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Mechanical and Thermal DEM analyses of baled MSW storage

Analyse mécanique et thermique moyennant éléments discrets des déchets urbains emballées

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ABSTRACT: Municipal solid waste is sometimes stored in baled form either before or after treatment. General design requirements for MSW landfills, such as slope stability and lining long-term integrity are still relevant for bale fills and need to be checked by calculation. However, the large size of the bales presents some difficult problems for traditional analytical and numerical modelling approaches, such as the pervasive presence of bale-bale contact discontinuities within the MSW mass. On the other hand, the discrete element method offers a rather natural framework in which to analyse bale fills. In this communication we exemplify that approach by presenting two separate analysis of a baled fill using the discrete element method. The first analysis is a thermal analysis in which the heat generated by biological evolution of the baled waste is taken into account to assess the thermal evolution of the baled waste storage as construction proceeds. The second is a mechanical analysis in which overall stability of the baled MSW storage is assessed.

RÉSUMÉ : Les déchets solides municipaux sont parfois entreposés sous forme de balles avant ou après leur traitement. Les exigences générales en matière de conception pour les décharges de déchets urbains, comme la stabilité de la pente et l'intégrité à long terme du revêtement sont toujours pertinentes pour les remplissages de balles et doivent être vérifiées par calcul. Cependant, la grande taille des balles présente quelques problèmes difficiles pour les approches traditionnelles de modélisation analytique et numérique, telles que la omniprésence de discontinuités de contact balle-balles dans la masse MSW. D'autre part, la méthode des éléments discrets offre un cadre plutôt naturel pour analyser les remplissages de balles. Dans cette communication, nous illustrons cette approche en présentant deux analyses distinctes d'un remplissage en balles à l'aide de la méthode des éléments discrets. La première analyse est une analyse mécanique dans laquelle on évalue la stabilité globale du stockage des déchets solides en balles. La seconde est une analyse thermique dans laquelle la chaleur générée par l'évolution biologique des déchets emballés est prise en compte pour évaluer la charge thermique sur le revêtement au fur et à mesure de la construction

KEYWORDS: municipal solid waste, thermal analysis, stability analysis, discrete element method.

1 INTRODUCTION.

1 .1 *Baled MSW deposits*

Many efforts have been devoted to minimize the volume and environmental impact of municipal waste disposal schemes. One technique that is sometimes adopted is that of baling. Baling involves wrapping up in plastic pre-processed MSW for intermediate or long term storage. Baling results in a compacted waste, requiring less storage space. Baled waste is also easier to transport and handle. An overview of the pros and cons of baling may be found in Baldassaro et al. (2003).

Bales of waste are typically wrapped up in low density polyethylene (LDPE). There are two main types of bales: rectangular and cylindrical, generally weighting around 1 mT and having meter-sized dimensions. Baled waste can be disposed of in long-term or temporary deposits, frequently as an intermediate storage to incineration. The former approach, leading to bale-landfills, has been used in countries such as USA, Lebanon, Iceland, New Zealand, Italy and Spain (Nammari, 2006). When long-term storage of baled MSW is envisaged, liners and other protective design features similar to those applied in regular MSW deposits need to be engineered. An idealized scheme of a baled MSW deposit is shown in Figure 1.

Most research on baled waste has focused in environmental and/or safety aspects, such as the biochemical evolution of waste inside the bales, the heating potential on incineration or the self-combustion hazard (Nammari, 2006; Passamani et al., 2016). Little attention has been paid instead to geo-environmental problems such as slope stability and thermal loads on the lining.

1 .2 *DEM*

The discrete element method (DEM) is now extensively used in geomechanics for the exploration of fundamental soil and rock behaviour (O'Sullivan, 2011). Although the best-known applications of the method are in single-phase mechanical problems, extension to multi-phase (e.g. Climent et al., 2014) or thermal (El-Shamy et al., 2011) problems is relatively straightforward. Direct application of the method to large-scale boundary value problems is certainly possible (e.g. Ciantia et al., 2016) but, to overcome computational limitations, generally requires the use of carefully designed scaling-up or coarse-graining techniques.

Baled MSW deposits offer a favourable setting for DEM-based analysis. Due to the relative large dimensions of the bales, it is feasible to establish a one-on-one map in which each bale is represented by a single element without incurring in excessive computational costs. In this communication we illustrate this point by presenting mechanical and thermal analyses of baled MSW.

1 .3 *Case description*

The analyses described below were inspired by studies for a potential long-term deposit. The deposit in question was planned to recover a pre-extant quarry. The site was approximately elliptic in plan with a 350 m long-axis and 200 m short-axis. The maximum planned height of the deposit above its base is 110 m, and the maximum height above its surroundings is 75 m. The bales to be stored were shaped as parallelepipeds (1.1 m x1.1 m x1.65 m). The waste wrapped was the output of a plant where MSW underwent mechanic-biological treatment (MBT).

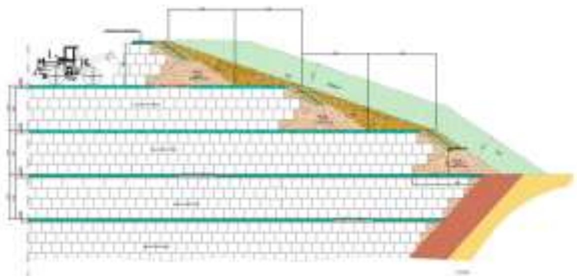

Figure 1 Scheme of a baled MSW deposit.

2 SLOPE STABILITY ANALYSYS

Slope stability analysis of MSW deposits is most frequently performed using limit equilibrium. Only more recently finite element based analyses have also been used for this purpose (Zekkos et al., 2010). Shear strength characterization of MSW is famously difficult and backanalysis of failures play a large role in the selection of strength parameters for design (Cañizal et al., 2011). In the case of baled waste deposits the pervasive presence of bale-to-bale contacts poses additional problems of characterization.

Van Impe & Bouazza (1998) report large scales shear test on baled waste. The shear plane was directed through the bale to bale contact and, therefore, an interface friction angle was measured. No clear limit failure was attained in the tests, and the mobilized friction angle increased between 10° and 38° at shear strains of 5 and 10%, respectively. These values are not very different to those observed on generic MSW, perhaps a reflection of the large fraction of plastics in current MSW.

2 .1 *Slope stability using DEM*

The use of DEM for slope stability is increasing, largely because of the attractive of the method for studies that require precise run-out estimations (Katz et al. 2014). Evaluation of safety factors may be done using a similar approach to that followed in FEM-based slope stability analysis in which a strength parameter is increasingly reduced from the estimated value until failure is observed in the model. The reduction factor applied to the strength parameter is the computed safety factor. For this approach to work it is necessary to have a criterion for the onset of failure and to identify clearly the parameter controlling strength in the model.

Boon et al. (2014) argued that the most practical method to identify failure in DEM based slope stability analyses was obtained by tracking motion at several key monitoring points, rather than by using global measures of dynamic equilibrium or kinetic energy. The selection of the strength parameter may be more problematic. In general shear strength in DEM is a result of both grain to grain friction and fabric interlocking. While grain to grain friction is a model input parameter and therefore easy to factor, the effect of interlocking is more difficult to factor directly, as it may depend on ensemble properties such as grain size and shape distributions and porosity. An interpretation problem may arise if, as it is generally the case, the discrete model is a scaled up analogue of the field material, since not all scaling procedures preserve fabric.

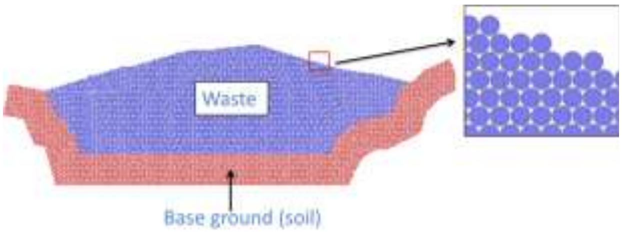

Figure 2 DEM model of a plane strain section of baled MSW deposit

2 .2 *Application to the baled MSW deposit*

For the case described here an equivalent plane strain model was created alongside the major axis of the site (Figure 2) In the model each bale was represented by a spherical element of 1.1 m diameter -hence preserving bale height. Density of the elements was selected (760 kg/m^3) so that the weight of each element was equal to that expected for the bales. The elements were arranged following an hexagonal packing, which mimicked the planned disposition of the bales. To represent the shape effect rotation of the spherical elements was blocked.

Monitoring points for particle velocity were selected at the deposit surface (Figure 3) and friction at the contact was reduced. An initial constant value of 19° was selected for the computation. The results revealed a safety factor of 8 (Figure 4) which made further computational refinement unnecessary.

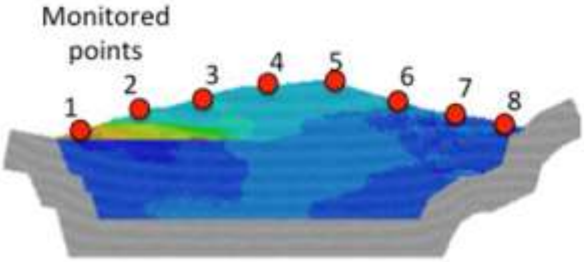

Figure 3 Monitoring points for velocity in stability analysis and velocity contours at failure.

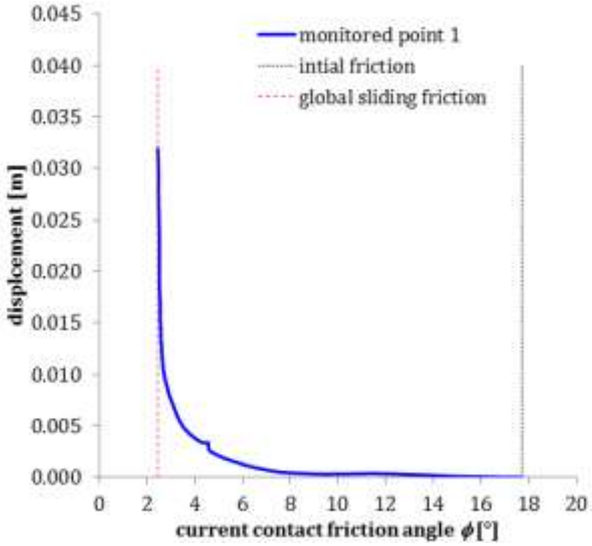

Figure 4. Displacement history at monitoring point

3 THERMAL ANALYSYS

3 .1 *Need for thermal analyses*

There are several reasons for which predictions of temperature and heat evolution of MSW deposits may be required. Heat balance analyses are essential when heat generated in landfills is directly exploited as an energetic resource (Coccia et al., 2013). But they are also necessary for optimization for their performance as bioreactors (Megalla et al., 2015). On the other hand historical predictions of temperature evolution for the MSW at the contact with the lining are also a necessary input to perform detailed studies of geomembrane service life (Rowe & Islam, 2009) or liner desiccation (e.g. Zhou & Rowe, 2005).

3 .2 *Heat generation in MSW*

Heat is generated in MSW deposits as a byproduct of the biochemical evolution of the waste. The evaluation of heat generation potential from direct thermochemical analysis of the waste is quite complex and prone to large error, and empirical approaches based on field observations are currently favoured (Yesiller et al., 2015). From these observational studies, equations such as

$$H = A\left(\frac{Bt}{B^2 + 2Bt + t^2}\right)\exp\left(\frac{t}{D}\right)^{\frac{1}{E}} \tag{1}$$

may be proposed to describe the elementary heat source per unit volume. Another useful outcome of these studies is the identification of heat conduction as the dominant mechanism involved in heat transfer, some 20 times larger than convection (Yesiller et al., 2005). This allows a relatively simple numerical analysis based on the heat conduction equation. Currently those analyses are typically performed numerically using finite elements (Hanson et al., 2008; Rowe et al., 2010; Megalla et al., 2015). None of this studies, however, has dealt with the case of baled MSW for which DEM offers an interesting alternative.

3 .3 *Thermal modelling using DEM*

Heat transfer analysis in DEM is based on a discretized version of the heat transfer equation (Itasca, 2014) in which each particle acts as a heat reservoir and each contact as a heat conduit. The energy balance for each particle is expressed as

$$Q_v = m_b C_v \frac{\partial T}{\partial t} + \sum_{p=1}^{N} Q^p \tag{2}$$

Where m_b stands for particle mass, C_v for the constant-volume specific heat assigned to the particle, Qv for heat source power and Qp for the heat flow through contact p. This, in turn, is obtained using

$$Q^p = -\frac{\Delta T}{\eta^p l^p} \tag{3}$$

where ΔT is the temperature gradient between contacting particles, l^p the branch vector of the contact and η^p the thermal resistivity per unit length assigned to the contact.

3 .4 *Thermal model of baled MSW deposit*

The thermal model is run on the same model employed for the mechanical analysis (Figure 2). Thermal boundary conditions are represented by a constant temperature at the lower boundary - deduced from the local geothermal gradient to be 19℃ at 25 m below ground. At the upper boundary a sinusoidal simplification of local annual atmospheric mean temperature oscillation is applied. The oscillation limits are 6℃ and 30℃.

The upper boundary is a moving boundary, to represent the progressive filling of the deposit. The model is raised in 9 steps; at each step a layer of 9 bales height is activated. This is equivalent to total operation period of 27 years for the particular case considered here.

For initial estimations the heat generation function (1) was used for each bale with parameters given in Table 1. These parameters were adjusted taking into account the composition of the MBT urban waste that was considered for the site. This was dominated by plastics (30%) and textile/paper (55%), with an estimated methanogenetic potential of approximately 70 Nm^3 CH_4 / t.

Table 1 Parameters for heat source function (eq. 1)

A	B	D	E
W/m^3	-	-	-
5.5	2200	1200	0.83

For identical spheres in hexagonal packing an analytical relation may be established between the equivalent continuum conductivity, k, and contact resistivity, η,

$$\eta = \frac{1}{k\sqrt{2}R^2} \tag{4}$$

This allows to exploit data on conductivity available from other MSW deposits (e.g. Yesiller et al., 2015). The parameters used in the simulation are presented in Table 2

Table 2 Material parameters for the thermal simulation

C_v	k	η
J/(kgK)	W/mK	K/(Wm)
5.5	2200	1200

3 .4 *Thermal analysis: results*

The model results indicate an evolution of temperature within the deposit that peaks somewhat below 60℃ and has its maximum in the upper part of the section (Figure 5). These observations are in line with observations of temperature evolution on other MSW deposits (Hanson et al., 2010).

Temperature evolution history at individual bales may be easily extracted from the model (Figure 6, Figure 7). In the particular case being analysed the temperature at the layer in contact with the liner - point 1- raises to 30℃ quickly and is maintained at that value with little variation throughout the period under study. This kind of local temperature evolution may then be used as input in analysis of liner integrity.

4 CONCLUSION

The analysis presented above focused necessarily on a simplified case to illustrate the capabilities of the DEM based method. Despite the simplifications the results obtained are clearly in line with those obtained using current methods.

The main interest of the method presented, however, may lie in its potential extensions, particularly for the case of baled MSW deposits. On the one hand a model similar to the one described may be adapted for control during exploitation. It would then be straightforward to accommodate the variability of waste. Compositional properties of each stored bale are directly feed into the model, for instance to individualize the heat source function. It is also relatively simple to implement different thermo-mechanical couplings, like a temperature-dependent interface friction.

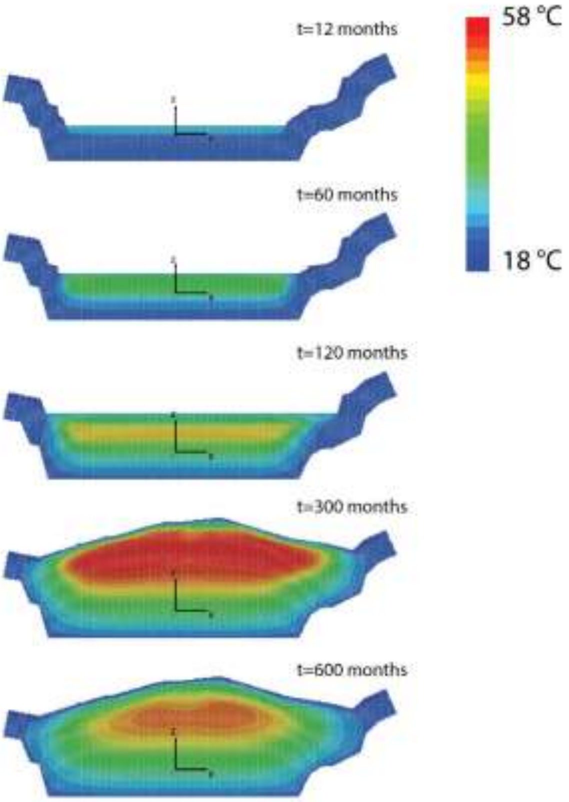

Figure 5 Temperature evolution in the analysed section

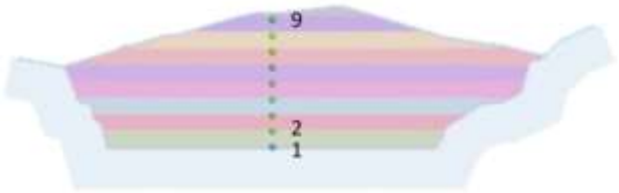

Figure 6 Observation points for temperature

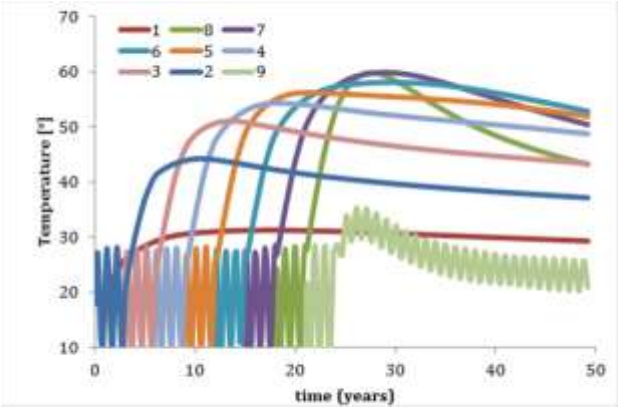

Figure 7 Temperature evolution at observation points

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6 REFERENCES

Baldassano, J. M., Gasso, S., & Perez, C. (2003). Environmental performance review and cost analysis of MSW landfilling by baling-wrapping technology versus conventional system. Waste Management, 23(9), 795-806

Boon, C. W., Houlsby, G. T., & Utili, S. (2014). New insights into the 1963 Vajont slide using 2D and 3D distinct-element method analyses. Geotechnique, 64(10), 800-816.

Cañizal, J., Lapeña, P., Castro, J., Costa, A., & Sagaseta, C. (2011). Determination of shear strength of MSW. field tests vs. laboratory tests. In Fourth International Workshop "Hydro-Physico-Mechanics of Landfills," Santander, Spain.

Ciantia, M. O., Arroyo, M., Butlanska, J., & Gens, A. (2016). DEM modelling of cone penetration tests in a double-porosity crushable granular material. Computers and Geotechnics, 73, 109-127.

Climent, N., Arroyo, M., O'Sullivan, C., & Gens, A. (2014). Sand production simulation coupling DEM with CFD. European Journal of Environmental and Civil Engineering, 18(9), 983-1008.

Coccia, C. J., Gupta, R., Morris, J., & McCartney, J. S. (2013). Municipal solid waste landfills as geothermal heat sources. Renewable and Sustainable Energy Reviews, 19, 463-474.

El Shamy, U., De Leon, O., & Wells, R. (2011). Discrete Element Method Study on Effect of Shear-Induced Anisotropy on Thermal Conductivity of Granular Soils. International Journal of Geomechanics, 13(1), 57-64.

Hanson, J. L., Liu, W. L., & Yesiller, N. (2008). Analytical and numerical methodology for modeling temperatures in landfills. Geotechnics of waste management and remediation, ASCE GSP No, 177, 24-31

Hanson, J.L., Yesiller, N., Oettle, N.K., (2010) Spatial and temporal temperature distributions in municipal solid waste landfills. J. Environ. Eng., ASCE 136 (8), 804–814

Itasca (2014) PFC 3D-V5.0 Online documentation. Minneapolis: Itasca Consulting Group

Katz, O., Morgan, J. K., Aharonov, E., & Dugan, B. (2014). Controls on the size and geometry of landslides: Insights from discrete element numerical simulations. Geomorphology, 220, 104-113.

Megalla, D., Van Geel, P. J., & Doyle, J. T. (2015). Simulating the heat budget for waste as it is placed within a landfill operating in a northern climate. Waste Management.

Nammari, D. R. (2006). Seasonal and long-term storage of baled municipal solid waste (Doctoral dissertation, Department of Environmental Engineering, Aalborg University, Aalborg, Denmark)

O'Sullivan, C. (2011). Particulate discrete element modelling. Taylor & Francis.

Passamani, G., Ragazzi, M., & Torretta, V. (2016). Potential SRF generation from a closed landfill in northern Italy. Waste Management, 47, 157-163.

Rowe, R. K., Hoor, A., & Pollard, A. (2010). Numerical examination of a method for reducing the temperature of municipal solid waste landfill liners. Journal of Environmental Engineering, 136(8), 794-803

Van Impe, W. F., & Bouazza, A. (1998). Large shear tests on compacted bales of municipal solid wastes. Soils and foundations, 38(3), 199-200

Yeşiller, N., Hanson, J. L., & Liu, W. L. (2005). Heat generation in municipal solid waste landfills. Journal of Geotechnical and Geoenvironmental Engineering, 131(11), 1330-1344.

Yeşiller, N., Hanson, J. L., & Yee, E. H. (2015). Waste heat generation: A comprehensive review. Waste Management, 42, 166-179

Zekkos, D., Vlachakis, V. S., & Athanasopoulos, G. A. (2013). The 2010 Xerolakka landfill slope instability. Environmental Geotechnics, 1(1), 56-65

Zhou, Y., & Rowe, R. K. (2005). Modeling of clay liner desiccation. International Journal of Geomechanics, 5(1), 1-9