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PREDICTION OF STRAIN STATE OF LANDFILL CONSIDERING SOIL FOUNDATION AND ANGLE OF SLOPE

Н.С. Ремез, Т.А Осіпова. **Прогнозування деформованого стану полігона твердих побутових відходів з врахуванням ґрунтової основи і кута нахилу схилу.** Сьогодні серйозною проблемою світового масштабу виступає збільшення обсягів накопичення побутових відходів. Україна займає одне з перших місць в світі за кількістю сміття на одиницю населення. В країні вже близько 7 % території знаходиться під твердими побутовими відходами, крім того щороку утворюється понад 52 млн. тонн побутового сміття. У зв'язку з цим гостро постає питання про стійкість полігонів після їх закриття для використання в подальшому як основи для інженерних споруд і конструкцій. ***Мета:*** Метою роботи є встановлення залежності осідання закритого полігона твердих побутових відходів від властивостей підстельних ґрунтів, а також від кута нахилу схилу полігона для прогнозування можливості використання його як основи споруди. ***Матеріали і методи:*** Під час дослідження було враховано поетапне навантаження полігона шарами відходів, а також кут його нахилу. Покриваючий і підстельний шари описано моделлю Кулона-Мора. Тіло полігона було змодельовано як слабкий ґрунт з урахуванням його повзучості, для цього використано модель Soft Soil Creep (SSC). Для чисельного розв'язання задачі використано метод скінченних елементів. ***Результати:*** В роботі вперше побудовано математичну модель осідання полігона твердих побутових відходів з врахуванням геометричних і фізико-механічних параметрів полігона і ґрунтової основи, що дозволить у подальшому прогнозувати можливість використання полігона для будівництва на ньому споруд різного призначення. В результаті досліджень встановлено, що зі зменшенням кута нахилу схилу відбувається значне зменшення осідання полігона. Так, при зменшенні кута з 75° до 30° осідання зменшується на 5…22 % в залежності від типу ґрунтів основи. Найбільше зменшення осідання спостерігається у найменш щільного грунту — у піску.
Ключові слова: осідання, тверді побутові відходи, деформація, математичне моделювання.

N.S. Remez, T.A. Osipova. **Prediction of strain state of landfill considering soil foundation and angle of slope**. Today increase in volumes of accumulation of a household waste acts as a global serious problem. Ukraine occupies one of the first places on the list in the world by garbage quantity per capita. Already about 7 % of the territory in the country are under municipal solid waste, besides more than 52 million tons of household waste are annually formed. In this regard, sharply raises the question of the stability of landfills after their closure for further use as a basis for engineering constructions and designs. ***Aim:*** The aim of this research is to establish the dependence of settlement of the closed landfill on the properties of the underlying soil, as well as the landfill slope angle to predict the possibility of using it as a basis for construction. ***Materials and Methods:*** The phased load of landfill by waste layers and angle of inclination were taken into account during the research. The covering and underlying layers are described by Coulomb-Mohr model. The body of landfill was modeled as a weak ground considering its creep. The Soft Soil Creep (SSC) model was applied for this. The finite elements method was used for numerical solution of the problem. ***Results:*** In this work the mathematical model of sedimentation of municipal solid waste constructed for the first time, taking into account geometrical and physical and mechanical parameters of landfill and soil base, which will allow further prediction the use of landfill for building structures on it for various purposes. As a result of researches was found that with decreasing of inclination angle of the landfill slope there is a significant decrease in settlement. Thus, while reducing the angle from 75° to 30° the settlement is reduced by 5...22% depending on the type of soil foundation. The largest landfill reduction is observed for the least dense soil (sand).
Keywords: landfill, municipal solid waste, strain, mathematical modelling.

Introduction. Today increase in volumes of accumulation of a household waste acts as a global serious problem. Ukraine occupies one of the first places on the list in the world by garbage quantity per capita. Already about 7 % of the territory in the country are under municipal solid waste, besides more than 52 million tons of household waste are annually formed. In this regard, sharply raises the question of the stability of landfills after their closure for further use as a basis for engineering constructions and designs.

Ukraine has about 6 thousand dumps and landfills of 7.4 thousand hectares total area, 32 thousand illegal dumps, 15 sorting lines and only two waste incineration plants. Very often landfills (about 5 %) are overloaded or they do not meet the standards of environmental safety (about 16 %). It should also be noted that in Ukraine, unfortunately, no waste treatment plants, common in economically developed countries [1].

In this connection the question arises about firmness of landfills after their closure for use as a basis for engineering buildings and structures in the future.

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To predict the firmness of the landfill is necessary to study its settling considering angle of landfill and stress-strain state of the underlying soil base.

Often, to assess the stability of the landfill the experimental techniques are using, namely the method of inverse analysis, laboratory tests and more. Analysis of the literature showed that the experimental methodology for assessing of the stability of the landfill is financially costly and effective only for specific conditions. For example, the method of inverse analysis is based on consideration of the properties already destroyed landfills. This method is not satisfactory for other landfills due to the difference of waste, environmental conditions, properties of landfill body and underlying soil mass. In turn, through laboratory tests the landfill conditions can't be displayed – to capture in one sample all the layers of waste and take into account the geotechnical, physical and mechanical properties. Therefore, to consider the stress-strain state of the polygon layers and underlying soil mass and its characteristics the mathematical modeling is advisable to apply.

Applied mathematical models for the prediction of settling can be divided into the following classes: rheological; empirical; models based on soil mechanics; models that take into account biodegradation.

Park and Lee [2] proposed a model of settling, taking into account the time-dependent biodegradation of waste: sedimentation rate is expressed through plurality of settlings directly proportional to the amount of solids that decompose; and the process of dissolving of organic materials can be described by equations of the first order kinetics.

Note that the definition of kinetic coefficients and/or hydrolysis constants with the possibility of monitoring of their changes in the environment in a real time is a non-trivial task.

Empirical models predict a total waste behavior by adjusting of empirical parameters for a specific site.

Marques *et al.* [3] have developed the rheological model to account the primary and secondary compression mechanisms that governed by the rheological parameters that is also included in the biodegradation of waste. Note that the primary compression does not depend on time.

The common feature of these and other models [4...7] is that they just adapted to model the behavior and properties of solid waste, ignoring such an important part of the landfill as soils that lie at its core. Exactly the type, strength, geotechnical properties of the underlying soil affect on the stability of the landfill, because the ground has the greatest burden.

Given the fact that some steep slopes of dumps remain stable, we can conclude that the focus in the analysis of the landfill firmness should be given to materials that are the basis of municipal solid waste (MSW). Therefore, to forecast the estimation the landfill firmness in this paper first studied the settling as well as the stress-strain state of the underlying soil base.

The aim of this research is to establish the dependence of settlement of the closed landfill on the properties of the underlying soil, as well as the landfill slope angle to predict the possibility of using it as a basis for construction.

Materials and Methods. During the study we will take into account the phase loading of landfill waste layers and angle of inclination. To predict the settling of closed landfill MSW the following mathematical models were used.

Covering and underlying layers described the Coulomb-Mohr model [8].

The body of landfill was modeled as a weak ground considering its creep for this a model uses Soft Soil Creep (SSC). Currently, this model more fully describes the properties of weak soil as stress-dependent stiffness and compression based secondary creep. It should be noted that the SSC model takes into account both physical and geometric nonlinearity of soil deformation process.

Total volume deformation ε_v, caused by the growth of effective stress from the initial value p_0' to p' for the period of time T ($T = t_c + t'$) consists of an elastic ε_v^e and viscoplastic ε_v^{vp} components. Viscoplastic component is the amount of deformation during consolidation $\varepsilon_{v\ c}^{vp}$ and after consolidation $\varepsilon_{v\ ac}^{vp}$. Rangeard [9] showed that the relationship between the deformations is expressed as follows:

$$\varepsilon_v = \varepsilon_v^e + \varepsilon_{v\ c}^{vp} + \varepsilon_{v\ ac}^{vp},$$

where

$$\varepsilon_v^e = \kappa^* \ln\left(\frac{p'}{p'_0}\right),$$

$$\varepsilon_{v\ c}^{vp} = (\lambda^* - \kappa^*)\ln\left(\frac{p'_{pc}}{p'_0}\right),$$

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

where μ^* — modified creep factor;

τ_c — time of consolidation that depends on the geometry of the sample under study;

t' — time pass from the start of loading of landfill;

κ^* — modified swelling ratio;

λ^* — modified compression ratio;

t_c — completion of primary consolidation;

p'_0 — initial effective stress;

p' — effective stress;

p'_{pc} — effective pre consolidation pressure.

The ratio of model parameters with internationally standardized parameters as follows:

$$\mu^* = \frac{C_\alpha}{2.3(1+e_0)},\ \lambda^* = \frac{C_C}{2.3(1+e_0)},\ \kappa^* = \frac{2C_S}{2.3(1+e_0)}\ ;$$

where C_C — compression ratio;

C_S — swelling ratio;

C_α — creep factor.

As noted above, the underlying soil is described by the Coulomb-Mohr model. Full yield condition of Coulomb-Mohr model consists of six functions (surfaces yield *f*), which are formed as follows:

$$f_{1a} = \frac{1}{2}(\sigma'_2 - \sigma'_3) + \frac{1}{2}(\sigma'_2 + \sigma'_3)\sin\varphi - c\cos\varphi \le 0;$$

$$f_{1b} = \frac{1}{2}(\sigma'_3 - \sigma'_2) + \frac{1}{2}(\sigma'_3 + \sigma'_2)\sin\varphi - c\cos\varphi \le 0;$$

$$f_{2a} = \frac{1}{2}(\sigma'_3 - \sigma'_1) + \frac{1}{2}(\sigma'_3 + \sigma'_1)\sin\varphi - c\cos\varphi \le 0;$$

$$f_{2b} = \frac{1}{2}(\sigma'_1 - \sigma'_3) + \frac{1}{2}(\sigma'_1 + \sigma'_3)\sin\varphi - c\cos\varphi \le 0;$$

$$f_{3a} = \frac{1}{2}(\sigma'_1 - \sigma'_2) + \frac{1}{2}(\sigma'_1 + \sigma'_2)\sin\varphi - c\cos\varphi \le 0;$$

$$f_{3b} = \frac{1}{2}(\sigma'_2 - \sigma'_1) + \frac{1}{2}(\sigma'_2 + \sigma'_1)\sin\varphi - c\cos\varphi \le 0,$$

where c — clutch;

$\sigma'_1, \sigma'_2, \sigma'_3$ — normal stresses;

φ — angle of internal friction.

In addition to the yield surface a Coulomb-Mohr model presented by six plastic potential functions g:

$$g_{1a} = \frac{1}{2}(\sigma'_2 - \sigma'_3) + \frac{1}{2}(\sigma'_2 + \sigma'_3)\sin\psi;$$

$$g_{1b} = \frac{1}{2}(\sigma'_3 - \sigma'_2) + \frac{1}{2}(\sigma'_3 + \sigma'_2)\sin\psi;$$

$$g_{2a} = \frac{1}{2}(\sigma'_3 - \sigma'_1) + \frac{1}{2}(\sigma'_3 + \sigma'_1)\sin\psi;$$

$$g_{2b} = \frac{1}{2}(\sigma'_1 - \sigma'_3) + \frac{1}{2}(\sigma'_1 + \sigma'_3)\sin\psi;$$

$$g_{3a} = \frac{1}{2}(\sigma'_1 - \sigma'_2) + \frac{1}{2}(\sigma'_1 + \sigma'_2)\sin\psi;$$

$$g_{3b} = \frac{1}{2}(\sigma'_2 - \sigma'_1) + \frac{1}{2}(\sigma'_2 + \sigma'_1)\sin\psi,$$

where ψ — angle of dilation.

Hydrodynamic aspects consist in the account of seepage forces acting on the skeleton of the soil environment and interaction parameters of liquid and solid phases of soil (pressure, tension and porosity) in the process of consolidation. Assuming the vortex seepage flow and distribution of the resistance element evenly over the section we will use the generalized Darcy law and equation of continuity. We assume that the compressibility of the skeleton and pore fluid is low, which leads to a linear dependence of the porosity of the soil pressure.

The interaction of soil skeleton and fluid characterize by volume force which proportional to the pressure gradient.

According to [10], the equation of continuity we supplement with the initial and boundary conditions.

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

Landfill for which was conducted simulation consists of ten layers of waste, thickness of 3 m each. Subsidence was defined based on incremental load of landfill in 30 years after its closure. The basis of Landfill is clay, sand and loam.

Simulations were conducted at three slopes angle of the polygon 30, 60 and 75°. Linear dimensions of polygons with different angles of slopes chosen so that the volume of landfill body remained unchanged. Settings of underlying soils are presented in Table 1. Parameters of waste are presented in Table 2 (Layer №1 — latest, Layer №10 — first of underlying polygon).

Table 1

Physical and mechanical parameters of soils

Parameter	Soils		
	Sand	Loam	Clay
Deformations module E_{ref}, kN / m^3	18000	10000	9000
Poisson’s ratio ν, units.	0.34	0.36	0.37
Soil specific weight γ_{unsat}, kN/m^3	18.0	13	19.0
Specific weight of water-saturated soil γ_{sat}, kN/m^3	20.7	14.6	21.8
Filtration coefficient in the horizontal direction k_x, units.	0.5	0.006	0.004
Filtration coefficient in the vertical direction k_y, units.	0.5	0.006	0.004
Module of deformation E, MPa	50	33	28
The specific adhesion c, kPa	3	34	81
The angle of internal friction φ, degrees	31	14	13

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Table 2

Physical and mechanical parameters of waste

Parameter	Values
Specific weight γ_{unsat}, kN/m^3	7.504
Specific weight of water-saturated soil γ_{sat} , kN/m^3	10.0
The specific adhesion *c*, kPa	25
The angle of internal friction φ, degrees	20
The initial coefficient of porosity e_0, units.	0.4268
Compression ratio C_C, units.	0.3987
Swelling ratio C_S, units.	0.0394
Creep factor C_α, units :	
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

Results and Discussion. In [11] the calculations of landfill strain at the slope angle of 75° was conducted. They amounted to 4.95 m for landfill with sand base, with clay base — 3.83 m, with loam base — 4.47 m.

Deformed estimated area of landfill with clay base and with his body angle of 60° shown in Fig. 1. An analysis of numerical calculations shows that vertical deformation of landfill totaled 3.8 m.

As a result of numerical calculation found that at the same angle the maximum vertical deformation was: for landfill of sand — 4.34 m (Fig. 2), with loam — 4.27 m. A comparison of these results shows that the angle of inclination of the landfill body significantly affects the vertical deformation, decreasing the angle from 75° to 60° deformations decreased by 1...12 % depending on the type of soil base.

To establish the impact of slope angle of landfill on its settling the simulations for landfill with angle of 30° was conducted. As a result of studies it was found that with decreasing of slope angle of landfill the impact on the underlying soil subsidence reduced and the difference between the values of deformation decreases.

Thus, if the underlying layer is sand, it can be observed that the vertical deformation reaches 3.94 m (Fig. 3), if the loam — 3.89 m (Fig. 4). If we use clay as underlayment then vertical deformation is the least compared to the previous two versions — 3.63 m (Fig. 5).

Comparing the value of settling showed that decreasing of the angle from 60° to 30° deformity decreased by 5...9 % depending on the type of soil base.

With decreasing of angle from 75° to 30° vertical deformation reduction was greatest for sand (20.4 %), while the same value for loam is 13 % and for clay is 5.22 %.

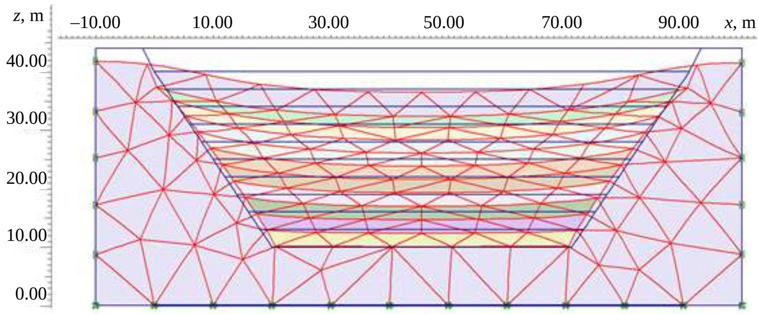

Fig. 1. Deformed calculated area of landfill with clay soil underlying (slope angle of landfill 60°)

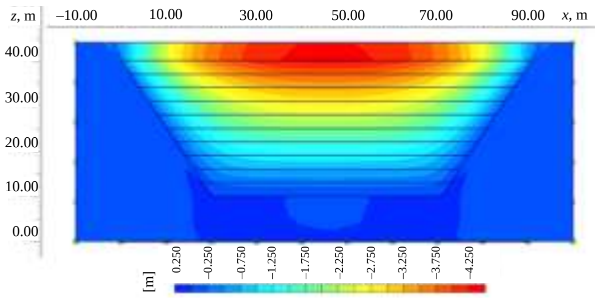

Fig. 2. Vertical deformation of landfill with sandy soil (angle of slope of landfill 60°)

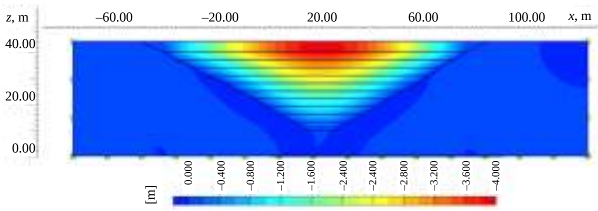

Fig. 3. The vertical deformation of landfill with sandy soil underlying (angle of landfill 30°)

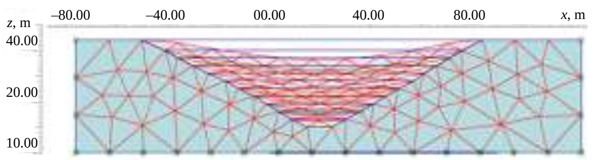

Fig. 4. Deformed calculated area of polygon with loam, as the underlying soil (angle of landfill 30°)

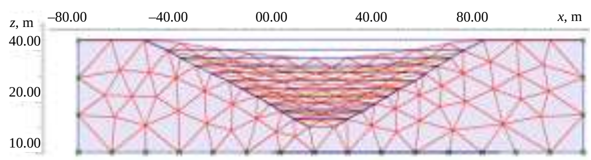

Fig. 5. Deformed calculated area of polygon with clay as underlying soil (angle of landfill 30°)

Fig. 6 shows the dependence of landfill settling from the slope angle of ground for three types of underlying soil.

Conclusions. The modeling of strain state of landfill in view of soil foundations and angle of landfill using finite element method was held. As a result of studies we found that with decreasing of slope angle of landfill the settling is significant reduce. Thus, decreasing the angle from 75° to 30° settling decreases by 5...22 % depending on the type of soil base. The largest decrease is observed in less dense soil — sand.

We have got the dependencies of settling from the angle of slopes for different soil foundations as a second-degree polynomial. They are as follows:

— For clay — $y = -0.07x^2 + 0.18x + 3.72$;

— For loam — $y = -0.09x^2 + 0.07x + 4.49$;

— For sand — $y = 0.105x^2 - 0.925x + 5.77$.

Using these dependences can be defined the settling for intermediate values of slope angles. With decreasing of slope angle the difference between settlings of landfill on different bases is decreasing. The results can be used in predicting of landfill settling with different geometric, physical and mechanical parameters for assessing the possibility of further exploitation of landfill as the foundation structures for various purposes.

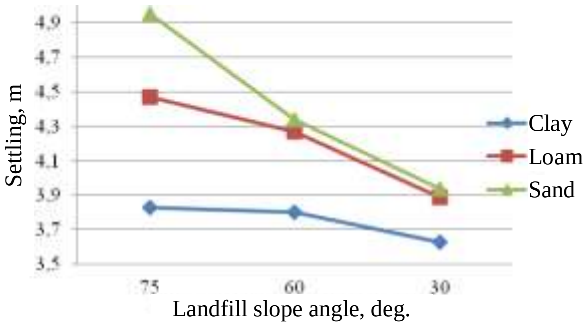

Fig. 6. Dependence of settling from the angle of slopes for MSW landfill

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