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ON SOME SOIL SUBSIDENCE ESTIMATIONS BASED ON THE PARTICLE SIZE DISTRIBUTION

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ПРО ДЕЯКІ ОЦІНКИ ПРОСІДАННЯ ГРУНТІВ НА ПІДСТАВІ ГРАНУЛОМЕТРИЧНОГО АНАЛІЗУ

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О НЕКОТОРЫХ ОЦЕНКАХ ОСЕДАНИЯ ГРУНТОВ НА ОСНОВЕ ГРАНУЛОМЕТРИЧЕСКОГО АНАЛИЗА

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Annotation. In our previous investigations we studied subsidence of soils, which are alluvial, alluvial-dealluvial loess-like deposits of the Middle-Upper Pleistocene age, lying on the Right-Bank Loess and Upland Plain (Middle Dnieper, Ukraine). In this paper we study Neogene clays. Under some additional conditions of fractal nature of the loess soil, obtained certain predictive estimations of the coefficient of porosity after the disintegration of micro-aggregates. We discovered that under such conditions two different situations of particles packing may occur after disintegration of micro-aggregates. Let k' be the coefficient of porosity and K' be the porosity of the soil after the disintegration of micro-aggregates. These situations strongly depend on the fractal dimension of particle distribution by size. The results of our experiments and calculations show that on the basis of the new theoretical models and the "Microstructure" technique, having the values of the fractal dimension of the particle size distribution, it is possible to forecast the volume deformations after the disintegration of the micro-aggregates. With dispersed and semi-dispersed methods of preparation, the micro-aggregates disintegration occurs, resulting in increased content of fractions less than 0.01 mm. Unlike loess soils, with the semi-dispersed method of preparation, increased content of clay particles is characteristic for red-brown clays. Depending on the type of loess soil and specific experimental conditions, there may be the subsidence deformation, swelling or suffusion. By using the results obtained, we study properties of undifferentiated Neogene-Lower Quaternary, Neogene clays selected in Nikopol and Kamenskoye. The predicted values of the porosity coefficient will vary from 0.499 to 0.635 for different types of exposure, accompanied by the decomposition of aggregates. The most resistant to different types of impacts were undifferentiated Neogene-Lower Quaternary red-brown clays. The method allows you to develop a new classification of soils, based on the stability of the soil structure as the stability of micro-aggregates.

Key words: loess, fractal, porosity, deformation, granulometric analysis

In modern publications devoted to the problems of deformation and destruction of various geo-materials, considerable attention is paid to the description of the geometric properties of the structures formed by particles and pores. In [1,2] Russell described soil compaction using an example of a medium with particle and pore sizes that change during crushing. In [3,4] we have begun investigations of soil subsidence based on the fractal dimension of the particle size distribution. Using elements of fractal analysis by Zhang and Zhang [5] showed that the ratio between volumetric deformation and the index of crushing is constant during crushing. Seblany et al. [6] performed an analysis of the distribution of pores in the granular material. The effect of dispersion and cohesion on the behavior of soils is also very essential. In [7] internal and external factors of soil aggregates stability were studied, the author identified the types and explained the mechanism of soil aggregates stability. The above brief review of publications shows that the search for new models of geomaterials and soils is carried out in various aspects, a common tendency is to study materials as complex dynamic systems.

In [1], the particle size distribution $N_s(L>d_s)$ was defined as the number of particles being of any size L larger than d_s, where d_s runs over the real numbers.

The fractal dimension D_s of the particle size distribution is defined as follows

$$D_s = \lim_{d_s \to 0} - \frac{\ln(N_s(L>d_s))}{\ln(d_s)} \tag{1}$$

It follows from (1) that $-D_s \ln(d_s) \approx \ln(N_s(d_s))$ hence $\ln(d_s^{-D_s}) \approx \ln(N_s(d_s))$ and finally

$$N_s(L>d_s) \approx \gamma d_s^{-D_s} \tag{2}$$

where γ is a coefficient and the sign $\approx$ means "approximately". In our further equations we use the sign = taking in mind (2) and realizing that the obtained formulas give us just some estimations of the real situation.

In fact (2) gives us an estimation of the particle size distribution $N_s(L>d_s)$ which is based on a fractal topological invariant D_s. As it was mentioned in [1], modeling the particle size distribution using fractals provides a good fit to experimental data [8, 9,10].

The particles forming the ground may have only a finite set of sizes

$$d_1, d_2, ..., d_{n-1}, d_n \tag{3}$$

which are running from the largest d_1 to the smallest d_n.

We assume that the porous structure A_J, formed only by particles of size d_j, is similar to the porous structure A_i, formed only by particles of size d_i, for all $1 \le i, j \le n$. We will use the following denotations:

V_s - the volume of all considered particles,

A_j - the structure formed only by particles of size d_j,

$V_s(d_j)$ - the volume of particles of size d_j, which form the structure A_j,

$V_p(d_j)$ - the volume of pores of the structure A_j,

$V(d_j) = V_p(d_j) + V_s(d_j)$ - the volume of the whole structure A_j,

$A_{j_1} + A_{j_2} + ... + A_{j_k}$ the porous structure, formed only by particles of size, $d_{j_1}, d_{j_2}, ..., d_{j_k}$, where $k \le n$,

$V(A_{j_1} + A_{j_2} + ... + A_{j_k})$ - the volume of the structure $A_{j_1} + A_{j_2} + ... + A_{j_k}$.

V - the volume of the soil after subsidence,

$V_p = V - V_s$ - the volume of the pores of the soil after subsidence.

Then, as the structure A_J is similar to A_i for all $1 \le i, j \le n$, we can assume that,

$$V_p(d_j)/V_s(d_j) = V_p(d_i)/V_s(d_i) = \mathrm{k}_p \quad (4)$$

for all $1 \le i, j \le n$, i.e. the coefficient of porosity k_p of A_J does not depend on j. Hereby the porosity

$$V_p(d_j)/V(d_j) = k_p/(1+k_p) = K_p \quad (5)$$

of A_j also does not depend on j.

Equation (2) allows us to estimate the number $N_s(d_s)$ of particles of size d_s. Since an increment of the function $N_s(L > d_s)$ is only due the particles of sizes from (3) (i. e. in points $d_1, d_2, ..., d_{n-1}, d_n$), according to equation (2) we can estimate the number of particles of size d_j for each d_j from (3)

$$N_s(d_j) \approx \gamma d_{j+1}^{-D_s} - \gamma d_{j.}^{-D_s} = \gamma(d_{j+1}^{-D_s} - d_{j.}^{-D_s}), \quad (6)$$

where $1 \le j \le n-1$. It will be convenient for us to introduce an imaginary particle of the smallest size d_{n+1} so that the equation (6) holds for all $1 \le j \le n$ and we have

$$N_s(d_j) \approx \gamma(d_{j+1}^{-D_s} - d_{j.}^{-D_s}) = \gamma d_{j.}^{-D_s}((d_{j+1}/d_j)^{-D_s} - 1) \quad (7)$$

for all $1 \le j \le n$.

Following Russell [1], we assume that each particle of size d_j has volume d_j^3. Then, according to (7) we can estimate the volume $V_s(d_j)$ of all particles of size d_j as

$$V_s(d_j) = d_j^3 N_s(d_j) = \gamma d_{j.}^{3-D_s}((d_{j+1}/d_j)^{-D_s} - 1). \quad (8)$$

for all $1 \le j \le n$.

We introduce the following denotations (*):

1. $\alpha_j = d_{j+1}/d_{j.}$, where $1 \le j \le n$, note that $\alpha_j < 1$ because $d_{j+1} < d_{j.}$
2. $\beta_j = (d_{j+1}/d_{j.})^{-D_s} - 1 = \alpha_j^{-D_s} - 1$, where $1 \le j \le n$.

Everywhere below we assume that the relation $\alpha = \alpha_j = d_{j+1}/d_j$ holds, where $1 \le j \le n$. This assumption corresponds to the idea of the self-similarity of fractal structures. Then we have $\beta = \beta_j = \alpha^{-D_s} - 1$ does not depend on j, where $1 \le j \le n$,. Then it follows from (8) that

$$V_s(d_j) = \gamma\beta d_j^{3-D_s} \quad (9)$$

and it follows from the definition of the coefficient of porosity k_p that

$$V_p(d_j) = \gamma\beta \mathrm{k}_p d_j^{3-D_s}, \quad (10)$$

where $1 \le j \le n$. Thus, (9) and (10) give the following

$$V(d_j) = V_s(d_j) + V_p(d_j) = \gamma\beta(1+\mathrm{k}_p)d_j^{\,3-D_s}, \tag{11}$$

where $1 \le j \le n$.

We can calculate the total volume of particles by the following formula:

$$V_s = \gamma\beta\left(\sum\nolimits_{j=1}^{n} d_j^{\,3-D_s}\right) \tag{12}$$

Properties of structures $A_{j-1} + A_j$ formed by particles of adjacent sizes were studied in [3], where the case of the soil formed by particles of only two different sizes was considered. By (10) and (11), $V(d_j) < V_p(d_{j-1})$ if and only if $\gamma\beta(1+\mathrm{k}_p)d_j^{\,3-D_s} < \gamma\beta \mathrm{k}_p\, d_{j-1}^{\,3-D_s}$. After evident reductions we obtain $(d_j / d_{j-1})^{3-D_s} < \mathrm{k}_p / (1+\mathrm{k}_p)$. As $k_p / (1+k_p) = K_p$ and $d_j / d_{j-1} = \alpha$, we have $\alpha^{3-D_s} < K_p$. Thus $V(d_j) < V_p(d_{j-1})$ if and only if

$$\alpha^{3-D_s} < K_p \tag{13}$$

and it immediately implies that $V(d_j) > V_p(d_{j-1})$ if and only

$$\alpha^{3-D_s} > K_p \,. \tag{14}$$

If $\alpha^{3-D_s} < K_p$ then, by (13), $V(d_j) \le V_p(d_{j-1})$ and it means that the structure A_j is completely enclosed in pores of the structure A_{j-1} and the volume of the soil after subsidence (that is, the volume of the structure $A_{j-1} + A_j$) is equal to the volume of the structure A_{j-1}. Thus, $V(A_{j-1} + A_j) = V(d_{j-1})$. So, if $\alpha^{3-D_s} < K_p$ then

$$V(A_{j-1} + A_j) = V(A_{j-1}) \,. \tag{15}$$

If $\alpha^{3-D_s} > K_p$ then, by (14), $V(d_j) > V_p(d_{j-1})$ and it means that the structure A_j completely fills the pores of the structure A_{j-1} and hence pores of the structure A_{j-1} are absent in the structure $A_{j-1} + A_j$. Therefore, the structure $A_{j-1} + A_j$ consists of the structure A_j and particles of the size d_{j-1}. It implies that $V(A_{j-1} + A_j) = V_s(d_{j-1}) + V(d_j)$. Thus, if $\alpha^{3-D_s} > K_p$ then

$$V(A_{j-1} + A_j) = V_s(A_{j-1}) + V(A_j)\,. \tag{16}$$

As the next assertion shows, in the case of formation of the complete structure

$A_1 + A_2 + ... + A_n$ after subsidence there are possible two fundamentally different situations.

Assertion 1. In the above denotations we have *:*

1. If $\alpha^{3-D_s} < K_p$ then the structure $A_2 + ... + A_n$ is completely enclosed in pores of the structure A_1 and $V = V(A_1 + A_2 + ... + A_n) = V(A_1)$ *;*

2. If $\alpha^{3-D_s} > K_p$ then pores of the structure $A_1 + A_2 + ... + A_{n-1}$ are completely filled with structure A_n and $V = V(A_1 + A_2 + ... + A_n) = V(A_n) + \sum_{j=1}^{n-1} V_s(A_j)$.

Proof. The proof is by induction on n, if $n = 2$ then the assertion follows from (15) and (16).

1. Suppose that $K_p > \alpha^{3-D_s}$ then, by the induction hypothesis, $V(A_2 + ... + A_n) = V(A_2)$. However, by (13), we have $V(A_2) < V_p(A_1)$ and hence $V(A_2 + ... + A_n) < V_p(A_1)$. It implies that the structure $A_2 + ... + A_n$ is completely enclosed in pores of the structure A_1. Therefore, $V = V(A_1 + A_2 + ... + A_n) = V(A_1)$.

2. Suppose that $K_p < \alpha^{3-D_s}$ then, by the induction hypothesis, pores of the structure $A_1 + A_2 + ... + A_{n-2}$ are completely filled with structure A_{n-1} and $V(A_1 + A_2 + ... + A_{n-1}) = V(A_{n-1}) + \sum_{j=1}^{n-2} V_s(A_j)$. However, by (14), we have $V(A_n) > V_p(A_{n-1})$ and pores of the structure A_{n-1} are completely filled with the structure A_n. It implies that pores of the structure $A_1 + A_2 + ... + A_{n-1}$ are completely filled with structure A_n and $V = V(A_1 + A_2 + ... + A_n) = V(A_n) + \sum_{j=1}^{n-1} V_s(A_j)$.

Proposition 2. In the above denotations we have *:*

1. if $K_p > \alpha^{3-D_s}$ then $V = \gamma\beta(1 + \mathrm{k}_p) d_1^{3-D_s}$ *;*

2. if $K_p < \alpha^{3-D_s}$ then $V = \gamma\beta(\mathrm{k}_p\, d_n^{3-D_s} + \sum_{j=1}^{n} d_j^{3-D_s})$.

Proof. 1. If $K_p > \alpha^{3-D_s}$ then, by assertion 1.1, $V = V(A_1)$ and it follows from (11) that $V = \gamma\beta(1 + \mathrm{k}_p) d_1^{3-D_s}$.

2.If $K_p < \alpha^{3-D_s}$ then, by assertion 1.2, $V = V(A_n) + \sum_{j=1}^{n-1} V_s(A_j)$ and it follows from (11) and (12) that $V = \gamma\beta(1 + \mathrm{k}_p) d_n^{3-D_s} + \sum_{j=1}^{n-1} \gamma\beta d_j^{3-D_s}$ and after evident simplifications we obtain $V = \gamma\beta(\mathrm{k}_p\, d_n^{3-D_s} + \sum_{j=1}^{n} d_j^{3-D_s})$.

We put $V_p = V - V_s$ for the volume of pores after subsidence. Then

$$k' = V_p / V_s = (V - V_s) / V_s = (V / V_s) - 1 \quad (17)$$

is the coefficient of porosity of the soil after subsidence and

$$K' = V_p / V = (V - V_s) / V = 1 - (V_s / V) \quad (18)$$

is the porosity of the soil after subsidence.

Proposition 3. In the above denotations we have *:*

1. If $K_p > \alpha^{3-D_s}$ then $k' = \dfrac{(1+k_p)d_1^{3-D_s}}{\sum_{j=1}^{n} d_j^{3-D_s}} - 1$ and $K' = 1 - \dfrac{\sum_{j=1}^{n} d_j^{3-D_s}}{(1+k_p)d_1^{3-D_s}}$.

2. If $K_p < \alpha^{3-D_s}$ then $k' = \dfrac{k_p d_n^{3-D_s}}{\sum_{j=1}^{n} d_j^{3-D_s}}$ and $K' = \dfrac{k_p d_n^{3-D_s}}{k_p d_n^{3-D_s} + \sum_{j=1}^{n} d_j^{3-D_s}}$.

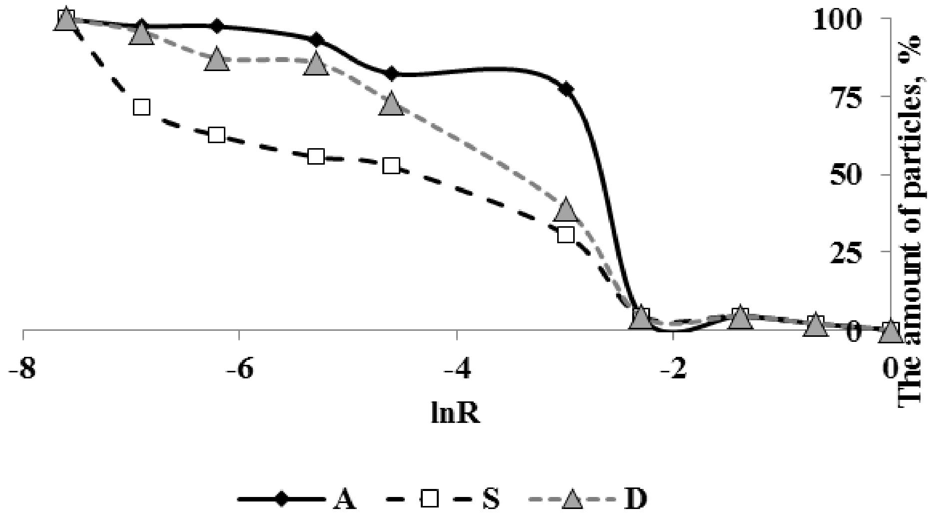
Proof. 1. If $K_p \geq \alpha^{3-D_s}$ then, by proposition 2.1, $V = \gamma(1+k_p)d_1^{3-D_s}\beta$ and it follows from (12), (17) that $k' = (V/V_s) - 1 = \dfrac{(1+k_p)d_1^{3-D_s}}{\sum_{j=1}^{n} d_j^{3-D_s}} - 1$ and by (18)

$$K' = 1 - (V_s/V) = 1 - \frac{\sum_{j=1}^{n} d_j^{3-D_s}}{(1+k_p)d_1^{3-D_s}}.$$

2. If $K_p < \alpha^{DV_s}$ then, by proposition 2.2, $V = \gamma\beta(k_p d_n^{3-D_s} + \sum_{j=1}^{n} d_j^{3-D_s})$ and it follows from (12) , (17) that $k' = (V/V_s) - 1 = \dfrac{k_p d_n^{-DV_s} + \sum_{j=1}^{n} d_j^{3-D_s}}{\sum_{j=1}^{n} d_j^{3-D_s}} - 1 = \dfrac{k_p d_n^{3-D_s}}{\sum_{j=1}^{n} d_j^{3-D_s}}$ and by (18)

$$K' = 1 - (V_s/V) = 1 - \frac{\sum_{j=1}^{n} d_j^{3-D_s}}{k_p d_n^{3-D_s} + \sum_{j=1}^{n} d_j^{3-D_s}} = \frac{k_p d_n^{3-D_s}}{k_p d_n^{3-D_s} + \sum_{j=1}^{n} d_j^{3-D_s}}.$$

Using the results obtained in proposition 3 we study the properties of undifferentiated Neogene-Lower Quaternary clays selected in Nikopol. The details of our experiments and techniques are described in [4]. The specific weight of the soil is 2.58 g/sm^3, natural soil moisture is 0.08. The granulometric content of the composition is characterized by predominant of particle size less than 0.1 mm (Figure 1).



Explanations to Fig. 1, 2: (A)- Aggregate method of sample preparation; (S) - semi-dispersed method of sample preparation; (D) - dispersed method of sample preparation.

Figure1 - The curves of granulometric composition of undifferentiated Neogene-Quaternary red - brown clays N_2-Q_1 (Nikopol)

Under dispersed and semi-dispersed methods of preparation of micro-aggregates disintegration occurs, resulting increase in the content of fractions less than 0.01 mm. Unlike loess soils, increased content of clay particles under semi-dispersed method of preparation is characteristic for red-brown clays.

The study of the properties of Neogene clays (***N_{1-2}*** gray and ***N_2bv*** red-brown clays) selected in the city of Kamenskoye shows that the content of clay particles is very high (fig.2). The same patterns are characteristic of loess soils.

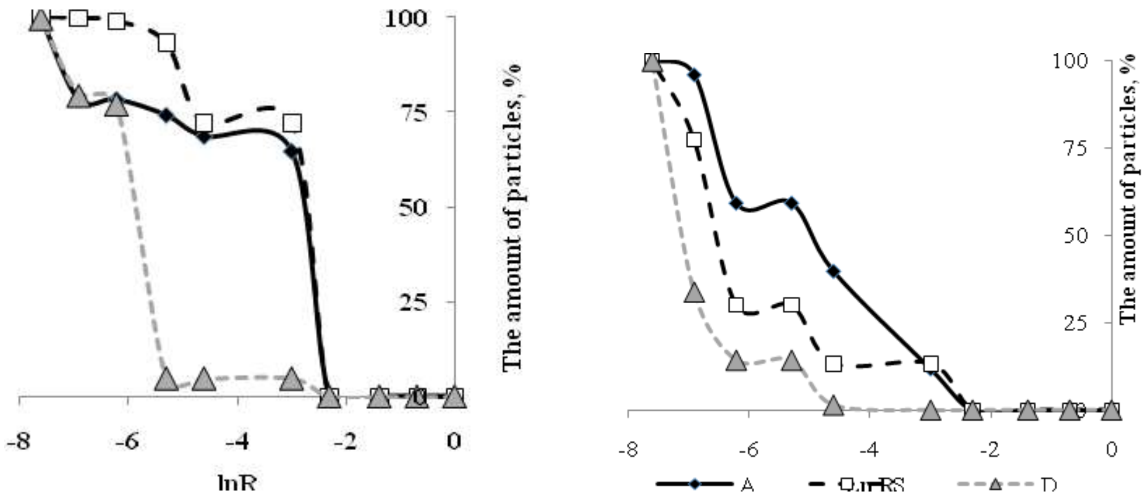
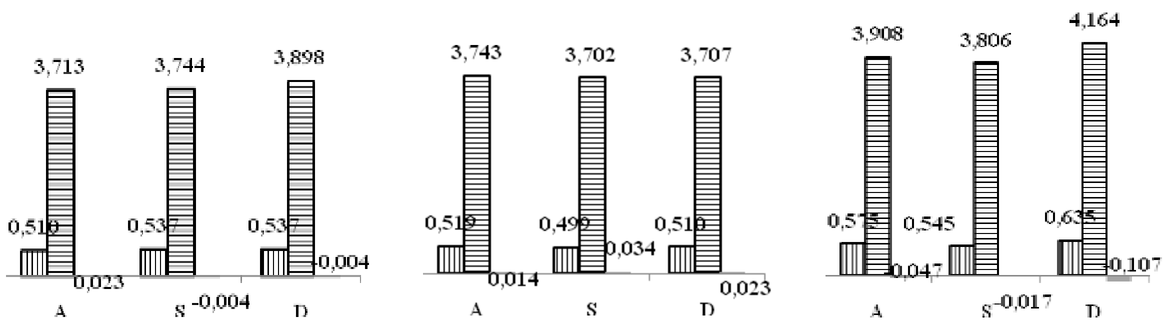


Figure 2 - The particle size distribution curves of clays gray ***N_{1-2}*** (a); clays red-brown ***N_2bv*** (b) (Kamensk)

The calculation of the predicted values of the volumetric deformation during the decomposition of soil aggregates subjected by mechanical and chemical influences shows that the clay in the Neogene age is characterized by a commonality in the predicted behavior caused by changes in the micro-aggregate state (Fig. 3). The predicted values of the porosity coefficient will vary from 0.499 to 0.635 for different types of exposure, accompanied by the decomposition of aggregates.

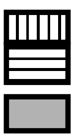


a b c

Figure 3 - Predicted values of the fractal dimension of the particle size distribution and volumetric deformations of: Neogen - Quaternary clays ***N_1-Q*** (a); Neogen clays ***N_2bv*** (b); ***N_{1-2}***, Kamenskoe, Nikopol (c)

Explanations for Fig 3:

A, S, D - aggregate, semi-dispersed and dispersed method of preparation;


- porosity coefficient predicted values.
- the value of the fractal dimension of the particle size distribution.
- predicted values of volumetric deformation of soils.

The most resistant to different types of impacts were undifferentiated Neogene-Lower Quaternary red-brown clays. The atypical behavior of the red-brown Miocene clays is manifested in the fact that the greatest deformations are possible as a result of chemical influences (semi-dispersed method), in this case the micro-aggregate structure is preserved. The most sensitive were the oldest gray-blue montmorillonite clay N_{1-2}, they are prone to swelling soaking and, as a result, decompression.

Conclusion. Deformation associated with the processes of destruction of aggregates, accompanied by the destruction of the soil structure and changes in strength properties. As a result of predictive determinations of the fractal dimension of the particle size distribution and a quantitative assessment of the expected deformations, we make conclusions about clay sensitivity. Red-brown calcareous clay, regardless of the rock formation age, will be characterized by less sensitivity compared to clays of the montmorillonite composition. The method allows you to develop a new classification of soils, based on the stability of the soil structure as the stability of micro-aggregates.

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Анотація. У попередніх наших дослідженнях ми вивчали просідання ґрунтів, які є елювіальними, елювіально-делювіальними лесоподібними відкладами середньо-верхнього плейстоцену, що присутні на Правобережній Лесовій рівнині (Середнє Придніпров'я, Україна). У представленій роботі ми вивчаємо глини Неогену. За деяких додаткових умов фрактальної природи льосового ґрунту ми отримали певні прогнозні оцінки коефіцієнта пористості після розпаду мікроагрегатів. Ми виявили, що за таких умов можуть статися дві різні ситуації упаковки часток грунту після розпаду мікроагрегатів.. Ці ситуації дуже залежать від фрактальної розмірності розподілу часток за розміром. Результати наших експериментів та розрахунків показують, що на основі нових теоретичних моделей та методики "Мікроструктура", якщо є значення фрактальної розмірності розподілу розміру частинок, можна передбачити об'ємні деформації після дезінтеграції мікроагрегатів. На відміну від льосових ґрунтів, для червоно-бурих глин характерний підвищений вміст глинистих частинок при напівдисперсному способі приготування. Залежно від типу льосового ґрунту та конкретних експериментальних умов може виникнути осідання, набряк або суфозія. Використовуючи результати, отримані в статті, ми вивчаємо властивості неоген-нижньочетвертинних та неогенових глин, відібраних у Нікополі, Каменському. Прогнозовані значення коефіцієнта пористості будуть змінюватися від 0,499 до 0,635 для різних типів впливу, що супроводжуються розкладанням агрегатів. Найбільш стійкими до різних типів ударів були недиференційовані неоген-нижньочетвертинні червоно-бурі глини. Метод дозволяє розробити нову класифікацію ґрунтів, засновану на стійкості структури ґрунту як стійкості мікроагрегатів.

Ключові слова: лес, фрактал, пористість, деформація, гранулометричний аналіз

Анотация. В предыдущих наших исследованиях нами было изучено оседание грунтов, представляющих собой элювиальные, элювиально-делювиальные лессовидные отложения среднего и верхнего плейстоцена, залегающие на Правобережной лессовой возвышенной равнине (Средний Днепр, Украина). В представленной работе мы изучаем неогеновые глины. При некоторых дополнительных условиях фрактальной природы лессового грунта были получены определенные прогнозные оценки коэффициента пористости после распада микроагрегатов. Мы обнаружили, что в таких условиях могут возникнуть две разные ситуации упаковки частиц после распада микроагрегатов. Эти ситуации сильно зависят от фрактальной размерности распределения частиц по размерам. Результаты наших экспериментов и расчетов показывают, что на основе новых теоретических моделей и метода «Микроструктура», имея значения фрактальной размерности распределения частиц по размерам, можно прогнозировать объемные деформации грунта после распада микроагрегаты. В отличие от лессовых почв повышенное содержание глинистых частиц при полудисперсном способе приготовления характерно для красно-коричневых глин. В зависимости от типа лесса и конкретных условий эксперимента, могут наблюдаться деформации уплотнения, набухания или суффозия. Используя результаты, полученные в статье, мы изучаем свойства нерасчлененных неоген-нижнечетвертичных неогеновых глин, отобранных в Никополе, Каменском. Прогнозируемые значения коэффициента пористости будут варьироваться от 0,499 до 0,635 для разных типов воздействия, сопровождающихся разложением агрегатов. Наиболее устойчивыми к различным типам ударвоздействий были недифференцированные неоген-нижнечетвертичные красно-коричневые глины. Способ позволяет разработать новую классификацию грунтов, основанную на стабильности структуры почвы как стабильности микроагрегатов.

Ключевые слова: лесс, фрактал, пористость, деформация, гранулометрический анализ

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