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THE RESEARCH OF AN IMPACT IN STRENGTH CHARACTERISTICS OF OIL-CONTAMINATED SANDY SOILS

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Abstract: A review of existing studies by domestic and foreign authors on changes in the angle of internal friction of sandy soils contaminated with oil products is provided. The main experimentally confirmed results of studies of the angle of internal friction of sandy soils interacting with oil products are outlined. Laboratory tests were conducted to determine the strength characteristics of sandy soils contaminated with oil products using the in-plane shear method. Coarse, medium and fine sands contaminated with A-95 gasoline, diesel fuel, and heavy oil at a concentration of 0-12% by dry soil weight were used as test samples. A methodology for conducting laboratory tests using the in-plane shear method for sands contaminated with oil products is described and tested. The degree of influence of viscosity and oil product concentration factors on the value of the angle of internal friction of sands of different sizes was determined and mathematically substantiated using regression multifactorial analysis. The sensitivity analysis of the adopted regression equation with six degrees of freedom is performed. The scope of application of the proposed function is designated. It is shown that the use of polynomials of the second kind in linear regressions leads to a significant complication of the model associated with the impossibility of explicitly identifying individual influence coefficients without additional calculation of partial derivatives to compile the function gradient with its subsequent analysis.

A decrease in the angle of internal friction of coarse, medium and fine sandy soils regardless of the type of oil product and its concentration has been laboratory confirmed. A graph of the dependence of the angle of internal friction of sands of different sizes on the concentration of oil products is presented. It has been statistically substantiated that the greatest influence on the angle of internal friction of sandy soils contaminated with oil products is exerted by concentration, to a lesser extent - the type (viscosity) of oil products.

Keywords: sandy soil, oil products, in-plane shear, angle of internal friction, regression analysis, concentration

УСТАНОВЛЕНИЕ ВЛИЯНИЯ ЗАГРЯЗНЕНИЯ ПЕСЧАНЫХ ГРУНТОВ НЕФТЕПРОДУКТАМИ НА ИЗМЕНЕНИЕ ИХ ПРОЧНОСТНЫХ ХАРАКТЕРИСТИК

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Аннотация: Выполнен обзор существующих исследований отечественных и зарубежных авторов об изменении угла внутреннего трения песчаных грунтов при загрязнении нефтепродуктами. Обозначены основные экспериментально подтвержденные результаты исследований угла внутреннего трения песчаных грунтов при взаимодействии с нефтепродуктами.

Проведены лабораторные испытания по определению прочностных характеристик песчаных грунтов, загрязненных нефтепродуктами, методом одноплоскостного среза. В качестве испытуемых образцов применялись пески крупный, средней крупности и мелкий, загрязненные бензином А-95, дизельным топливом, тяжелой нефтью в концентрации 0-12% по массе сухого грунта. Описана и апробирована методика проведения лабораторных испытаний методом одноплоскостного среза для песков, загрязненных нефтепродуктами. Посредством регрессионного многофакторного анализа определена и математически обоснована степень влияния факторов вязкости и концентрации нефтепродукта на величину угла внутреннего трения песков различной крупности. Проведен анализ чувствительности принятого уравнения регрессии с шестью степенями свободы. Обозначена область применения предложенной функции. Показано, что

использование полиномов второго рода в линейных регрессиях ведёт к значительному усложнению модели, связанному с невозможностью явного выделения отдельных коэффициентов влияния без дополнительного вычисления частных производных для составления градиента функции с его последующим анализом.
Лабораторно подтверждено снижение угла внутреннего трения песчаных грунтов крупных, средней крупности и мелких вне зависимости от вида нефтепродукта и его концентрации. Представлен график зависимости угла внутреннего трения песков различной крупности от концентрации нефтепродуктов. Статистически обосновано, что наибольшее влияние на угол внутреннего трения песчаных грунтов, загрязненных нефтепродуктами, оказывает концентрация, в меньшей степени – вид (вязкость) нефтепродуктов.

Ключевые слова: песчаный грунт, нефтепродукты, одноплоскостной срез, угол внутреннего трения, регрессионный анализ, концентрация

1. INTRODUCTION

According to the Ministry of Energy, the number of accidents accompanied by oil product spills (hereinafter - OP) exceeded 17000 in 2019 in the territory of the Russian Federation [1], [2]. Oil spills are accompanied by infiltration into the soil mass, resulting in changes in the physical and mechanical characteristics of soils [3].
Mechanical properties are the most important in the design and construction of bases and foundations, since they form the stress-strain state of the soil along with the acting loads on the base. It is known that the strength of sandy soils is ensured by friction forces arising at the contact points of mineral particles.
According to studies [4-8], contamination of sandy soils with oil products is accompanied by the formation of oily envelope around mineral particles, resulting in the effect of “slipping” of sand particles relative to each other. Hence, the angle of internal friction is reduced.
Thus, in the studies of C. Shin, J.B. Lee, B.M. Das [9] as an object of investigation were considered medium coarse sands with relative density of 50% and 75% samples, contaminated with oil in concentration from 0% to 4.5% by weight of dry sand. Single plane shear tests were conducted at a vertical pressure of 40 kPa. As a result of the experiment, the angle of internal friction decreased significantly at oil concentration C = 1.3%, with further increase in concentration, the decrease in the angle of internal friction continued, but was insignificant (Fig.1). Decrease of the angle of internal friction is also noted in [10-13].
The opposite result was reached by Z. N. Rasheed, F. R. Ahmed, H. M. Jassim in the research [14], where the object was coarse sand contaminated with gasoline and kerosene. According to the results obtained, the angle of internal friction increased by 3-8° as the.

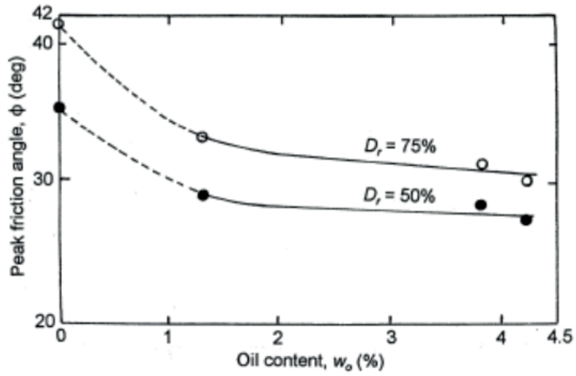

Figure 1. Graph of relationship between the peack angle of internal friction of medium-sized sand and oil concentration [9]

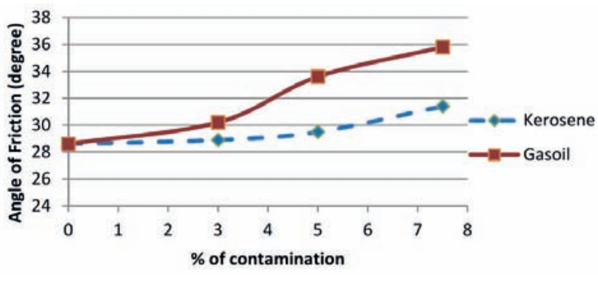

Figure 2. Graph of relationship between the angle of internal friction of coarse sands and the concentration of gasoline and kerosene [14]

At the same time, the results of the study [15] indicate that there is no obvious law of change in the angle of internal friction with increasing oil products concentration.
Taking into account the contradictions in the results of domestic and foreign authors, the aim of the study is to substantiate the degree of influence of variable parameters such as sand coarseness, type (viscosity) and concentration of oil products on the degree of change in the angle of internal friction of sandy soils contaminated with oil products, as well as to establish their regression dependencies.

Objectives of the study:
1. Determine the nature and degree of change in the angle of internal friction of sands of different coarseness at contamination of oil products (heavy oil, diesel fuel, gasoline A-95) in different concentrations (0,2,6,12%) by mass of dry soil.
2. By means of regression multi-factor analysis, using the results of laboratory tests, to identify the degree of influence of sand size, type of oil products and its concentration on the change in the angle of internal friction.

2. LABORATORY TEST PROCEDURE

Tests for determining the angle of internal friction were carried out by the method of single-plane-bone shearing on monofractional samples of sand of different sizes (coarse, medium and fine), contaminated with gasoline A-95, diesel fuel and heavy oil at a concentration of C = 0, 2, 6, 12% by weight of dry soil.
Concentration of oil products and humidity in the tested samples were set so that complete filling of pores with pore fluid (oil products + water) was ensured. Thus, the maximum and minimum oil products concentrations were provided at minimum and maximum soil moisture, respectively.
The volumes of oil products (1) and water (2) added to the test samples were calculated according to the expressions:

$$V_{нп} = C \cdot V_s \cdot \frac{\rho_s}{\rho_{нп}}, \quad (1)$$

$$V_w = V_s \cdot \left(e - C \frac{\rho_s}{\rho_{нп}} \right), \quad (2)$$

where C is the concentration of oil products; V_s is the volume of soil particulate, cm^3; ρ_s is the soil particulate density, g/cm^3; $\rho_{нп}$ is the oil products density, g/cm^3, e is the porosityfactor.

Figure 3. Sandy soil sample contaminated with diesel fuel after the single plane shear test

2.1. Results of Laboratory Tests (Input Data for Regression Analysis)

Coarse sand:
The angle of internal friction of coarse sand decreases from 9% to 19% for heavy oil contamination, from 6% to 11% for A-95 gasoline contamination, and from 8% to 14% for diesel contamination compared to clean sand.
Medium coarse sand:
The angle of internal friction of medium coarse sand decreases from 8% to 19% for heavy oil contamination, from 5% to 8% for A-95 gasoline contamination, and from 5% to 14% for diesel fuel contamination compared to clean sand.
Fine sand:
The angle of internal friction of fine sand decreases from 14% to 22% when polluted with heavy oil, from 7% to 17% when polluted with gasoline A-95, from 13% to 19% when polluted with diesel fuel in comparison with clean sand.
It is worth noting the similar character of decrease in the angle of internal friction for sands

of different sizes when polluted with all considered oil products: the maximum decrease at a concentration not exceeding 6%, with further increase in concentration the angle of internal friction insignificantly decreases.

The results of laboratory tests of sandy soils contaminated with oi products are presented in Fig. 4. Numerical values of the angle of internal friction are summarized in Table 1.

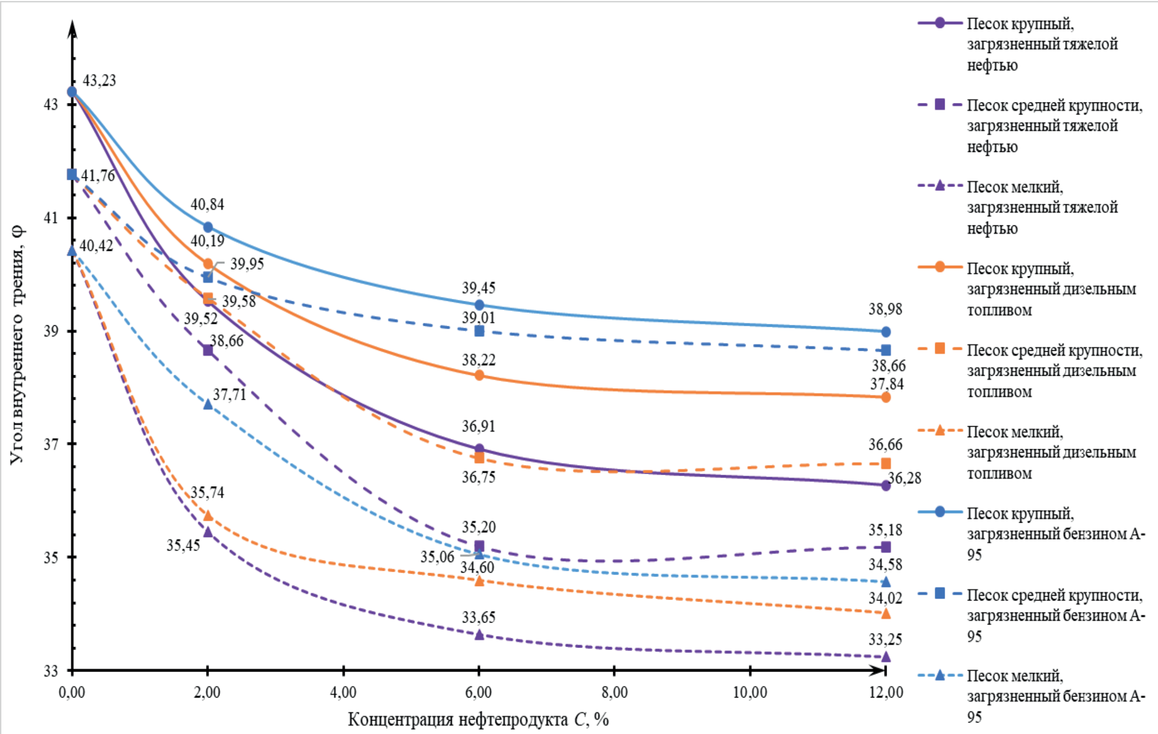

Figure 4. Graph of the relationship between the angle of internal friction and oil products concentration for sands of different sizes at different types of pollutant oil products

Table 1. Values of the angle of internal friction of sands of different coarseness depending on the type and concentration of oil products

	Coarse sand				**Medium coarse sand**				**Fine sand**			
The pore space is filled with heavy oil and water												
C, %	0,00	2,00	6,00	12,00	0,00	2,00	6,00	12,00	0,00	2,00	6,00	12,00
φ,°	43,23 (0%)	39,52 (9%↓)	36,91 (17%↓)	36,28 (19%↓)	41,76 (0%)	38,66 (8%↓)	35,2 (19%↓)	35,18 (19%↓)	40,42 (0%)	35,45 (14%↓)	33,65 (20%↓)	33,25 (22%↓)
The pore space is filled with A-95 gasoline and water												
C, %	0,00	2,00	6,00	12,00	0,00	2,00	6,00	12,00	0,00	2,00	6,00	12,00
φ,°	43,23 (0%)	40,84 (6%↓)	39,45 (10%↓)	38,98 (11%↓)	41,76 (0%)	39,95 (5%↓)	39,01 (7%↓)	38,66 (8%↓)	40,42 (0%)	37,71 (7%↓)	35,06 (15%↓)	34,58 (17%↓)
The pore space is filled with diesel fuel and water												
C, %	0,00	2,00	6,00	12,00	0,00	2,00	6,00	12,00	0,00	2,00	6,00	12,00
φ,°	43,23 (0%)	40,19 (8%↓)	38,22 (13%↓)	37,84 (14%↓)	41,76 (0%)	39,58 (5%↓)	36,75 (14%↓)	36,66 (14%↓)	40,42 (0%)	35,74 (13%↓)	34,6 (17%↓)	34,02 (19%↓)

Note: *n*%↓ is the decrease in the angle of internal friction of sandy soil contaminated with oil products, compared to clean sand, expressed in percentage.

3. METHOD OF STATISTICAL ANALYSIS

3.1. Solving regression equation with number of degrees of freedom m=5

The multiple linear regression model can be generally expressed as:

$$y = \sum_{i=1}^{k} x_i \cdot \beta_i + \varepsilon = x_1 \cdot \beta_1 + x_2 \cdot \beta_2 + \ldots + x_k \cdot \beta_k + \varepsilon, \quad (3)$$

where $x_1; x_2; \ldots; x_k -$ are the factors influencing the value of the function (predictors);

$\beta_1; \beta_2; \ldots; \beta_k -$ model parameters (influence coefficients);

ε – is the random unpredictable error.

To determine the degree of influence of each factor on the intensity of change in the angle of internal friction of sands contaminated with oil products, a multiple linear regression model will be written for the case under consideration:

$$y = \beta_1 \cdot x_1 + \beta_2 \cdot x_2 + \beta_3 \cdot \Delta_к + \beta_4 \cdot \Delta_с + \beta_5 \cdot \Delta_м + \varepsilon, \quad (4)$$

where:

Factor 1: $x_1 = C \in [0;12], \% -$ independent variable of **oil products concentration** by mass of dry soil, in the range from 0 to 12 %;

Factor 2: $x_2 = \kappa \in [0,596; 49,702] -$ independent variable of **coventional viscosities of oil products**, calculated as $\kappa = \dfrac{\eta_{загрязнитель}}{\eta_{вода}}$. Since the conventional viscosity of water $\kappa = 1,000$ and kinematic viscosity of water $\eta \approx 1 \cdot 10^{-6} \dfrac{м^2}{с}$, then in the equations with the conventional viscosity η it is possible to perform substitution for the kinematic viscosity with a change of their corresponding coefficients by a factor of 10^6 (Table 2).

Factors 3-5: $\Delta_к; \Delta_с; \Delta_м \in \{0;1\} -$ discrete independent variables indicators **of sand size** (dummy variables): $\Delta_к -$ coarse sand; $\Delta_с -$ medium sand; $\Delta_м -$ fine sand, where 1 indicates the presence of sand of a given size in the test, and 0 indicates the absence.

<u>Table 2.</u> Physical properties of pore fluids

Pore fluid	Water	Gasoline A-95	Diesel fuel	Heavy oil
Density $\rho, \dfrac{кг}{м^3}$	1000,0	737,8	837,8	898,4
Kinematic viscosity $\eta \cdot 10^{-6}, \dfrac{м^2}{с}$	1,006	0,600	3,452	50,000
Conventional viscosity κ	1,000	0,596	3,431	49,702

Since the tests were carried out on monofractional sand samples, the indicators for coarse, medium coarse and fine sands are as follows:

$$\left[\begin{array}{l} \Delta_к = 1 \rightarrow \Delta_с = \Delta_м = 0 \\ \Delta_с = 1 \rightarrow \Delta_к = \Delta_м = 0 \\ \Delta_м = 1 \rightarrow \Delta_к = \Delta_с = 0 \end{array}\right. ; \quad (5)$$

$\beta_1; \beta_2; \beta_3; \beta_4; \beta_5 -$ model parameters (influence coefficients), which take into account the change in the angle of internal friction when changing the values of predictors.

The initial data for the multifactor regression analysis are presented in Table 3.

Assume $y = \varphi^\circ$, where $\varphi^\circ -$ is the angle of internal friction according to the results of laboratory tests. Then the equation of multiple linear regression can be represented as:

$$\tilde{\varphi} = \beta_1 \cdot C + \beta_2 \cdot \kappa + \beta_3 \cdot \Delta_к + \beta_4 \cdot \Delta_с + \beta_5 \cdot \Delta_м,$$

or

$$\tilde{y} = \beta_1 \cdot x_1 + \beta_2 \cdot x_2 + \beta_3 \cdot \Delta_к + \beta_4 \cdot \Delta_с + \beta_5 \cdot \Delta_м \quad (6)$$

Table 3. Initial data for regression analysis and list of accepted factors

No	φ° based on the results laboratory tests	factor 1	factor 2	factor 3	factor 4	factor 5
	y	x_1	x_2	$\Delta_к$	$\Delta_с$	$\Delta_м$
The sand is coarse. The pore space is filled with heavy oil and water						
1	43,23	0	1,000	1	0	0
2	39,52	2	49,702	1	0	0
3	36,91	6	49,702	1	0	0
4	36,28	12	49,702	1	0	0
Medium-sized sand. The pore space is filled with heavy oil and water						
5	41,76	0	1,000	0	1	0
6	38,66	2	49,702	0	1	0
7	35,20	6	49,702	0	1	0
8	35,18	12	49,702	0	1	0
The sand is fine. The pore space is filled with heavy oil and water						
9	40,42	0	1,000	0	0	1
10	35,45	2	49,702	0	0	1
11	33,65	6	49,702	0	0	1
12	33,25	12	49,702	0	0	1
The sand is coarse. The pore space is filled with gasoline A-95 and water						
13	40,84	2	0,596	1	0	0
14	39,45	6	0,596	1	0	0
15	38,98	12	0,596	1	0	0
Medium coarse sand. The pore space is filled with gasoline A-95 and water						
16	39,95	2	0,596	0	1	0
17	39,01	6	0,596	0	1	0
18	38,66	12	0,596	0	1	0
The sand is fine. The pore space is filled with gasoline A-95 and water						
19	37,71	2	0,596	0	0	1
20	35,06	6	0,596	0	0	1
21	34,58	12	0,596	0	0	1
The sand is coarse. The pore space is filled with diesel fuel and water						
22	40,19	2	3,431	1	0	0
23	38,22	6	3,431	1	0	0
24	37,84	12	3,431	1	0	0
Medium coarse sand. The pore space is filled with diesel fuel and water						
25	39,58	2	3,431	0	1	0
26	36,75	6	3,431	0	1	0
27	36,66	12	3,431	0	1	0
The sand is fine. The pore space is filled with diesel fuel and water						
28	35,74	2	3,431	0	0	1
29	34,60	6	3,431	0	0	1
30	34,02	12	3,431	0	0	1

Using the least squares method we determine the values of influence coefficients: $\beta_1 = -0,309$, $\beta_2 = -0,041$, $\beta_3 = 41,633$, $\beta_4 = 40,664$, $\beta_5 = 37,971$.

Substituting the influence coefficients into the multiple linear regression equation, we obtain:

$$\tilde{y} = -0,309 \cdot x_1 - 0,041 \cdot x_2 + 41,633 \cdot \Delta_к + 40,664 \cdot \Delta_с + 37,971 \cdot \Delta_м, \quad (7)$$

Comparison of the results of laboratory results of internal friction angle with the predicted values is presented in Table 4.

Table 4. Comparison of values of the results of laboratory measurement of the angle of internal friction with predicted values

No	φ° based on the results of laboratory tests	Predicted value φ° at the calculated influence coefficients	Total error	Relative error
	y	$\tilde{y}$	$\varepsilon = \tilde{y} - y$	$\xi = \frac{\tilde{y}_i - y_i}{y_i} \cdot 100\%$
The sand is coarse. The pore space is filled with heavy oil and water				
1	43,23	41,59	-1,64	-3,79
2	39,52	38,97	-0,55	-1,40
3	36,91	37,73	0,82	2,22
4	36,28	35,88	-0,40	-1,10
Medium-sized sand. The pore space is filled with heavy oil and water				
5	41,76	40,62	-1,14	-2,72
6	38,66	38,00	-0,66	-1,71
7	35,20	36,76	1,56	4,44
8	35,18	34,91	-0,28	-0,78

The sand is fine. The pore space is filled with heavy oil and water				
9	40,42	37,93	-2,49	-6,17
10	35,45	35,31	-0,15	-0,42
11	33,65	34,07	0,42	1,26
12	33,25	32,22	-1,03	-3,11
The sand is coarse. The pore space is filled with gasoline A-95 and water				
13	40,84	40,99	0,15	0,38
14	39,45	39,75	0,30	0,76
15	38,98	37,90	-1,08	-2,78
Medium coarse sand. The pore space is filled with gasoline A-95 and water				
16	39,95	40,02	0,07	0,19
17	39,01	38,78	-0,22	-0,57
18	38,66	36,93	-1,73	-4,48
The sand is fine. The pore space is filled with gasoline A-95 and water				
19	37,71	37,33	-0,38	-1,02
20	35,06	36,09	1,03	2,94
21	34,58	34,24	-0,34	-0,99
The sand is coarse. The pore space is filled with diesel fuel and water				
22	40,19	40,99	0,80	2,00
23	38,22	39,75	1,53	4,01
24	37,84	37,90	0,06	0,16
Medium coarse sand. The pore space is filled with diesel fuel and water				
25	39,58	39,90	0,32	0,81
26	36,75	38,67	1,91	5,21
27	36,66	36,81	0,15	0,42
The sand is fine. The pore space is filled with diesel fuel and water				
28	35,74	37,21	1,47	4,11
29	34,60	35,97	1,38	3,99
30	34,02	34,12	0,10	0,30

Thus, the executed model has the following characteristics:

1) *Coefficient of determination:*

$$R^2 = \frac{\sum_{i=1}^{n}\left(\tilde{y}_i - \overline{y}\right)^2}{\sum_{i=1}^{n}\left(y_i - \overline{y}\right)^2} = \frac{161,20}{192,73} \approx 0,833\,, \quad (8)$$

High R^2 indicates a small share of unexplained variance and, therefore, a high level of fit of the linear regression model to the laboratory data.

2) *Fisher's criterion:*

$$F = \frac{MSR}{MSE} = \frac{R^2}{1-R^2}\cdot\frac{n-m}{m} = \frac{0,833}{1-0,833}\cdot\frac{30-5}{5} \approx 24,94\,, \quad (9)$$

where $MSR = \dfrac{SSR}{m}$ – is the *Mean Square Regression*;

$MSE = \dfrac{SSE}{n-m}$ – is the *Mean Square Error*;

$SSR = SST\cdot R^2 = \sum_{i=1}^{n}\left(\tilde{y}_i - \overline{y}\right)^2$ – is the *Sum of Squares for Regression*;

$SST = \dfrac{SSE}{1-R^2} = \sum_{i=1}^{n}\left(y_i - \overline{y}\right)^2$ – is the *Total Sum of Squares*;

$SSE = \sum_{i=1}^{n}\left(y_i - \tilde{y}_i\right)^2$ – is the *Sum of Squares for Error*;

$n = 30$ – is the total number of observations in the sample;

$m = 5$ – is the number of parameters in the model;

$R^2 = 1 - \dfrac{SSE}{SST} = 0,833$ – coefficient of determination (*R-squared*).

Comparing the obtained value of Fisher's criterion with the tabulated value, we obtain the following results:

$$F_{табл}\left(\alpha; k_1 = m; k_2 = n-m\right) = F_{табл}\left(0,05; 5; 25\right) \approx 2,60$$
$$F = 24,94 > F_{табл} = 2,60\,, \quad (10)$$

Therefore, the regression equation is statistically significant.

3) *P-value* is determined using the Fisher distribution function. The level of significance obtained from the p-value is $2{,}1\cdot 10^{-9}$, that confirms the high statistical significance of the model against the null hypothesis, according to which all additional parameters are equal to zero and do not improve the explanatory power of the model.

Thus, we can reject the null hypothesis and conclude that the included parameters are significant.

4) *Average approximation error index*

$$\overline{A} = \frac{1}{n}\cdot\sum_{i=1}^{n}\left|\frac{y_i - \tilde{y}_i}{y_i}\right|\cdot 100\% \approx 2,14\%\,, \quad (11)$$

indicates that, on average, the predicted values of the angle of internal friction deviate from the laboratory values by 2.14 %, which indicates a high accuracy of the equation.

Conclusion: the proposed regression equation with the number of degrees of freedom has a high level of explained variance and the level of statistical significance. However, according to Table 5, the coefficient of influence $\beta_4 = 40,664$ has *p*-value = 0,06719 $> \alpha = 0,05$, which is not statistically significant. In order to ensure statistical significance of all influence coefficients, we perform the regression analysis again, increasing the number of degrees of freedom to $m = 6$.

3.2. Solving regression equation with number of degrees of freedom m=6

In the course of calculations of different variants of mathematical description of graphs of relationships between the angle of internal friction and concentration for different sands and oil products in the regression analysis, the variable x_1 is represented in the form of a polynomial of degree 2, in connection with which the equation will have an additional degree of freedom:

$$y = \beta_1 \cdot x_1 + \beta_2 \cdot x_1^2 + \beta_3 \cdot x_2 + \beta_4 \cdot \Delta_к + \beta_5 \cdot \Delta_с + \beta_6 \cdot \Delta_м + \varepsilon, \quad (12)$$

Table 5. Regression analysis of model parameters (influence coefficients)

Predictor	Values of the influence coefficients, β_i	Standard error	t-statistics	*p*-value	Confidence intervals	
					low 95%	Top 95%
x_1	$\beta_1 = -0,309$	0,0475	-6,51	$8,0 \cdot 10^{-7}$	-0,407	-0,211
x_2	$\beta_2 = -0,041$	0,0094	-4,38	0,00019	-0,061	-0,022
$\Delta_к$	$\beta_3 = 41,633$	0,4710	88,39	$9,9 \cdot 10^{-33}$	40,663	42,603
$\Delta_с$	$\beta_4 = 40,664$	21,2901	1,91	0,06719	39,650	41,589
$\Delta_м$	$\beta_5 = 37,971$	5,2519	7,23	$1,4 \cdot 10^{-7}$	36,957	39,044

The initial data for the regression analysis and the list of accepted factors taking into account the additional degree of freedom of the regression equation are presented in Table 6.

Table 6. Initial data for regression analysis and the list of accepted factors taking into account the additional degree of freedom of the regression equation

No	$\varphi°$ based on the results of laboratory tests	factor 1	factor 2	factor 3	factor 4	factor 5	factor 6
	y	x_1	x_1^2	x_2	$\Delta_к$	$\Delta_с$	$\Delta_м$
The sand is coarse. The pore space is filled with heavy oil and water							
1	43,23	0	0	1,000	1	0	0
2	39,52	2	4	49,702	1	0	0
3	36,91	6	36	49,702	1	0	0
4	36,28	12	144	49,702	1	0	0
Medium coarse sand. The pore space is filled with heavy oil and water							
5	41,76	0	0	1,000	0	1	0
6	38,66	2	4	49,702	0	1	0
7	35,20	6	36	49,702	0	1	0
8	35,18	12	144	49,702	0	1	0
The sand is fine. The pore space is filled with heavy oil and water							
9	40,42	0	0	1,000	0	0	1
10	35,45	2	4	49,702	0	0	1
11	33,65	6	36	49,702	0	0	1
12	33,25	12	144	49,702	0	0	1
The sand is coarse. The pore space is filled with gasoline A-95 and water							
13	40,84	2	4	0,596	1	0	0
14	39,45	6	36	0,596	1	0	0
15	38,98	12	144	0,596	1	0	0

Sand of medium coarseness. The pore space is filled with gasoline A-95 and water							
16	39,95	2	4	0,596	0	1	0
17	39,01	6	36	0,596	0	1	0
18	38,66	12	144	0,596	0	1	0
The sand is fine. The pore space is filled with gasoline A-95 and water							
19	37,71	2	4	0,596	0	0	1
20	35,06	6	36	0,596	0	0	1
21	34,58	12	144	0,596	0	0	1
The sand is coarse. The pore space is filled with diesel fuel and water							
22	40,19	2	4	3,431	1	0	0
23	38,22	6	36	3,431	1	0	0
24	37,84	12	144	3,431	1	0	0
Medium coarse sand. The pore space is filled with diesel fuel and water							
25	39,58	2	4	3,431	0	1	0
26	36,75	6	36	3,431	0	1	0
27	36,66	12	144	3,431	0	1	0
The sand is fine. The pore space is filled with diesel fuel and water							
28	35,74	2	4	3,431	0	0	1
29	34,60	6	36	3,431	0	0	1
30	34,02	12	144	3,431	0	0	1

A comparison of the results of laboratory determination of the angle of internal friction with the predicted values within the regression analysis is presented in Table 7.

Table 7. Comparison of values of the results of laboratory determination of the angle of internal friction with the predicted values within the regression analysis

No	$\varphi°$ based on the results of laboratory tests	Predicted value $\varphi°$ at the calculated influence coefficients	Total error	Relative error
	y	$\tilde{y}$	$\varepsilon = \tilde{y} - y$	$\xi = \frac{\tilde{y}_i - y_i}{y_i} \cdot 100\%$
The sand is coarse. The pore space is filled with heavy oil and water				
1	43,23	42,95	-0,28	-0,65
2	39,52	39,25	-0,27	-0,69
3	36,91	36,78	-0,13	-0,35
4	36,28	36,57	0,29	0,80
Medium coarse sand. The pore space is filled with heavy oil and water				
5	41,76	41,97	0,21	0,51
6	38,66	38,28	-0,38	-0,99
7	35,20	35,81	0,61	1,74
8	35,18	35,59	0,41	1,17
The sand is fine. The pore space is filled with heavy oil and water				
9	40,42	39,28	-1,14	-2,83
10	35,45	35,58	0,13	0,36
11	33,65	33,12	-0,53	-1,57
12	33,25	32,90	-0,35	-1,05
The sand is coarse. The pore space is filled with gasoline A-95 and water				
13	40,84	41,03	0,20	0,48
14	39,45	38,57	-0,89	-2,24
15	38,98	38,35	-0,63	-1,62
Sand of medium coarseness. The pore space is filled with gasoline A-95 and water				
16	39,95	40,06	0,11	0,28
17	39,01	37,60	-1,41	-3,62
18	38,66	37,38	-1,28	-3,31
The sand is fine. The pore space is filled with gasoline A-95 and water				
19	37,71	37,37	-0,34	-0,91
20	35,06	34,90	-0,16	-0,45
21	34,58	34,69	0,11	0,31
The sand is coarse. The pore space is filled with diesel fuel and water				
22	40,19	41,03	0,85	2,11
23	38,22	38,57	0,35	0,91
24	37,84	38,35	0,51	1,36
Medium coarse sand. The pore space is filled with diesel fuel and water				
25	39,58	39,96	0,37	0,94
26	36,75	37,49	0,74	2,01
27	36,66	37,28	0,62	1,68
The sand is fine. The pore space is filled with diesel fuel and water				
28	35,74	37,26	1,52	4,26
29	34,60	34,80	0,20	0,59
30	34,02	34,58	0,56	1,66

The obtained coefficients at variables have high statistical significance (Table 8). Substituting the influence coefficients into the expression for multiple linear regression we obtain:

$$\tilde{y} = -1,08 \cdot x_1 + 0,058 \cdot x_1^2 - 0,036 \cdot x_2 + \\ +42,984 \cdot \Delta_к + 42,01 \cdot \Delta_с + 39,317 \cdot \Delta_м , \quad (13)$$

The addition of a degree of freedom resulted in a change in characteristics:

1. *coefficient of determination:*

$$R^2 = \frac{\sum_{i=1}^{n}\left(\tilde{y}_i - \bar{y}\right)^2}{\sum_{i=1}^{n}\left(y_i - \bar{y}\right)^2} = \frac{180,15}{192,74} \approx 0,935, \quad (14)$$

2. *Fisher's criterion*:

$$F = \frac{R^2}{1-R^2} \cdot \frac{n-m}{m} = \frac{0,935}{1-0,935} \cdot \frac{30-6}{6} \approx 57,23$$

$$F \approx 57,23 > F_{табл}\left(0,05;6;24\right) \approx 2,51, \quad (15)$$

3. *p-value* $= 4,6 \cdot 10^{-13}$,

4. *average percentage of approximation error:*

$$\bar{A} = \frac{1}{n} \cdot \sum_{i=1}^{n}\left|\frac{y_i - \tilde{y}_i}{y_i}\right| \cdot 100\% \approx 1,38\%, \quad (16)$$

Conclusion: since the coefficient of determination and Fisher's criterion have increased, and the p-value and average percentage of approximation error decreased in comparison with similar ones at $m = 5$, it can be concluded that the function at $m = 6$ has higher statistical significance than the equation with $m = 5$ degrees of freedom of re-regression.

Table 8. Estimation of regression coefficients (regression analysis of model parameters)

Predictor	Values of influence coefficients, β_i	Standard error	t-statistics	*p*-value	Confidence intervals	
					low 95%	top 95%
x_1	$\beta_1 = -1,080$	0,1301	-8,30	$1,6 \cdot 10^{-8}$	-1,349	-0,812
x_1^2	$\beta_2 = 0,058$	0,0095	6,10	$2,7 \cdot 10^{-6}$	0,038	0,078
x_2	$\beta_3 = -0,036$	0,0061	-6,00	$3,4 \cdot 10^{-6}$	-0,049	-0,024
$\Delta_к$	$\beta_4 = 42,984$	0,3738	114,99	$2,0 \cdot 10^{-34}$	42,212	43,755
Δ_c	$\beta_5 = 42,010$	0,3745	112,19	$3,6 \cdot 10^{-34}$	41,237	42,783
$\Delta_м$	$\beta_6 = 39,317$	0,3745	105,00	$1,8 \cdot 10^{-33}$	38,544	40,090

3.3 Comparison of the proposed linear multiple regressions with different regression degrees of freedom m=5 and m=6 by Fisher's criterion

The quality of models with m=5 and m=6 was compared using F-test (Fisher's exact test). The results are presented in Table 9.

Table 9. Comparison of regression equations with m=5 and m=6 (F-test)

Null hypothesis (H0)	Alternative hypothesis (H1)
Parameter $\beta_2 \cdot x_1^2$, added to the regression equation compared to the equation with m=5, **insignificantly** improves the predictive ability of the model.	The regression equation with m=6 degrees of freedom **significantly** improves the predictive power compared to the equation with m=5
Fisher's criterion value $F \approx 10,30$	
p-value = 0,00376 < α = 0,05	

Conclusion: since p-values $0,00376 < \alpha = 0,05$, null hypothesis (H0) deviates and the addition of the summand $\beta_2 \cdot x_1^2$ into the equation statistically significantly improves the regression equation in comparison with the model with the number of degrees of freedom $m = 5$. Thus, to identify the degree of influence of the given factors on the angle of internal friction of sandy soils at oil products pollution, we take the regression equation with the number of degrees of freedom $m = 6$.

3.4. Verification of error variance by the Goldfeld-Quandt method for the adopted regression equation with m=6 degrees of freedom

To check the homogeneity of the random error variance of the regression model, we will perform the Goldfeld-Quandt test. We introduce the null hypothesis (H0) about homoscedasticity of the model and the alternative hypothesis (H1) about heteroscedasticity of the model. For the calculation, we order and divide the existing sample of trials $n = 30$ into 2 groups: $N_1 = \{1;...;10\}$ and $N_2 = \{21;...;30\}$, excluding $N = \{11;...;20\}$ of the central observations. We determine the sum of squares of regression errors for group 1 $ESS_1 \approx 0,537$ and for group 2 - $ESS_2 \approx 0,475$. Thus, the Fisher criterion is determined and compared with the tabulated value in the form:

$$F = \frac{ESS_1 / m}{ESS_2 / m} = \frac{ESS_1}{ESS_2} = \frac{0,537}{0,475} \approx 1,13$$

$$F = 1,13 < F_{табл}\left(0,05;6;4\right) \approx 6,16, \qquad (17)$$

Since the calculated value F is less than $F_{табл}$, the null hypothesis (H0) of homoscedasticity is accepted, which, in turn, indicates a constant error variance.

We accept the final regression equation that satisfies the main tests with a 95% confidence level:

$$\tilde{y} = -1,08 \cdot x_1 + 0,058 \cdot x_1^2 - 0,036 \cdot x_2 + \\ +42,984 \cdot \Delta_к + 42,01 \cdot \Delta_с + 39,317 \cdot \Delta_м,$$

or

$$\tilde{\varphi} = -1,08 \cdot C + 0,058 \cdot C^2 - 0,036 \cdot \kappa + \\ +42,984 \cdot \Delta_к + 42,01 \cdot \Delta_с + 39,317 \cdot \Delta_м, \qquad (18)$$

The graphical representation of the regression model with the experimental points obtained through laboratory experiments is presented in Fig. 5.

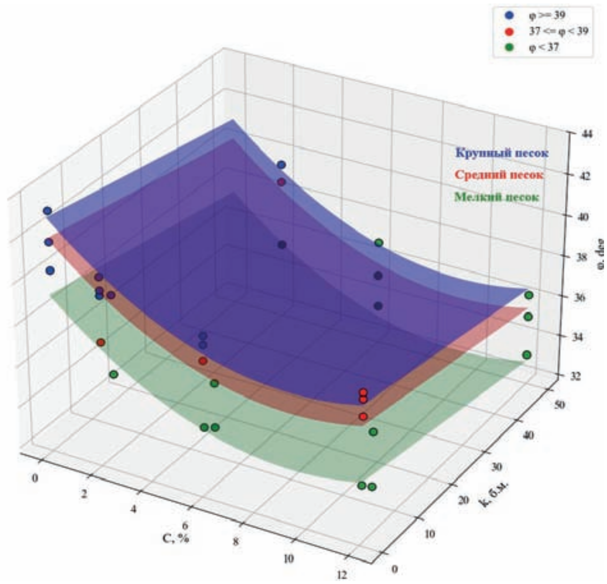

Figure 5. Graphical representation of the regression model with experimental points obtained through laboratory tests

3.5. Sensitivity analysis of the adopted regression equation with the number of degrees of freedom m=6

To analyze the sensitivity of the function, we calculate the gradient, which shows how changes in individual variables affect the function in order to determine which variables are most critical for changing the values of the function:

$$\nabla\tilde{y} = \left(\frac{\partial\tilde{y}}{\partial x_1};\frac{\partial\tilde{y}}{\partial x_2};\frac{\partial\tilde{y}}{\partial\Delta_к};\frac{\partial\tilde{y}}{\partial\Delta_с};\frac{\partial\tilde{y}}{\partial\Delta_м}\right), \qquad (19)$$

$$\nabla\tilde{y}\left(x_1;x_2;\Delta_к;\Delta_с;\Delta_м\right) = \\ = \left[-1,08 + 0,116 \cdot x_1; -0,036; 42,984; 42,01; 39,317\right], \qquad (20)$$

It should be noted that the value of the partial derivative $\frac{\partial\tilde{y}}{\partial x_1} = -1,08 + 0,116 \cdot x_1$ depends on x_1. The initial sensitivity value is -1.08 and changes by 0.116 for each unit change in x_1. Since the dummy variables $(\beta_4, \beta_5, \beta_6)$ indicate only the reference point, they cannot be taken into account to analyze the degree of change in the angle of internal friction. The obtained dependence gives an extremum at the point

$x_1 = \frac{1,08}{0,116} \approx 9,3\%$. This feature of the model is associated with a sharp drop in the angle of internal friction at low oil products concentrations. For example, for a point with a low oil products concentration $x_1 = 2\%$, the change in the angle of internal friction $\Delta\tilde{y}$ with a change in concentration by $\Delta x_1 = 1\%$ will be calculated as the scalar product of a vector consisting of partial derivatives of functions for each parameter (function gradient $\nabla\tilde{y}$) and a vector containing changes in the variables under consideration (vector of changes ΔX):

$$\Delta\tilde{y} \approx \nabla\tilde{y} \cdot \Delta X = \nabla\tilde{y} \cdot (\Delta x_1; \Delta x_2; 0; 0; 0) = \\ = (-0,848; -0,036; 42,984; 42,01; 39,317) \cdot \\ \cdot (1; 0; 0; 0; 0), \quad (21)$$

$$\Delta\tilde{y} \approx (-0,848 \cdot 1) + (-0,036 \cdot 0) + (42,984 \cdot \\ \cdot 0) + (42,01 \cdot 0) + (39,317 \cdot 0) = -0,848 \approx -1$$

Such a value $\Delta\tilde{y}$, indicates a decrease in the angle of internal friction of approximately 1 degree. However, in the region of oil products concentrations from about 8 to 10%, the change in the angle of internal friction will be smaller than in the region of small concentrations from 0 to 4%. As the conditional viscosity of the NP changes, the angle of internal friction will change linearly by -0.036 for each unit change in conditional viscosity: if the viscosity increases by 10 units, the angle of internal friction will change by an insignificant -0.36 degrees.

3.6. Assumptions and scope of the adopted function

1. The equation is valid in the range of concentrations $C = x_1 \in (0;12]\%$.
2. The presence of oil products in soil pores implies a non-zero concentration.
3. The equation is valid if the dummy values fulfill the following condition: $\Delta_i = 1$, then $\forall\Delta_{j \neq i} = 0$.

4. CONCLUSIONS:

The influence of the considered factors on the intensity of the decrease of the angle of internal friction is expressed by the values of derivatives: at any point within the given interval $(0;12]$ % for concentration and constant for viscosity $\frac{\partial\tilde{y}}{\partial x_2} = \beta_2 = -0,036$. The highest value of the derivative corresponds to the concentration of the oil product, the lowest value corresponds to the viscosity, thus, the concentration of the oil product has the greatest influence on the angle of internal friction of sandy soil, and the viscosity has the least influence.

Dispersity (coarseness) had no effect on the reduction of the angle of internal friction for oil product contamination because sand coarseness was set as a fictitious parameter indicating only the initial values of the angle of internal friction, i.e. $\varphi(C = 0)$. Consequently, the granulometric composition cannot be considered as a factor influencing the change in the angle of internal friction of sandy soils contaminated with oil products.

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