# Geo-environmental problems in landfills of MSW with high organic content

## Problèmes géo-environnementaux dans les sites d'enfouissement de déchets urbains à hautes teneurs organiques

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ABSTRACT: The municipal solid wastes (MSWs) in China are high in organic and moisture content, as compared with the MSWs in developed countries. Large amounts of leachate and landfill gas are generated and significant settlement takes place during the decomposition process of the MSWs. A build-up of leachate mound and gas pressure might take place in the landfills of MSWs. Waste stability is highly concerned for such landfills having excessive pore-water and pore-gas pressure. A bio-hydro-mechanical coupled model is presented in this paper, based on laboratory and in-situ investigations, to predict leachate production, gas pressure and settlement. Based on the prediction obtained by the proposed model, discussions are made on the geo-environmental problems in landfills of MSW with high organic content. The work is valuable for the development of bioreactor landfilling technologies in the Asian developing countries such as China.

RÉSUMÉ : Les déchets urbains en Chine ont des teneurs élevées en matières organiques et en humidité, par rapport aux déchets produits dans les pays développés. De grandes quantités de lixiviats et de gaz sont dégagées et un tassement significatif apparait lors du processus de décomposition des déchets. Il peut se produire dans les décharges une augmentation de l'accumulation des lixiviats et de la montée en pression des gaz. La stabilité de l'entreposage de ces déchets est fortement impactée par l'augmentation de pression du fluide et du gaz dans les vides. Un modèle couplé bio-hydro-mécanique est proposé dans cet article, basé sur des études expérimentales de laboratoire et in situ, pour prévoir la production de lixiviat, la pression de gaz et le tassement. Sur la base des résultats obtenus par le modèle proposé, les discussions portent sur les problèmes géo-environnementaux dans les sites d'enfouissement de déchets à hautes teneurs organiques. Le travail est très utile pour le développement des technologies de bioréacteurs dans les pays asiatiques en voie de développement telle que la Chine.

KEYWORDS: MSW, organic content, gas, leachate, settlement, stability

## 1 INTRODUCTION.

Municipal Solid Wastes (MSWs) contain biodegradable component, which results in the difference in engineering property between MSWs and traditional soil. Landfilling will remain the dominant disposal method for MSWs in China for the foreseeable future. An understanding of engineering characteristics of MSWs and landfill behavior is important for the planning, design, and operation of landfills.

The MSWs in China contain much more putrescible organic waste and higher initial moisture content than the MSWs generated in developed countries (Chen et al. 2010a). In this paper, engineering properties of MSWs with high organic content are discussed, and a Bio-Hydro-Mechanical (BHM) coupled model is proposed to estimate a series of coupled phenomena in such landfills. Based on the simulation results, geo-environmental problems associated with this kind of landfills of MSWs were discussed. The work is valuable for the development of bioreactor landfilling technologies in the Asian developing country such as China.

## 2 ENGINEERING PROPERTIES OF MSW WITH HIGH ORGANIC CONTENT

### 2.1 *MSW composition*

MSW typically consists of food and vegetable wastes, paper products, plastics, textiles, wood, cinder, and soils. Table 1 shows a comparison of waste composition among China, India, Korea, Singapore, UK, and USA as of 2000. The MSWs in China and India contain much more putrescible organic wastes (i.e., kitchen food and vegetable wastes which account for 40-50%) than the MSWs generated in UK, and USA. The content of mineral materials (i.e., cinder, dust, concrete, etc.) in China and India is also higher than that in UK and USA. These differences are likely attributable to the differences in cooking styles and the living standard among the countries.

Table 1. Comparison of MSW composition among China, India, Korea, Singapore, UK, and USA generated in 2000 (%) (Chen and Zhan 2007)

| Country | Food Vegetable | Dust Cinder | Paper | Plasitc Textile Wood Rubber | Metal Glass | Others |
|---|---|---|---|---|---|---|
| China | 43.6 | 23.1 | 6.7 | 16.7 | 3.4 | 6.5 |
| India | 41.8 | 40.3 | 5.7 | 8.2 | 4.0 | 0 |
| Korea | 24.6 | NA | 25.8 | NA | 13.5 | NA |
| Singapore | 23.5 | 17.1 | 21.6 | 11.1 | 24.0 | 2.7 |
| UK | 20.0 | 12.0 | 34.0 | 21.0 | 15.0 | 0 |
| USA | 15.3 | 10.9 | 29.8 | 29.4 | 12.7 | 1.9 |

### 2.2 *Initial moisture content and moisture retention characteristic of the MSWs*

For Chinese MSWs, more than 40% of the waste in wet weight is occupied by moisture for most of the data reported, as illustrated in Figure 1. At the rainy seasons, the initial moisture content (wet/wet) of the waste may reach 70% in the humid regions of southern China (Chen et al. 2010a). Compared with Chinese wastes, the MSWs of developed countries commonly have a lower initial moisture content (< 30%, Qian et al. 2002). High content of organic component (see Table 1) is the main factor that contributes to the high initial moisture content of Chinese MSW.

According to the literatures, the field capacity of wastes is generally assumed to be equivalent with the water content corresponding to a matric suction of 10 kPa, and its value for the Chinese wastes ranges from 33% to 45% (Chen et.al. 2010a), greater than that of the UK waste (22%) and the US waste (22.4%)(Sharma and Lewis 1994). For decomposed wastes filled in landfills for a long time, the average value of field capacity of MSWs in different countries is 37% (Chen et.al. 2010a).

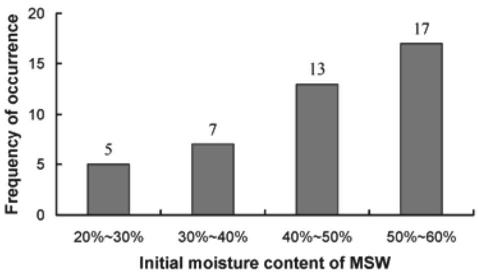


Figure 1. Initial moisture content of MSWs in China

## 2.3 *Hydraulic conductivity and gas permeability of the MSWs*

Results of laboratory tests on borehole samples and in situ pumping tests of Qizishan landfill, Suzhou, China show that hydraulic conductivity ($k_s$) of MSW decreases with an increase in burial depth or overburden pressure due to compaction and degradation of waste (Chen et al. 2010a). Results of laboratory tests on the borehole samples also indicate that (see Figure 2) the gas permeability decreases with an increase in the degree of saturation (or a decrease in volumetric gas content, $\theta_g$), and the decrease is much more significant at the high range of degree of saturation ($S_r$) (Wei 2007).

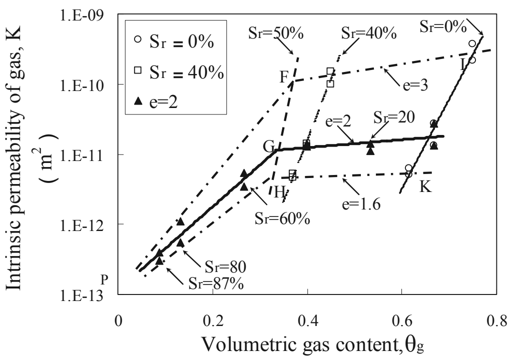


Figure 2. Gas permeability for MSW sampled from the Qizishan landfill, China (Wei 2007)

## 2.4 *Compression characteristics of the MSWs*

The compression characteristics of MSWs are of greater complexity than soils, whose solids can be normally regarded as inert materials. Based on laboratory tests on borehole samples and artificial wastes, it was found that creep is usually insignificant compared with the sum of primary and biodegradation compression for MSWs under favorable decomposition conditions, and the modified primary compression index tends to decrease with an increase of waste depth and age (Chen et al. 2009, 2010b). Laboratory study showed that MSW with a higher organic content tends to have larger $C_C$'(see Eq. 1) and secondary compression potential (Liao et al. 2007, Xu 2012). A one-dimensional compression model which considers the coupled effect of stress and age is proposed to express mechanical compression of MSWs (Chen et al. 2010b):

$$\varepsilon = C_C' \lg \frac{\sigma'}{\sigma_0'} + \varepsilon_{tS}(1 - e^{-ct}) \quad (1)$$

where $\varepsilon$ is the total strain corresponding to $\sigma'$ and $t$, $C_C'$ is the modified primary compression index for fresh wastes, $\sigma'$ (Pa) is effective stress, $\sigma_0'$ (Pa) is the initial stress for fresh MSWs, $\varepsilon_{tS}$ is ultimate secondary strain which can be calculated as the ultimate strain under long-term compression minus the primary compression strain of fresh wastes, and $c$ ($s^{-1}$) is the secondary compression rate constant related to biodegradation process.

## 2.5 *Shear strength characteristics of MSW*

Groups of consolidated drained triaxial compression tests were carried out to investigate the shear strength characteristics of borehole samples obtained from Qizishan landfill (Zhan et al. 2008). The results showed that the MSW samples exhibited a strain-hardening and contractive behavior (see Figure 3). As the fill age of the waste increased from 1.7 years to 11 years, the cohesion mobilized at a strain level of 10% was found to decrease from 23.3 kPa to 0 kPa, and the mobilized friction angle at the same strain level increasing from 9.9° to 26°. For a confinement stress level greater than 50 kPa, the shear strength of the recently-placed MSW seemed to be lower than that of the older MSW. The observed changes of shear strength with the fill age can be explained by considering the change in the MSW composition with age (Zhan et al. 2008).

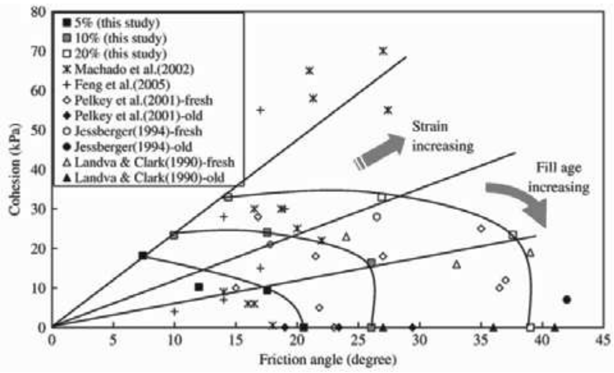


Figure 3. Summary of mobilized shear strength parameters reported in the research literatures (Zhan et al. 2008)

# 3 BHM COUPLED MODEL AND CASE STUDY

A Bio-Hydro-Mechanical (BHM) coupled model was proposed to investigate solid-liquid-gas interaction behaviors in landfilled MSWs with high organic content (Xu 2011, Chen et al. 2012). Apart from solid mass loss and gas generation, another key issue during biodegradation process is the release of celluar moisture within biodegradable matter, especially for MSWs high in organic content. Based on first-order kinetics, the source terms of liquid $f_{L,t}$ ($kgm^{-3}s^{-1}$) and gas $f_{G,t}$ ($kgm^{-3}s^{-1}$) due to biodegradation are expressed as:

$$f_{L,t} = \frac{\eta dm_{Sd}}{(V_S + V_V)dt} = \frac{\eta \sum (m_{dSi} c_i' f_{water} e^{-c_i' f_{water} t})}{(1-\varepsilon)(V_{S0} + V_{V0})} \quad (2)$$

$$f_{G,t} = \frac{(1-\eta) dm_{Sd}}{(V_S + V_V)dt} = \frac{(1-\eta) \sum (m_{dSi} c_i' f_{water} e^{-c_i' f_{water} t})}{(1-\varepsilon)(V_{S0} + V_{V0})} \quad (3)$$

where $\eta$ is the reaction coefficient, $m_{Sd}$ (kg) represents solid mass loss at the time $t$(s),$V_S$ and $V_V$($m^3$) are the volumes of solid matter and void space respectively, $m_{dSi}$ (kg) is the initial mass of biodegradable component $i$, $c_i'$ ($s^{-1}$) is the decomposition rate constant of biodegradable component $i$, $V_{S0}$ and $V_{V0}$ ($m^3$) are the initial volumes of solid matter and void space respectively, $\varepsilon$ is the compression strain, and $f_{water}$ is the water impact factor.

Mass conservation equations and Darcy's law for liquid and gas are used to model fluid flow in landfills (see Eqs. 4 and 5). Hydraulic conductivity, gas permeability and water retention characteristics of MSW are estimated based on laboratory studies as discussed in section 2.2 and 2.3.

$$\frac{\partial(\rho_L n S_L)}{\partial t} = f_{L,t} - \frac{\partial(\rho_L v_L)}{\partial z} \quad (4)$$

$$\frac{\partial(\rho_G n S_G)}{\partial t} = f_{G,t} - \frac{\partial(\rho_G v_G)}{\partial z} \quad (5)$$

where $\rho_G$ and $\rho_L$ are liquid density and gas density respectively, $n$ is the porosity which is determined by $m_{sd}$ and $\varepsilon$, $S_L$ and $S_G$ are liquid saturation and gas saturation respectively, $v_L$ and $v_G$ (m/s) are liquid velocity and gas velocity respectively.

Mechanical compression of MSW is expressed by the one-dimensional compression model expressed as Eq.1. The effective stress $\sigma'$ is expressed as Bishop's equation for unsaturated soils (Bishop 1959).

Main governing equations of the BHM coupled model are shown as Eqs.1-5.The BHM coupled model is numerically solved by the finite difference method and Gauss-Newton method.

Based on Chen et al. 2009 and Reddy et al. 2008, two hypothetical waste samples with a height of 5m are studied for MSWs in Qizishan landfill, China and Orchard Hills landfill, USA, respectively. As shown in Figure 4, top boundary is impervious for liquid but free for gas flow, and the bottom boundary is impervious for gas but free for liquid flow. The total stress is set to be zero at the top boundary, and compression strain is set to be zero at the bottom boundary. Each element is 0.5m high, and the time step is $10^{-5}$day$^{-1}$. Parameters applied are shown in Table 2. Gas pressure, leachate/gas production and settlement are analysed through the BHM coupled model.

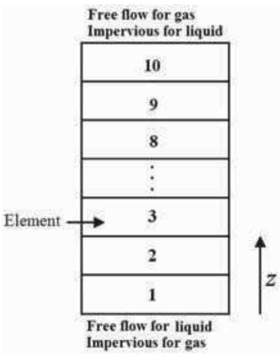


Figure 4. Schematic diagram of a hypothetical waste sample

Table 2. Parameters applied in the BHM coupled model

| $m_{ds1}/m_{s0}$ | $m_{ds2}/m_{s0}$ | $m_{ds3}/m_{s0}$ | $w_0$(wet) |
|---|---|---|---|
| 0.35* | 0.20* | 0.10* | 0.60* |
| 0.05# | 0.25# | 0.20# | 0.44# |
| $f_{water}$ | $d_S$ | $\gamma_0$(kN/m$^3$) | $e_0$ |
| 1.0* | 1.87* | 7.5* | 3.0* |
| 1.0# | 0.85# | 5.0# | 1.4# |
| $C_C'$ | $C_{C\infty}'$ | $\sigma_0'$ (kPa) | $\varepsilon_{tS}(\sigma_0')$ |
| 0.25* | 0.17* | 10* | 0.38* |
| 0.28# | 0.17# | 10# | 0.20# |
| $m_{vG}$ | $n_{vG}$ | $\alpha_{vG}$(m$^{-1}$) | $\gamma_{vG}$ |
| 0.26*# | 1.35*# | 25.6*# | 3.0*# |
| $\mu_L$(kgm$^{-1}$s$^{-1}$) | $\mu_G$ (kgm$^{-1}$s$^{-1}$) | $Mol_G$ (kgmol$^{-1}$) | $R$ (m$^3$PaK$^{-1}$mol$^{-1}$) |
| 1.0×10$^{-3}$*# | 1.4×10$^{-5}$*# | 0.03*# | 8.314472*# |
| $c_1'$(day$^{-1}$) | $c_2'$(day$^{-1}$) | $c_3'$(day$^{-1}$) | $c$ (day$^{-1}$) |
| 0.00023*# | 0.00013*# | 0.00003*# | 0.0016*# |
| $k_0$(m$^2$) | $\theta_S$ | $\theta_r$ | $\eta$ |
| 10$^{-11}$*# | 0.75*# | 0.035*# | -0.11*# |
| $T$ (K) | $g$ (ms$^{-2}$) | $\rho_L$(kgm$^{-3}$) | $P_a$(Pa) |
| 303*# | 9.8*# | 994.13*# | 101320*# |

Note: * is for MSWs in Qizishan landfill, China
# is for MSWs in Orchard Hills landfill, USA

As shown in Table 2, waste sample from Qizishan landfill has higher organic content (i.e. $m_{ds1}$ which represents highly degradable component) and initial moisture content (i.e.$w_0$), compared to that from Orchard Hills landfill. Two samples are both assumed to have an optimum biodegradation condition (i.e. $f_{water}$=1.0). Simulation results are shown in Figure 5-8. It indicates that gas pressure of waste sample from Qizishan landfill have larger gas pressure during the early stage. Gas generation rate, gas production, leachate production and surface settlement of waste sample from Qizishan landfill are all much greater than that from Orchard Hills landfill.

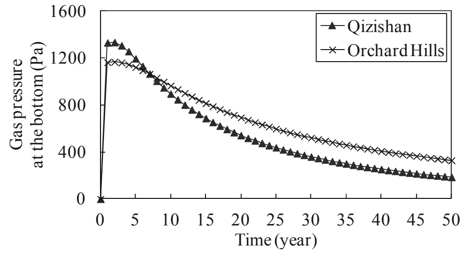


Figure 5. Gas pressure at the bottom of waste samples

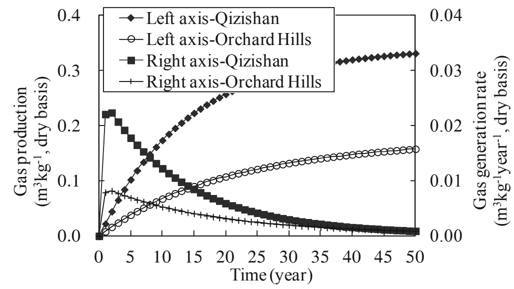


Figure 6. Gas generation rate and gas production of waste samples

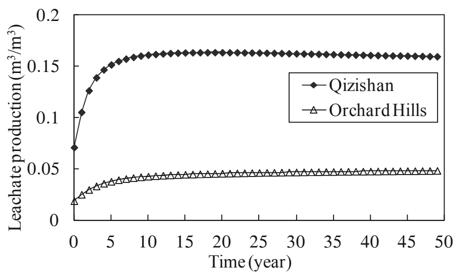


Figure 7. Leachate production per volume of waste samples

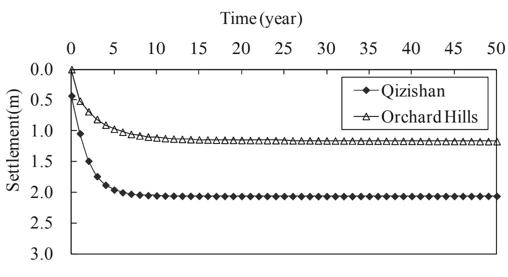


Figure 8. Settlement of waste samples

## 4 GEO-ENVIRONMENTAL PROBLEMS IN LANDFILLS WITH HIGH ORGANIC CONTENT

### 4.1 *Leachate generation*

As mentioned in section 2.2, the difference between the initial moisture content and the field capacity of the Chinese MSW is greater than that of western countries, which is the main factor causing high leachate production. Simulation result (see Figure 7) also shows that MSW with higher organic content and moisture content has larger leachate production. Therefore, calculation of leachate production in landfills with high organic content MSW cannot neglect the effect of initial moisture content and moisture release via decomposition of organic. Under certain circumstances (e.g. clogging of leachate collection system, etc.), high leachate mound might be resulted due to the high leachate production in Chinese landfills.

### 4.2 *Settlement in landfills*

The biodegradation-induced settlement rate is highly dependent on the decomposition condition of landfill. Under optimum biodegradation condition, Figure 8 shows that both samples will accomplish their settlement within about 5 years. Therefore, if the condition is adjusted via leachate recirculation or air injection, most settlement would occur during landfilling stage, which can significantly decrease post-closure settlement of landfill. Figure 8 also shows that instant settlements (i.e., $t = 0$) of the two samples are close to each other. It is mainly due to the relatively higher $C_C'$ for Orchard Hills sample which is pre-shredded before tests. However, MSW from Qizishan landfill has much more long-term compression, which indicates the necessity of accelerating the biodegradation-induced settlement of landfills with high organic content.

### 4.3 *Landfill stability*

Based on the method of slices and the effective stress equation proposed by Bishop 1959, the factor of safety for the *i*th slice can be written as the following equation by neglecting lateral forces (see Figure 9):

$$F_S = \frac{R_i}{T_i} = \frac{\left[c_i' l_i + \left[W_i \cos\alpha_i - \left((1-\chi)u_{ai} - \chi u_{wi}\right) l_i\right] tg\varphi_i'\right]}{W_i \sin\alpha_i} \tag{6}$$

where $R_i$ and $T_i$ are resisting shear force and shear force acting along the slip surface respectively, $c_i'$ and $\varphi_i'$ are cohesion and the the effective stress friction angle respectively, $\alpha_i'$ is the slope angle, $W_i$ is the self weight, $l_i$ is the bottom length which equals $b_i/cos\alpha_i'$, $b_i$ is the width of each slice, and $u_{ai}$ and $u_{wi}$ are the pore gas pressure and pore liquid pressure.

Landfill stability need to be assessed during the whole bio-hydro-mechanical coupled processes as:

(i) Higher organic content and moisture content may promote gas generation. However, more gas may be trapped in high moisture content MSW due to the lowered gas permeability (see Figure 2). Figure 10 shows that a mixture of leachate and landfill gas was ejected to a height of up to 5 m when drilling vertical extraction wells in Xiaping landfill, China. It indicates that very high pore pressure ($u_{ai}$ and $u_{wi}$) may exist in waste body, which will decrease $F_S$ and cause a decrease in slope stability.

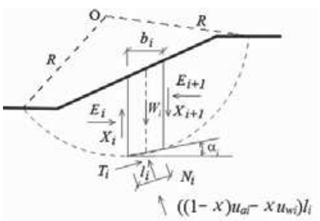


Figure 9. Method of slices

Figure 10. Ejection of leachate/gas

(ii) Higher moisture content will increase the self weight of waste body especially under leachate recirculation. As indicated by Eq.6, $F_S$ will decrease with an increase of $W_i$.

(iii) During the bio-hydro-mechanical coupled process, the cohesion and friction angle mobilized at a certain strain level tend to change with an increase of waste age (see Figure 3). This makes the determination of $F_S$ even more complex.

## 5 CONCLUSION

Engineering properties of landfilled MSWs with high organic content in Asian developing countries are distinguished from those in developed countries. Numerical study through the BHM coupled model showed that landfilled MSWs with higher organic content tend to have larger leachate production, long-term settlement and possibility of slope failure. The model developed can be used to study the application of bioreactor landfilling technologies in landfills with high organic content.

## 6 ACKNOWLEDGEMENTS

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