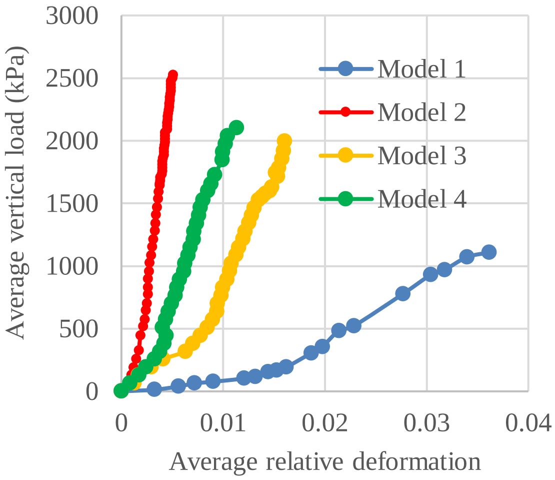


Fig. 11. Results of analytical calculations of DSM models: Model 1 - without reinforcement; Model 2– I-beam reinforcement; Model 3– pipe reinforcement; Model 4 – reinforcement with reinforcement cage.

In the analytical calculation, only 3 models were simulated. The model reinforced with a pipe was considered ineffective for technological reasons.

When the pipe was immersed in a soil-cement column, the internal cavity of the pipe was most often not filled with soil cement and the model turned out to be hollow. Therefore, this decision was accepted as ineffective.

A comparison of the results of relative deformation during axial compression of models in laboratory conditions and according to the results of analytical calculations of DSM in a soil massif is shown in Fig. 10 and Fig. 11.

7. CONCLUSIONS

In the article, studies on the properties of soil-cement columns in laboratory and field conditions with various models of internal reinforcement were carried out. The following conclusions were drawn:

- Given the complexity of traditional deep foundation strengthening methods, mechanical hardening techniques, which involve mixing soils with cement mortar, are increasingly used in Kazakhstan.
- Initial studies of soil-cement column properties at pilot sites by JSC KAZRICA involved sampling from depths of 3-4 meters. Tests, conducted under natural and soaked conditions using uniaxial and triaxial compression devices, provided actual values of ultimate strength. The results revealed 20-28% anisotropy in compressive strength and up to a 10% reduction in strength upon water saturation.
- Laboratory studies at the International Educational Corporation were conducted on 1:10 scale models of soil-cement columns with various reinforcement types (I-beam, pipe, and reinforcement cage) compared to real-site columns. Compression tests showed a 100-150% increase in load-bearing capacity due to reinforcement. However, the physical modeling lacked lateral compression, a key factor in DSM operation. Ongoing research is addressing this limitation by testing models under lateral compression.
- Laboratory results, confirmed by PLAXIS 3D analysis, show that reinforcing soil-cement columns increases strength, reduces compression deformations, and improves load-bearing capacity. Field calculations reveal I-beam reinforcement as most effective. However, the introduction of stiffer materials enhances anisotropic properties, necessitating further research.
- The article's data reflect only static conditions for reinforced soil-cement columns. Seismic effects, influencing column and soil mass performance, require further study to refine recommendations for real projects. Optimal methods depend on soil properties and reinforcement type, but selecting the best approach remains challenging and necessitates additional research.

8. REFERENCES

[1] Mustafaev S. T., Smolyar V. A., Burov B. V., Hazardous geological processes in the territory of southeastern Kazakhstan. Almaty, 2008. pp 1-261.

[2] Hydrogeology of the USSR. Volume 36. Southern Kazakhstan. Nedra, Moscow, 1970, pp. 1-473

[3] Khomyakov V.A., Gumenyuk V.V., Dursynov S.B. Restoring the serviceability of buildings in areas where loess macroporous foundations are widespread. In the journal "Industrial and Civil Construction", No. 8, 2022, p. 48-56.

[4] Khomyakov V.A., Shalkaev B., Emenov Yu.M. Application of various methods of soil strengthening for stabilization of slopes in seismic areas. “Foundations”. Scientific and practical magazine for designers and builders., No. 1, 2020, pp. 11-14.

[5] Suleimenov B.M., Mirdadayev, S. Tanirbergenov M., Poshanov A., Basmanov T., Sharypova. Research and ways of solving the problem of waterlogging of arable land in northern Kazakhstan. International Journal of GEOMATE, Oct. 2023, Vol. 25, Issue 110, pp.29-39 DOI: 10.21660/2023.110.3895.

[6] Kleveko V.I., Study of the work of reinforced clay foundations. Bulletin of PNIPU Construction and Architecture. – 2014. – No. 4. – P.101-110.

[7] Ofrichter V.G. Methods of construction of reinforced soil structures . V.G. Ofrichter, A.B. Ponomarev, V.I. Kleveko, K.V. Reshetnikova. – Perm: Perm Publishing House. State Tech University, 2010. – 145 p.

[8] Nuzhdin L.V. Reinforcement of foundation soils with vertical rods. Proceedings of the international seminar on soil mechanics, foundation engineering and transport structures. - M., 2000. - P. 204-206.

[9] Mirsayapov I.T. Stress-strain state of the soil foundation reinforced with vertical and horizontal elements. I.T. Mirsayapov, R.A. Sharafutdinov // News of KGA-SU. – 2017. – No. 1 (39). -WITH. 153-158.

[10] Malinin A.G. Jet cementation of soils. A.G. Malinin. – M.: OJSC “Publishing House “Stroyizdat”, 2010. – 226 p.

[11] Liu S.-Y., Du Y.-J., Li Y.-L., and Puppala A.J. Field investigations on performance of T-shaped Deep Mixed soil-cement columns supported embankment over soft ground.” J. Geotech. Geoenviron. Eng., 138(6), 2012, pp 718–727.

[12] Shen S.L., Han J., and Du Y.J. (2008). “Deep mixing induced property changes in sensitive marine clays.” J. Geotech. Geoenviron. Eng., 134(6): 845–854.

[13] Kodsi S.A., Oda K. & Awwad T., “Viscosity effect on soil settlements and pile skin friction distribution during primary consolidation,” International Journal of GEOMATE, Dec. 2018 Vol.15, Issue 52, pp.152 -159. DOI: 10.21660/2018.52.52744.

[14] I. Meepon P., Voottipruex and Jamsawang P., Behaviors of soil cement columns and stiffened soil cement column wall in shallow excavation. Lowland Technology International 2016; 18 (3): 197-208. International Association of Lowland Technology (IALT)

[15] . Yanaka A., Higashino T., Okazaki S., Matsumoto N. and Yoshida H. Material properties of concrete mixed with municipal solid waste incineration ash for cement replacement. International Journal of GEOMATE, Dec., 2023 Vol.25, Issue 112, pp.48-55, DOI: 10.21660/2023.112.g13186.

[16] Firmana Y. A, Adriani M., Arfiandoyo N., Salsabila M., Hafizhir Ridha. Chemically stabilized fiber of oil palm empty fruit bunch for soil stabilization. International Journal of GEOMATE, Dec., 2023 Vol.25, Issue 112, pp.75-82 DOI:10.21660/2023.112.4211.

[17] Shohei Koga, Koji Watanabe and Tadahisa Yamamoto. Evaluation of vertical bearing characteristics for soil-cement composite piles. International Journal of GEOMATE, Aug. 2023, Vol. 25, Issue 108, pp.146-153 DOI:10.21660/2023.108.3741.

[18] Awwad, T., Kodsi, S.A., Shashkin, A. Negative Skin Friction Distribution on a Single Pile - Numerical Analysis. In: El-Naggar, H., Abdel-Rahman, K., Fellenius, B., Shehata, H. (eds) Sustainability Issues for the Deep Foundations. Sustainable Civil Infrastructures. Springer, Cham. DOI:10.1007/978-3-030-01902-0_4

[19] Tatsuya D., Yoshitaka M., Hiromasa I., Feng Z. Numerical investigation of dynamic behavior of composite foundation composed of soilbags and piles by 3D elastoplastic FEM. Soils Found. 62 2022, DOI:10.1016/j.sandf.2022.101158.

[20] Awwad T., Gruzin V., Kim V. Sustainable Reconstruction in Conditions of Dense Urban Development. Weng MC., Lee J., Liu Y.(eds) Current Geotechnical Engineering Aspects of Civil Infrastructures. Sustainable Civil Infrastructures. Springer, Cham, pp 13-23. DOI: 10.1007/978-3-319-95750-0_2

[21] Ilyas Abdraimov, Awwad Talal, Bakhadyr Kopzhassarov, Mussa Kuttybai, Daniyar Akhmetov, and Rishat Tynybekov. Strength and durability effect of self-compacting concrete reinforcement with micro-silica and volume fiber. International Journal of GEOMATE, Vol. 27, Issue 119, 2024, pp.26-33. DOI:10.21660/2024.119.4334.