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Development of tools (laboratory facilities) for researching the effect of physical properties of landfill soils on slope stability

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Abstract. The paper presents a developed laboratory unit and a technique for conducting experimental studies of the effect of physical properties of landfill soils, such as moisture, density, temperature, on slope stability in order to verify the reliability of a mathematical model and a methodology for preventing emergencies associated with displacement developed on its basis. Conducted field studies of humidity, density, temperature of landfill soils of typical solid waste disposal facilities. The analysis of the conditions for obtaining the maximum amount of methane in the composition of biogas has been carried out. The basic requirements for the laboratory unit have been determined and the area of the factor space for conducting experimental laboratory studies has been established.

1. Introduction and literature review

At landfills of municipal solid waste (MSW) or landfills, there are numerous cases of hazardous events, emergency situations associated with fires and landslides [1–3]. The consequences of the emergency danger include a significant area of their distribution and a significant number of dead, injured, persons with violation of the living conditions. The basis of the process of limiting the spread of the consequences of emergencies is work aimed at changing the physical properties of landfill soils [4], taking into account the provision of conditions for their safe management [3], and the impact of hazardous factors outside the object of their occurrence on the environment and the population (for example, on the state of the atmospheric air, as the main source of transport of hazardous substances that can harm the population in the area of possible damage [5, 6]).

Humidity, density, temperature of landfill soils affect both the dynamic behavior of the MSW slopes, and the composition of the generated biogas – an alternative source of energy. Facilities of utilization biogas may be incur by hazardous emergency factors – lose their technical condition [7, 8]. The desire to obtain the maximum amount of methane in biogas at waste disposal facilities is an additional factor in studying the influence of the physical properties of MSW soils on the stability of slopes, in the context of solving civil security problems.

First of all, let's note that according to the modern interpretation, emergency is a conditional level of the course of an emergency, which is achieved behind one or more dominant signs, in terms of the level of threat and/or the possibilities of counteraction. In work [9], which additionally considers liquidation energy-intensive technological equipment (operating on biogas obtained from a disposal facility) as a zone of propagation of hazard consequences, it is indicated that solving problems of assessing moisture, density, temperature of landfill soil makes it possible to determine the conditions for the absence of victims and casualties among civilians and specialists of units of the State Emergency Service of Ukraine.

The solution to the problem of assessing the moisture content of landfill soil is an analytical relationship that describes the relationship of moisture in accordance with the variation of the input and output fluid flows. The solution to the problem of assessing the density describes the relationship



of density in accordance with variations in the load force, porosity, height of waste storage. The solution to the problem of assessing the temperature - describes the relationship of temperature in accordance with the variation in the amount of heat supplied or generated and removed from the landfill massif.

Today, in view of the development of a mathematical model and the methodology developed on its basis for the prevention of emergency situations of a cascade type of propagation associated with the displacement of landfill soil at potentially hazardous facilities, there is a need to verify their reliability. Thus, the unresolved part of the problem is the development of a simple and visual laboratory base for laboratory studies of the influence of the physical properties of landfill soils on the stability of slopes in order to solve civil security problems.

The mechanism of destruction and the mode of instability of MSW facilities are studied based on the results of field research, tests of physical models, and simulation.

With the help of ground engineering seismic exploration by the method of refracted waves, the physical and mechanical properties of the MSW facilities in natural bedding were established [10]. Field studies [11] have shown that landfills consist mainly of soil-bearing material (51 %) and plastic (31 %) with an average moisture content of 43 % at the surface and 53 % at a depth of about 11 meters.

The authors of [12], using the method of multichannel analysis of surface waves, obtained data on the speed of wave propagation in the waste mass, which were later used for extended interpretation of the sounding results - identifying solid waste as a soil-like material, obtaining information about the structure of the waste column, mechanical characteristics. The waste massif can be divided into several layers according to the age of the burial [13]. Each of the waste layers has an individual composition and shear strength characteristics. According to the results of the triaxial test [13], the MSW shear strength increases with the years. Slope stability decreases linearly with increasing external load [14].

The simulated situations [15] show the overall stability of the MSW facility without fire was 1.13; with fire, when the tensile strength has been lost, the overall stability is 1.00. Laboratory research program [16] using direct landslide (DS), triaxial and simple landslide tests, taking into account the influence of waste composition, orientation of fibrous particles, limited stress, stress rate of change, stress-strain compatibility and specific gravity showed that static strength MSW shear DS is best characterized by a cohesion of 15 kPa and a friction angle of 36° at a normal stress of 1 atm. with a decrease in the angle of friction by 5 V for each logarithmic cycle of normal stress growth.

A series of model tests of centrifuges [17, 18] demonstrated the development of failure processes in the stability of a waste array under conditions of an increased moisture level. The ratio of the critical water level and the height of the solid waste array were about 0,8 [18].

Scientists [19] investigated the shear strength by inverse analysis of failures on slopes: for normal stresses less than 200 kPa, the specific adhesion is 6 kPa, the angle of internal friction is 35° ; for normal stresses over 200 kPa, the specific adhesion is 30 kPa, the angle of internal friction is 30° .

The authors of [20], based on the analysis of existing trays and their structures, developed a laboratory unit and research methodology to identify a qualitative picture of the formation of cracks on model materials and cover deposits of landslide-prone slopes moistened with atmospheric precipitation of varying intensity. The slope model was erected in a transparent tray; to change the slope angle, vertical posts with holes and metal fixing rods of the corresponding height (slope angle 25°) were used. Work direction to study the effect of moisture, changes in the initial density, temperature were not taken into account.

Most of the works on determining the mechanism of destruction and the mode of instability of MSW facilities are based on the results of field research and simulation using computer programming, and the laboratory base used by the authors has insufficient visibility of the mutual influence of the physical properties of landfill soils, such as moisture, density, temperature on the stability of slopes. and the possibility of conducting research on the hazardous impact of landslide experimental blocks on process equipment. Modern trends in the reconstruction of MSW facilities include the placement of

liquidation energy-intensive technological equipment on the territory of potentially hazardous facilities, and are sources of the emergence and spread of man-made emergencies.

The aim of the paper is to develop a laboratory unit and a methodology for conducting experimental studies of the effect of physical properties of landfill soils on slope stability in the context of solving civil security problems, taking into account the results of field studies of humidity, density, temperature of landfill soils of typical solid domestic waste disposal facilities, analysis of conditions for obtaining the maximum amount of methane as part of biogas.

2. Construction of the model and its analysis

To achieve this aim, theoretical and experimental research methods were comprehensively used: analysis and synthesis, generalization, probability theory, decision theory, field and laboratory methods of observation and measurement.

The determination of the values of the physical properties of the landfill soil and sampling were carried out by the envelope method at five typical MSW landfills at a depth of 2.5 m at different times of the year. Moisture was measured using an MG-44 soil moisture meter, density – a LAN-M soil density meter, temperature – an electronic thermometer. Mechanical characteristics of strength (angle of internal friction, specific adhesion) were measured by the single-plane cut method in accordance with DSTU B V.2.1-4-96 (GOST 12248-96) “Bases and foundations of buildings and structures. Soils. Methods for laboratory determination of strength and deformability characteristics” [21].

The developed laboratory unit (Fig. 1) includes a rectangular experimental box with rotary (1) and fixed (2) parts, rotary (3) and locking mechanisms (4), tabletop heating plates (5), sprayer (6), system tangential load (7).

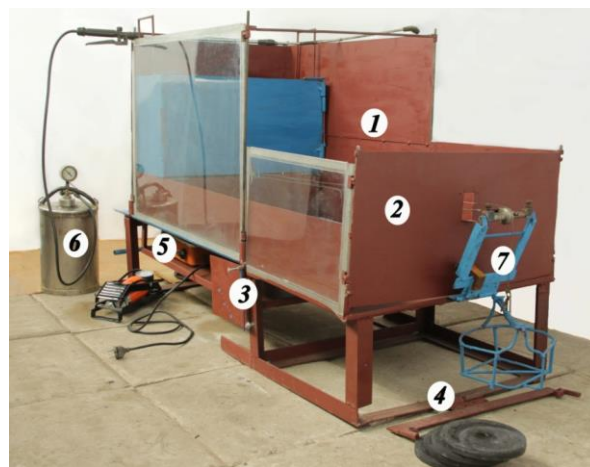


Figure 1. Laboratory unit for studying the influence of physical properties of landfill soils on the stability of slopes.

The base of the experimental box (1, 2) is made of sheet iron with a thickness of 3 mm with dimensions of 800x600x600 mm of swivel and 500x600x300 mm of fixed parts. At the bottom of the rotary part, ribs are provided for rigid fixation of the base of the sliding surface. The side walls on three sides are made of 2 mm thick sheet iron, and the fourth, a viewing window, is made of 4 mm thick glass edged with silicone slats.

The rotary mechanism (3) consists of loops, parts of the experimental box are fastened together, the tilt angle indicator is a protractor. The tilt angle is reproduced using a hydraulic bottle jack 5 t 80-030Miol 216-413 mm, which is installed on a shield with dimensions of 40x120x400 mm. The locking mechanism (4) is made in the form of a pedestal with an anchor made of a steel corner 50x50mm and a plate with dimensions of 50x500 mm and a thickness of 5 mm.

For heating the experimental material, there are electric tabletop heating plates (5) with mechanical rotary stepped power control, a 19 mm burner, 1.5 kW, 96x260x269 mm in size – 2 pcs., which are installed on a metal tray under the rotary part of the experimental box. The pallet is made of iron sheet and has a recess for the jack rod.

At the unit using a pneumatic sprayer (6) with a pressure gauge and a graduated tank of 8 liters, the effect of moisture on the stability of slopes on the shift of landfill soils is experimentally investigated. In force, the sprayer is driven by creating an overpressure with a foot pump. Excess liquid flows down the box into a measuring container (not shown in the figure).

The tangential load system (7) consists of 2 blocks (rollers) interconnected by a steel cable with a diameter of 4 mm, a basket for cargo, a dial gauge GOST 577-68, as far as the landslide block is concerned, graduation 0.01 mm, stroke arrows 10 mm.

The auxiliary equipment includes: mineral wool, metal clothespins to limit heat loss during heating of the experimental material, an electric tabletop, a 10-liter measuring metal tank for heating liquid, a universal household thermometer TP-3-M1-2 with a "float chamomile" for measuring the temperature of the liquid; trowel, shovel, Wimpex electronic scales up to 50 kg, III class of accuracy, metal mold for the experimental sliding block, hand-held metal mortar, 500 mm iron graduated probe for working with experimental material.

Fig. 2 shows the construction of a metal mold and a hand mortar that are used to form the landslide blocks and the base of the sliding surface.

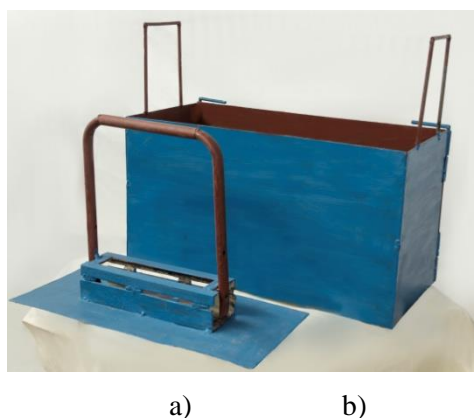


Figure 2. Design of auxiliary equipment for the formation of research samples: where a) a manual metal mortar, b) a metal mold.

Research using a laboratory unit (Figure 1) is based on the assumption that the transition of the landslide experimental block to the dynamic state will be considered the onset of the emergency of the object level of propagation.

Accordingly, the experimental research methodology includes the following stages:

1) Establishment of the initial and boundary conditions for experimental studies.

1.1) Selection of the experimental area and coding of natural values of the levels of factors in dimensionless quantities. For factors with a continuous range, the encoding is determined by the formula:

$$x_i = \frac{\tilde{x}_i - \tilde{x}_{i0}}{I_i}, \quad (1)$$

where x_i – coded value of the i -th factor; \tilde{x}_i – natural value of the i -th factor; \tilde{x}_{i0} – natural value of the i -th factor of the main (zero) level; I_i – interval of variation of the natural value of the i -th factor.

After coding, the levels of factors take on the following values: "1" – the lower level; "+1" – top level; "0" – zero level. The center of the interval in which the experiment is supposed to be carried out is selected as the zero level.

1.2) The choice of measuring instruments or methods of laboratory determination of physical and mechanical properties for compliance with the experimental area of the factor space. Temperature is measured using a soil thermometer or thermal rod, moisture – soil moisture meter or by drying to constant weight, density – soil density meter or by the cutting ring method, strength (angle of internal friction, specific adhesion) – by the single-plane cut method.

Moisture percentage is calculated by the formula [22]:

$$w = \frac{100 \cdot (m_1 - m_0)}{m_0 - m}, \quad (2)$$

where m – mass of an empty cup with a lid, (g); m_1 – mass of wet soil with a cup with a lid, (g); m_0 – the mass of the dried soil with a glass with a lid, (g).

Density ρ (g/cm³) is calculated by the formula [22]:

$$\rho = \frac{(m_1 - m_0 - m_2)}{V}, \quad (3)$$

where m_1 – mass of soil with a ring and plates, (g); m_0 – mass of the ring, m_2 – mass of the plates, (g); $V = \pi \cdot r^2 \cdot h$ – internal volume of the ring, (cm³) (r – radius, (cm); h – height, (cm)).

The angle of internal friction ϕ and specific adhesion C are calculated by the formulas [21]:

$$\operatorname{tg} \phi = \frac{n \cdot \sum \tau_i \cdot \sigma_i - \sum \tau_i \cdot \sum \sigma_i}{n \cdot \sum (\sigma_i)^2 - (\sum \sigma_i)^2}, \quad (4)$$

$$C = \frac{\sum \tau_i \cdot \sum \sigma_i^2 - \sum \sigma_i \cdot \sum \tau_i \cdot \sigma_i}{n \cdot \sum (\sigma_i)^2 - (\sum \sigma_i)^2}, \quad (5)$$

where τ_i – experimental values of the structural shear resistance at different values σ_i , (MPa); $n \geq 3$ – the number of tests ($n \geq 3$).

According to the values of the tangential and normal loads measured during the test, n the tangential and normal stresses τ and σ , (MPa) are calculated, according to the formulas:

$$\tau = \frac{X}{A}, \quad (6)$$

$$\sigma = \frac{N}{A}, \quad (7)$$

where X and N – respectively, tangential and normal forces to the shear plane, (kN) A – shear area, (cm²).

According to the values of shear deformations measured during the tests Δl , which correspond to different stresses τ , a graph of dependence $\Delta l = f(\tau)$ is plotted (Figure 3).

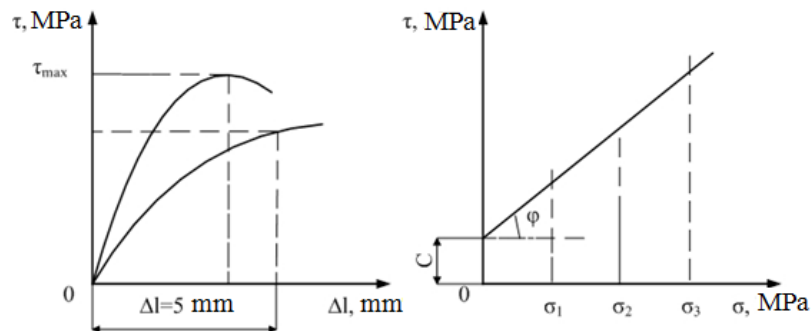


Figure 3. Graph of dependence of shear deformations Δl on stress τ : $\Delta l = f(\tau)$.

For the resistance of the soil to shear, the maximum value τ obtained from the graph $\Delta l = f(\tau)$ or diagram of the shear on a segment Δl is taken, which does not exceed 5 mm. If τ grows monotonously, then the shear resistance of the soil should be taken τ at $\Delta l = 5$ mm.

1.3) Preparation of the laboratory unit and experimental blocks.

The unit is placed on an open, flat, solid surface. The jack is installed on the type board, and its rod – to a special recess in the heating system pallet. Electrical appliances are supplied with a 220 V electric power supply. The sprayer is filled with water.

1.3.1) Selection and transportation of experimental material. The material is taken from the map of the MSW facility (depth of at least 3 m and 15 years old) and, if necessary, sorted from coarse fractions larger than 15x15 mm, and transported in plastic bags to the unit.

1.3.2) Formation of a horizontal sliding surface and experimental landslide blocks with a given density. The specified density value is achieved due to the fixed size of the molds V_{m_i} for the formation of the landslide block and sliding surface with a predetermined mass $m_{l.b.}$ and $m_{s.s.}$, accordingly:

$$m_{l.b(s.s.)} = V_{m_i} \cdot \rho_i \tag{8}$$

The experimental material is weighed to a certain mass, poured into metal molds installed on the base of the experimental box. With a manual metal mortar, the shapes are reproduced layer by layer according to the dimensions and the given density.

2) Conducting a series of experiments in accordance with the plan (matrix) of experimental studies (Table 1).

Determination of the angle of internal friction, specific adhesion and shear angle of experimental landslide blocks under conditions of different humidity, density and temperature.

2.1) Formation of research samples of a group of experiments with an initial density ρ_{in1} , kg/m³ in accordance with the plan of experimental research.

2.1.1) Determination of temperature T_{in} , °C and humidity w_{in} , % of experimental material.

2.1.2) Determination of the angle of internal friction, the specific cohesion of the experimental material due to the cyclic shear load, which creates shear and normal stresses.

Table 1 Matrix for planning experimental studies of the influence of the physical properties of landfill soils on the stability of slopes.

№ of test	Research procedure			Planning matrix		
				x_ρ	x_T	$x_{w(\alpha)}$
1	1	2	3	-1	-1	-1
2	4	5	6	-1	-1	+1
3	7	8	9	-1	0	0
4	10	11	12	-1	+1	-1
5	13	14	15	-1	+1	+1
6	16	17	18	0	-1	-1
7	19	20	21	0	-1	0
8	22	23	24	0	0	-1
9	25	26	27	0	0	+1
10	28	29	30	0	+1	0
11	31	32	33	+1	-1	-1
12	34	35	36	+1	-1	+1
13	37	38	39	+1	0	0
14	40	41	42	+1	+1	0
15	43	44	45	+1	+1	+1

2.1.3) Changing the angle of inclination of the sliding surface using a jack until the moment of displacement of the landslide block. Record the value of the shift angle on the protractor of the rotary mechanism of the laboratory unit

2.2) Formation of research samples of a group of experiments with an initial density ρ_{in1} , kg/m³ in accordance with the plan of experimental research.

2.2.1) Raising the moisture content of the landslide block and the base of the sliding surface to the specified value w_1 by uniform spraying with heated water to the specified temperature at $T_m = const$.

2.2.2) Determination of the angle of internal friction, the specific cohesion of the experimental material due to the cyclic shear load, which creates shear and normal stresses.

2.2.3) Changing the angle of inclination of the sliding surface using a jack until the moment of displacement of the landslide block. Record the value of the shift angle on the protractor of the rotary mechanism of the laboratory unit

2.2.4) Cyclic repetition of actions from paragraphs 2.2 inclusive for different values of humidity w_i and $T_m = const$ in accordance with the plan of experimental studies.

2.3) Formation of research samples of a group of experiments with an initial density ρ_{in1} , kg/m³ in accordance with the plan of experimental research.

2.3.1) Raising the temperature of the landslide block and the base of the sliding surface to T_i with the help of the tabletop plates of the heating system, adjusting the power and heating time, provided $w_m = const$ (maintaining humidity). To limit heat loss with mineral wool, wrap the lower part of the unit and fix it with metal clothespins. When the set temperature T_i is reached, turn off and remove the plates from the pallet.

2.3.2) Determination of the angle of internal friction, the specific cohesion of the experimental material due to the cyclic shear load, which creates shear and normal stresses.

2.3.3) Changing the angle of inclination of the sliding surface using a jack until the moment of displacement of the landslide block. Record the value of the shift angle on the protractor of the rotary mechanism of the laboratory unit

2.3.4) Cyclic repetition of actions from paragraphs 2.2 to 2.3 inclusive for different temperature values T_i and $w_m = const$ in accordance with the plan of experimental studies.

2.4) Formation of research samples of a group of experiments with an initial density ρ_{ini} , kg/m³ and cyclic repetition of actions from paragraphs 2.1 to 2.3 inclusive in accordance with the plan of experimental research.

Determination of humidity, temperature and density based on the displacement of experimental blocks, taking into account a gradual increase in humidity.

2.5) Formation of research samples of a group of experiments with an initial density ρ_{ini} , kg/m³ in accordance with the plan of experimental research.

2.5.1) Determination of temperature T_{in} , °C.

2.5.2) Changing the inclination angle of the sliding surface α using a jack until the moment of displacement of the landslide block in accordance with the plan of experimental studies.

2.5.3) An increase in the moisture content of the landslide block and the base of the sliding surface to the fact of displacement.

2.5.4) Determination of humidity w , temperature T , density ρ of the experimental material on the fact of displacement at $T_{liq} = 25$ °C and $T_{liq} = T_{heat}$.

2.5.5) Cyclic repetition of actions from paragraphs 2.5 inclusive for different values of the shift angle α .

2.6) Formation of research samples of a group of experiments with an initial density ρ_{in1} , kg/m³ in accordance with the plan of experimental research.

2.6.1) Raising the temperature of the landslide block and the base of the sliding surface to T_i in accordance with the plan of experimental studies using tabletop plates of the heating system, adjusting the power and heating time.

2.6.2) Cyclic repetition of actions from paragraphs 2.5 inclusive for different values of the inclination angle of the sliding surface α in accordance with the plan of experimental studies.

2.7) Formation of research samples of a group of experiments with an initial density ρ_{in1} , kg/m³ and cyclic repetition of actions from paragraphs 2.5 to 2.6 inclusive in accordance with the plan of experimental research.

In order to determine the experimental area of the factor space of laboratory studies of the influence of the physical properties of landfill soils on the stability of slopes, field studies of moisture w , density ρ , temperature T of landfill soils (Fig. 4), as well as the angle of slopes of the body of landfill soils α (Fig. 5) of typical MSW sites were carried out at different times of the year from closed maps. The research was conducted in 2019 (it is October) to 2020 (it is August). Including the values of mechanical properties, the angle of internal friction φ , specific adhesion, were determined according to the corresponding physical state.



Figure 4. Investigation of the physical state of landfill soils at the MSW landfill.

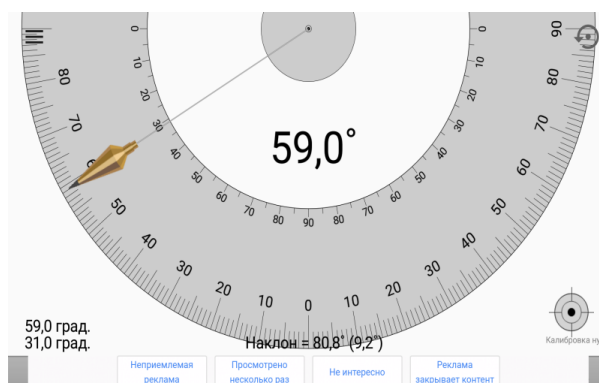


Figure 5. Mobile phone interface – investigation of the slope angle of the landfill soil body at the MSW.

The research results are reduced to the arithmetic mean of their values \bar{x} :

$$\bar{x} = \frac{1}{n} \sum_{i=1}^n x_i , \tag{9}$$

where x_i – indicator i of the parameter of landfill soils; n – the number of tests.

Analysis of the results shows that the dynamics of changes in humidity and temperature of landfill soils depends on the season (Fig. 6): in spring, humidity increases in accordance with an increase in atmospheric precipitation, which was typical for the year of research, and the temperature decreases, and in summer, humidity decreases with an increase in temperature. environment and landfill grounds. The lower the density of landfill soils (II object), the greater the ability to penetrate and saturate with moisture. The higher the density (III object), the less moisture is absorbed, and the more stable the temperature.

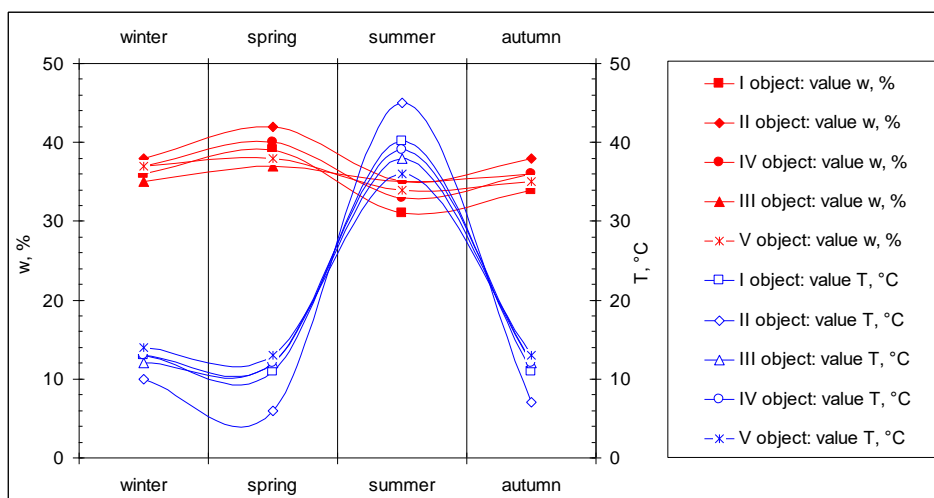


Figure 6. Dynamics of changes in humidity (upper group of curves) and temperature (lower group of curves) landfill soils in accordance with the season from 2019 to 2020.

Figures 7 and 8 show the dynamics of changes in the mechanical properties of landfill soils in accordance with the season. It has been determined that the values of the angle of internal friction and specific adhesion vary depending on the physical parameters: the higher the density (III object), the more stable the values of mechanical properties with the change of the season. Excessive moisture and high temperatures lead to instability. The object with the lowest density (II object) is characterized by more dynamic processes of changes in the angle of internal friction and specific adhesion.

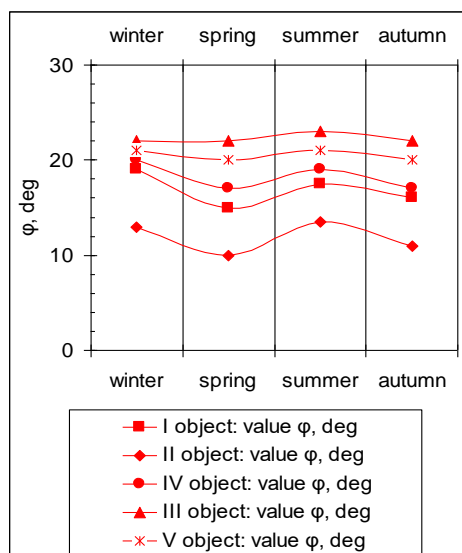


Figure7. Dynamics of changes in the angle of internal friction of landfill soils in accordance with the season from 2019 to 2020.

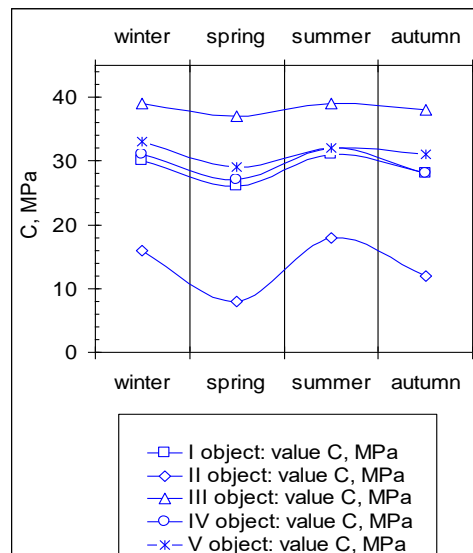


Figure8. Dynamics of changes in the specific cohesion of landfill soils in accordance with the season from 2019 to 2020.

The results of field studies of determining the angle of the slopes of the body of landfill soils at typical solid waste disposal facilities are in the range of 60°.

The qualitative and quantitative composition of biogas is individual for each MSW facility. The process of decomposition of the organic component of waste occurs unevenly and with different

intensity. On one part of the landfill, aerobic decomposition with the release of carbon dioxide may prevail, on the other, intense release of methane, and there may also be dead zones.

Biodegradation takes place under the influence of a large number of microorganisms. The main place is occupied by bacteria, which ensure the beginning of the decomposition process of the organic component and a rapid rise in temperature. First, a group of mesophilic bacteria develops, and after warming up the waste environment, a group of thermophilic bacteria begins to actively develop, which are able to break down more stable organic compounds. According to scientific research [23–25], it is customary to distinguish 5 phases of waste decomposition: phase 1 – aerobic decomposition; phase 2 – anaerobic decomposition without methane release (fermentation); phase 3 – anaerobic decomposition with variable release of methane (mixed fermentation); phase 4 – anaerobic decomposition with constant release of methane (methane fermentation); phase 5 –attenuation of anaerobic processes.

Aerobic decomposition occurs in the upper layers of the solid waste massif at a depth of 50–80 cm and, as a rule, is rather short, since its duration is limited by the amount of oxygen. This stage is characterized by the formation of carbon dioxide, water, nitrates, nitrites, nitrogen, organic residues and a large amount of heat. As the waste is compacted and isolated by soil, the aerobic phase of microbiological decomposition tends to become anaerobic – aerobic microorganisms become anaerobic. This is caused by an insufficient supply of oxygen to the waste mass to meet the conditions of the aerobic process.

Anaerobic decomposition proceeds more slowly and is accompanied by an order of magnitude less heat release. In the phase of hydrolysis under the action of bacteria, the decomposition of easily stored waste occurs, the hydrolysis of cellulose-containing wastes. In the acetogenic (acidic) phase – further decomposition of cellulose with the formation of low molecular weight acids, alcohols. The environment becomes very sour. Acids together with moisture release nutrients for methane-forming microorganisms. Then comes the methanogenic phase in which acids decompose with significant methane formation. Anaerobic microorganisms receive the energy necessary for life as a result of the decomposition of organic matter. High density slows down microbiological life.

The maximum amount of methane in the composition of biogas under the conditions of a MSW landfill can be obtained by observing temperatures within 30–40 °C, humidity within 60–80 %. Humidity, temperature is an indispensable factor for the life of methane-forming microorganisms.

As the main requirements for a laboratory unit, the possibility of conducting a series of experiments based on the use of experimental landslide blocks of different moisture, density, temperature and angle of inclination of the base of the sliding surface, as well as determining the angle of internal friction, specific adhesion is determined. Taking into account the significant variability of the problem, only general, fundamentally significant operating factors of influence and their values are reproduced, fully ensure adequate reproduction of the existing conditions for the functioning of the MSW facility.

The design features of the developed laboratory unit for studying the influence of physical properties of landfill soils (moisture, density, temperature) on the stability of slopes. In the developed laboratory unit the change of moisture of sliding experimental blocks is provided by means of a pneumatic sprayer, change of temperature is provided by means of electric tabletop heating plates, change of an angle of inclination is provided by means of a hydraulic bottle jack.

Based on the results of a series of field studies and taking into account the optimal range of the formation of the maximum amount of methane in the biogas composition, it was determined that the experimental area of the factor space of studies of the influence of the physical properties of landfill soils on the stability of slopes corresponds to: the value of moisture in the range from 30 % to 80 %, density – from 600 kg/m³ to 1300 kg/m³, temperature from 25 °C to 45 °C, slope angle of landfill soil body within 60°.

Table 2 shows the natural and coded values of the factors selected for a series of laboratory experiments to study the influence of the physical properties of landfill soils on the stability of slopes. The lower level of the values of the factors corresponds to the initial physical state of the experimental blocks.

Table 2. Natural and coded values of factors selected for a series of laboratory research experiments.

Factor designation	ρ , (kg/m ³)	T , (°C)	w , (%)	x_ρ	x_T	x_w
Main level	950	35	55	0	0	0
Upper level	1300	45	80	+1	+1	+1
Lower level	600	25	30	-1	-1	-1

The inclination angle of the landslide experimental blocks is of scientific and practical interest: the upper level corresponds to 60⁰, the main one – 45⁰, the lower one – 30⁰.

The choice of the experimental area of the factor space is associated with a thorough analysis of the a priori information. The limiting values of density close to the real position of compaction of MSW at disposal facilities, humidity are determined by the results of field studies and their optimal range for the formation of the maximum amount of methane in the biogas composition, temperature – by environmental conditions and the optimal temperature range for the formation of biogas.

3. Conclusions

A laboratory unit has been developed that allows experimental studies of the influence of the physical properties of landfill soils, such as humidity, density, temperature, on the stability of slopes in order to solve civil security problems – to check the reliability of the mathematical model and the methodology for preventing emergencies associated with displacement developed on its basis. The main elements of the unit are a rectangular experimental box with rotary and fixed parts, rotary and locking mechanisms, table heating plates, a sprayer, and a tangential load system.

A method for conducting experimental studies using the developed laboratory unit has been developed, which includes:

- establishment of the initial and boundary conditions of experimental research and coding of natural values of the levels of factors in dimensionless quantities; preparation of the laboratory facility and experimental blocks)

- carrying out a series of experiments (determination of the angle of internal friction, specific cohesion and shear angle of experimental landslide blocks under conditions of different humidity, density and temperature, determination of humidity, temperature and density based on the fact of displacement of the experimental blocks, taking into account a gradual increase in humidity). The results obtained are processed using the classical statistical method – Student's t-test.

The experimental area of the factor space of studies of the influence of the physical properties of landfill soils on the stability of slopes corresponds to the value of moisture in the range from 30 % to 80 %, density – from 600 kg/m³ to 1300 kg/m³, temperature from 25°C to 45°C, the angle of body slopes landfill soils within 60⁰.

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