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SIMULATION OF THE SOLID WASTE LANDFILL SETTLEMENT TAKING INTO ACCOUNT UNDERLYING SOIL

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Проведено моделювання осадки закритого полігону твердих побутових відходів із застосуванням методу скінчених елементів з метою прогнозування його використання в якості основи споруд. Характерною його особливістю було врахування геометричних та фізико-механічних параметрів полігону та ґрунтової основи. Встановлені залежності осадки полигону від властивостей підстилаючих ґрунтів, величини статичного привантаження і від кута нахилу схилу полігону

Ключові слова: полігон твердих побутових відходів, осадка, біорозкладання, метод скінчених елементів

Проведено моделирование осадки закрытого полигона твердых бытовых отходов с применением метода конечных элементов с целью прогнозирования его использования в качестве основы сооружений. Характерной его особенностью был учет геометрических и физико-механических параметров полигона и грунтового основания. Установлены зависимости осадки полигона от свойств подстилающих грунтов, величины статической пригрузки и от угла наклона склона полигона

Ключевые слова: полигон твердых бытовых отходов, осадка, биоразложение, метод конечных элементов

1. Introduction

The problems of environment in Ukraine and worldwide are gaining more relevance, given the increase in the level of anthropogenic impact on nature's objects. A major problem worldwide is the increasing amount in the accumulation of waste. Ukraine holds one of the first places in the world for the volume of waste per unit of the population. In the country around 7 % of the territory is under the solid waste already and 52 million tons of domestic garbage is produced annually, the amount of which increases each year by 1.5–2.5 %. Only 5 % of the waste is processed, the remaining 95 % is taken to landfills and polygons. In Ukraine there are about 6 thousand landfills and garbage polygons of the total area of 7.4 thousand hectares, 32 thousand unauthorized landfills and 15 sorting lines. Very often the polygons are overloaded (about 5 %) or do not comply with the established standards of environmental safety (about 16 %).

A typical method in Ukraine for dealing with the solid waste, the indivisible collection and burial, leads to the littering of the land, irreparable loss of resources and profits, which a properly established comprehensive process of recycling could earn, increase in the migration of waste into the environment (currently the amount of solid household waste that enters, surpasses the capabilities of natural ecosystems). The largest area of polygons is in Dnipropetrovsk Region (140 hectares), Donetsk Region (330 hectares), Odessa Region (195 hectares), Zaporizhzhia Region (153 hectares) and Luhansk Region (129 hectares).

It is also worth noting that Ukraine, unfortunately, lacks waste processing plants, common in the economically developed countries, in particular in Europe [1].

In this connection the acute issue is the stability of landfills after their closure for later use as a foundation for engineering structures and designs. Due to this, an urgent task is the forecasting of the solid waste landfill settlement, to be able to assess the possibility of the use of any landfill as a foundation for a construction. Therefore the research of its settlement is actual, taking into account the angle of inclination of a landfill and the stressed-strained state of the underlying ground foundation.

2. Analysis of scientific literature data and the problem statement

Landfills are a very complex system, in which many different processes are running simultaneously. In particular, the formation of landfill gas as a result of the decomposition of organic waste affects the pressure of gas and liquid in the body of the landfill. This leads to change in the porosity, general strain, degree of saturation of gases and liquids, which in its turn causes deformations, that is, settlement. These deformations have negative effect on the integrity of any structure that is built on the ground of a closed landfill. Unexpected settlements may eventually lead to a number of problems, such as the formation of cracks in the covering layer, damage to the integrity of the covering and underlying layers, damage to the systems of collection of gas and fluids and drainage systems. Therefore, the forecast of settlement and stability of landfills becomes a key issue in the design and construction of landfills, as well as in the use of closed landfills as a foundation for a construction.

The analysis of the scientific literature, in particular the back analysis of destroyed landfills in Warsaw (Poland), Istanbul (Turkey), Pajatas (the Philippines) and Giria (Israel) in [2] and the landfills' slopes in Cruz-das-Almas (Brazil) and Leuvigaya (Indonesia) in [3], has shown that the experimental methodologies of assessment of stability of landfill were expensive and effective only under specific conditions. The method of back analysis is based on taking into account the properties of the landfills, already destroyed, and it is not satisfactory for other landfills due to the difference in the composition of the waste, environmental conditions, properties of the body of a polygon and the underlying soil foundation.

In its turn, using the lab tests can not express the conditions of a landfill, failing to capture all layers of the waste in one sample and to take into account their geotechnical and physical-mechanical properties. Therefore, to take into account a stressed-strained state of landfill layers and underlying ground array and its characteristics, it is advised to apply mathematical simulation.

The mathematical models that forecast the settlement can be divided into rheological models, empirical models, models that are based on the soil mechanics, and the models that take into account biodegradation.

The authors in [4] proposed a model of the settlement that takes into account biodegradation of the waste dependent on time. It is assumed that the rate of settling is expressed through a set of settlements directly proportional to the amount of solid substances which are decomposed. The dissolution of organic materials is usually expressed using first-order kinetics equation. The sum of the two conditions gives the total deformation of the compression. However, determining kinetic coefficients or the hydrolysis constants, as well as their changes under environmental conditions, is very complicated. The paper [5] considers the models that take into account the biodegradation of the waste, but there are also similar drawbacks present.

Empirical models try to imitate the general behavior of the waste by adjusting the empirical parameters for a particular area of the landfill. Basically the following mathematical functions are used: logarithmic function, static function of creep and hyperbolic function of shrinkage. In particular, the settlement in the form of a logarithmic function was used in [6].

In the paper [7] they designed a component rheological model to take into account primary and secondary compression mechanisms that are guided by the rheological parameters, which are also included in the biodegradation of the waste.

For the simulation of the mechanical compression of a polygon, caused by biodegradation considering landfill gas that is formed, as well as alternating pressure and humidity, the model based on first-order decomposition equation was used. To test the results of the simulation, the tests of compression were carried out under laboratory conditions [8]. The paper [9] presented an extended Cam-Clay model, which allows forecasting the landfill's shrinkage under overloading, considering creep and the biodegradation dependent on time. The parameters of the model were assessed based on the results of triaxial test on compression.

One dimensional multiphase model of solid waste landfill's settlement allows us to estimate such parameters as porosity of the waste products, their stresses, pressure of liquid and gas. Stoichimetric equation is used to estimate the maximum formation of landfill gas [10].

A common drawback of those and other models [12–14] is that they take into account only the solid waste, its behavior and properties, neglecting such an important part of the landfill as soils that underly its foundation. But it is the type, strength and geotechnical properties of underlying ground that the stability of landfills depends on, since it is exposed to the most of the load. Based on the observations of the steep slopes of the landfills which remain stable, we can draw a conclusion that the main attention in the analysis of stability of a landfill should be paid to the materials that underlie a solid waste landfill.

Currently this issue is not paid attention to at all. For the forecasting of stability of a polygon, the study of its settlement is proposed, with the research of a stressed-strained state of the underlying ground foundation, while the phased loading of the landfill with layers of the waste is taken into account, as well as the angle of its inclination.

3. The purpose and objectives of the study

The aim of the studies is establishment of dependency of the settlement of a closed solid waste landfill on the properties of the underlying grounds, as well as on the angle of inclination of the slope of a polygon for forecasting a possibility of its usage as a foundation for a construction.

To achieve the goal, the following tasks were set:

– to choose the model of the body of a landfill and its underlying ground that best describes the settlement under static loads;

– on the basis of mathematical simulation using the method of finite elements, to explore the impact of the underlying layer of different types of soils on the settlement of a landfill;

– to investigate the influence of the angle of inclination of the slope of a landfill on its settlement.

4. Materials and the methods of research

To forecast the settlement of a closed landfill, mathematical simulation was carried out. The Mohr-Coulomb model described the covering and underlying soil layers. In this case the body of a landfill was simulated by weak ground taking into account the creep, the Soft Soil Creep (SSC) model applied [15].

Currently this model best describes such properties of weak ground as stiffness dependent on the stress, as well as secondary compression considering the creep. It should be noted that the SSC model takes into account both physical and geometrical nonlinearity of the process of soil deformation.

Full volumetric deformation ε_v, caused by the growth of effective stresses from the initial value p_0' up to p_0' for a period of time t_c+t', consists of elastic ε_v^e and viscous-plastic ε_v^{vp} components. Viscous-plastic component is the total of deformation during consolidation $\varepsilon_{v\,c}^{vp}$ and after consolidation $\varepsilon_{v\,ac}^{vp}$. The relationship between the deformations is expressed in the following form [16]:

$$\varepsilon_\upsilon = \varepsilon_v^e + \varepsilon_{v\,c}^{vp} + \varepsilon_{v\,ac}^{vp}, \quad (1)$$

$$\varepsilon_v^e = \kappa^* \ln\left(\frac{p'}{p_0'}\right), \quad (2)$$

$$\varepsilon_{v\,c}^{vp} = (\lambda^* - \kappa^*)\ln\left(\frac{p_{pc}'}{p_0'}\right), \quad (3)$$

$$\varepsilon_{v\,ac}^{vp} = \mu^* \ln\left(\frac{\tau_c + t'}{\tau_c}\right), \quad (4)$$

where μ^* is the modified coefficient of creep; τ_c is the time of consolidation, that depends on the geometry of the sample under consideration; t' is the time elapsed since the beginning of the loading of the landfill; κ^* is the modified coefficient of swelling; λ^* is the modified coefficient of compression; t_c is the time of completion of primary consolidation; p_0' is the initial effective stress; p' is the effective stress; p_{pc}' is the effective pre-consolidation stress.

The ratio of the parameters of the model to internationally-standardized parameters is as follows:

$$\mu^* = \frac{C_\alpha}{2{,}3(1+e_0)};\ \lambda^* = \frac{C_c}{2{,}3(1+e_0)};\ \kappa^* = \frac{2C_s}{2{,}3(1+e_0)}, \quad (5)$$

where C_c is the coefficient of compression; C_s is the coefficient of swelling; C_α is the coefficient of creep; e_0 is the initial coefficient of porosity.

Hydrodynamic aspects of the problem are in taking into account the filtration forces acting on the skeleton of the soil environment, and parameters of the interaction between liquid and solid phases of soil (pressure, tension and porosity) in the process of consolidation. Generalized Darcy's law and the equation of continuity apply to the assumption of vortex flow of the filtration flow and the distribution of forces of resistance evenly on the section element. It is assumed that the compressibility of the skeleton and porous fluid is low, which leads to the linear dependence of the porosity of the soil on pressure. The interaction of soil skeleton and fluid is characterized by a volume force proportional to the gradient of pressure. The equations are supplemented by the initial and boundary conditions [17].

For the numerical solution of the problem the finite elements method was used. The estimated area was divided into 265 finite elements.

5. Results of the research of settlement of a solid household waste landfill

In the first part we studied the influence of underlying soil (clay, sand or loam) foundation on settlement. The landfill for which the simulation was conducted consists of ten layers of the waste, the thickness of each layer is 3 m. The angle of inclination of the slope of the landfill was 75°.

The settlement was determined by taking into account the step-by-step loading of the polygon in 30 years after its closure. The parameters of the underlying soils are presented in Table 1.

The parameters for the waste products are presented in Table 2 (layer #1 is the latest layer, layer #10 is the first that lies in the foundation of the polygon).

Table 1

Physical and mechanical parameters of soils

Parameter	Soil		
	Sand	Loam	Clay
Modulus of deformation E_{ref}, (kN/m^3)	18000	10000	9000
Poisson's Ratio ν, (unit)	0,34	0,36	0,37
Specific gravity of soil γ_{unsat}, (kN/m^3)	18,0	13	19,0
Specific gravity of water-saturated soil γ_{sat}, (kN/m^3)	20,7	14,6	21,8
Filtration coefficient in horizontal direction k_x, (unit)	0,5	0,006	0,004
Filtration coefficient in vertical direction k_y, (unit)	0,5	0,006	0,004
Modulus of deformation E, (MPa)	50	33	28
Specific cohesion c, (kPa)	3	34	81
The angle of internal friction ϕ, (degree)	31	14	13

Table 2

Physical and mechanical parameters of the waste products

Parameter	Value
Specific weight γ_{unsat}, (kN/m^3)	7,504
Specific gravity of water-saturated soil γ_{sat}, (kN/m^3)	10,0
Specific cohesion c, (kPa)	25
The angle of internal friction ϕ, (degree)	20
The initial coefficient of porosity, e_0, (unit)	0,4268
Coefficient of compression, C_c, (unit)	0,3987
Swelling coefficient, C_s, (unit)	0,0394
The coefficient of creep, C_α, (unit):	
layer #1	0,0615
layer #2	0,0474
layer #3	0,0448
layer #4	0,0429
layer #5	0,0414
layer #6	0,0402
layer #7	0,0391
layer #8	0,0382
layer #9	0,0374
layer #10	0,0367

As a result of the numerical calculation it was determined that the maximum vertical deformation for a polygon with sand as soil of the foundation amounted to 4.95 m.

It was found that if the underlying soil was clay (Fig. 1), then much smaller deformations could be observed (3.83 m). It was also calculated that the settlement of the layer with underlying loam amounted to 4.47 m of maximum vertical deformation.

As a result of the conducted studies, it was found that with identical characteristics of the waste, the landfill's settlement with underlying clay soil foundation was 23 % less that of the polygon with an underlying sandy soil and 14 % less than that of sandy loam as the gound foundation of the landfill. This is due to the fact that the more porous and less dense the soil base is, the larger its settlement and, consequently, the larger settlement of the polygon.

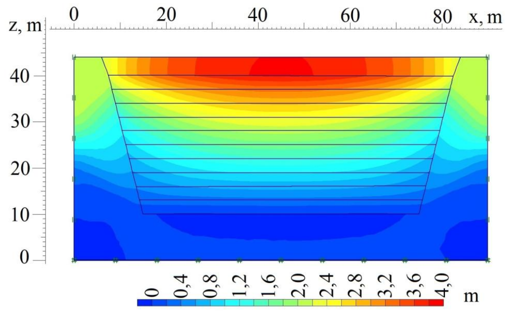

Fig. 1. Vertical deformations of the polygon with underlying clay soil foundation

Further studies were carried out of the influence of the overloading on the settlement of a landfill. Deformed estimated area of the polygon with sand as soil foundation, with vertical static distributed overloading equal to 5 kPa, is presented in Fig. 2.

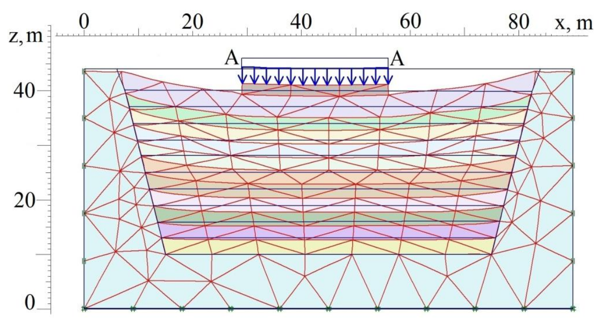

Fig. 2. Deformed estimated area of the polygon with vertical distributed static overloading of 5 kPa

The result of the numerical calculation determined that the maximum vertical deformation was 5.06 m. If the value of the vertical overloading increases to 50 kPa, one can see deformations reach 5.19 m.

It was established that with the same value of the overloading (50 kPa), vertical deformations of the landfill with underlying clay layer reached 4.23 m. With the value of overloading of 50 kPa, vertical deformations of the polygon with underlying loam layer will make 4.95 m.

Fig. 3 presents the dependence of the settling of a landfill on the value of the vertical static overloading for three types of soils.

It follows from Fig. 3 that the largest vertical deformations occur to the polygon with underlying sand as foundation. However, in percentage, the value of settling with the maximum overloading in relation to the initial settling without overloading is the the largest for clay and is 33.7 %, while the same value for sand – 19.2 %.

Next we determined the influence of the inclination angle of the slope of a polygon. The calculations for the angle of 75° are displayed above, while for comparison the simulation was carried out for the angle of inclination of slopes of 30° and 60°. Linear dimensions of polygons with different angles of inclination of slopes were selected in such a way so that the volume of the body of the polygon remained constant. A deformed estimated area of the landfill with underlying clay foundation and with the angle of the inclination of the landfill's body equal to 60° is presented in Fig. 4.

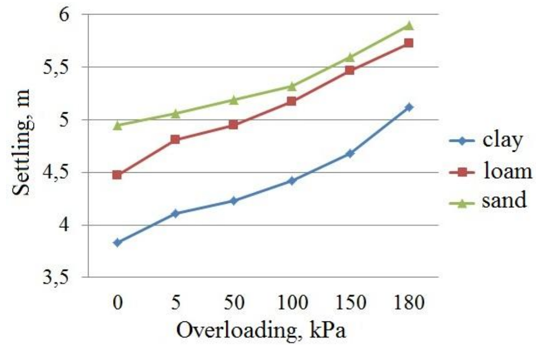

Fig. 3. Dependence of the settling of a landfill on the vertical distributed static overloading

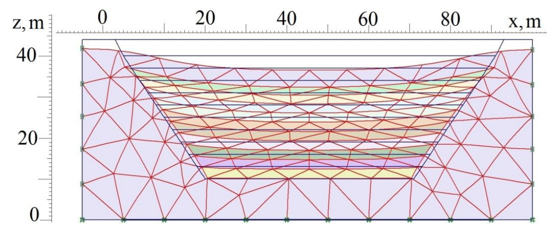

Fig. 4. Deformed estimated area of the landfill with underlying clay foundation (the angle of the inclination of the landfill's slope is 60°)

It follows from the analysis of numerical calculations that the vertical deformations of the landfill reached 3.8 m.

The result of the numerical calculation revealed that at the same angle of inclination, the maximum vertical deformation amounted to: for the polygon with sand – 4.34 m (Fig. 5), with loam – 4.27 m. It follows from the comparison of these results that the value of the angle of the inclination of the polygon's body significantly affects the vertical deformation: when decreasing the angle from 75° down to 60°, the deformation decreased by 1–12 % depending on the foundation soil type.

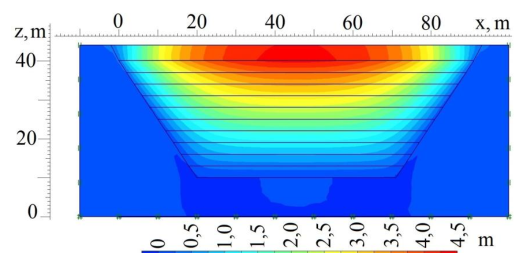

Fig. 5. Vertical deformations of the polygon with underlying sandy ground (the angle of inclination of the landfill's slope is 60°)

To establish the influence of the angle of inclination of the slope of the polygon on its settlement, the simulation was conducted for the landfill with the angle of 30°. As a result of the conducted studies it was found that the difference between the value of deformations had reduced significantly. Thus, if the underlying layer is sand (Fig. 6), one can observe that the vertical deformations occur (3.94 m), for loam – 3.89 m. With the underlying clay layer (Fig. 7) the vertical deformations are the lowest compared to the two previous variants (3.63 m).

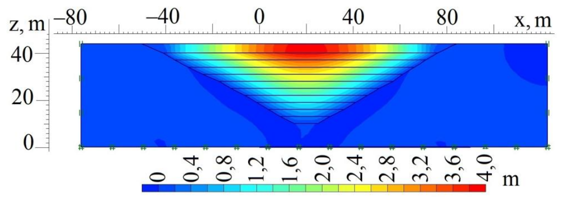

Fig. 6. Vertical deformations of the landfill with underlying sandy ground (the angle of inclination of the landfill's slope is 30°)

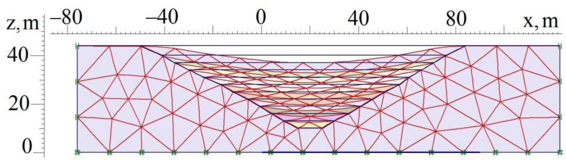

Fig. 7. Deformed estimated area of the landfill with underlying clay foundation (the angle of inclination of the landfill's slope is 30°)

With a decrease in the angle of inclination of the landfill, the influence of underlying soil on the settlement decreases and the difference between the values of the deformations reduces.

Comparison of the values of settlement shows that decreasing the angle from 60° down to 30°, the deformation decreased by 5–9 % depending on the foundation soil type.

With a decrease in the angle from 75° down to 30°, the decrease of the vertical deformations was the largest for sand (20.4 %), while this value is 13 % for loam and 5.22 % for clay.

6. Discussion of the results of the studies of the influence of the underlying soil layer, static loading and the angle of inclination of the landfill's slope on its settlement

Closed landfills occupy huge areas that grow annually in connection with the increasing pace of growth in the amount of the waste, that's why during their closing there appears a need to use them as foundations for different structures, which is impossible without a credible forecast of their stability.

In the work we proposed taking into account, when calculating the stability of a polygon, its underlying soil, as its properties are among the main factors in the formation of landfill's.

For the forecast of the landfill's of a solid household waste landfill, an effective method of calculation was designed, based on the numerical simulation of stressed-strained state of a polygon and its underlying soil with the use of the SSC models for a polygon and the Mohr-Coulomb models for ground foundation using the method of finite elements. The application of the SSC model for the simulation of the settlement of a landfill's body is substantiated by the fact that for now this model is by far the fullest for reflection of such processes of deformations of weak soils as the stiffness dependent on strain, secondary compression considering creep and it also takes into account both physical and geometric non-linearity of the process of deformation of soil.

As a result of the numerical solution is was established that with the same conditions of a polygon, the underlying ground layer significantly affects the value of settlement: the heavier and less porous is the soil, the smaller is the settlement. So, if the ground foundation is represented by clay, then the actual settlement is 23 % less than with the sand and 14 % less than with loam as the foundation. This obtained result proves that when forecasting the shrinkage of a polygon for using it as a foundation for a construction, the underlying soil array must be taken into account.

When studying the influence of the overloading on the value of the settlement, it was found that the largest vertical deformations occurred in the polygon with underlying sand as ground base. However, in percentage, the value of the settling with the maximum overloading in relation to the initial settling without overloading is the largest for clay and it is 33.7 % while the same value for sand – 19.2 %. This is due to the fact that the more porous unstable ground foundation of sand reached the largest maximum settling over 30 years and would deform in a lesser extent compared to clay, which has not yet reached the final deformation. It was established that with further increase in the load, the destruction of the polygon's body would occur. These established facts need to be considered in the design and operation of structures of various purposes, based on closed landfills.

The study of the influence of the angle of inclination of a landfill's slope made it possible to establish that the decrease in the angle of inclination of a polygon's slope leads to a significant decrease in settlement. Thus, with a decrease in angle from 75° to 30° the settlement reduces by 5–22 % depending on the type of soil foundation. And the greatest decline is observed in the least dense soil (sand).

With a decrease in the angle of inclination, the difference between the settlements of a landfill decreases for different soil foundations.

The obtained results can be used in forecasting the settlements of a landfill with various geometrical, physical and mechanical parameters for the evaluation of the possibility for its further use as the foundations for structures with various purposes.

This work is necessary to be supplemented with the research of influence of different dynamic overloadings on a closed polygon after its settlement, which will enable to give a forecasting assessment about the possibility of its usage as the foundation for a transport line.

7. Conclusions

1. An effective method of calculation was designed, based on the numerical simulation of a stressed-strained state of a polygon and the underlying ground with the use of the selected models: the Mohr-Coulomb model for the simulation of the covering and underlying layers of the soil and the SSC model for the waste products. The application of the SSC model for the simulation of the settlement of landfill's body is substantiated by the fact that for now this model is by far the fullest in reflecting the processes of deformation of the weak soils.

2. It was established that with the same conditions of a polygon, the underlying ground layer produces a significant impact on the value of the settlement: the more dense and less porous is the soil, the smaller is the settlement. In particular, if the ground foundation is represented by clay, then the settlement obtained is 23 % less than with the sand, and 14 % less than with loam as the foundation.

3. The studies of the influence of the angle of inclination of a landfill's slope made it possible to establish that the decrease in the angle of inclination of a landfill's slope leads to a significant decrease in settlement, with the greatest decline observed in the least dense soil (sand).

It is proposed to take into account, when calculating the stability of a landfill, the underlying ground, as it is one of the main factors in the formation of settling. The obtained results must be considered when using landfills as a foundation for buildings or structures.

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