УДК 624.15:631.431.6
DOI: http://doi.org/10.17721/1728-2713.95.12

D. Chomko, PhD (Geol.), Assoc. Prof.,
E-mail: Dimath@ukr.net,
Taras Shevchenko National University of Kyiv,
Institute of Geology, 90 Vasylkivska Str., Kyiv, 03022, Ukraine;
F. Chomko, Assoc. Prof.,
E-mail: Chomkofv@ukr.net;
N. Cherkashyna, Senior Lecturer,
E-mail: n.i.cherkashina@karazin.ua;
V.N. Karazin Kharkiv National University,
4 Svobody Sqv., Kharkiv, 61022, Ukraine;
V. Taranov, Dr. Sci. (Tech.), Prof.,
O.V. Beketov Kharkiv National University of Municipal Economy,
School of Geotechnics, 17, Marshal Bazhanov st., Kharkiv, 61000, Ukraine;
G. Seifeldin, PhD (Tech.), Assoc. Prof.,
Khartoum University, Sudan

STUDYING SWELLING SOILS BY MULTIDIMENSIONAL STATISTICAL ANALYSIS METHODS AS THE BASIS FOR ENGINEERING STRUCTURES FOUNDATIONS IN SUDAN

(Представлено членом редакційної колегії д-ром геол. наук, проф. О.М. Іванік)

A new way to study swollen soils as the basis for foundations by methods of mathematical statistics, including cluster, factor and correlation-regression analyses has been proposed in the article. Normative values of the strength characteristics of these soils depending on their physical properties and degree of swelling, application limits, predominant factors and correlations between different indicators of soil properties have been established according to the results of these analyzes. A method of the study area zoning, leading to possible differential application of soils normative characteristics, as well as proposals for designing foundations on swollen soils have been developed. The methods were tested on the soils of Sudan.

Keywords: swelling soils, physical properties, degree of swelling, bearing capacity, zoning of the territory, foundations, cluster, factor and correlation-regression analyzes, predominant factors and correlation dependencies.

Problem formulation. Sudan has the largest distribution area of swollen soils among African countries - about 25 million hectares. This is primarily the territory of Greater Khartoum (the capital) and the state of El Jaseera (the area between the White and Blue Nile). Intensive construction is underway here and, therefore, the issue of using swollen soils as a basis for foundations is very important.

Mass construction in Khartoum is reduced to building of relatively light two-, three-storey cottages and industrial structures. No special soil studies and foundation calculations are expected. After a few years these structures, built on swollen soils, begin to deform because of such a practice. Table 1 shows different types of damage to engineering structures due to negative manifestations of swollen soils properties. Fig. 1 and 2 illustrate typical examples of these structures' destruction.

The cost of repairing and restoring the structural elements of buildings is very high, the annual damage is estimated at tens of millions of Sudanese pounds. This is the case of the Asalyaya factory. The cost of its repairing is so high that it is recommended to move it to another site, composed of non-swollen soils.

Therefore, an acute issue now is to improve the existing and to develop new highly efficient computational and theoretical solutions to be used in the design, construction and operation of buildings and structures erected on swollen soils.

Analysis of publications and identification of unresolved issues

Many researchers (*Elsayed, 1999; Potts and Zdrakovis, 2001; Poulus, 2001; El Turabi, 1993; Hussein et al., 1993; Sorochan, 1989; Shutenko et al., 1989,* etc.) studied engineering and geological properties of the swollen soils in this region in natural and disturbed conditions. Depending on the distribution region, swollen soils in Sudan have different names: black tropical clays, black cotton soils, "margalitic soils", "reguri". A term "expansive soil" has recently been increasingly used in Sudan. According to local experts, it is more in line with the nature of the soil. These soils are highly swollen soils ($\varepsilon_{osw} \geq 0.12$). According to some researchers, the ground surface rises by 50–60 cm during the rainy season (*Proceeding of the …, 1983*).

Table 1

Information on damage to engineering structures in Sudan

	Engineering structure	Location	Number of floors	Year of construction	Type of foundation
1.	University of Jazzira, a detached house	State of Jazeera, Town of Wad Medani	2	1975	Monolithic
2.	"Druzhba" cotton spinning factory	State of Jazeera, Town of Hasahisa	2	~70-s	Monolithic
3.	Administrative building of the Rahad project	State of Jazeera	1	1977	Tape
4.	Asalyaya factory, separate buildings	White Nile State	3	2014	Monolithic
5.	Administrative building of the soil study corporation	State of Jazeera, Town of Wad Medani	2	1968	Monolithic
6.	Presidential Palace, Library	The city of Khartoum	2	1995	Tape
7.	Laboratory building, Ribat University	The city of Khartoum	4	2002	Monolithic
8.	"Druzhba" cotton spinning factory	State of Jazeera, Town of Hasahisa	2	2011	Tape

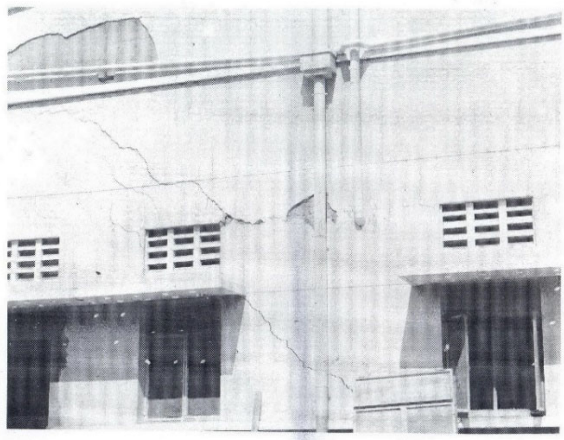

Fig. 1. Destruction of a brick wall

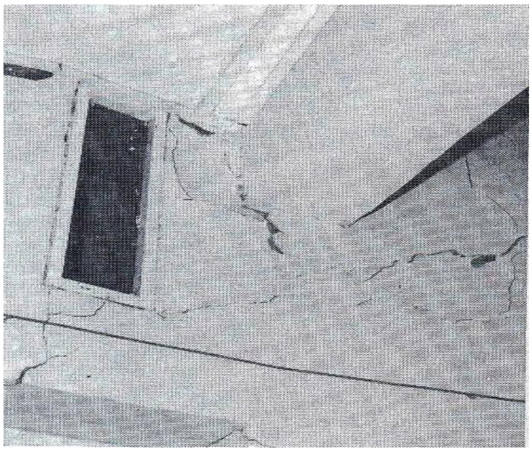

Fig. 2. A fragment of a brick wall's destruction ("Druzhba" cotton spinning factory, №8)

A number of papers are devoted to the design and construction of buildings and structures on Sudan's swollen soils and elimination of their negative impact (*Elsayed, 1999; El Turabi, 1993; Seifeldin, 2007, 2008; Sorochan, 1989; Taranov, 2008, 2014; Chomko D.F. et al., 2002, 2012, 2004, 2014 and Chomko F.V. et al., 2014; Shutenko et al., 1989*).

However, there is no literature on determining the similarity of physical and mechanical properties of swollen soils by methods of multidimensional statistical analysis and forecasting their change in Sudan.

The purpose of the research is to develop new calculation methods for creation of bases and foundations in special engineering and geological conditions (on swollen soils), ensuring efficient construction and operation of buildings and other engineering structures. To do this, the following problems should be solved:

1. To analyse regional construction features and methods of designing bases and foundations in Sudan;

• to determine physical and mechanical properties of swollen soils in the state of El Jazeera in Mesopotamia (the area between the White and Blue Nile);

• to establish development zones of different types of soils according to these properties;

• to find a generalized model of the process by which to establish the main dependences of the swelling forces on the indicators, determining the state and properties of them, using modern knowledge about the nature of Sudan' soils swelling.

2. To determine the most significant factors, operating in the study area, by physical and mechanical properties of swollen soils;

• to draw maps-schemes of factor loads on the basis of positive and negative load factors.

3. To identify areas with similar engineering and geological processes.

4. To identify physical characteristics of swollen soils with the greatest impact on mechanical ones.

5. To establish reliable regression dependences between physical and mechanical properties;

• to make tables of normative values of soils durability characteristics as functions of physical characteristics and a degree of swelling.

6. To get reliable regression equations to calculate deformations of raising bases and foundations.

The subject of the research is engineering-geological, hydrogeological, natural-climatic and physical-mechanical factors of swollen soils, affecting the reliability of the system "bases -foundations of buildings and engineering structures".

Main results. To achieve these goals, 57 engineering and geological wells were drilled in 11 areas with swollen soils in the cities of Khartoum and Jeziri (Khartoum Elm., Khartoum Bur., Khartoum Ria, Khartoum Soba, Khartoum Jbra, Khartoum Nile, Khartoum Elamar, Je` Singh., Jazeera Madan, Jazeera Manag and Jazeera Elnishch.) (Fig. 3). Soil samples from different depths were taken from each well at almost the same time. Physical and mechanical properties were studied at the engineering and geological laboratory of Ribat University in Khartoum**.**

Table 2 shows the results of physical and mechanical properties of soils study.

Various analytical methods and mathematical modeling are now used to determine similar physical and mechanical properties of swollen soils on new construction sites and areas where the destruction of buildings and structures has already taken place.

Physical-mechanical properties of swollen soils are the end product of the influence of not one, but a whole set of natural and man-made processes (conditions of formation, flooding, anthropogenic load, etc.). These processes affect the interrelated change in soil properties and the nature of the relationships between them. But these links are not stored in "pure" data sets. Paired correlations between the observed values of variables actually make it impossible to determine the similarity of physical and mechanical properties and which processes are decisive in changes in the engineering and geological properties of swollen soils.

To determine similar properties of swollen soils in different parts of the study area, we used cluster analysis, and to identify processes that are decisive in changes in the engineering and geological properties of these soils - factor analysis. These research methods were developed by (*Davis, 1990* and *Jereskog et al., 1980*). In hydrogeological and engineering-geological research they were widely used by (*Reshetov, 2004; Seifeldin, 2007, 2008; Taranov, 2008, 2014; Chomko D.F. et al., 2002, 2012, 2004, 2014* and *Chomko F.V. et al., 2014)*.

The essence of the agglomerative (unifying) cluster procedure is a step-by-step calculation of the Euclidean distance between all pairs of soil samples in different areas and combination of the pair at each step for which a minimum of this distance has been achieved. In our case, it is combining soils physical and mechanical characteristics. Engineering and geological surveys in Khartoum and El Jazeera were used to implement this technique. The sample consisted of 57 test soil samples and included the following predictors: γ, w, wL, wp, Ip, φ, c, εsw psw, wsw (thus, each soil sample was interpreted as a point in ten-dimensional space).

Based on the results of cluster analysis of the general data matrix, a diagram of Euclidean distances of the consolidation was constructed step by step (Fig. 4), as well as a dendrogram (Fig. 5) - a one-dimensional graph containing information about the location and numbers of objects and wells, interrelationships between different soil samples. Fig. 4 shows that all samples were combined in 56 steps with a minimum consolidation distance (Euclidean distance) in the first step of 0.000 and a maximum of 292,628 in the last step.

Considering the tree-like hierarchical structure in Fig. 5, it follows that it can be divided into seven clusters (see symbols), split into smaller subclusters. The first four clusters (counting from right to left) are consolidated at short distances, from 0.000 to 99.812, which allows us to speak about the homogeneous properties of these soils. The soils of clusters 5–7 differ from the soils of the first four clusters and from each other: the Euclidean distances at which the consolidation took place, more than 125, indicate a noticeable difference in their physical and mechanical characteristics.

A taxonomy was performed to clarify the results - a hierarchical clustering of two equal matrices (obtained by dividing the total), characterizing the soils of Khartoum region and peripheral areas, which clearly shows a significant difference in their Euclidean distances.

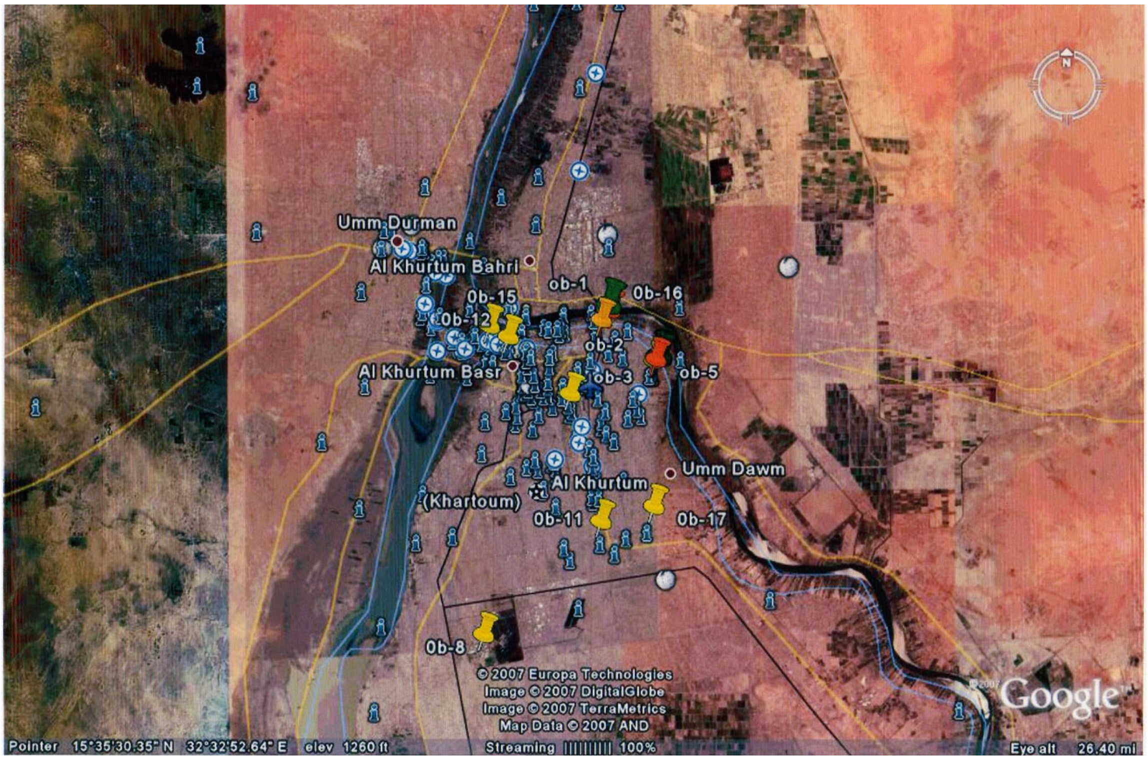

Fig. 3. A fragment of the space map of El Jazeera, where the buttons indicate the places of drilling wells and soil sampling

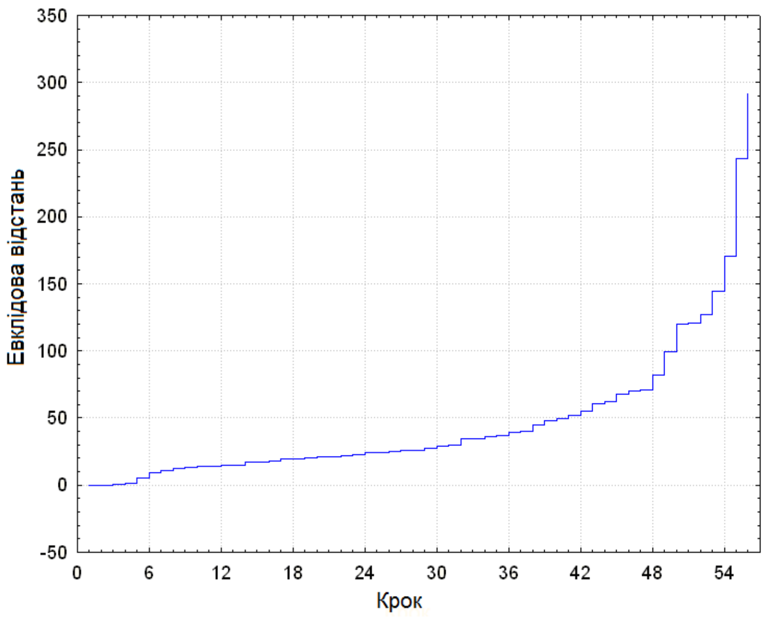

Fig. 4. Diagram of stepwise consolidating distances

ISSN 1728-2713

Table 2

Physical and mechanical properties of soils

Area	№ of well	Sampling depth	Specific gravity	Upper limit	Lower limit	Natural moisture	Plasticity number	Internal friction angle	Adhesion	Swelling pressure	Load bearing capacity
Khart(Elm) №1	1	2	19,1	58,0	22,8	16,6	35,2	33,0	20,0	120	146
Khart(Elm) №3	5	2	19,0	71,2	32,4	19,6	38,8	29,0	30,0	170	146
Khart Харт (Bur) №8	1	2	19,2	101,0	24,0	20,1	77,5	28,0	30,0	205	156
Khart (Bur -2) №12	1	2	19,2	101,9	24,5	20,1	77,4	28,0	30,0	205	156
Khart (Bur -3) №13	1	2	19,1	53,8	15,2	12,0	38,6	28,0	25,0	143	156
Khart(Elm) №1	2	3	19,8	59,1	23,4	18,8	35,7	26,0	15,0	122	162
Khart(Elm) №1	6	3	18,9	57,1	21,7	17,6	35,4	27,0	35,0	128	162
Khart(Elm) №1	3	3	19,2	59,5	23,6	18,6	35,9	31,0	18,0	132	162
Khart (Ria) №4	5	3	17,4	59,5	25,0	18,9	34,5	32,1	18,7	136	169
Khart (Bur) №8	2	3	19,5	74,7	22,0	20,2	52,7	29,0	20,0	167	169
Khart (Soba) №10	2	3	19,4	62,7	21,3	17,4	41,4	29,0	25,0	157	153
Khart (Nile)№11	5	3	19,4	50,8	24,0	20,3	26,8	31,0	15,0	131	145
Khart (Nile) №11	4	3	19,5	56,6	24,8	20,3	31,8	27,0	40,0	136	145
Khart (Nile) №11	1	3	19,0	51,8	21,6	21,1	30,2	28,0	25,0	132	145
Khart (Bur -2) №12	2	3	19,5	74,7	22,0	20,2	52,7	29,0	20,0	167	156
Khart (Bur-3) №13	2	3	19,4	77,0	17,4	10,6	59,6	30,0	20,0	152	164
Khart(Elm) №1	7	4	19,3	106,1	31,5	21,0	74,6	31,0	35,0	200	171
Khart(Elm) №1	5	4	18,9	68,3	19,8	15,8	48,5	30,0	15,0	136	171
Khart (Bur) №8	3	4	19,3	53,9	22,0	19,7	31,9	22,0	50,0	125	169
Khart (Bur -2) №12	3	4	19,3	53,9	22,0	19,7	31,9	22,0	50,0	172	156
Khart (Bur-3) №13	3	4	19,0	65,7	17,9	11,5	47,8	25,0	30,0	151	179
Khart(Elm) №1	7	9	19,1	115,5	35,4	19,9	80,1	28,0	35,0	191	182
Khart (Soba) №10	1	9	19,2	80,9	17,3	16,8	63,6	24,0	30,0	168	180
Khart (Soba) №10	2	10	19,5	75,6	19,7	15,8	55,9	30,0	40,0	159	180
Khart (Nile) №11	3	10	19,6	51,9	24,0	21,1	27,9	23,0	30,0	139	169
Khart (Nile) №11	6	10	19,5	53,3	23,0	19,8	30,3	26,0	50,0	140	169
Khart (Soba) №10	4	12	19,5	83,4	18,8	15,0	64,6	32,0	20,0	127	180
Khart (Nile) №11	2	6	19,3	58,6	28,1	22,0	30,5	30,0	20,0	176	158
d'Jezz (Singh) №6	2	1	18,2	81,0	35,0	18,0	46,0	17,0	26,5	315	170
d'Jezz (Madan) №2	3	2	20,1	52,0	16,0	11,4	36,0	19,0	30,0	105	187
d'Jezz (Madan) №2	7	2	19,3	73,0	18,0	18,6	55,0	22,0	50,0	140	186
d'Jezz (Singh) №6	1	2	18,3	84,0	31,0	23,0	53,0	35,0	13,0	315	204
d'Jezz (Manag) №16	2	2	20,1	59,0	25,0	20,1	34,0	14,0	165,0	274	231
d'Jezz (Manag) №16	1	2	20,0	46,0	20,0	17,0	26,0	21,0	110,0	274	186
Khart(Elm) №19	3	2	20,6	69,0	25,0	19,5	44,0	9,0	129,0	131	194
Khart(Elm) №19	4	2	20,1	77,0	26,0	20,1	51,0	23,0	99,0	175	198
Khart(Elm-2) №20	9	2	19,3	54,0	24,0	14,1	30,0	37,0	51,6	220	201
Khart(Elm -2) №20	2	2	19,7	90,0	30,0	20,8	60,0	18,0	95,8	60	169
d'Jezz (Elnishch) №23	2	2	18,0	47,0	19,0	24,0	28,0	6,0	115,0	80	153
d'Jezz (Madan) №2	5	3	19,2	51,0	13,0	14,1	38,0	16,0	16,5	200	145
d'Jezz (Singh) №6	3	3	19,6	82,0	32,0	21,0	50,0	29,0	40,0	107	145
d'Jezz (Singh) №6	1	3	18,8	82,0	31,0	20,0	51,0	38,0	10,0	350	145
d'Jezz (Elnishch)№22	4	3	21,1	49,0	20,0	16,0	29,0	27,0	45,0	200	156
d'Jezz (Elnishch)№22	5	3	21,4	56,0	20,0	15,6	36,0	14,0	120,0	240	164
Khart (Elamar) №9	1	4	19,1	80,9	45,5	21,0	35,4	30,0	30,0	175	171
Khart (Elamar) №9	2	4	19,1	80,9	45,5	21,0	35,4	30,0	30,0	183	171
d'Jezz (Elnishch) №22	5	6	19,8	46,0	24,0	24,4	22,0	26,0	70,0	183	169
d'Jezz (Elnishch) №22	1	4	18,8	85,0	31,0	24,0	54,0	17,0	75,0	250	156
d'Jezz (Elnishch)№22	2	4	20,0	49,0	22,0	24,0	27,0	6,0	102,0	210	179
d'Jezz (Elnishch) №22	4	4	19,8	67,0	27,0	23,8	40,0	22,0	95,0	250	182
Khart (Jbra) №18	3	5	19,6	57,0	19,0	10,0	38,0	4,0	18,5	170	156
Khart (Jbra) №18	1	5	19,6	56,0	20,0	10,0	36,0	26,0	6,2	105	179
d'Jezz (Manag) №7	5	5	19,8	88,0	29,0	20,5	59,0	14,0	23,0	150	182
d'Jezz (Elnishch) №22	1	5	18,8	53,0	26,0	17,0	27,0	37,0	10,0	180	180
d'Jezz (Elnishch) №22	3	5	19,0	61,0	30,0	23,0	31,0	15,0	100,0	300	180
d'Jezz (Singh) №6	1	6	20,0	74,0	30,0	20,0	44,0	15,0	14,0	150	169
d'Jezz (Singh) №6	2	6	20,4	70,0	33,0	25,0	37,0	9,0	13,5	190	169

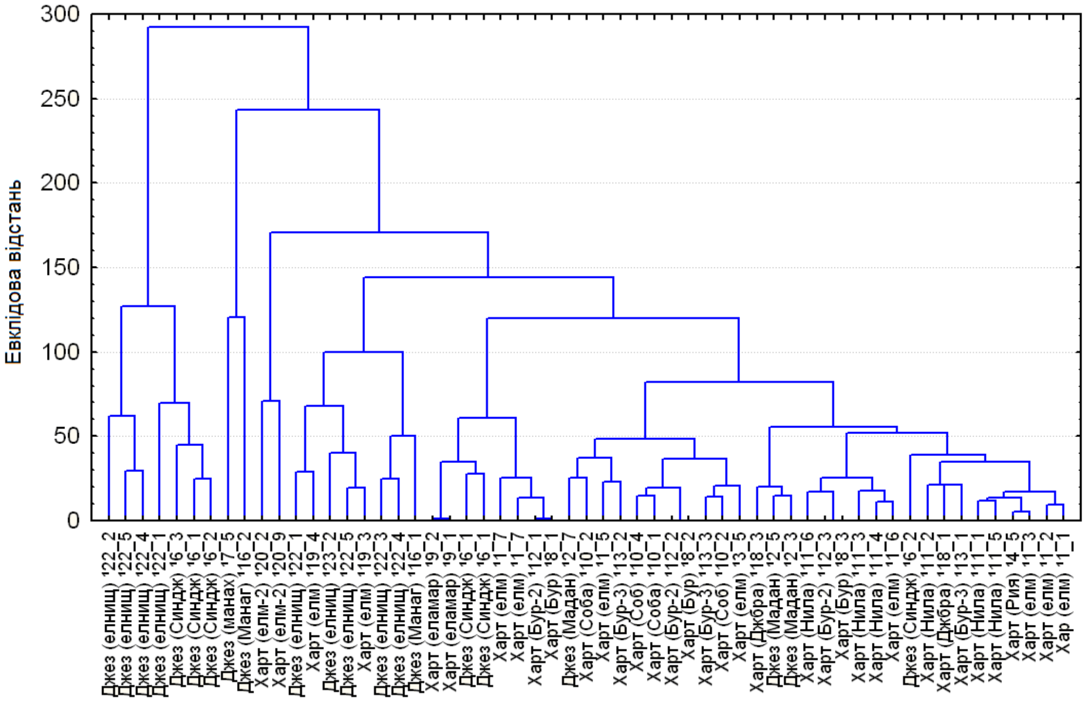

Fig. 5. Dendrogram combining 57 objects (10 parameters)

In Fig. 6 all points of soil sampling are plotted on the map of Mesopotamia. The cluster of objects in Khartoum and the adjacent area is noteworthy. This is explained, apparently by the factor of capitalism, by their sparseness in the rest of Mesopotamia. However, there is a visible trend, suggesting that the study area can be "divided" into two zones: Northern El Jazeera with Greater Khartoum where the soils are more homogeneous (the first four clusters), and Southern Mesopotamia where the soils are very different (clusters five - seven). Obviously, the boundary (dotted line) between these zones is quite conditional due to the lack of data because of a relatively small volume of construction in the agricultural part of the region.

At the next stage of data processing the overall matrix was subjected to factor analysis.

This method is one of the most effective means of identifying patterns hidden in data sets. As a rule, in engineering geology, there is no possibility to directly observe and measure factor processes. They can be judged only by the final results of the processes manifestation that are reflected in the values of different physical and mechanical characteristics of soils.

The factor analysis is a very effective means of compressing information by moving from the original data to new variables - factors. There is a minimum number of new factors that are linear combinations of the source data, and these new variables contain the same amount of information.

According to the results of factor analysis (R-modification) of the initial matrix, a number of factors which account for 100% of the total effect on the indicators of physical and technical properties of swollen soils have been identified. Only three factors make a significant contribution, their weight after the rotation of the matrix being more than 10%. They reflect the contribution of each of the factors to the total variance of the sample.

In addition, factor analysis revealed characteristic elements of physical and technical characteristics of swollen soils in each of the factors (Table 2).

The first factor (weight 22.65%) contains the following soil properties: natural moisture (bond strength 0.738074), plasticity number (bond strength 0.728427) and lower limit (bond strength 0.400961). Other elements do not make a significant contribution to this factor due to their bonding. Characteristic elements of the first factor are natural humidity, the amount of plasticity and the lower limit.

Table 3

Factor loads after rotation (R-modification)

Elements	Factors		
	F 1	F 2	F 3
Specific weight	-0,068978	0,037214	0,138759
Top limit	-0,191672	**-0,512390**	-0,042167
Low limit	**0,400961**	0,093466	**0,891289**
Natural humidity	**0,738074**	0,100484	0,137497
Plasticity number	**0,724027**	-0,172343	-0,070449
Angle of internal friction	0,048338	0,045934	**0,966581**
Adhesion	-0,002466	**0,717359**	0,142884
Swelling pressure	0,171705	**-0,748681**	-0,038446
Swelling humidity	0,039216	0,158950	0,195642
Number of wells	57	**57**	57
Value of factors, %	22,65	15,09	10,50

The second factor (weight 15.09%) includes swelling pressure (bond strength -0.748681), adhesion (0.717359) and upper limit (-0.512390). The swelling pressure and the upper limit are included in this factor with a negative bond strength. Other elements do not significantly contribute to this factor due to the bonding strength. Characteristic elements of the second factor are the pressure of swelling and adhesion.

The third factor (weight 10.50%) includes the angle of internal friction (bond strength 0.966581) and the lower limit (0.891289), which are the characteristic elements of this factor.

The characteristic elements of each factor are used to compile the regression equation, determining the characteristics of soil strength φ and c in different zones of Mesopotamia.

To analyze the obtained factors distribution on the territory of Mesopotamia, the load of each of them on all wells was determined, using Q-modification of factor analysis.

This allowed to draw a map-scheme of factor loads. Distribution of these three factors values in the territory of Mesopotamia is shown in Fig. 6.

Analyzing the joint distribution of all three factors in Mesopotamia, several areas where two or three factors act simultaneously, can be identified. Thus, the first and second factors intersect in the area of sites № 18 and № 10 in Khartoum. The same is true between № 5 and № 22 in El Jazeera. In the area of sites № 3, № 20 and № 19 in Khartoum, the second and third factors intersect.

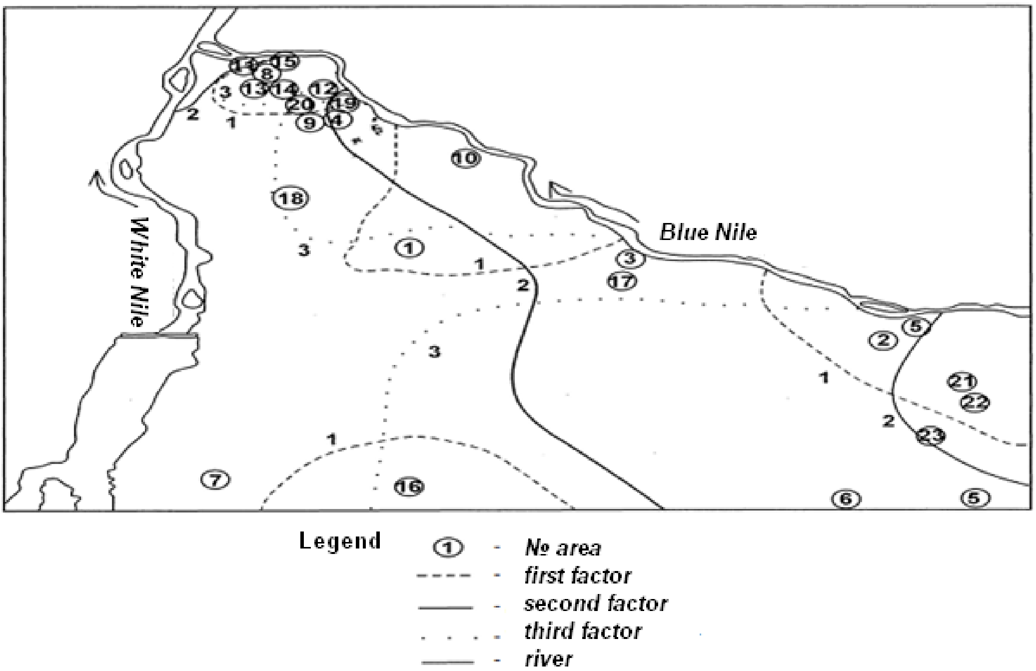

Fig. 6. Factor distribution scheme

The intersection of the same factors is observed in the area between sites № 3 and № 16 in El Jaseera. The first and third factors intersect in the area of site № 9 in Khartoum. The intersection of the same factors is observed in the area between sites № 3 and № 5. This indicates the similarity of engineering and geological processes in these areas.

At the final stage the regression equation was obtained to determine the characteristics of soil strength in the first zone (correlation coefficients are equal to 0.95 and 0.545, respectively) by the method of stepwise regression analysis, using characteristic elements.

$$\varphi = 13.86 \cdot \gamma - 0.014 \cdot Ir - 237.48;$$

$$c = 17.23 \cdot \gamma + 0.133 \cdot Ir - 300.45.$$

Using these expressions, the values of the internal friction angle φ and the specific adhesion c due to the degree of soil swelling were calculated. The obtained results are given in Table 4 and can be used in the design of buildings and structures in Greater Khartoum and Northern El Jaseera.

Table 4

Normative values of expansive soil characteristics in Greater Khartoum and Northern El Jazeera

Degree of swelling	I_p, %	Index	γ,кН/м³											
			18,2	18,4	18,6	18,8	19	19,2	19,4	19,6	19,8	20	20,2	20,4
Low	<20	φ	15	17	20	23	26	28	31	34	37	39	42	45
		c	16	19	23	26	29	33	36	40	43	47	50	54
Average	20–35	φ	14	17	20	23	25	28	31	34	36	39	42	45
		c	17	20	24	27	31	34	37	41	44	48	51	55
High	350	φ	14	17	20	22	25	28	31	34	36	39	42	45
		c	19	22	26	29	33	36	39	43	46	50	53	57
Very high	>50	φ	14	17	20	22	25	28	31	33	36	39	42	44
		c	20	23	27	30	34	37	40	44	47	51	54	58

A detailed regression analysis of different predictors interdependence was also performed, the results of which can also be used in design practice. In particular, we obtained the equation to calculate the angle of internal friction φ and specific adhesion c as a function of the porosity coefficient (e) and the percentage content (k) in swollen soils (expansive soil) of clay fractions with a diameter of 0.002 mm. In addition, a regression equation (in the common form for a foreign user) to determine the relative swelling εsw and swelling pressure psw was built. It can be used in test calculations of deformations of bases and foundations rise:

$$\varepsilon sw = 0.130wL + 0.172w-4.932;$$

$$psw = -0.905\gamma d + 1.244wL + 0.892w + 61.951.$$

Conclusions. 1. The cluster analysis method, based on the construction of diagrams of Euclidean distances and dendrograms of objects association, has found that physical and mechanical properties of soils in the state of El Jaseera in Mesopotamia (the area between the White and Blue Nile) change in the direction from north to south. According to the results of the study, it is proposed to divide the whole region into two unequal zones.

2. According to the results of a factor analysis, the most significant factors, operating in the study area, are identified. This allowed to make maps-schemes of factor loads on the basis of positive and negative load factors. Analyzing the joint distribution of three factors in Mesopotamia, we can identify several areas where two or three factors act simultaneously. This indicates the similarity of engineering and geological processes that take place in these areas.

3. The results of a factor analysis of experimental data revealed physical characteristics of soils, which have the greatest impact on mechanical ones. Such predictors for zone I, covering about 80% of the territory of Mesopotamia, are the specific gravity γ and the number of plasticity Ir.

4. Multiple step-by-step regression analysis of these physical and mechanical properties of the swellable soils of Mesopotamia in zone I, allowed to establish reliable regression dependences between the angle of internal friction φ and the number of plasticity Ir. With the help of these dependencies, tables of normative values of soil strength characteristics as a function of physical characteristics and degree of swelling were compiled. They are recommended for practical application in foundations design of low-rise buildings and structures in Greater Khartoum and Northern El Jaseera.

5. Reliable regression equations have been obtained. They differ from those used in foreign practice by numerical coefficients, making it possible to calculate deformations of the rise of bases and foundations.

References / Список використаних джерел

Amjadi, A., Chomko, D.F., Rahbar, E. (2014). Case Record of Multivariate Statistical Analysis in the Groundwater Study of the Western Part of Iran (The Zagros Mountains). *Journal of Applied Environmtntal and Biological Sciences*, 4(2s). Text Road Publication. Retrieved from www.textroad.com.

Chomko, D.F., Chomko, F.V., Seifeldin, G. Kh., Taranov, V.G. (2012). Experience of applying cluster analysis in study of swelling soils of Sudan. *Bulletin of V.N. Karasin Kharkiv National University*, 1033. [in Russian]

Chomko, D.F., Koshliakov, O.Ye., Chomko, F.V., Udalov I.V., Chomko, R.F. (2017). Ukrainian-Russian-English dictionary-reference book of hydrogeological terms. Kyiv: Publ.house "Kyiv university". [in Ukrainian]

Chomko, D.F., Reshetov, I.K., Chomko, F.V., Chomko, R.F. (2002). Multidimensional statistical analysis in the study of man-made groundwater pollution. *Geological Journal*, 2. [in Russian]

Chomko, D.F., Reshetov, I.K., Chomko, F.V., Chomko, R.F. (2004). Multidimensional statistical analysis in hydrogeology. Kyiv: Publ.house "Kyiv university" [in Ukrainian]

Chomko, F.V, Chomko, D.F., Taranov, V.G. (2014). Complex application of multidimensional statistical analysis in studies of swollen soils as the basis of foundations. *Bulletin of Kharkiv National University*, 1128. [in Ukrainian]

Davis, D.S. (1990). Statistical analysis of data in geology. Moscow: Nedra. [in Russian]

El Turabi, M.A. (1993). A Study on Expansive Soils in Sudan. U of K., Khartoum, Sudan.

Elsayed, A.E. (1999). Soil Mechanics. Cairo: Scientific House Corporation.

Jereskog, K.G., Klovan, D.I., Rejment, R.A. (1980). Geological factor analysis. Leningrad: Nedra. [in Russian]

Nhesis, F. (1985). Submitted for Degree of M.Sc. Civil Engineering BRRI, U of K., Khartoum, Sudan.

Potts, D.V. and Zdrakovis, L. (2001). Finite Element Analysis on Geotechnical engineering Application. Publisher: Thomas Telford, London.

Poulus, H.G. (2001) Piled Rafts in Swelling or Consolidating Soils. *Journal of Geotechnical Engineering Vjl.*, 119, 2.

Proceeding of the Seminar on Expansive Clay Soils Problem in Sudan. (1983). University of Khartoum.

Seifeldin, G.H, Taranov, V.G. (2008). Foundations on the swelling soils of Sudan. Municipal economy utilities. Kharkiv: NAME. [in Russian]

Seifeldin, G.H. (2007). Radiography of the swelling soils of the Sudan. Municipal economy utilities. Kharkiv: NAME.

Selfeldin, G.H., Taranov, V.G., Chomko, F.V. (2008). Application of multidimensional statistical analysis in the study of swelling soils of Sudan. *Bulletin of Kharkiv National University*, 824. [in Russian]

Shutenko, L.N., Gilman, A.D., Lupan, Yu.T. (1989). Bases and foundations. Kiev. [in Russian]

Sorochan, E.A. (1989). Construction of structures on swollen soils. Moscow: Stroyizdat. [in Russian]

Taranov, V.G., Alexandrovich, V.A., Luchkovsky, I.Ya. et al. (2014). Peculiarities of the "structure-foundation" system's behavior under static and dynamic loads. *World of Geotechnics*, 1. Retrieved from: http: nbuv.gov.ua.

Надійшла до редколегії 01.08.21

Д. Чомко, канд. геол. наук, доц.,
E-mail: Dimath@ukr.net,
Київський національний університет імені Тараса Шевченка,
ННІ "Інститут геології", вул. Васильківська, , 90, м. Київ, 03022, Україна;
Ф. Чомко, доц.,
E-mail: Chomkofv@ukr.net;
Н. Черкашина, ст. викл.,
E-mail: n.i.cherkashina@karazina.ua,
Харківський національний університет імені В.Н. Каразіна,
Факультет іноземних мов, майдан Свободи, 4, м. Харків, 61022, Україна;
В. Таранов, д-р техн. наук, проф.,
Харківський національний університет міського господарства ім. О.М. Бекетова,
Факультет геотехніки, вул. Марш. Бажанова, 17, м. Харків, 61000, Україна;
Г. Сейфельдін, д-р філософії, канд. техн. наук, доц.,
Хартумський університет, м. Хартум, Судан

ДОСЛІДЖЕННЯ МЕТОДАМИ БАГАТОВИМІРНОГО СТАТИСТИЧНОГО АНАЛІЗУ НАБРЯКАЮЧИХ ҐРУНТІВ ЯК ОСНОВИ ФУНДАМЕНТІВ ІНЖЕНЕРНИХ СПОРУД У СУДАНІ

Запропоновано новий спосіб дослідження набрякаючих ґрунтів як основи фундаментів методами математичної статистики, що включає кластерний, факторний і кореляційно-регресійний аналізи. За результатами цих аналізів встановлено нормативні значення характеристик міцності цих ґрунтів залежно від їх фізичних властивостей і ступеня набрякання, межі застосування, переважальні фактори і кореляційні залежності між різними показниками властивостей ґрунтів. Запропоновано спосіб зонування досліджуваної території, що призводить до можливості диференційного застосування нормативних характеристик ґрунтів. Розроблено пропозиції з проєктування основ і фундаментів на набрякаючих ґрунтах. Методи опробовано на ґрунтах Судану.

Ключові слова: набрякаючі ґрунти; фізичні властивості; ступінь набрякання; несуча здатність; зонування території; фундаменти; кластерний, факторний і кореляційно-регресійний аналізи; переважальні фактори і кореляційні залежності.

Д. Чомко, канд. геол. наук, доц.,
E-mail: Dimath@ukr.net,
Киевский национальный университет имени Тараса Шевченко,
ННИ "Институт геологии", ул. Васильковская, 90, г. Киев, 03022, Украина;
Ф. Чомко, доц.,
E-mail: Chomkofv@ukr.net;
Н. Черкашина, ст. преп.,
E-mail: n.i.cherkashina@karazina.ua,
Харьковский национальный университет имени В.Н. Каразина,
пл. Свободы, 4, г. Харьков, 61022, Украина;
В. Таранов, д-р техн. наук, проф.,
Харьковский национальный университет городского хозяйства им. А.М. Бекетова,
ул. Марш. Бажанова, 17, г. Харьков, 61000, Украина;
Г. Сейфельдин, д-р философии, канд. техн. наук, доц.,
Хартумский университет, г. Хартум, Судан

ИССЛЕДОВАНИЕ МЕТОДАМИ МНОГОМЕРНОГО СТАТИСТИЧЕСКОГО АНАЛИЗА НАБУХАЮЩИХ ГРУНТОВ КАК ОСНОВАНИЯ ФУНДАМЕНТОВ ИНЖЕНЕРНЫХ СООРУЖЕНИЙ В СУДАНЕ

Предложен новый способ исследования набухающих грунтов как основания фундаментов методами математической статистики, включающей кластерный, факторный и корреляционно-регрессионный анализы. По результатам этих анализов установлены нормативные значения характеристик прочности этих грунтов в зависимости от их физических свойств и степени набухания, границы применения, преобладающие факторы и корреляционные зависимости между разными показателями свойств грунтов. Предложен способ зонирования исследуемой территории, что позволяет дифференцировано применять нормативные характеристики грунтов. Разработаны предложения по проектированию оснований и фундаментов на набухающих грунтах. Методы испытаны на грунтах Судана.

***Ключевые слова:** набухающие грунты; физические свойства; степень набухания; несущая способность; зонирование территории; фундаменты; кластерный, факторный и корреляционно-регрессионный анализы; преобладающие факторы и корреляционные зависимости.*