Effect of coupling hydro-mechanical–biodegradation process on the slope stability of a bioreactor landfill

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ABSTRACT

In a bioreactor landfill, waste biodegradation, generation of gas and leachate, two-phase flow and mechanical deformation closely couple with each other. Recirculated leachate can accelerate waste biodegradation and generation of landfill gas. A significant mechanical deformation occurs due to biodegradation and suction change, and the increase in both gas pressure and leachate pressure could affect the slope stability due to a decrease in effective stress. In this paper, a full coupled hydro-mechanical-biodegradation (H-M-B) model is proposed to study the effect of the coupling processes in a bioreactor landfill on the slope stability, and a solver is implemented in OpenFOAM platform based on finite volume method. Considering the effect of volume change of solid waste, the spatial and temporal distributions of gas and leachate pressures are calculated by two-phase flow model and the corresponding slope stability is evaluated by the factor of safety calculated by the strength reduction technique method. The results characterize the effect of waste biodegradation, gas recovery and leachate recirculation on the mechanical deformation and slope stability of a bioreactor landfill, which will benefit to its design and decision-making.

Keywords: two-phase flow, coupling process, waste deformation, leachate recirculation, slope stability

1 INTRODUCTION

Bioreactor landfills have become a popular approach for the disposal of municipal solid waste (MSW) in more and more countries and regions. A bioreactor landfill is a sanitary landfill site that uses enhanced microbiological processes to transform and stabilize the readily and moderately decomposable organic waste constituents (Warith et al., 2003). Leachate recirculation, which helps to distribute moisture contents and nutrients throughout the bioreactor, is a commonly used method to accelerate waste biodegradation and generation of landfill gas (Sharma and Reddy 2004). To improve the leachate quality and accelerate the stabilization of MSW, various methods including surface irrigation, infiltration ponds, vertical injection wells, and horizontal trenches are used for leachate recirculation in bioreactor landfills.

In a bioreactor landfill, waste biodegradation, generation of gas and leachate, two-phase flow and mechanical deformation closely couple with each other. Numerous models for the coupling processes in bioreactor landfills have been proposed in literature. McDougall (2007) presented a conceptual framework for landfilled waste in relation to coupled hydraulic, biodegradation and mechanical behaviour, which was implemented by a finite element method. Liu et al. (2011) proposed a one-dimensional model for MSW considering coupled mechanical-hydraulic-gaseous effect. White and Beaven (2013) simulated the transport and bio-chemical behaviour of the solid, liquid and gas phases of waste contained in a landfill by the landfill degradation and transport model (LDAT). Lu et al. (2019) presented a finite-volume numerical model for bio-hydro-mechanical behaviours of MSW in landfills. Furthermore, Feng et al. (2019) analysed the effect of void ratio on the coupled processes in landfills during leachate recirculation by an improved HBM-coupled model. More recently, Chen et al. (2020) established a degradation–consolidation model to describe the biological degradation and consolidation behaviour of landfilled MSW. These studies contribute to understanding the coupling processes for further practical applications and assessments.

At present, landfill gas emission, leachate leakage, waste deformation and stability are the main problems in landfills, which are closely related to leachate and gas flow. Numerous studies have analysed the effect of leachate recirculation on landfill slope stability (Xu et al., 2012; Giri and Reddy, 2014; Townsend et al., 2015; Feng et al., 2018 and 2019). A significant mechanical deformation occurs due to biodegradation and suction change, and the increase in both gas pressure and leachate pressure could affect the slope stability due to a decrease in effective stress.

This paper proposed a full coupled hydro-mechanical-biodegradation (H-M-B) model to study the effect of the coupling processes in a bioreactor landfill on the slope stability, and a solver is implemented in OpenFOAM platform based on finite volume method. Using the spatial and temporal distributions of gas and leachate pressures calculated by the two-phase flow model, the volume change of waste due to coupling processes of biodegradation, hydraulic and mechanical deformations are analysed. Moreover, the corresponding slope stability is evaluated in terms of the factor of safety calculated by the strength reduction technique method.

2 COUPLED MODEL

An advanced finite-volume coupled multi-phase model is updated from the bio-hydro-mechanical model proposed by Lu et al. (2019) for further slope stability analysis. This coupled model is implemented on the OpenFOAM platform as an updated new solver.

2.1 Biodegradation model

Components of nutrients and solutes in the waste, leachate or landfill gas have little effect on the two-phase flow and slope stability. A simplified one-stage biodegradation model is then adopted in this study, which can be expressed as:

$$Q_{\mathrm{w}} = \eta \rho_{\mathrm{d}} \sum\nolimits_{i=1}^{4} A_i c_i f_{\mathrm{w}} e^{-c_i f_{\mathrm{w}} t} \tag{1}$$

$$Q_{\mathrm{g}} = (1-\eta) \rho_{\mathrm{d}} \sum\nolimits_{i=1}^{4} A_i c_i f_{\mathrm{w}} e^{-c_i f_{\mathrm{w}} t} \tag{2}$$

where Q_{w} and Q_{g} are the source terms of leachate and landfill gas during biodegradation; η is the reaction coefficient; ρ_{d} is the dry density of MSW; A_i and c_i are the proportion and the decomposition rate constant of biodegradation component i, respectively; f_{w} is the water content factor and t is the time of biodegradation.

2.2 Hydraulic model

The classic two-phase flow model for unsaturated porous materials is adopted to describe the leachate and gas flow in a landfill, the mass conventional equation can be expressed as:

$$\begin{cases} \dfrac{\partial (n S_{\mathrm{w}} \rho_{\mathrm{w}})}{\partial t} + \nabla \cdot (\rho_{\mathrm{w}} \mathbf{v}_{\mathrm{w}}) = Q_{\mathrm{w}} \\ \dfrac{\partial (n S_{\mathrm{g}} \rho_{\mathrm{g}})}{\partial t} + \nabla \cdot (\rho_{\mathrm{g}} \mathbf{v}_{\mathrm{g}}) = Q_{\mathrm{g}} \end{cases} \tag{3}$$

where n is the porosity; S_{w} and S_{g} are the saturation degrees of leachate and gas, and S_{w}=1-S_{g}; ρ_{w} and ρ_{g} are the densities of leachate and gas; and the velocity vectors for leachate and gas, $\mathbf{v}_{\mathrm{w}}$ and $\mathbf{v}_{\mathrm{g}}$, can be calculated according to Darcy's law, written as:

$$\begin{cases} \mathbf{v}_{\mathrm{w}} = -K_{\mathrm{w}}(\theta)(\nabla p_{\mathrm{w}} - \rho_{\mathrm{w}} \mathbf{g}) / \rho_{\mathrm{w}} \mathbf{g} \\ \mathbf{v}_{\mathrm{g}} = -K_{\mathrm{g}}(\theta)(\nabla p_{\mathrm{g}} - \rho_{\mathrm{g}} \mathbf{g}) / \rho_{\mathrm{g}} \mathbf{g} \end{cases} \tag{4}$$

The conductivity function (K) for unsaturated MSW can be given as:

$$K_{\mathrm{w}}(\theta) = K_{\mathrm{sw}} k_{\mathrm{rw}}(\theta) \tag{5}$$

$$K_{\mathrm{g}}(\theta) = K_{\mathrm{sg}} k_{\mathrm{rg}}(\theta) \tag{6}$$

where K_{sw} and K_{sg} are the saturated conductivity for leachate and gas; and k_{rw} and k_{rg} are the relative conductivity for leachate and gas based on van Genuchten-Mualem (VGM) model (van Genuchten, 1985):

$$k_{\mathrm{rw}}(\theta) = S_{\mathrm{e}}^{l} \left[1 - (1 - S_{\mathrm{e}}^{1/m})^{m} \right]^2 \tag{7}$$

$$k_{\mathrm{rg}}(\theta) = (1 - S_{\mathrm{e}})^{l} (1 - S_{\mathrm{e}}^{1/m})^{2m} \tag{8}$$

where θ is the water content; and the effective liquid saturation S_{e} can be derived by the relationship:

$$S_{\mathrm{e}} = \frac{\theta - \theta_{\mathrm{r}}}{\theta_{\mathrm{s}} - \theta_{\mathrm{r}}} = \left(\frac{1}{1 + (\alpha s)^{n_{\mathrm{v}}}} \right)^{m} \tag{9}$$

where l is the pore connectivity constant; θ_{s} is the saturated water content and θ_{r} is the residual water content; α, n_{v} and m are the VGM model parameters for the MSW; s is the suction.

Considering the effect of volume change, the air-entry related parameter α can be defined as:

$$\alpha = \phi (v - 1)^{\psi} \tag{9}$$

where ϕ and ψ are the soil constants, and v is the specific volume (Gallipoli, 2003).

2.3 Mechanical model

The deformation behavior of waste can be described by the comprehensive effect of elastic deformation, plastic deformation, biodegradation and mechanical creep. The increment of strain can be derived by:

$$\mathrm{d}\boldsymbol{\varepsilon} = \mathrm{d}\boldsymbol{\varepsilon}^{e} + \mathrm{d}\boldsymbol{\varepsilon}^{p} + \mathrm{d}\boldsymbol{\varepsilon}^{b} + \mathrm{d}\boldsymbol{\varepsilon}^{c} \tag{10}$$

where $\mathrm{d}\boldsymbol{\varepsilon}^{e}$, $\mathrm{d}\boldsymbol{\varepsilon}^{p}$, $\mathrm{d}\boldsymbol{\varepsilon}^{c}$ and $\mathrm{d}\boldsymbol{\varepsilon}^{b}$ denote elastic, plastic, creep and biodegradation induced strain increments, respectively. Detailed information can be found in Lu et al. (2019). The stress and strain fields of the whole landfill at any time could be imported into the slope stability analysis as the initial mechanical boundary.

3 SLOPE STABILITY ANALYSIS

3.1 Strength reduction method

The finite volume method (FVM) is one of the most popular methods used to deal with computational fluid dynamics (CFD) problems. The coupling model established above has been programmed into the OpenFOAM platform based on FVM. This study further adds a slope stability analysis sub-program which can increase the portability of the developed coupled model and expand the ability to handle landfill problems by FVM.

The results calculated by the coupled model will be directly imported to the slope stability analysis model base on the strength reduction method. In response to a given stress field under the static equilibrium state, the internal stress filed is set as the initial geostress filed. The strength parameters c and φ are gradually reduced to examine the response of landfill following:

$$\begin{cases} c_R = c / FS \\ \varphi_R = \arctan((\tan\varphi)/FS) \end{cases} \tag{11}$$

The reduced strength parameters are entered into the yield surface function to judge the yield state. The non-associated flow law of Mohr-Coulomb model is employed. In principal stress space, the yield function f and plastic potential g are written as:

$$f = (\sigma_1' - \sigma_3') + (\sigma_1' + \sigma_3')\sin\varphi_R - 2c_R\cos\varphi_R \tag{12}$$

$$g = (\sigma_1' - \sigma_3') + (\sigma_1' + \sigma_3')\sin\varphi_R \tag{13}$$

The explicit returning mapping method is adopted to get the modified plastic strain increment $\mathrm{d}\boldsymbol{\varepsilon}^p$. Detailed information can be found in Clausen et al. (2005) and Tang et al. (2015).

Following the mass equilibrium equation for solid waste in deformation model, the relationship between plastic strain increment and deformation increment could be derived from:

$$\begin{aligned} &\nabla\cdot\left[\mu\nabla(\mathrm{d}\mathbf{u}) + \mu\nabla(\mathrm{d}\mathbf{u})^T + \lambda\mathbf{I}\,\mathrm{tr}(\nabla(\mathrm{d}\mathbf{u}))\right] \\ &= \nabla\cdot\left[2\mu(\mathrm{d}\boldsymbol{\varepsilon}^p) + \lambda\mathbf{I}\,\mathrm{tr}(\mathrm{d}\boldsymbol{\varepsilon}^p)\right] + \nabla\cdot(b\mathbf{I}\mathrm{d}p) \end{aligned} \tag{14}$$

where μ and λ are Lame constants, which can be derived from the Young's modulus E_s and Poisson's ratio v.

The modified plastic strain increment can be introduced into the Eq. (14) to get the deformation increment. Loop above calculation process, and the final deformation field can be calculated until the reduce coefficient reaches the fact of safety FS.

3.2 Factor of safety

The factor of safety FS of slope is commonly estimated according to the result of displacement at the failure moment. For FVM, the maximum displacement of the slope sharply increases with an increase in the FS which reduces the strength parameters, i.e., Eq. 11 (Fig. 1). The FS value with the largest curvature is defined as the final FS, that is, 1.79. This value is close to that calculated by finite element method (FEM), that is, 1.72, with acceptable difference. Thus, FVM is effective for further slope stability analysis.

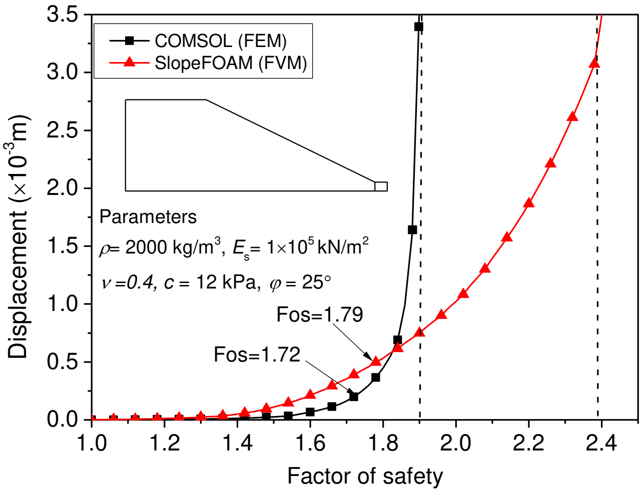

Fig. 1. The determination of factor of safety.

4 MODELING OF A LANDFILL SLOPE

A two-dimensional conceptual landfill slope is built in Fig. 2 with a height of 10 m, a length of 20 m and a slope gradient of 1:2. The top of the platform is set as an imperious boundary to simulate surface leachate recirculation, and the bottom is set as a constant pressure to simulate a leachate drainage system.

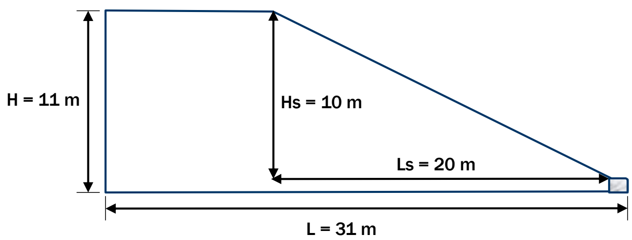

Fig. 2. The geometric of a conceptual landfill slope.

Some model parameters for slope stability analysis are listed in Table 1, with others listed in Lu et al. (2019). This coupled model has been verified with the results of two tests.

Table 1. Parameters for slope stability analysis.

Parameter	Unit	Value
Density ρ	kg/m^3	2000
Young's modulus E_s	kN/m^2	1×10^5
Poisson's ratio v	/	0.4
Cohesion c	kPa	12
Friction angle φ	°	25

5 RESULT AND DISCUSSION

5.1 Hydraulic properties

The hydraulic properties of waste related to the suction and void ratio change are significant for leachate and gas flows. The variation of saturated and relative hydraulic conductivity with respect to void ratio is studied in Fig. 3. Void ratio has a significant influence on the saturated hydraulic conductivity K_{sat}. When the void ratio increases from 0.5 to 4.0, K_{sat} increases from 10^{-9} to 10^{-5} m/s. However, void ratio has an opposite influence on the relative hydraulic conductivity K_r. For a specific suction, K_r decreases with an increase in void ratio, that is, from 10^{-5} to 10^{-9} m/s as the void ratio increases from 0.5 to 4.0. For a larger suction, K_r shows a significant decrease and the effect of void ratio on K_r is more pronounced.

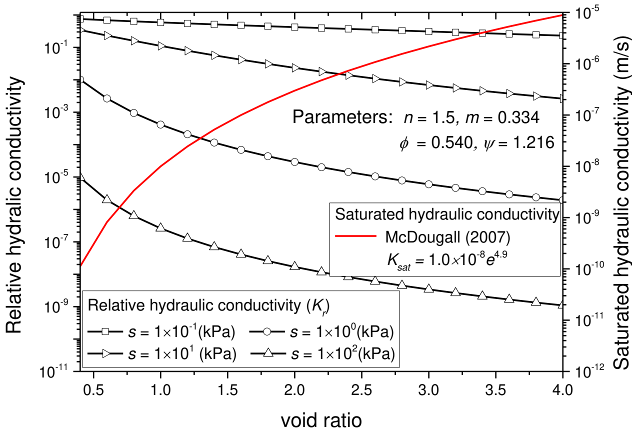

Fig. 3. The effect of void ratio on hydraulic conductivity.

5.2 Leachate and gas flow

Fig. 4 shows the distributions of leachate pressure with depth and time during the coupled processes. It increases with an increase in depth and time to a maximum value at approximately 5 m deep and 5th day. This is mainly due to the recirculated leachate and the accelerated biodegradation that accompanies it. As the reaction of biodegradation becomes weakened and the leachate is drained out of the landfill at the bottom under gravity, the leachate pressure gradually decreases in the deep waste and later days.

Fig. 5 shows the distributions of landfill gas pressure with depth and time during the coupled processes. The gas pressure shows a similar trend with the leachate pressure, that is, increasing to maximum values in 5th days before a reduction. Due to the accumulation of produced landfill gas in the landfill, the maximum gas pressure can reach 9.1 kPa at the depth of 5.8 m.

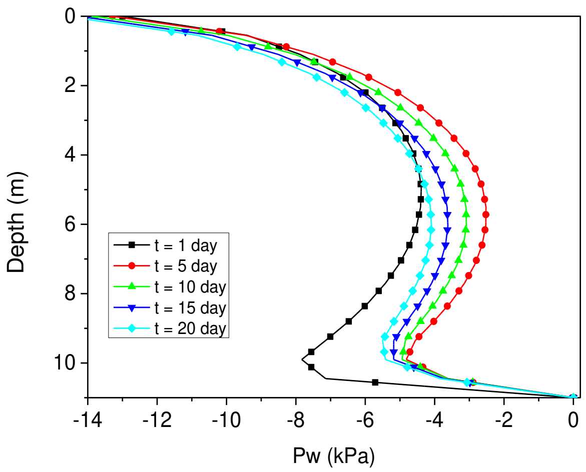

Fig. 4. Leachate pressure distribution.

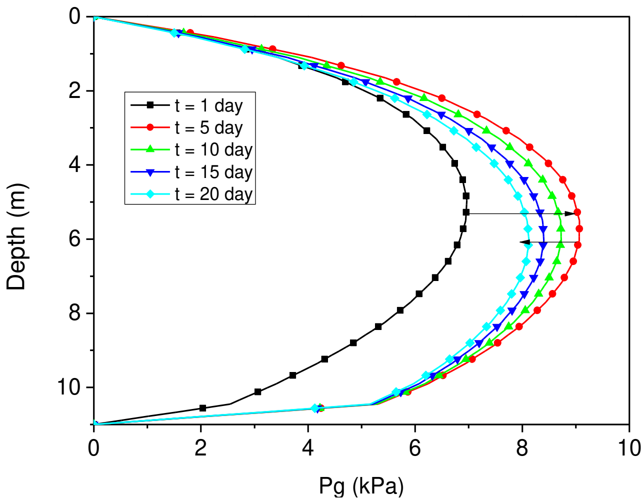

Fig. 5. Landfill gas pressure distribution.

In summary, the biodegradation is accelerated at the first stage of leachate recirculation and the source terms of leachate and landfill gas sharply increases resulting in a decreased effective stress for solid waste. As the microbiology and chemical reaction slow down, leachate and gas gradually dissipate and the leachate and gas pressures in landfill decrease.

5.3 Slope stability

Excess leachate and gas pressures in a landfill due to leachate recirculation will increase the risk of slope instability. Fig. 6 shows that the final *FS* decreases by approximately 0.16 in 5 days before rising up. This corresponds to the changing process of leachate and gas pressure in Figs. 4 and 5.

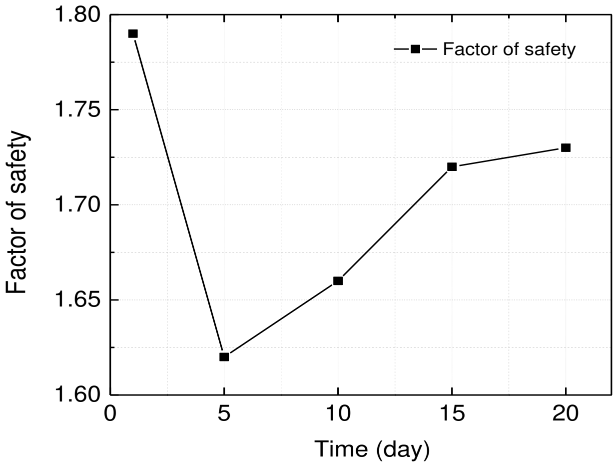

Fig. 6. The relationship between *FS* and biodegradation time.

As a comparison, the leachate and gas pressures due to a continuous biodegradation process for 20 days calculated by the coupled model are imported into the slope stability analysis of Case 2, but not into Case 1. Case 1 can be regarded as a conventional landfill without leachate recirculation process, and Case 2 represents a modern bioreactor landfill with complex leachate and landfill gas interactions. As shown in Fig. 7, the final factor of safety of Case 1 is 1.79, which is 0.13 larger than that of Case 2. It also can be seen that the waste deformations at the failure moment in Case 2 are also more apparent than Case 1. Thus, the stability of a landfill slope would be overestimated if the effect of leachate pressure and gas pressure were ignored.

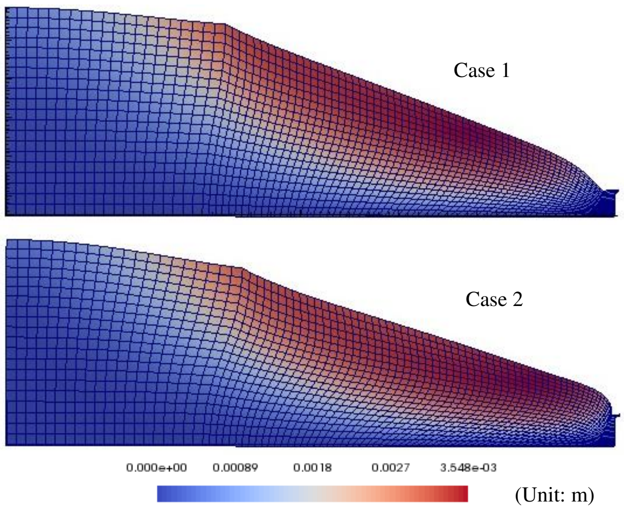

Fig. 7. The comparison of deformation results between case 1 (without considering the effect of coupled process) and case 2 (considering the effect of coupled process).

6 CONCLUSIONS

To study the effect of coupling processes on the slope stability of a bioreactor landfill, this study implemented a slope analysis model into a full coupled hydro-mechanical-biodegradation (H-M-B) model based on finite volume method and OpenFOAM platform. Leachate recirculation will accelerate the biodegradation at first, which will increase the leachate and gas pressures and then decrease the slope stability. The further on-going leachate and gas flows can gradually increase the effective stress and slope stability. The proposed model provides a framework for slope stability analysis of bioreactor landfills. More analyses of coupling behaviors and practical engineering applications will be done in future.

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REFERENCES

1) Chen, Y.M., Xu, W.J., Ling, D.S. Zhan, L.T. and G, W. (2020): A degradation–consolidation model for the stabilization behavior of landfilled municipal solid waste, *Computers and Geotechnics*, 118, 103341.
2) Clausen, J., Damkilde, L. and Andersen, L. (2007): An efficient return algorithm for non-associated plasticity with linear yield criteria in principal stress space, *Computers and Structures*, 85(23-24), 1795–1807.
3) Feng, S.J., Chen, Z.W., Chen, H.X., Zheng, Q.T. and Liu, R. (2018) Slope stability of landfills considering leachate recirculation using vertical wells, *Engineering Geology*, 241, 76-85.
4) Feng, S.J., Fu,W.D., Zhou, A.N. and Lyu, F. (2019) A coupled hydro - mechanical - biodegradation model for municipal solid waste in leachate recirculation, *Waste management*, 98, 81–91.
5) Feng, S.J., Lu, S.F., Chen, H.X., Fu, W.D. and Lü, F. (2018) Three-dimensional modelling of coupled leachate and gas flow in bioreactor landfills, *Computers and Geotechnics*, 84, 138-151.
6) Gallipoli, D., Gens, A., Sharma, R. and Vaunat, J. (2003) An elasto-plastic model for unsaturated soil incorporating the effects of suction and degree of saturation on mechanical behaviour, *Géotechnique*, 53(1), 123-36.
7) Giri, R.K. and Reddy, K.R. (2014) Slope stability of bioreactor landfills during leachate injection: effects of heterogeneous and anisotropic municipal solid waste conditions, *Waste management & research*, 32(3), 186–197
8) Liu X.D., Shi J.Y. and Qian X.D. (2011) One-dimensional model for municipal solid waste (MSW) settlement considering coupled mechanical-hydraulic-gaseous effect and concise calculation, *Waste Management*, 2011, 31(12), 2473-2483.
9) Lu, S.F., Xiong, J.H., Feng, S.J., Chen, H.X., Bai, Z.B., Fu, W.D. and Lü, F. (2019) A finite-volume numerical model for bio-hydro-mechanical behaviors of municipal solid waste in landfills, *Computers and Geotechnics*, 109, 204–219
10) McDougall, J. (2007) A hydro-bio-mechanical model for settlement and other behaviour in landfilled waste, *Computers and Geotechnics*, 34(4), 229-46.
11) Sharma, H.D. and Reddy, K.R. (2004) *Geoenvironmental*

engineering, Wiley, Hoboken
12) Tang, T., Hededal, O., and Cardiff, P. (2015) On finite volume method implementation of poro-elasto-plasticity soil model, *International journal for numerical and analytical methods in geomechanics*, 39(13), 1410–1430.
13) Townsend, T.G., Powell, J., Jain, P., Xu, Q.Y., Tolaymat, T. and Reinhart, D. (2015) *Sustainable practices for landfill design and operation*. Springer, Berlin
14) Van Genuchten, M.T. and Nielsen, D.R. (1985) On describing and predicting the hydraulic properties. Annales Geophysicae, 3(5), 615-628.
15) Warith, M.A. (2003) Solid waste management: new trends in landfill design, *Emirates Journal for Engineering Research*, 8(1), 61-70.
16) White, J.K. and Beaven, R.P. (2013) Developments to a landfill processes model following its application to two landfill modelling challenges, *Waste Management,* 33(10), 1969–1981.
17) Xu, Q.Y, Tolaymat, T. and Townsend, T.G. (2012) Impact of pressurized liquids addition on landfill slope stability, *J Geotech Geoenviron*, 138(4), 472–480