

MATHEMATICAL MODELING OF THE STRENGTH PROPERTIES OF LESSES BY THE METHOD OF CORRELATION-REGRESSION ANALYSIS

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Abstract. The strength properties of subsiding loess soils are considered in the mathematical modeling of their compaction by deep explosions. Soil compaction is carried out in order to eliminate their subsidence properties. Correlation and regression analyzes of the dependences of strength on the physical characteristics of loess were carried out, using the soils of the North Caucasus as an example. The correlation dependence of the specific cohesion and the angle of internal friction on the physical characteristics of the subsidence soil is established. Correlation coefficients were obtained for various indices of moisture content and loess density. The studies were carried out before and after soil compaction in this way. Both positive and negative correlations between the studied characteristics of subsiding loess soil were recorded. With an increase in moisture, a high correlation was observed with the strength characteristics of the soil before and after its compaction by deep explosions. The equations of regression of specific cohesion and the angle of internal friction on soil moisture and density are constructed. The reliability coefficients of approximation of theoretical regression equations and experimental data demonstrate high values. The regression equations of specific adhesion and the angle of internal friction on soil moisture showed that the values of strength characteristics increase with decreasing values of soil moisture. The regression dependence of the specific cohesion and the angle of internal friction on the density of subsidence loess has been studied. It has been established that an increase in the values of strength characteristics was recorded with an increase in the density of loess soil before and after its compaction by deep explosions. The constructed regression equations make it possible to predict the strength characteristics of loess at the stage of designing the bases and foundations of construction objects.

Keywords: loess, subsidence, compaction, specific cohesion, angle of internal friction, correlation, regression

МАТЕМАТИЧЕСКОЕ МОДЕЛИРОВАНИЕ ПРОЧНОСТНЫХ СВОЙСТВ ЛЁССОВ МЕТОДОМ КОРРЕЛЯЦИОННО-РЕГРЕССИОННОГО АНАЛИЗА

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Аннотация. Рассмотрены прочностные свойства просадочных лёссовых грунтов при математическом моделировании их уплотнения глубинными взрывами. Уплотнение грунтов производится с целью устранения их просадочных свойств. Проведены корреляционный и регрессионный анализы зависимостей прочностных от физических характеристик лёссов, на примере грунтов Северного Кавказа. Установлена корреляционная зависимость удельного сцепления и угла внутреннего трения от физических характеристик просадочного грунта. Коэффициенты корреляции получены для различных показателей значений влажности и плотности лёсса. Исследования проводились до и после уплотнения грунта указанным способом. Зафиксирована как положительная, так и отрицательная корреляционная зависимость между исследуемыми характеристиками просадочного лёссового грунта. С ростом влажности наблюдалась высокая корреляционная зависимость с прочностными характеристиками грунта до и после его уплотнения глубинными взрывами.

Построены уравнения регрессии удельного сцепления и угла внутреннего трения от влажности и плотности грунта. Коэффициенты достоверности аппроксимации теоретических уравнений регрессий и экспериментальных данных демонстрируют высокие значения. Регрессионные уравнения удельного сцепления и угла внутреннего трения от влажности грунта показали, что значения прочностных характеристик увеличиваются при уменьшении значений влажности грунта. Исследована регрессионная

зависимость удельного сцепления и угла внутреннего трения от плотности просадочного лёсса. Установлено, что рост значений прочностных характеристик фиксировался при увеличении плотности лёссового грунта до и после его уплотнения глубинными взрывами. Построенные регрессионные уравнения позволяют прогнозировать прочностные характеристики лёссов на этапе проектирования оснований и фундаментов объектов строительства.

Ключевые слова: лёсс, просадочность, уплотнение, удельное сцепление, угол внутреннего трения, корреляция, регрессия

INTRODUCTION

Loess subsidence soils are widespread on the Earth's surface and have different origins. Loess covers more than 17% of Russia's territory. It is most common in the North Caucasian and Southern Federal Districts (about 80%). Loess is a dusty-clay soil containing at least 50% of dusty particles [1, 2]. Elimination of subsidence properties of such soils is an urgent task of contemporary engineering geology [3-6]. Correlation-regression analysis-based mathematical modeling of soil compaction with deep explosions allows estimating the relationship between strength and physical properties of soils.

Realization of engineering calculations during design of bases and foundations of construction objects, various earthworks, slopes, etc. requires information about strength and physical characteristics of soils [3, 4, 7, 8]. This determines the necessity of their application to solve a number of scientific and applied problems of engineering geology [9-13]. Therefore, the engineering practical task of assessing changes in the strength properties of subsidence soils and their influence on the stability of buildings and structures depending on natural and anthropogenic conditions is of special importance [14-16].

The main strength characteristics of dispersed subsidence soils are specific cohesion and angle of internal friction. As a rule, their values are determined in laboratory conditions according to standards, e.g. [17]. Triaxial compression devices, stabilimeters, shear gauges, etc. can be used in practice. It should be noted that the test results of the different evaluation methods may differ slightly from each other. This is explained

by the difference in the stress state of soils [3, 18, 19].

RESEARCH METHODS

Let us describe the mathematical model of the problem of compaction of loess soils by deep explosions in the form [9]

$$\begin{aligned} \frac{\partial q}{\partial t} + U \frac{\partial q}{\partial x} = \frac{\partial}{\partial x} K_x \frac{\partial q}{\partial x} + \\ + \frac{\partial}{\partial y} K_y \frac{\partial q}{\partial y} + \frac{\partial}{\partial z} K_z \frac{\partial q}{\partial z} + f, \end{aligned} \quad (1)$$

$$t \in [t_0, T],$$

with initial and boundary conditions

$$\begin{aligned} q(t_0, x, y, z) = \\ = Q \delta(x - x^0) \delta(y - y^0) \delta(z - z^0), \end{aligned} \quad (2)$$

$$q(t, x, y, z)|_{z=z^0} = 0, \quad t > t_0. \quad (3)$$

$$K_z \frac{\partial q}{\partial z} \Big|_{z=z^0} = 0, \quad t > t_0, \quad (4)$$

where $q(t, x, y, z)$ is the soil density at time unit t at the point with coordinates (x, y, z) ; U is the vector of horizontal gas drift along the Ox axis; f is the source function; Q is the charge (source) capacity; δ is the unit impulse Dirac function; K_x , K_y , K_z is the diffusion coefficients.

Problems (1) ... (3) correspond to the case of complete absorption of gas atoms by the surrounding soil in the borehole (consolidation

of the subsidence soil occurs). Problems (1), (2) and (4) describe the case of complete reflection of gas atoms from the surrounding ground (ground ejection to the surface occurs). The solutions of problems (1) - (3) and (1), (2), (4) are [9]

$$q(t, x, y, z) = \frac{Q}{(2\pi)^{3/2} K_x K_y K_z t^3} \times \exp \left\{ -\frac{(x - Ut)^2}{2K_x^2 t} - \frac{y^2}{2K_y^2 t} \right\} \times \left[\exp \left\{ -\frac{(z - H)^2}{2K_z^2 t} \right\} \pm \exp \left\{ -\frac{(z + H)^2}{2K_z^2 t} \right\} \right],$$

where H is the depth of charge embedment. Values of diffusion coefficients K_x , K_y , K_z depend on physical characteristics of soils. Let us investigate the correlation between strength and physical properties of soils, which include density and moisture content. Let us construct regression equations of strength characteristics of loess in order to predict their condition [10, 16, 20].

RESULTS AND DISCUSSIONS

This section provides a correlation-regression analysis of strength and physical properties of soils based on experimental data [3]. We study the construction site "Severny microdistrict in Budennovsk". At the construction site the thickness of subsidence soils reaches 20 m. According to the data the density of the soil before compaction is equal to $q_0 = 1.51 - 1.54 \text{ g/cm}^3$. The natural moisture content took values of $\omega = 10\% - 30\%$. 198 combined drainage-explosion wells with diameter of 180 mm and depth of 6 m were drilled. Through them soaking of the subsidence stratum was carried out in the excavation. As a result of compaction by the method of deep explosions of concentrated explosive charges, the density of the soil took the value of $q = 1.56 - 1.73 \text{ g/cm}^3$.

Table 1 shows correlation dependence of specific adhesion and angle of internal friction of loess soil before and after its compaction on soil moisture and density. Pearson correlation coefficient was adopted as a measure of interdependence between soil characteristics.

Table 1. Correlation between strength and physical indices of loess soil of Budyonnovsk city

<i>Strength parameters</i>	<i>Physical parameters</i>	<i>Before compaction</i>	<i>After compaction</i>
Specific adhesion C	Moisture ω , 10%±2%; Density q , g/cm ³	-0.055 0.189	-0.155 0.094
	Moisture ω , 20%±2%; Density q , g/cm ³	-0.363 0.272	-0.191 0.146
	Moisture ω , 30%±2%; Density q , g/cm ³	-0.809 0.837	-0.911 0.890
Angle of internal friction φ	Moisture ω , 10%±2%; Density q , g/cm ³	-0.040 0.086	-0.159 0.249
	Moisture ω , 20%±2%; Density q , g/cm ³	-0.363 0.220	-0.230 0.578
	Moisture ω , 30%±2%; Density q , g/cm ³	-0.848 0.848	-0.846 0.846

Correlation is recorded between strength (specific adhesion, angle of internal friction) and physical (moisture, density) characteristics of loess. Both positive and negative linear correlation is observed. In the first case, higher (low) values of specific adhesion and angle of internal friction correspond to higher (lower) values of soil moisture. In the second case, higher (low) values of strength characteristics correspond to lower (high) values of physical characteristics [20].

The values of Pearson correlation coefficient more than 0.8 module demonstrate high correlation of investigated strength and physical characteristics of loess soil. The proximity to

unity of Pearson's coefficient is observed mainly at high moisture values, $30\% \pm 2\%$. Approximation to zero modulus of the values of correlation coefficients indicate not the absence of correlation relationship between the studied characteristics, but the presence of unknown factors affecting these relationships. The modulus value of Pearson correlation coefficient less than 0.5 shows weak correlation of loess soil characteristics.

Figures 1 and 2 show regression correlations of specific cohesion C with moisture ω before and after compaction of subsidence soils by I.M. Litvinov's deep explosions [4], respectively.

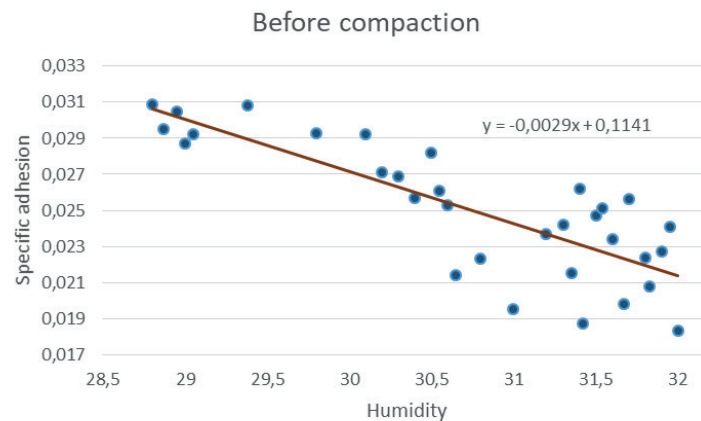


Figure 1. Regression correlation between specific cohesion and soil moisture before compaction

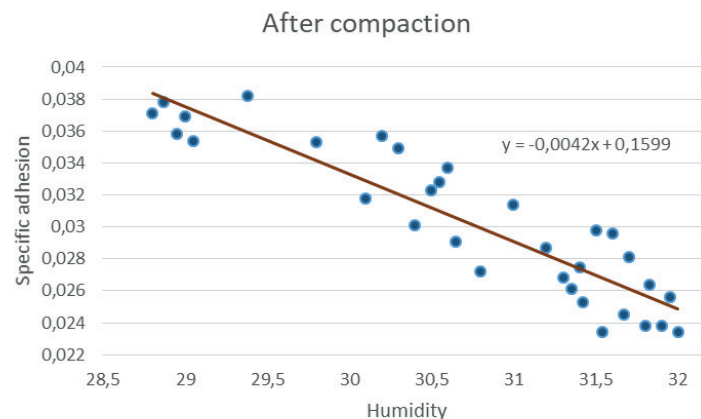


Figure 2. Regression correlation between specific cohesion and soil moisture after compaction

The equations of the regressions presented in Figures 1 and 2 have the following form

$$C = -0.0029 \cdot \omega + 0.1141, \quad (5)$$

$$C = -0.0042 \cdot \omega + 0.1599. \quad (6)$$

The approximation confidence factor for equation (5) is 0.6543. For equation (6), the approximation reliability coefficient is 0.8301. The closeness of the coefficients to unity indicates a significant degree of dependence of the regression model on the experimental data [3]. It is noted that with the increase in the moisture content of the subsidence soil, there is a decrease in the values of specific cohesion. This feature is characteristic of the corresponding regression dependences both before and after soil compaction.

Regression dependences of specific cohesion C on density q of loess soil are shown in Figures 3 and 4. The corresponding graphs both before and after realization of compaction of subsidence soils by the method of deep explosions are depicted. The regression lines are given by the following equations, respectively

$$C = 0.2684 \cdot q - 0.3835, \quad (7)$$

$$C = 0.0927 \cdot q - 0.1196. \quad (8)$$

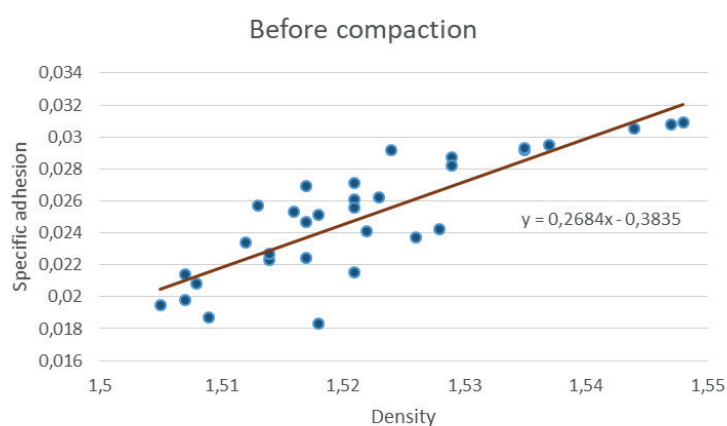


Figure 3. Regression correlation between specific cohesion and soil density before compaction

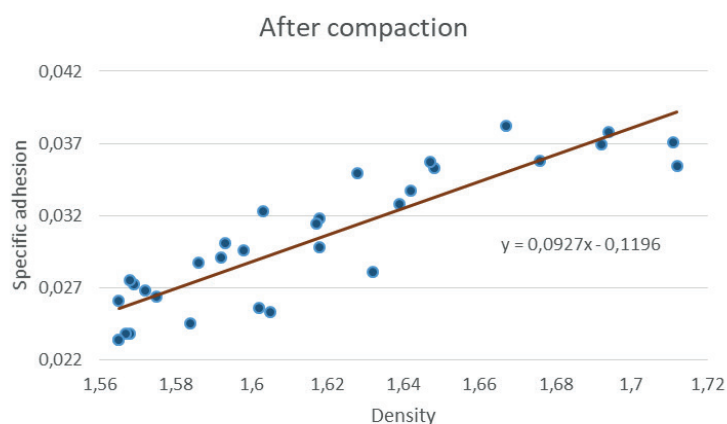


Figure 4. Regression correlation between specific cohesion and soil density after compaction

A positive regression correlation between specific cohesion and soil density was observed before and after compaction of loess soils by deep explosions. The increase in soil density leads to an increase in its strength characteristic, specific cohesion. Thus, for the regression

equation before soil compaction (7) the approximation reliability coefficient is equal to 0.7003. After compaction of the subsidence soil for the regression equation (8) this indicator takes the value 0.7929.

According to Table 1, the angle of internal friction of the soil correlates with the indicators of physical characteristics of soils. Correlation between φ , moisture content ω and density ρ of loess soil is assessed by regression analysis.

Graphs of regression correlations of the angle of internal friction φ with soil moisture ω are presented in Figures 5 and 6. The regression equations show the dependences of the strength characteristic on the physical index for the state of the soil before and after its compaction by I.M. Litvinov's method of deep explosions [4].

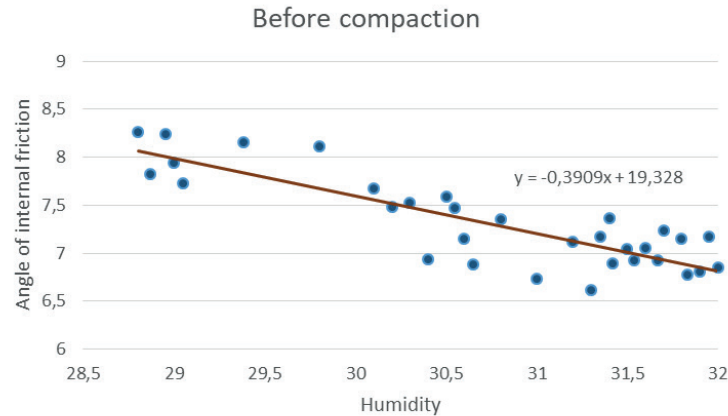


Figure 5. Regression correlation between the angle of internal friction and the moisture content of loess soil before compaction

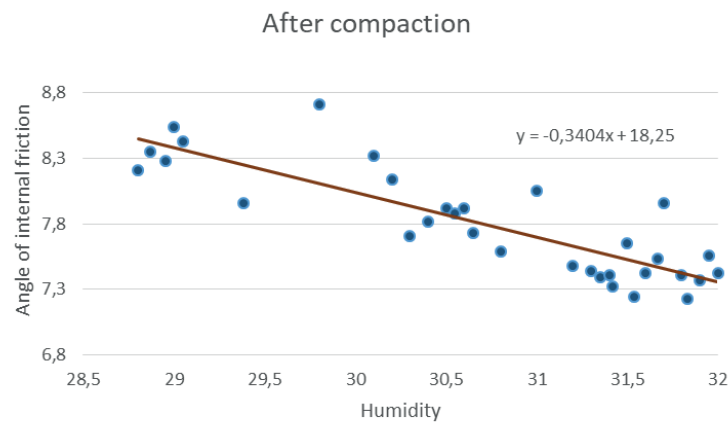


Figure 6. Regression correlation between the angle of internal friction and the moisture content of loess soil after compaction

The regression equations corresponding to Figures 5 and 6 have analytical representations of the following form

$$\varphi = -0.3909 \cdot \omega + 19.328, \quad (9)$$

$$\varphi = -0.3404 \cdot \omega + 18.25. \quad (10)$$

Analysis of the results showed the following. The regression equation (9) shows the degree of approximation to the experimental data with the approximation confidence coefficient 0.719. The approximation reliability coefficient of equation (10) is equal to 0.7157. The change of coefficient values is observed at realization of elimination of subsidence properties of soils by

depth explosions. Measurements of strength and physical characteristics of soil were carried out before and after engineering and production works.

The graphs of regression equations (Fig. 5, 6) show that the value of the angle of internal friction φ increases with decreasing values of loess soil moisture index ω . Table 1 also notes

the negative linear correlation of the investigated soil characteristics.

The study of regression dependences of the angle of internal friction on the density of loess soil is presented in Figures 7 and 8. The graph of Figure 7 shows the dependence before soil compaction, and in Figure 8 after compaction.

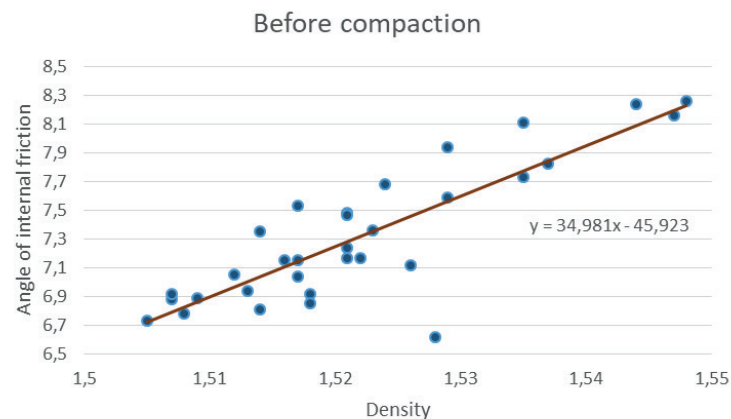


Figure 7. Regression correlation between the angle of internal friction and density of loess soil before compaction

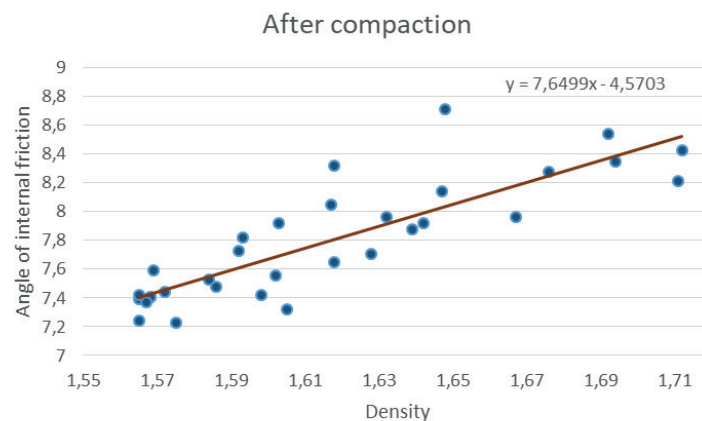


Figure 8. Regression correlation between the angle of internal friction and density of loess soil after compaction

The regression equations (Figs. 7, 8) are described by analytical relations, respectively

$$\varphi = 34.981 \cdot q - 45.923, \quad (11)$$

$$\varphi = 7.6499 \cdot q - 4.5703. \quad (12)$$

Regression equations (11) and (12) have a high degree of approximation to the experimental data. The approximation confidence coefficient for equation (11) is equal to 0.7192. For equation (12), the approximation confidence factor takes the value 0.7156. With increasing values of the angle of internal friction, there is

an increase in the density values of loess soil both before and after its compaction by deep explosions.

CONCLUSION

The article provides a mathematical modeling of the compaction of subsidence soils by explosion and studies the strength properties of loess by correlation and regression analysis. Specific cohesion and angle of internal friction correlate with moisture content and density of loess. Pearson correlation coefficients of strength and physical characteristics of soil showed that at soil moisture of $30\% \pm 2\%$ their high intercorrelation is observed. This is characteristic of loess soils before and after elimination of their subsidence properties by depth explosions. Regression equations of specific adhesion, angle of internal friction and humidity, density, respectively, of subsidence soils before and after their compaction have been constructed. It is established that with the increase of soil moisture the values of indicators of soil strength characteristics decrease. With increasing density of loess the growth of values of specific cohesion and angle of internal friction is fixed. Regression equations can be used in calculation mathematical models of engineering-geological systems in the design of construction objects on subsidence loess soils. They allow predicting indicators of soil strength characteristics on the basis of their physical characteristics.

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