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STUDY OF DEGRADATION PATTERNS OF STRENGTH PROPERTIES IN SOIL MASSIF DUE TO DYNAMIC (EXPLOSIVE) LOADING

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ДОСЛІДЖЕННЯ ЗАКОНОМІРНОСТЕЙ ДЕГРАДАЦІЇ МІЦНІСНИХ ВЛАСТИВОСТЕЙ ҐРУНТОВОГО МАСИВУ ВНАСЛІДОК ДИНАМІЧНИХ (ВИБУХОВИХ) НАВАНТАЖЕНЬ

Purpose. Establishing the patterns of changes in physical and mechanical properties of loess loams of the Dnipro region under the influence of explosive loading in conditions of a technogenically altered geological environment for assessment of stability and prediction of soil behavior during further engineering development of the territories.

Methods. A series of laboratory experiments is conducted on samples of loess loams collected from the right-bank part of the city of Dnipro, specifically from an area damaged by an explosion. The samples are analyzed for their physical parameters (density, moisture content, porosity), as well as for their granulometric and chemical composition. Tests are carried out using the TriSCAN (VJTech) software to determine strength parameters before and after explosive loading. Thixotropic changes in the soils are also analyzed over a period of 35 days following the explosion.

Results. The patterns of strength changes in the zone compacted by the explosion are established, with a 2–2.5-fold increase in specific cohesion observed in the area of maximum impact. This increase gradually decreased to natural values at a distance of 13–14 meters, and then dropped below the initial level. Over the course of 6–7 days following the explosion, cohesion increased by 25–30%, confirming the manifestation of thixotropy. The internal friction angle changed during the first 5–7 days, after which it stabilized.

Scientific novelty. For the first time, changes in physical and mechanical characteristics of loess loams of the Dnipro region due to degradation under explosive loading have been experimentally established. The dependency of cohesion and internal friction angle changes on time after loading is determined, which makes it possible to justify the mechanism of massif degradation under technogenic impact conditions.

Practical significance. The obtained experimental results can be used in the design, construction, and operation of engineering structures in areas affected by explosive loading. Taking into account the changes in physical and mechanical properties of the soil massif allows improving safety and durability of construction projects, particularly on specific loess soils.

Keywords: *loess loams, explosive loading, thixotropy, cohesion, internal friction angle, compaction, technogenesis, Dnipro region.*

Introduction. The necessity of ensuring stability of slopes, structures, and assessing the strength and load-bearing capacity of rock massifs affected by explosive loads is associated with changes in soil parameters over time and space. Some theoretical and empirical prerequisites for conducting a series of laboratory studies on loess soils, which are characteristic of the Dnipro region, are highlighted in works [1–3]. A significantly new approach to understanding the geodynamic mechanism of these soils under modern technogenic loading conditions is outlined in these papers. Therefore, the main objective of this study is to establish patterns that characterize the range of parameter changes in loess soil mass degradation due to dynamic (specifically, explosive) loads. Their technogenesis under various conditions is taken into account. This study provides a comprehensive approach to solving the pressing issue and allows obtaining new scientific results regarding the mechanism of soil destruction.

Previous studies [4] have not given enough attention to the study of physical-mechanical parameters of different types of loess soils and the establishment of correlation relationships between volumetric deformation processes and corresponding soil parameters. In particular, material and granulometric composition, porosity, or degree of water saturation. Previously, the research was focused primarily on sands, while volumetric dynamic compression of loess formations under such conditions has not been sufficiently described. However, in the territory of Right-bank Ukraine, many applied tasks related to this research are specifically realized in loess soils [4–5]. Considering the above, studying the complex of hydrogeodynamic, energetic, and geomechanical criteria for degradation of loess structures, considering their technogenesis under dynamic loading conditions, allows obtaining fundamentally new scientific results regarding their stability.

The main part. The study area is located on the terraced right-bank part of the city of Dnipro, in its southern part. It is represented by a sedimentary sequence of Quaternary and Upper Pliocene deposits that overlie crystalline rocks and their weathering crust, specifically kaolins and grus material. The deposits consist of sands from the Poltava series, variegated and red-brown clays, and the loess series (fig. 1).

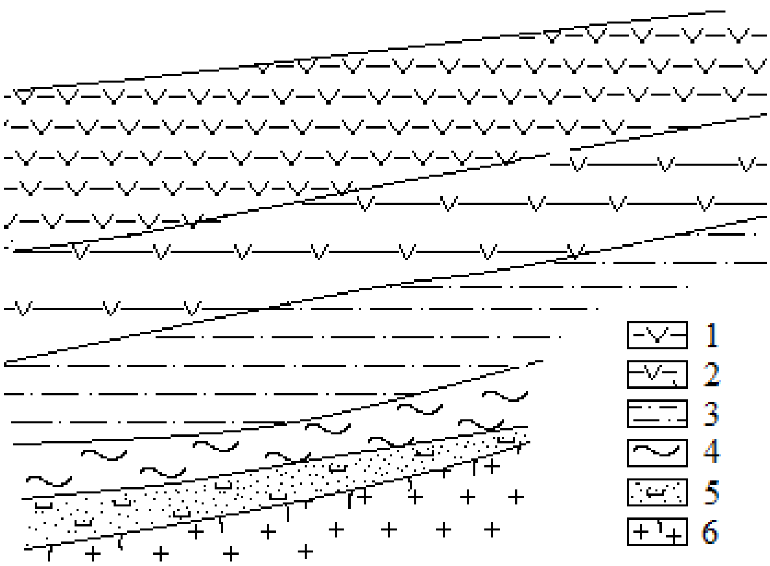

Fig. 1. Schematic cross-section of study area: 1 – brownish-gray and light brown sandy loess loam with carbonates; 2 – yellowish-gray sandy loess loam with carbonates, interbedded with fossil soils; 3 – yellowish-gray sandy light loess loam with carbonates, transitioning into sandy loam at the lower part; 4 – clay; 5 – sand with kaolin inclusions; 6 – fractured weathering crust of acidic crystalline rocks

Various types of loess loams are selected as samples for the experiments. Loam parameters are – bulk density of 1.8–1.95 g/cm^3; skeletal bulk density of 1.7–1.74 g/cm^3; porosity of 35–36%; and moisture content (by weight) of 13–15.5%. Additionally, a granulometric analysis of the selected sample is conducted (fig. 2).

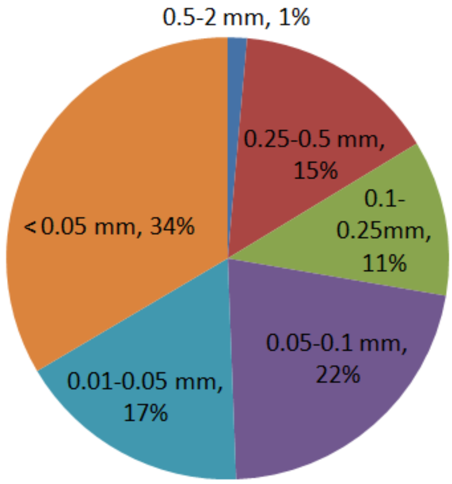

Fig. 2. Results of granulometric analysis of selected loess loam samples

These loess variants predominantly have a siliceous-clay composition with admixtures of carbonates and metal oxides. The primary component is silica (SiO_2), with a content ranging from 55% to 65%. There is a significant portion of aluminum oxides (Al_2O_3) at 10–15% and iron oxides (Fe_2O_3) at 4–7%. Carbonates, mainly represented by calcium oxide (CaO) and magnesium oxide (MgO), are present in amounts of 3–7% and 1–3%, respectively. Alkali elements, such as potassium oxide (K_2O) and sodium oxide (Na_2O), constitute 2–4% and 1–2%, respectively. The loss on ignition (LOI), which includes carbonates, organic matter, and hygroscopic water, can reach 8–15% [5–6]. The presence of carbonates indicates moderate resistance of loess loam to moisture exposure.

Soil moisture is one of the key factors determining soil behavior under loading, especially in the case of loess rocks, whose specific properties complicate the prediction of their behavior both in natural conditions and under technogenic loads. Depending on the type of loading – static or dynamic – the effect of moisture on soil deformation differs both quantitatively and qualitatively due to differences in deformation mechanism. Under static loading, deformation is associated with changes in a ratio of soil components due to the removal of free moisture as deformations stabilize (the consolidation process). Under dynamic loading (e.g., from explosions or impacts), deformation occurs mainly due to the short-term effect of excess pressure, leading to a reduction in free porosity and, to some extent, the elastic compression of water and the mineral skeleton. Thus, under dynamic loading, there is the concept of optimal moisture content [4, 7], at which irreversible soil deformations are at their maximum. However, this parameter is not constant for all soil types – it depends on the character of loading and the velocity of load application.

When an explosive wave impacts a soil massif within the zone of inelastic deformations, stress on the front decreases with simultaneous loading mode change. This means its velocity decreases, approaching quasistatic conditions. Based on the analysis of selected samples and corresponding laboratory studies, it is established that in cohesive soils, the greatest changes in density occur in the zone directly adjacent to the explosion crater. Accordingly, with an increase in soil moisture, compaction is significantly higher (18–20%), but when moisture content approaches full saturation, a size of the compacted zone increases, while the change in density within this zone becomes insignificant. Similar results are obtained in other studies [7–8].

Based on the selected samples, studies of strength parameters are conducted for loess loams, focusing primarily on their changes in the explosion-compacted zone, as well as thixotropic changes in the soil under explosive loading. The values of specific cohesion and friction coefficient are determined using the triaxial compression method, specifically by utilizing the TriSCAN (VJTech, UK). The advantage of this method for testing loess formations is in the close approximation of hydrogeomechanical testing conditions to the real soil state conditions within the massif. The device allows automated monitoring of pressure in the loading chamber, linear and volumetric deformations of the sample, as well as the water flow passing through the sample in real time. A series of tests of filtration parameter are conducted under triaxial compression at different loading values. The geostatic pressure is set within ranges corresponding to depths from which the samples are taken (5–7 m), with natural moisture content reflecting the actual conditions of the loess massif. The testing duration is 24 hours. Before conducting the tests, the samples undergo consolidative pre-compaction under loads corresponding to geostatic pressure, until the deformation stabilizes according to applicable standards. The samples are collected 6–7 days after the explosions in the studied area.

Processing the experimental results allows drawing the following conclusions:

Soil cohesion value immediately near the walls of the explosion crater and further into the massif, increases by 2 to 2.5 times compared to the soil's natural undeformed state.

According to the research, it is determined that the change in cohesion (fig. 3) decreases sharply as the distance from the explosion center increases. At approximately 13–14 meters, the cohesion value becomes equal to that of the undeformed soil. Further into the massif, cohesion decreases to values 1.5 to 2 times smaller than the initial ones, and as it approaches the boundaries of the deformation zone, it increases again to its natural values.

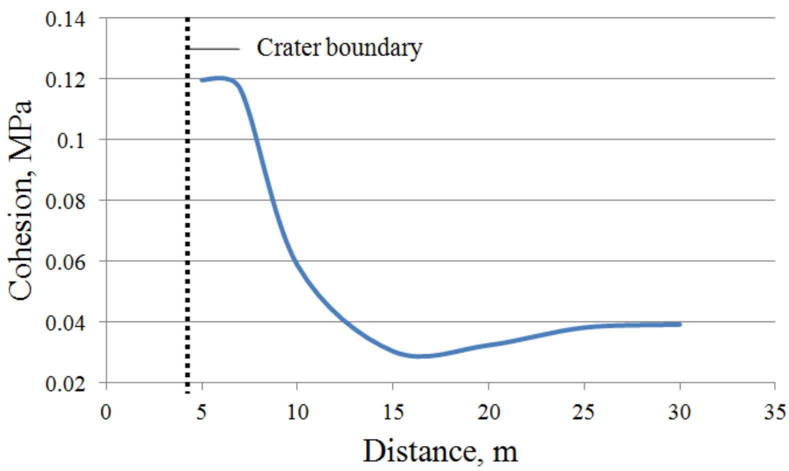

Fig. 3. Change in cohesion value of loess loams as a function of distance from an explosion crater boundary

The angle of internal friction in the compacted zone changes as follows: at the crater contour (in the compaction zone), its value increases by 3–4.5 degrees compared to the initial value before the explosion (fig. 4). As the distance from the explosion center increases, the value of φ decreases back to the initial values. Furthermore, the zone size where this change occurs, is significantly smaller than the size of zones where the cohesion changes.

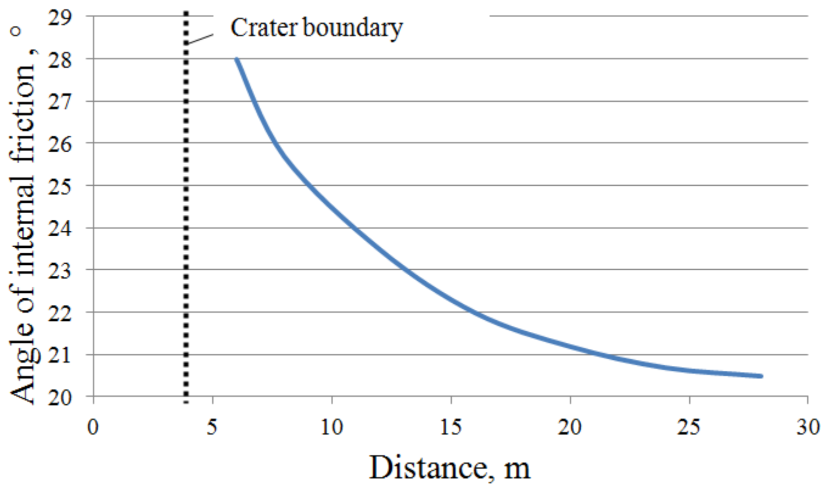

Fig. 4. Change in an angle of internal friction of loess loams as a function of distance from a crater boundary formed by explosion

Thus, changes in strength characteristics of loess loams in the explosion-compacted zone are sign-variable: in some areas the soil gains additional strength, while in other corresponding areas it loses strength compared to its initial state, i.e., it undergoes deconsolidation.

There are research data [8–9], which indicate that soil cohesion increases over time. Interestingly, the main increase is observed around 6–7 days after the explosion (the same period during which the samples for this study are taken). In terms of absolute values, the increase in cohesion is approximately 25–30% of the values observed immediately after the explosive loading. The cohesion increases most intensely in the zone of maximum deformations and less so in the peripheral zones. About 30–35 days after the explosive load, a slight increase in cohesion can be observed, although the rate of these changes is small, meaning the thixotropic process can be considered complete. Over time, the internal friction angles φ of the explosion-compacted zone increase, with this change occurring only within the first 5–7 days. After that, changes in φ are practically unnoticeable.

Analysis of the research results shows that thixotropic changes occur in the explosion-deformed loamy soils. This is confirmed by the changes over time in the cohesion values in areas of the compacted zone. With this, negligible volumetric deformations occur outside it, where no changes in density (bulk weight) are observed. These behavioral characteristics of soils are even more evident in explosions involving charges in loamy soils and water-saturated loess loams [4, 7].

The relatively small number of experiments allows making a qualitative confirmation of the results described above. It is also noted that these characteristics are more pronounced in clays and water-saturated loess loams. At the same time, the zones with reduced cohesion values, both in terms of absolute magnitude and the size of zones of deconsolidation, exceed those observed for loess loams.

Conclusions.

1. It is experimentally confirmed that explosive loading significantly affects the physical and mechanical characteristics of loess loams in the Dnipro region, causing changes in their density, cohesion, and internal friction angle. It is established that in the area directly affected by the explosion (near the explosion crater), there is an increase in the specific cohesion of soil by 2–2.5 times compared to its natural state. This value gradually decreases with increasing distance from the explosion epicenter, reaching natural values at a distance of 13–14 meters, and then decreases in certain zones to 1.5–2 times lower than the initial values.

2. The study also identified sign-variable patterns in the behavior of strength characteristics of loess loams in the explosion-compacted zone. In some areas, there is compaction and an increase in strength, while in others, there is deconsolidation and a decrease in strength. Thixotropic changes in loess loams lead to a gradual increase in cohesion during the first 6–7 days after the explosion, with this increase being 25–30% of the initial values. Over the next 30–35 days, the rate of these changes significantly decreases, indicating the completion of the thixotropic process. A change in the internal friction angle occurs during the first 5–7 days after the explosion, after which this parameter remains almost stable, indicating the irreversibility of a deformation processes in the studied rocks.

3. The research results highlight the need to consider changes in physical and mechanical parameters of loess loams when designing and operating engineering structures in areas subjected to explosive loading, in order to ensure their stability and durability.

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АНОТАЦІЯ

Мета. Встановити закономірності змін фізико-механічних властивостей льосових суглинків Придніпров'я під впливом вибухового навантаження в умовах техногенно зміненого геологічного середовища для оцінки стійкості та прогнозування поведінки ґрунтів при подальшого інженерному освоєнні територій.

Методика. Проведено серію лабораторних експериментів на зразках льосових суглинків, відібраних з правобережної частини міста Дніпро. Зразки проаналізовано за їх фізичними параметрами (щільність, вологість, пористість), а також за гранулометричним та хімічним складом. Випробування здійснювались з використанням TriSCAN (VJTech) для визначення параметрів міцності до та після вибухового навантаження. Аналізувалися також тиксотропні зміни ґрунтів протягом 35 діб після вибуху.

Результати. Встановлено закономірності зміни міцності у зоні, ущільненої вибухом, де у зоні максимального впливу спостерігалося зростання питомого зчеплення у 2–2,5 рази, яке поступово зменшувалося до природних значень на відстані 13–14 м, а потім — знижувалося нижче за початковий рівень. Протягом 6–7 днів після вибуху відбувалося зростання зчеплення на 25–30 %, що підтверджує прояв тиксотропії. Кут внутрішнього тертя змінювався у перші 5–7 діб, після чого стабілізувався.

Наукова новизна. Вперше експериментально встановлено зміни фізико-механічних характеристик льосових суглинків Придніпров'я внаслідок деградації під дією вибухового навантаження. Визначено залежність зміни зчеплення та кута внутрішнього тертя від часу після навантаження, що дозволяє обґрунтувати механізм деградації масиву в умовах техногенного впливу.

Практична значимість. Одержані експериментальні результати можуть бути використані при проєктуванні, будівництві та експлуатації інженерних споруд на територіях, що знаходяться під впливом вибухових навантажень. Врахування змін фізико-механічних властивостей ґрунтового масиву дозволяє підвищити безпеку та довговічність об'єктів будівництва, зокрема на специфічних льосових ґрунтах.

Ключові слова: *льосові суглинки, вибухове навантаження, тиксотропія, зчеплення, кут внутрішнього тертя, ущільнення, техногенез, Придніпров'я.*