Environ Earth Sci (2016)75:132
DOI 10.1007/s12665-015-4923-4

ORIGINAL ARTICLE

A three-dimensional model for flow slides in municipal solid waste landfills using smoothed particle hydrodynamics

Zili Dai[1] · **Yu Huang**[1,2]

Received: 10 July 2014 / Accepted: 13 August 2015

Abstract Flow slides at municipal solid waste (MSW) landfills can lead to a leak of toxic MSW and leachate over a large area, and result in serious pollution to the environment in the surrounding region. It is therefore important to predict the propagation of failed MSW in the environment, and then take protective measures. In this paper, a three-dimensional (3D) model based on the smoothed particle hydrodynamics method, which is an improved version of the previous two-dimensional (2D) model (Huang et al. in Waste Manag Res 31(3):256–264, 2013), is established to reproduce the propagation stage of the failed MSW across complex terrain. The Navier–Stokes equations and Bingham model are adopted as the governing equations and constitutive model, respectively. A no-slip boundary condition is incorporated to consider the effect of a solid boundary on the MSW movement. The 3D performance of the new model is verified and evaluated through the simulation of a MSW flow model test. The established 3D model and the former 2D model are applied to simulate a typical flow slide that occurred at the Ümraniye-Hekimbasi landfill. The final shape of the waste deposit simulated with the 3D model well matches the field observation; the performance of the new model in simulating flow slides for MSW in three dimensions across complex terrain is highlighted. The presented model can play a role in defining and mapping hazardous areas, and provide a means for the identification and design of appropriate protective measures for landfills with potential flow slides.

Keywords Municipal solid waste · Flow slide · Smoothed particle hydrodynamics · Three-dimensional model · Environmental disaster management

Introduction

Landfills have been the dominant option for the disposal of solid waste for many years and will remain so for a long time (Brunner and Fellner 2007; Ghobadi et al. 2013). Flow slides of unstable slopes, which fortunately are not common, can lead to the loss of life and the leaking of dumped municipal solid waste (MSW), fermentation gases and leachate over a large area. These poisonous substances can seriously pollute the surrounding environment and result in substantial environmental cleanup costs (Liu et al. 2007). For example, the flow slide at the Bandung landfill in Indonesia resulted in around 2.7×10^6 m^3 of waste flowing down the hillside, covering a 200–250 m wide stripe along a length of 900 m. The toxic refuse killed almost all plants and animals in this region, seriously polluted the soil, water and air nearby, and caused severe and even fatal damage to the local ecosystem (Koelsch et al. 2005). Additionally, several MSW flow failures were reported in the existing literature, such as the landfills in Dona Juana, Bogota, Columbia (Hamilton et al. 1998; Hendron et al. 1999; Caicedo et al. 2002), Payatas, Quezon City, Philippines (Merry et al. 2005; Jafari et al. 2013), and

✉ Yu Huang
yhuang@tongji.edu.cn

[1] Department of Geotechnical Engineering, College of Civil Engineering, Tongji University, Shanghai 200092, China

[2] Key Laboratory of Geotechnical and Underground Engineering of the Ministry of Education, Tongji University, Shanghai 200092, China

Durban, South Africa (Brink et al. 1999; Blight 2004), all of which caused widespread environmental damage. To benefit environmental disaster management, the dynamic characteristics of the flowing MSW and the disaster area should be predicted for the establishment and management of appropriate protective measures.

Due to the unpredictable and destructive features of flow slides in landfills, it is difficult to record the movement of MSW and measure the flow behavior on site. Some model test studies were carried out to investigate the dynamic behavior of MSW. For example, Thusyanthan et al. (2006a, b) obtained seismic behaviors of a MSW simulant using centrifuge model tests. Dai et al. (2015) presented a MSW simulant that has physical properties similar to those reported by investigators for real MSW and analyzed its mobility and flow behavior (e.g. velocity, flow depth, run-out distance) through a series of model tests.

Besides model tests, some simple empirical methods have been widely used to predict slope displacements or run-out distances. For example, Fan et al. (2014) developed an empirical method to estimate the potential run-out of co-seismic landslides. Zhao and Song (2012) presented some empirical formulas to estimate the co-seismic displacements of slopes for hazard zonation. Unfortunately, these methods are only valid when they can be applied to regions where seismic acceleration time histories are recorded, and they usually include empirical parameters which often lack clear physical significance and have to be determined by a lot of experiments.

To overcome these difficulties, numerical modeling was widely used as a robust tool in the analysis of slope stability in landfills. Computer program FLAC, which is based on finite difference method (FDM), was widely used to analyze the slope stability and predict the displacement. For example, Liu et al. (2009) utilized this program to analyze the slope stability of the Fuxin Landfill; Chugh et al. (2007) used this program to simulate a municipal landfill slope failure near Cincinnati. Another commonly used technique for stability analysis of landfill slopes is the finite element method (FEM). Liu et al. (2010) developed a TMC-Slope FEM program to analyze slope stability in landfills and calculated safety coefficients. Lu et al. (2014) presented an FEM procedure to evaluate the seismic slope stability in a landfill. All the researches mentioned above obtained promising results in the slope stability analysis in landfills. However, both FDM and FEM are mesh-based numerical methods and might suffer from numerical difficulties, (e.g. mesh winding, twisting and distortion), particularly when it comes to extremely large deformations. As a result, they are unable to simulate the flow process of the MSW after failure.

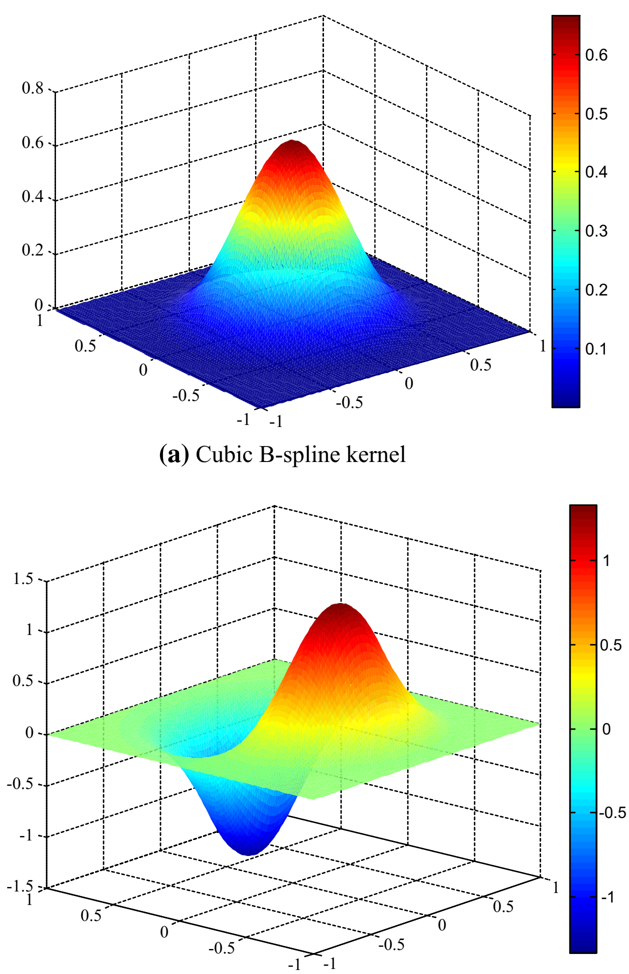
To deal with the flow failure problems, several new models have been presented and used to simulate the flow process. For example, a depth-averaged continuum dynamic model called "dynamic analysis" (DAN) was introduced to analyze rapid landslides (Hungr 1995). Then, this model was extended and widely applied in the analysis of flow-like landslides, debris flows, and rock avalanches (McDougall and Hungr 2004; Pastor et al. 2009; Cascini et al. 2013). This model has many unique features, such as the ability to account for material entrainment along the slide path, and rheology variation. However, the pressure and forces in the depth-integrated model are not fully correct due to the limited information in vertical direction (Pastor et al. 2014). For more reliable results, a SPH-based numerical model with fully Navier–Stocks equations was presented to predict the sliding velocity and run-out distance of the flow slides of landfills, and a series of SPH simulations were conducted with promising results (Huang et al. 2013). This model simulates MSW movement along a user-prescribed two-dimensional (2D) path and is only suitable for plain-type landfills with simple surrounding topography. However, many landfills, such as the Sarajevo landfill, Ümraniye-Hekimbashi landfill, and Bandung landfill, have been built on a hillside or in a valley. While moving across complex three-dimensional (3D) terrain, the dynamic behavior of the failed MSW can apparently be controlled by the local landform. For example, the waste in the Dona Juana landfill traveled more than 0.5 km horizontally after failure, and the complex topography notably changed its sliding direction and path (Hamilton et al. 1998; Hendron et al. 1999; Caicedo et al. 2002; Blight 2008). Therefore, when it comes to landfills with complex surrounding terrain, 2D modeling cannot truly reproduce the evolution from slide initiation to the final cessation of slide movement. Moreover, to benefit environmental disaster management in the landfill area, the potential 3D disaster area resulting from a flow slide at the landfill should be predicted, and 3D modeling is thus required.

In this paper, a 3D SPH model (based on the previous 2D work) that simulates the flow slide at a landfill across complex terrain is presented. In the application of this model to flow slides of the Ümraniye-Hekimbasi landfill, the dynamic behaviors of the MSW during propagation, including the sliding path, flow velocity, maximum distance reached, and distribution of the deposits, are obtained. These factors play an important role in defining and mapping hazardous areas and estimating hazard intensity (which serves as input in risk studies), and also the identification and design of appropriate protective measures.

Modeling approaches

Smoothed particle hydrodynamics method

The SPH method is a meshfree particle method based on a pure Lagrangian description. It was first developed to solve astrophysical problems in 3D open space (Lucy 1977; Gingold and Monaghan 1977) and has later been extended to model a wide range of problems. SPH methodology follows the motion of a material by representing the material as randomly distributed particles. These particles have material quantities, such as mass, a position vector, and a velocity vector, and form the computational frame for the conservation equations. In this method, each particle concerned interacts with all other neighboring particles within a given horizon. The interaction is weighted by a so-called smoothing (or kernel) function. In this paper, a cubic B-spline function, originally used by Monaghan and Lattanzio (1985), is selected as the smoothing function; see Fig. 1. The major advantage of this function is that it is efficient owing to its compact searching domain (Monaghan and Lattanzio 1985; Liu and Liu 2003). On this basis, the value of a continuous function, or its derivative, can be calculated at any particle from the known values at the neighboring particles:



(a) Cubic B-spline kernel

(b) First derivative of the kernel

Fig. 1 Cubic B-spline kernel and its first derivative

$$\langle f(x_i)\rangle = \sum_{j=1}^{N} \frac{m_j}{\rho_j} f(x_j) W_{ij}, \tag{1}$$

$$\langle \nabla \cdot f(x_i)\rangle = \sum_{j=1}^{N} \frac{m_j}{\rho_j} f(x_j) \nabla_i W_{ij}, \tag{2}$$

where the angle brackets <> denote an SPH approximation, N is the total number of neighboring particles, m is the mass, ρ is the density, and W is the smoothing function.

Compared with traditional grid-based numerical methods, the SPH method has at least two advantages. (1) The SPH method is a numerical method based on a pure Lagrangian description. The motion of particles can be traced and the features of the entire physical system can be easily obtained. Therefore, the time history of field variables at each material point can be naturally obtained in the process of simulation. (2) In the SPH method, the object under consideration can be discretized into a series of particles. The main advantage of this distinct meshfree feature is that there is no need for a numerical grid to calculate spatial derivatives. This avoids problems associated with mesh tangling and distortion, which are common in large deformation simulations. More details about the SPH technique can be found in related publications (Liu and Liu 2010).

Governing equations

The governing equations for dynamic fluid flows can be written as a set of partial differential equations. Applying the SPH approximation method mentioned above, the SPH versions of the equation of continuity and equation of motion are expressed as

$$\frac{\mathrm{d}\rho_\mathrm{i}}{\mathrm{d}t} = \sum_{j=1}^{N} m_j \left(u_i^\alpha - u_j^\alpha\right) \frac{\partial W_{ij}}{\partial x_i^\alpha}, \tag{3}$$

$$\frac{\mathrm{d}u_i^\alpha}{\mathrm{d}t} = \sum_{j=1}^{N} m_j \left[\frac{\sigma_i^{\alpha\beta}}{(\rho_i)^2} + \frac{\sigma_j^{\alpha\beta}}{(\rho_j)^2} + \delta^{\alpha\beta}\Pi_{ij}\right] \frac{\partial W_{ij}}{\partial x_i^\beta} + F_i^\alpha, \tag{4}$$

where α and β denote the Cartesian components x, y and z; u is the velocity; σ is the total stress tensor, which corresponds to the effective stress tensor of MSW; and F is the component of acceleration due to the external force, which is gravity in this study. Π_{ij} is the so-called artificial viscosity, which was first proposed by Monaghan and Gingold (1983) to convert kinetic energy into heat, and then to avoid numerical oscillation and prevent the physical penetration of particles.

Constitutive law

To close the system of governing equations, a constitutive equation for the total stress tensor σ is required. In the traditional SPH method for a fluid, the total stress tensor is normally divided into two parts: an isotropic hydrostatic pressure p and a deviatoric shear stress τ:

$$\sigma^{\alpha\beta} = -p\delta^{\alpha\beta} + \tau^{\alpha\beta}, \tag{5}$$

where $\delta^{\alpha\beta}$ is Kronecker's delta; $\delta^{\alpha\beta} = 1$ if $\alpha = \beta$ and $\delta^{\alpha\beta} = 0$ if $\alpha \neq \beta$. The hydrostatic pressure in SPH is normally calculated as a function of density change using an '*equation of state*' proposed by Batchelor (1967):

$$p_d = p_0\left[\left(\frac{\rho}{\rho_0}\right)^{\gamma} - 1\right], \tag{6}$$

where ρ is the density of liquid calculated using the continuity Eq. (3) and ρ_0 is the reference density. Here, γ is set equal to 7 according to Monaghan (1994).

The deviatoric shear stress is typically purely viscous and depends on the fluid models. As stated in the previous work (Huang et al. 2013), the liquefied MSW was modeled as a Bingham fluid, which is a viscoplastic model that considers the minimum shear strength. The Bingham fluid model in this work makes two assumptions: (1) there is no flow slide when the driving shear stress due to gravity is less than the minimum shear strength and (2) flow slide occurs when the driving shear stress due to gravity exceeds the minimum shear strength. At this time, the MSW behaves as a fluid with a linear relation between the shear stress and shear strain rate and deforms considerably. The detailed expression of the Bingham fluid model is as follows:

$$\tau = \left(\eta + \frac{\tau_y}{(D_\Pi)^{1/2}}\right)D \tag{7}$$

where τ is the shear stress, η is the yield viscosity coefficient, characterizing the ability of the deformation resistance of fluid.

τ_y is the yield strength. Introducing the Mohr–Coulomb yield criterion in classical soil mechanics, τ_y can be defined by:

$$\tau_y = p\tan\varphi + c \tag{8}$$

where p is the pressure; c and φ are the cohesion and frictional angle, respectively.

D is the tensor of strain rates which can be defined by:

$$D^{\alpha\beta} = \frac{1}{2}\left(\frac{\partial u^{\alpha}}{\partial x^{\beta}} + \frac{\partial u^{\beta}}{\partial x^{\alpha}}\right) \tag{9}$$

where u is velocity of particle, and x represents the coordinate.

D_Π is the second invariant of the tensor of strain rates and can be defined by:

$$D_\Pi = \frac{1}{2}D^{\alpha\beta}D^{\alpha\beta} \tag{10}$$

In this work, the flowing MSW is treated as a Bingham fluid, an equivalent viscosity η', first suggested by Uzuoka et al. (1998), is used to express the Bingham viscosity. However, the equivalent viscosity could be infinite when D_Π is zero in the initial state of the simulation. To avoid such an infinite value, the maximum for equivalent viscosity $\eta_{\max}$ is determined as suggested by Uzuoka et al. (1998).

$$\begin{aligned} \eta' &= \eta + \frac{\tau_y}{(D_\Pi)^{1/2}} \quad \text{if} \quad \eta' \le \eta_{\max} \\ \eta' &= \eta_{\max} \quad \text{if} \quad \eta' > \eta_{\max} \end{aligned} \tag{11}$$

Averaging the velocity field

In a Lagrangian frame, the new position of a particle is derived by time integration of the velocity at all moments. In the SPH literature, a variant called XSPH was proposed with the goal of modifying and smoothing SPH particle movement, but the acceleration equation was unchanged. The smoothed velocity was defined by an average over the velocities of neighboring particles according to Monaghan (1992):

$$v_i' = v_i + \chi\sum_{j=1}^{N}\frac{m_j}{\rho_{ij}}(v_j - v_i)W_{ij}, \tag{12}$$

where v and v' are the particle velocity before and after correction, respectively; χ is a constant, the value of which is between 0 and 1. Numerical experiments show that $\chi = 0.5$ is effective at smoothing out local fluctuations in velocity (Monaghan 2002). ρ_{ij} denotes an average density of particles i and j.

Solid boundary treatment

Many landfills have been built in valleys, such as the Ümraniye-Hekimbashi landfill in Istanbul, Turkey, and the Bandung landfill in Indonesia. After failure, the flow of MSW has been heavily affected by the complex local topography, with repulsive forces greatly changing the dynamic behavior. To truly represent the flow

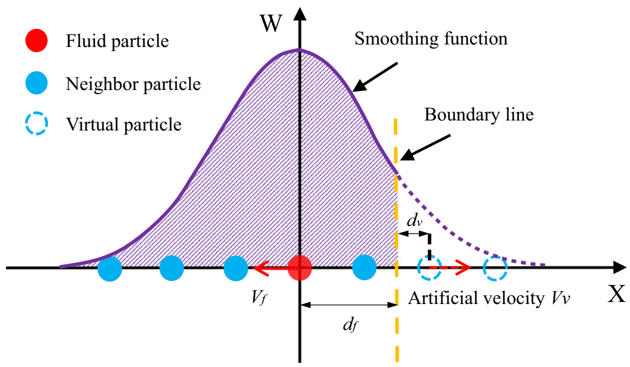


Fig. 2 SPH particle approximations near a no-slip boundary for one-dimensional case

process of the MSW, it is therefore important to accurately consider the effect of the solid boundary on the MSW movement. The conventional SPH method suffers from particle deficiency near the boundary area, which always leads to inaccurate solutions because there are only neighboring particles inside the boundary contributing to the SPH summation of the particle interaction, and no contribution from the outside (see Fig. 2). Improvements with promising results have been proposed to treat the boundary condition in the relevant literature (Libersky et al. 1993; Monaghan 1994; Randles and Libersky 1996). In this case, a no-slip boundary condition, which is similar to that used by Takeda et al. (1994), was incorporated. As shown in Fig. 2, the normal distance of a fluid particle to the solid boundary is denoted as d_f and that of a virtual particle to the boundary is denoted as d_v. With a no-slip condition (velocity on the boundary is zero), the velocity of the concerned virtual particle should be $V_v = -(d_v/d_f)V_f$. Hence, the velocity difference between the fluid and virtual particles is $V_{fv} = (1 + d_v/d_f)V_f$, which can be used to calculate the viscous forces (Morris et al. 1997). Note that the artificial velocities of virtual particles are used here to calculate the viscous force rather than to update the boundary particle positions.

Integration schemes

Since the SPH method reduces the original partial differential equations (PDEs) to sets of ordinary differential equations, any stable time-stepping algorithm for ordinary differential equations can be introduced. The velocity Verlet algorithm, similar to the leapfrog method, was used for the time integration to update positions, velocities, and accelerations. For the details of this iterative method, refer to the original paper (Ercolessi 1997).

Verification and validation of the SPH model

As for any numerical model, the first step is to make sure that the model is able to provide accurate results. The previous 2D SPH model was successfully applied to reproduce the flow slides in Sarajevo and Bandung landfills (Huang et al. 2013). In this section, a physical model test on MSW simulant flow is simulated to verify and evaluate the 3D performance of the new model; the details about the model test refer to Dai et al. (2015). The unit weight, shear strength and flow behavior of the MSW simulant used in the model test have already been verified to be similar to those of real MSW (Dai et al. 2015).

Figure 3 shows the initial state of the model. The left side of the MSW mass abuts the left boundary of the model container, while the right side is free. The angle of the container is set to be 5°. The MSW then simply flows along the fixed boundary at the base of the model container under the action of gravity. The dimensions of the MSW mass and the boundary are presented in Fig. 3. The details about the model test please refer to Dai et al. (2015).

In the SPH model, there are 17,964 particles used in total, among which 8464 for the MSW mass and other 9500 for the boundary. The initial distance between adjacent particles is 0.01 m. Table 1 lists the parameters used in the simulation. The selection of material properties, e.g., shear strength and viscosity, plays an important role in the numerical analysis. To investigate the model's sensitivity to the variations in Bingham fluid rheological parameters, back analysis was conducted in the previous 2D work (Huang et al. 2013). It showed that the viscosity coefficient and shear strength can both affect the numerical result, but the model is more sensitive to the shear strength. In this study, the shear strength parameters of this MSW simulant are from the triaxial shear test (Zhu et al. 2012), and the viscosity coefficient is based on the previous back analysis (Huang et al. 2013).

The model test results and corresponding SPH simulated results are shown in Fig. 4. To compare the results clearly, the outlines of MSW simulant configuration are indicated by different color lines, as shown in sketch (Fig. 3). The

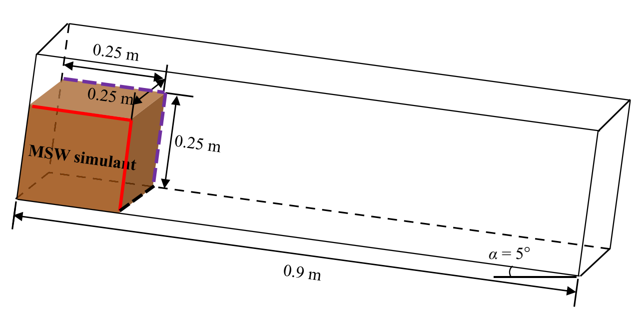


Fig. 3 Model of MSW simulant flow

Table 1 Parameters used in the SPH simulation of model test

Density	ρ (kg/m^3)	1340
Cohesion	c (kPa)	18
Angle of internal friction	φ (°)	18
Viscosity coefficient	η (Pa·s)	1.0
Acceleration of gravity	g (m/s^2)	9.8
Unit time step	Δt (s)	2.0×10^{-4}
Time step	n	3.0×10^4

red and purple lines show the MSW shapes on the front and back boundaries of the container, respectively, and the black line represents the flow front. Figure 4 shows that the SPH simulated results agree well with the model test data.

In Fig. 5, the red triangles represent the run-out history of the MSW simulant recorded by a high-speed camera in the model test, while the blue squares represent the numerical results, the two sets of results agree well. The color of particles in Fig. 4 represents the predicted velocity of MSW mass, as shown in the color legend on the bottom of the figures. To evaluate the performance of the SPH model further, the simulated and tested velocity histories of the flow front are compared in Fig. 6. Based on the comparisons above, the calculated results agree well with the model test data, which proves the applicability and reliability of the new 3D SPH model.

Application

The failure of the Ümraniye-Hekimbasi landfill was a typical case of a flow slide in an MSW dump that caused notable damage and casualties. In this section, the established 3D SPH model and the previous 2D model (Huang et al. 2013) are applied simultaneously to simulate flow slide at this landfill. The simulation results obtained with the two models are compared and the advantages of the new 3D model are detailed. In this work, the SPH model focuses on the post-failure behavior prediction of the MSW in the Ümraniye-Hekimbasi landfill, rather than the trigger conditions and failure modes. Therefore, to simplify the calculation, the failed MSW is assumed as a Bingham viscous fluid, and the effect of leachate and gas on the model properties is ignored.

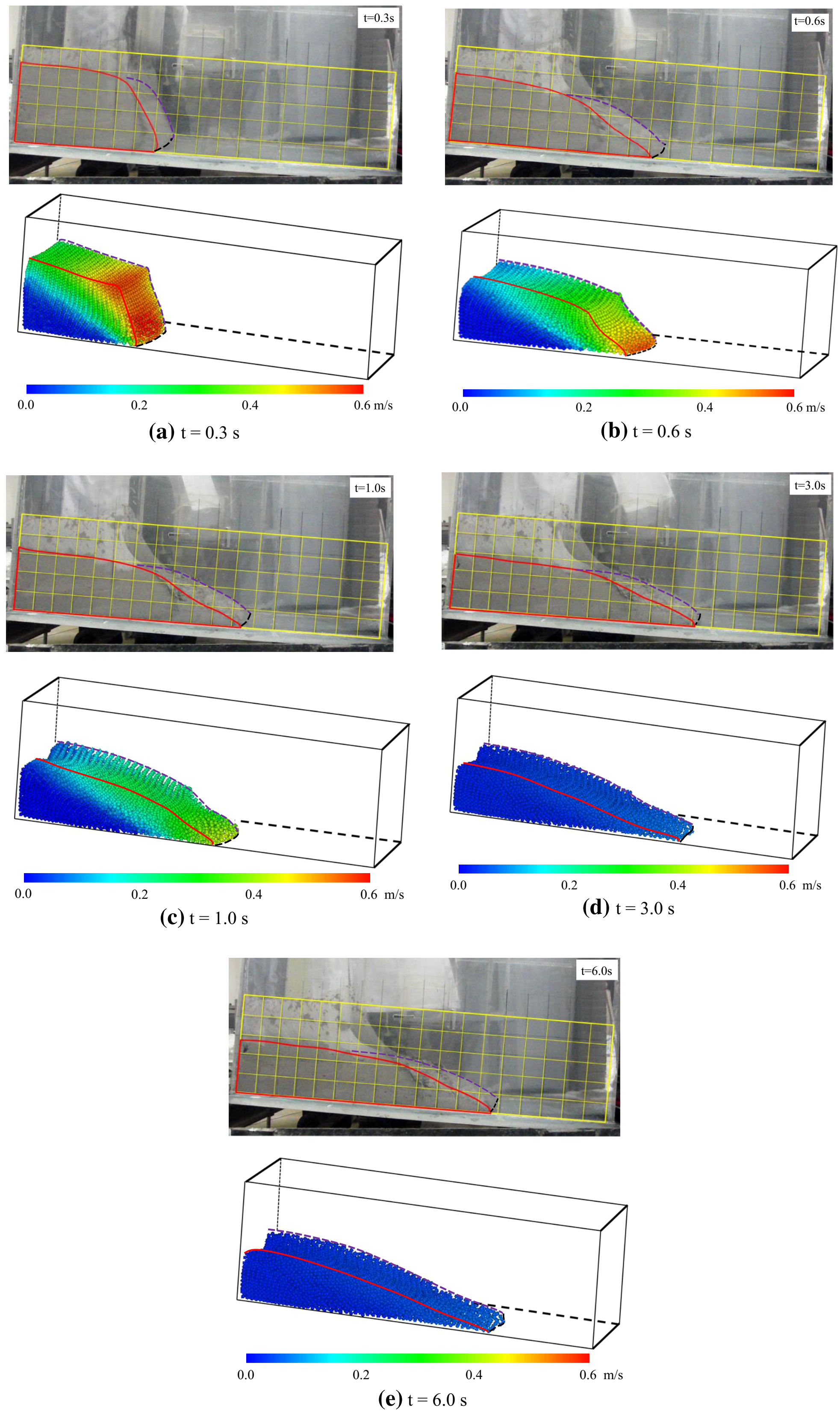
The Ümraniye-Hekimbasi landfill is located approximately 30 km from the center of Istanbul, Turkey. According to Kocasoy and Curi (1995), the main components of the MSW in this landfill were food remains, paper, cardboard, plastic, glass and other loose and uncompacted waste. These solid wastes were disposed of at the top of a side valley along a main valley and were neither compacted nor covered with soil. The slope created by the solid wastes was very steep. The main dimensions of the dump were measured after the failure occurred (Blight 2008), including the 45° slope of those parts of the tipping face that had not failed.

The accident at the Ümraniye-Hekimbasi landfill on 28 April 1993 was accompanied by a loud bang. A 12,000 m^3 wedge of solid waste started to move from the side valley, then slid out of the tipping face and flowed down into the main valley rapidly. Some of the waste was carried by its momentum a short way up the opposite slope, and the movement of other waste changed direction. The valley was filled rapidly; 11 brick houses and 39 occupants were buried by the moving waste.

In earlier work, a 2D SPH model was established for flow slides at a landfill, and two numerical examples were presented and good results obtained (Huang et al. 2013). Applying this model, the flow slide along a prescribed 2D path at the Ümraniye-Hekimbasi landfill was simulated. In the numerical model, there were 2468 SPH particles in total. The failed MSW is assumed as a homogeneous viscous fluid and represented by 958 moving particles. The volume, which is not failed and mobilized, is considered to be the solid boundary, and represented by 1510 fixed particles. The shear strength and viscosity coefficient used in the simulation were based on back analysis in the 2D work (Huang et al. 2013); see Table 2. The evolution of the distribution of the deposit is shown in Fig. 7. In the figure, the red particles are the flowing MSW after slope failure, and the black particles represent the natural ground. It is easy to determine from the figure that (a) the duration of the movement was about 40 s and (b) the maximum depth of the MSW sediment in the valley was about 18.6 m. The Lagrangian property of the SPH method allows the dynamic character of the particles to be traced. Figures 8 and 9, respectively, show the velocity and displacement time histories of the failed MSW, from which it is clear that the MSW particles reached their maximum velocity of 13.1 m/s around 9.0 s after failure. The run-out of the flow slide was about 88.4 m. Note that the velocity and displacement shown in these figures are the average values for all MSW particles.

The numerical results provided above were confined to local dynamic characteristics in a cross section. However, the Ümraniye-Hekimbasi landfill was located in a valley with very complicated surrounding topography. As a result, the movement of the failed MSW could be significantly affected by the complicated local topography in three dimensions. Therefore, a 3D model is needed to truly represent the evolution process of a flow slide. Using the 3D SPH modeling technique, the flow failure of the Ümraniye-Hekimbasi landfill was simulated, the evolution of the failure process was represented, and the dynamic characteristics of failed MSW during the movement were studied. Data of the initial topography and the initial

Fig. 4 Configuration of the model test and SPH simulation



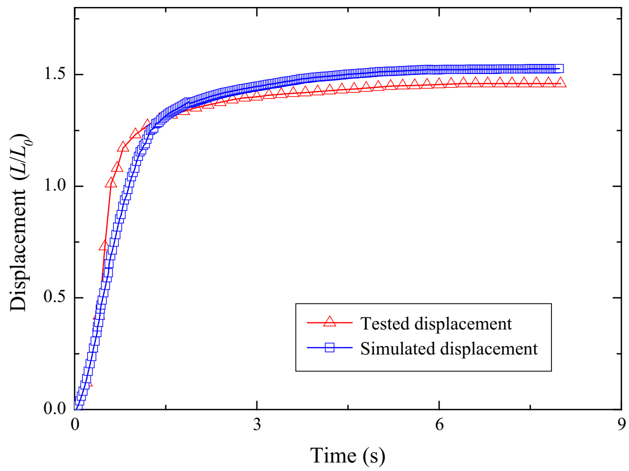


Fig. 5 Tested and simulated displacement time history of the MSW simulant flow

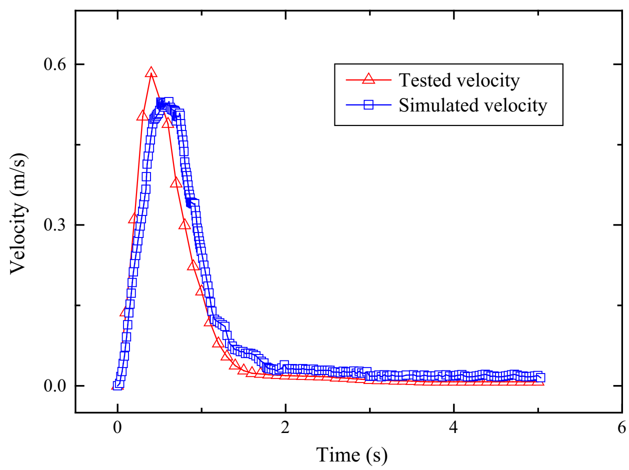


Fig. 6 Tested and simulated velocity time history of the MSW simulant flow

Table 2 Parameters used in the SPH simulation of the MSW flow slide

Density	ρ (kg/m^3)	1000
Cohesion	c (kPa)	16
Angle of internal friction	φ (°)	22
Viscosity coefficient	η (Pa·s)	1.0
Acceleration of gravity	g (m/s^2)	9.8
Unit time step	Δt (s)	2.0×10^{-4}
Time step	n	2.0×10^5

position of the MSW were taken from field work carried out by Kocasoy and Curi (1995). In the SPH model, the initial 3D topography was discretized into 15,000 boundary particles, and 7064 SPH particles were used to represent the initial MSW on the slope, with a space between particles of 1.2 m, see Fig. 10a. Just as in the real situation, the MSW particles can be deformed both horizontally and vertically with gravitation only applied in the vertical direction. To compare the numerical results with those for the 2D model, the parameters used here were exactly the same as those in the 2D simulation (Table 2). The programs were compiled using Microsoft Visual C++ 2010 in a PC with the quad-core 8-thread CPU, Intel Core i7-2675QM, and run at 2.20 GHz clock with 16 GB main memory under the Windows 7 Professional 64-bit operating system. This simulation took about 5 h and 36 min in total.

The SPH simulation result is shown in Fig. 10. The simulation reproduced the entire flow process of the failed MSW at the Ümraniye-Hekimbasi landfill and showed the evolution of the distribution of the deposit. At the beginning, waste mass with a height of more than 40 m moved from the side valley; a little hill in front of the dumping site then changed the direction of flow so that the flow was directed to a relatively narrow section. After about 10 s, the front of the moving MSW reached the bottom of the valley; some waste washed up on the opposite slope and other waste expanded along the valley bottom at a relatively low speed. In about 40 s, the waste mass gradually stopped and the valley was filled. To analyze the movement characteristics of the MSW after failure, the displacement time history and the velocity time history are shown in Figs. 11 and 12, respectively. It is clear that the velocity of the MSW increased rapidly after failure and reached its maximum value of 16.45 m/s at about 8.5 s. After reaching the opposite slope, the MSW slowed sharply and gradually came to a stop. The total displacement of the MSW was around 101.55 m. To check the quality of the SPH analysis of the flow slide at the Ümraniye-Hekimbasi landfill, the SPH simulated and measured deposit areas are compared in Fig. 13. It is obviously that shape of the deposit area is modeled satisfactorily. Note that the contour map and the measured waste distribution after failure are quoted from Blight (2008). Therefore, besides its merit in run-out analysis, the 3D model can be applied in defining and mapping hazardous areas for flow slides at landfills, which is an important breakthrough not possible with the previous 2D model. To compare with the 2D simulation results directly, the results along the same cross section (line ABCD in Fig. 13) were selected, and the SPH simulated geometry and landfill configuration are compared in Fig. 14. The solid line represents the post-failure topography, which was based on Blight (2008). The dotted line is the 2D SPH simulation results, and the dash-dotted line is the geometry simulated using the 3D SPH model established in this work. From the comparison, it is obvious that the run-out, slope coverage, and thickness calculated using the 3D model have a high degree of similarity with the post-failure topographical map. For the 2D simulation,

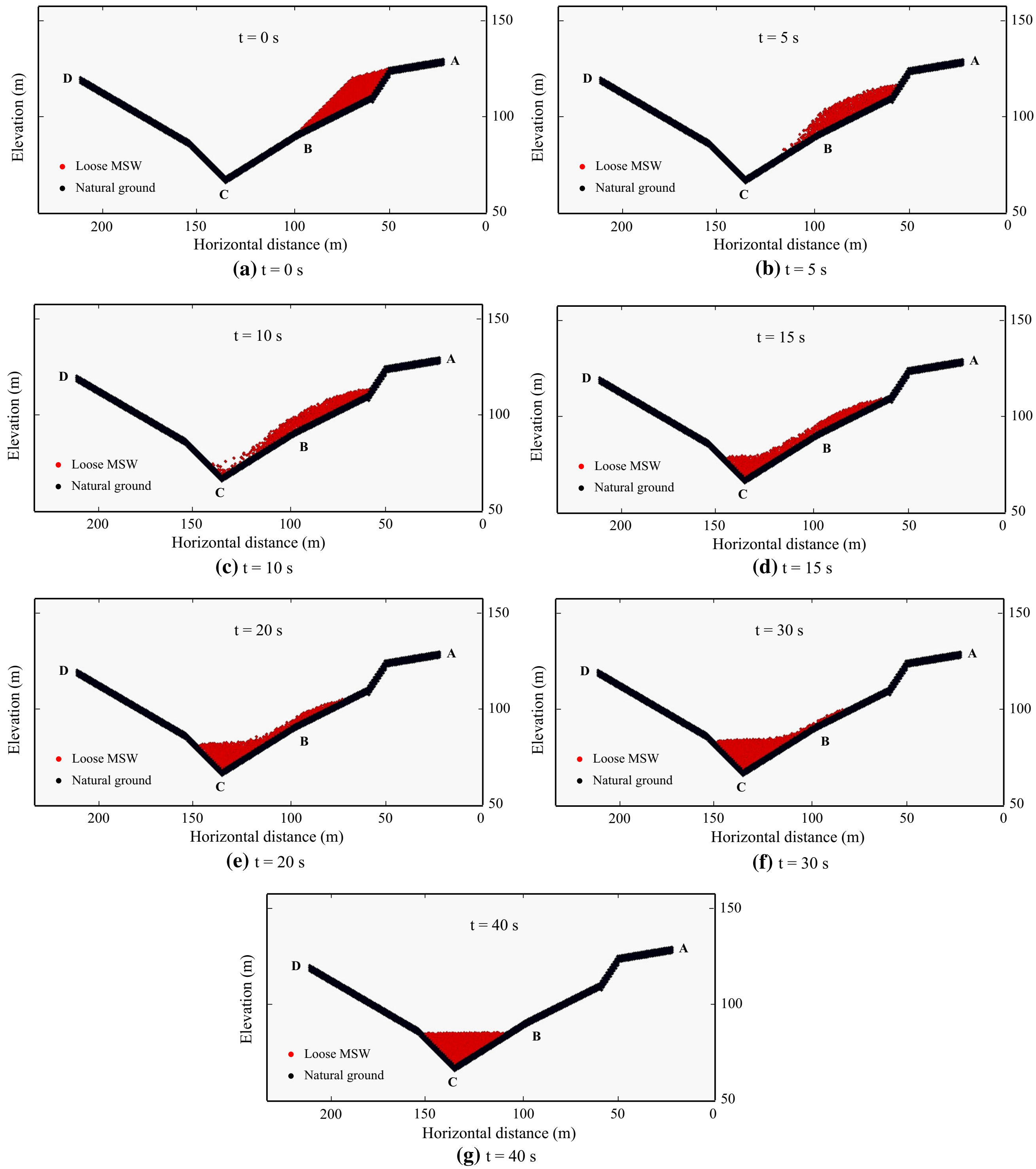


Fig. 7 Simulated flow process of the Ümraniye-Hekimbasi landfill in two dimensions

there is a little deviation. The main reason for this is that when the MSW reached the opposite slope it changed direction and extended along the valley. The 2D model cannot simulate this phenomenon and instead accumulates all the MSW in the cross section, which makes the modeled deposit a little thicker than the measured deposit.

Compared with the earlier 2D model, the 3D model has several advantages. (1) The influence of the complex 3D local topography on the MSW movement can be simulated well, and the evolution of the flow slide can be truly represented. (2) The scope of damage and extent of deposit after flow failure of the landfills can be defined and the

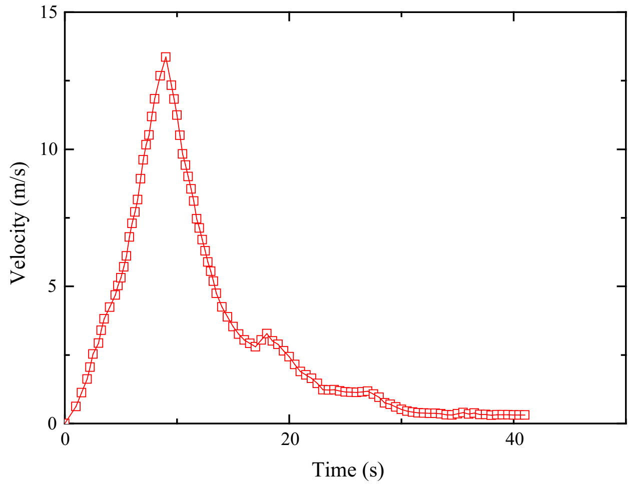


Fig. 8 Velocity time history of the flow slide from the 2D simulation

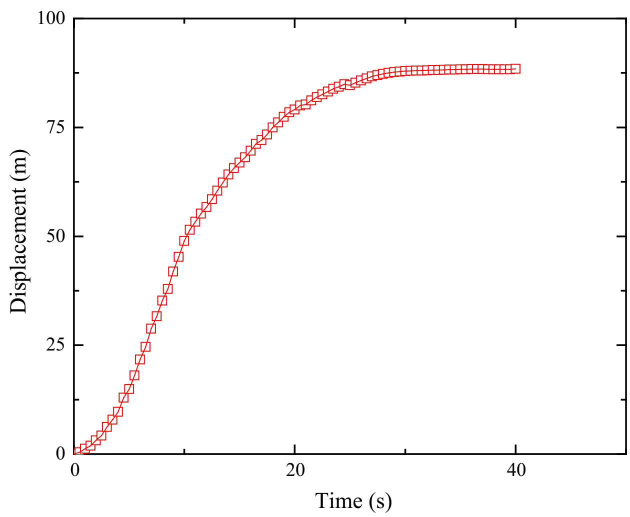


Fig. 9 Displacement time history of the flow slide from the 2D simulation

hazardous areas mapped. (3) The computation accuracy is higher. Though the main achievement of this work is to extend the previous 2D model into 3D, there are still some detailed improvements, such as the no-slip boundary treatment and the XSPH velocity correction, which improve the efficiency and accuracy of the model.

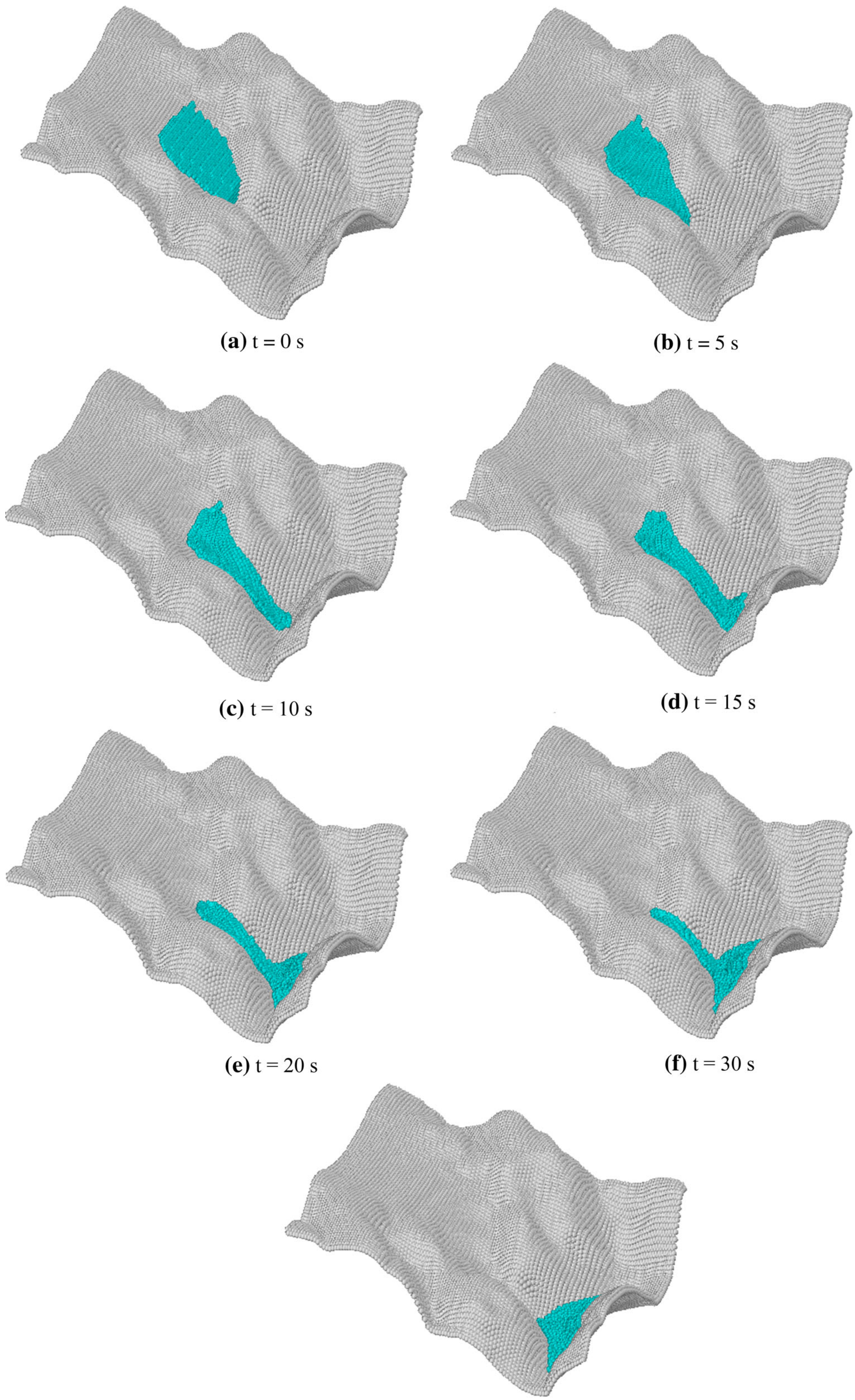
In this section, the 3D SPH model was applied to simulate the propagation of the failed MSW in Ümraniye-Hekimbasi landfill. The velocity and displacement time histories of the waste mass were predicted, and the scope of damage and extent of deposit were defined. The results from the 3D SPH simulation were compared with the measured data and 2D results; then the applicability and reliability of the 3D model were confirmed.

Discussion

In the established model, the MSW was assumed as a viscous Bingham fluid. Therefore, rheological parameters, including the yield shear strength and viscosity coefficient, are of importance in describing the dynamic characteristics. Unfortunately, despite considerable research on MSW mechanical behavior (Zhan et al. 2008; Bray et al. 2009; Stark et al. 2009), the experimental results obtained have been inconsistent. On the other hand, there has been no characterization of the viscosity coefficient of the MSW at the Ümraniye-Hekimbasi landfill in the existing technical literature. As a result, the reasonable determination of these parameters may be a major challenge in applying the Bingham flow model to the performance analysis of this landfill. To explore the effects of each individual rheological parameter on the simulation results, a back analysis was carried out in the former work (Huang et al. 2013) and some recommended values of these rheological parameters were provided, which were adopted in the above simulation in this paper.

Besides the rheological parameters, material density is another important parameter in many engineering analyses (Haddad et al. 2010). As shown in the 'equation of state', the density of the MSW can significantly affect the hydrostatic pressure, and then change the velocity through the equation of motion. Therefore, the density plays an important role in describing the dynamic behavior of MSW. However, the density of MSW differs in different places and at different times since the composition of MSW varies greatly from country to country and changes significantly with time. As a result, the density continues to be a major source of uncertainty in landfill performance analyses. Different methods have been used to test and evaluate the density of MSW (Gabr and Valero 1995; Chen et al. 2003; Reddy et al. 2009; Machado et al. 2010). Unfortunately, there is significant scatter in the reported values. Hence, it is difficult for an engineer to estimate with confidence a representative MSW density profile for use in engineering analyses. Zekkos et al. (2006) presented in-place large-scale MSW unit weight measurements from 11 different studies. The values varied from 5 to more than 18 kN/m^3. Therefore, to explore the effect of material density, the flow slide at the Ümraniye-Hekimbashi landfill was reproduced for varying densities from 500 to 2000 kg/m^3. The parameters used to study the influence of material density are given in Table 3. Note that the main idea of this section is to investigate the effect of the material density on the flow behavior through a back analysis method. Therefore, rheological parameters are kept unchanged, though they may change with the material density (Komatina and Jovanovic 1997).

Fig. 10 Simulated flow process of the Ümraniye-Hekimbasi landfill in three dimensions



(a) t = 0 s

(b) t = 5 s

(c) t = 10 s

(d) t = 15 s

(e) t = 20 s

(f) t = 30 s

(g) t = 40 s

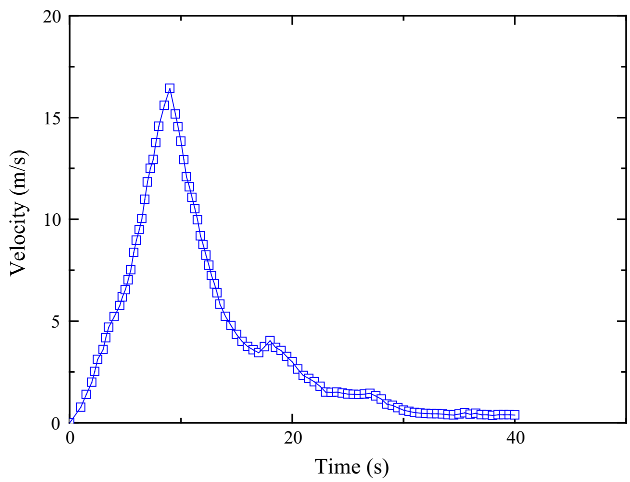


Fig. 11 Velocity time history of the flow slide from the 3D simulation

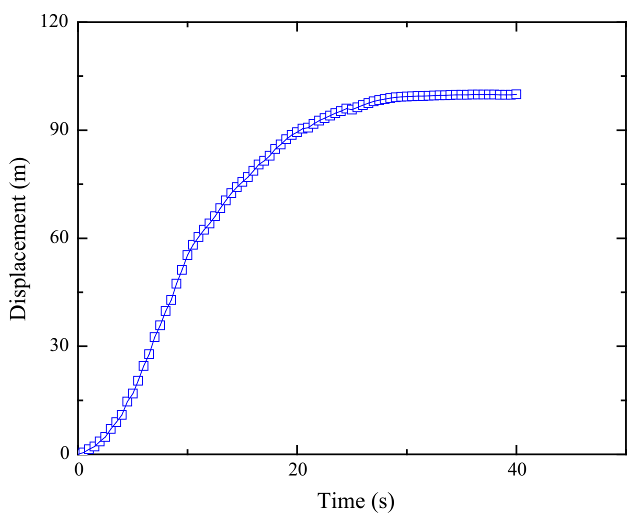


Fig. 12 Displacement time history of the flow slide from the 3D simulation

In all cases, the model correctly reproduced the trajectory of the flow slide at the Ümraniye-Hekimbashi landfill, but the velocity and final run-out were affected by material density. Figures 15 and 16 show the time histories of the simulated displacement and velocity. The final run-outs and maximum velocities during the movement are listed in Table 4. It is seen that the velocities are higher and the propagation front moves farther downstream when the density of the material increases.

Velocity is a crucial parameter in risk evaluation and the design of supporting structures. However, at a practical level, it is difficult to record the specific real-time velocity of the MSW during the movement. In this section, the simulated velocity is calibrated using the velocity estimated from the law of energy conservation. Blight and Fourie (2005) proposed an approach to estimate the flow velocity of MSW in cases where a downhill flow crosses a valley and stagnates at a given elevation on the opposite slope:

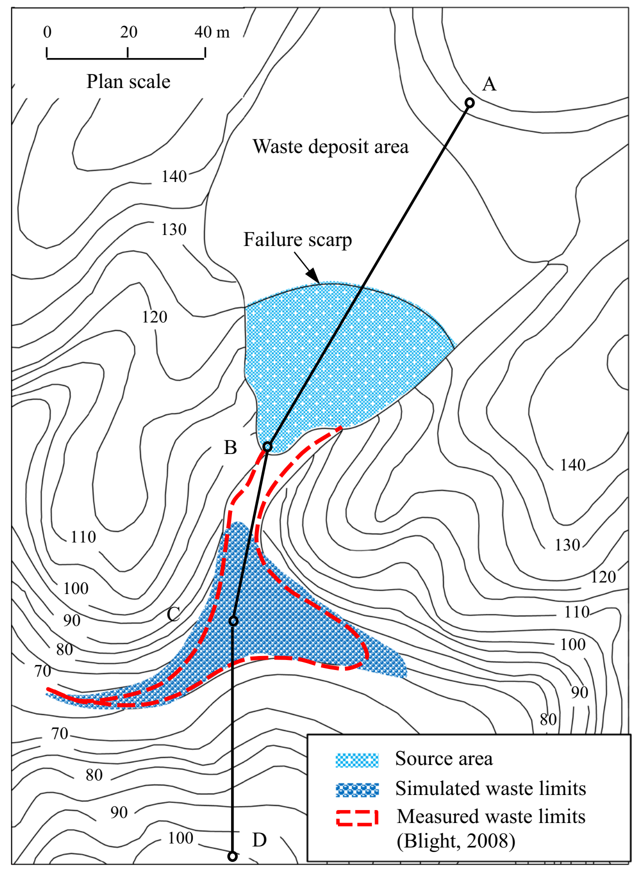


Fig. 13 Comparison of the simulated and measured scopes of damage for the deposition zone of the flow slide at the Ümraniye-Hekimbasi landfill (based on Blight 2008)

$$v = (2g\Delta h)^{1/2}, \quad (13)$$

where v is the velocity of flow at the bottom of the valley and Δh is the stagnation height above the bottom of the valley. For the Istanbul case, $\Delta h = 15.0$ m and the flow velocity is $v = 17.1$ m/s. Then the percentage error (E) is defined according to the relationship between the estimated value (E_v) and the simulated calculated value (S_v): $E = (E_v - S_v)/E_v$. For this definition, the errors of the maximum velocity in the three cases above were 39.94, 3.80 and −22.73 %, respectively. Therefore, the result for case D2 with MSW density of 1000 kg/m^3 is closest to the estimates made taking the approach described above.

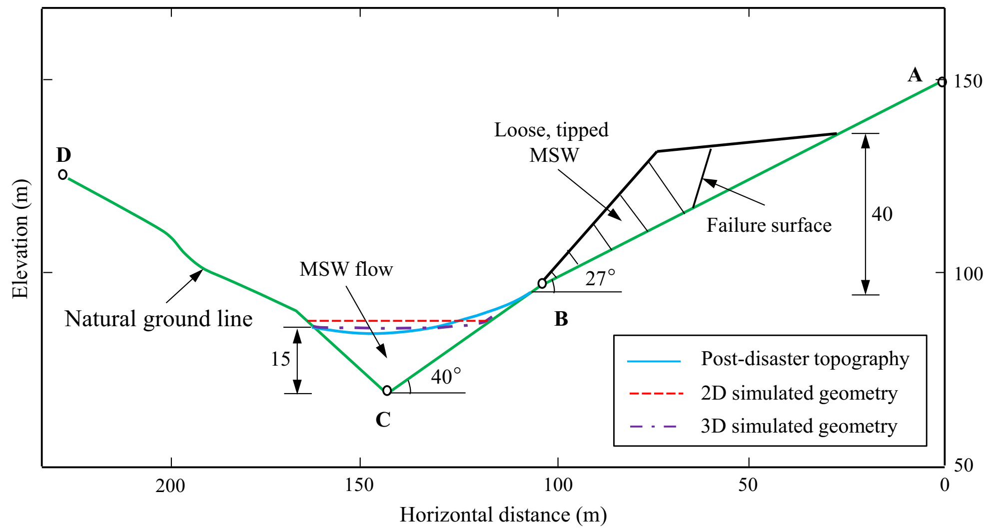


Fig. 14 Comparison of the simulated and surveyed post-disaster slope shape at the Ümraniye-Hekimbasi landfill, drawn along line ABCD of Fig. 13

Table 3 Parameters used to study the influence of material density

Case	Density	Viscosity	Yield strength	
	ρ (kg/m^3)	η (Pa s)	c (kPa)	φ (°)
D1	500.0	1.0	16.0	22.0
D2	1000.0	1.0	16.0	22.0
D3	2000.0	1.0	16.0	22.0

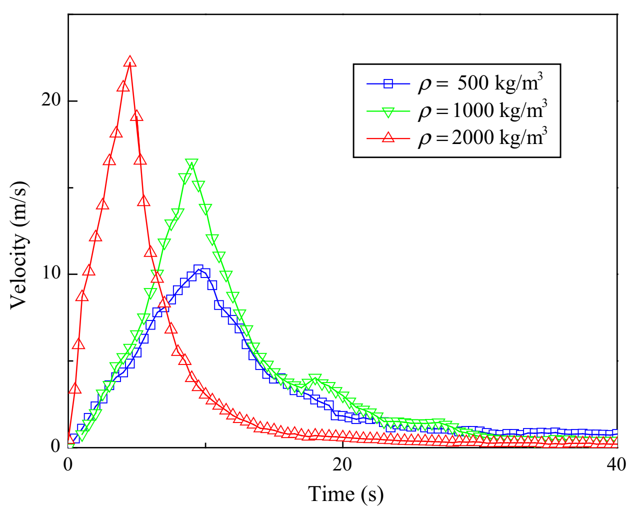


Fig. 15 Simulated velocity time history for different material densities

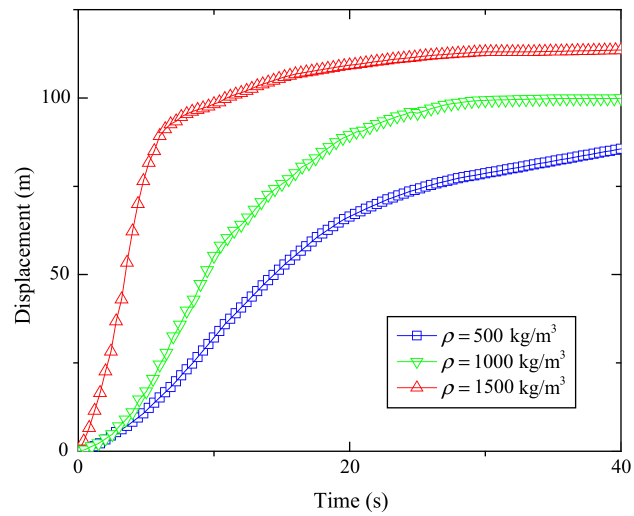


Fig. 16 Simulated run-out time history for different material densities

Table 4 Predicted maximum velocities and run-out in different cases

Case	D1	D2	D3
Maximum velocity (m/s)	10.27	16.45	22.13
Run-out (m)	85.59	101.55	113.56

Conclusions

Catastrophic flow slides have occurred at MSW landfills with increasing frequency and caused a large number of fatalities and much destruction of infrastructure and contamination of the environmental. To deepen the understanding of flow characteristics in such waste slides, a 3D numerical model for flow slides at MSW landfills based on the SPH method was presented in this paper. The SPH modeling technique was established providing an attractive modeling framework for flow slides in MSW landfills, and a basis for environmental disaster evaluation and management.

A typical flow slide at the Ümraniye-Hekimbasi landfill was simulated using both the previously established 2D model and the established 3D model. A comparison of the results obtained with the two models revealed the advantages of the 3D model. The propagation of the MSW across complex terrain and the velocity and displacement time histories of the waste mass were obtained. The modeled scope of damage and extent of deposit well match observations. All these results are beneficial for mapping hazardous areas and environmental disaster management.

The sensitivity of the 3D model to variations in density was studied. Back analysis showed that material density is a factor that affects the propagation of the failed MSW. The velocity increased and the front moved farther as the density increased. Then the flow velocity model was calibrated using the estimated velocity provided in a technical paper. The second case with a density of 1000 kg/m^3 provided the maximum velocity closest to that estimated, and this value is recommended for future simulation and prediction of flow slides at MSW landfills.

This paper aims to present a 3D SPH model to simulate the propagation stage of flow slides in MSW landfills. The sliding velocity and run-out distance during the propagation could be predicted, and the risk zoning map could be determined. These hazardous areas should be avoided in the planning and designing of new structures, and appropriate protective measures should be taken to the existing structures in the hazardous areas.

Acknowledgments This work was supported by the National Basic Research Program of China (973 Program) through Grant No. 2012CB719803.

References

Batchelor GK (1967) An introduction to fluid dynamics. Cambridge University Press, Cambridge

Blight GE (2004) A flow failure in a municipal solid waste landfill: the failure at Bulbul, South Africa. In: The skempton conference: advances in geotechnical engineering, Thomas Telford, London, 2, pp 777–788

Blight GE (2008) Slope failures in municipal solid waste dumps and landfills: a review. Waste Manag Res 26(5):448–463

Blight GE, Fourie AB (2005) Catastrophe revisited: disastrous flow failures of mine and municipal solid waste. Geotech Geol Eng 23:219–248

Bray JD, Zekkos D, Kavazanjian E, Athanasopoulos GA, Riemer MF (2009) Shear strength of municipal solid waste. J Geotech Geoenviron Eng 135(6):709–722

Brink DP, Day PW, du Preez L (1999) Failure and remediation of Bulbul Drive landfill: KwaZulu-Natal, South Africa. In: 7th International waste management and landfill symposium, Cagliari, Italy, pp 555–562

Brunner PH, Fellner J (2007) Setting priorities for waste management strategies in developing countries. Waste Manag Res 25(3): 234–240

Caicedo B, Giraldo E, Yamin L, Soler N (2002) The landslide of Dona Juana landfill in Bogota: a case study. In: Proceedings of the 4th international congress on environmental geotechnics (4th ICEG), Rio de Janeiro, Brazil, 11–15 August 2002, pp 171–175

Cascini L, Cuomo S, Pastor M, Sacco C (2013) Modelling the post-failure stage of rainfall-induced landslides of the flow type. Can Geotech J 50(9):924–934

Chen YM, Luo CY, Ke H (2003) Geotechnical properties of municipal solid waste in China. In: Proceedings of the 12th Asian Regional conference on soil mechanics and geotechnical engineering 1–2, pp 365–368

Chugh AK, Stark TD, DeJong KA (2007) Reanalysis of a municipal landfill slope failure near Cincinnati, Ohio, USA. Can Geotech J 44(1):33–53

Dai ZL, Huang Y, Jiang FH, Huang MS (2015) Modeling the flow behavior of a simulated municipal solid waste. Bull Eng Geol Environ. doi:10.1007/s10064-015-0735-8

Ercolessi F (1997) A molecular dynamics primer. Spring College in Computational Physics, ICTP, Trieste, pp 24–25

Fan XM, Rossiter DG, van Westen CJ, Xu Q, Gorum T (2014) Empirical prediction of coseismic landslide dam formation. Earth Sci Process Landf 39(14):1913–1926

Gabr MA, Valero SN (1995) Geotechnical properties of municipal solid waste. Geotech Test J 18(2):241–251

Ghobadi MH, Babazadeh R, Bagheri V (2013) Siting MSW landfills by combining AHP with GIS in Hamedan province, western Iran. Environ Earth Sci 70(4):1823–1840

Gingold RA, Monaghan JJ (1977) Smoothed Particle Hydrodynamics: theory and application to non-spherial stars. Mon Not R Astron 181:375–389

Haddad B, Pastor M, Palacios D, Munoz-Salinas E (2010) A SPH depth integrated model for Popocatépetl 2001 lahar (Mexico): sensitivity analysis and runout simulation. Eng Geol 114(3–4): 312–329

Hamilton SM, Reyes DV, Kolb WW (1998) Remediation of a major landfill slope failure in Bogota, Columbia. In: Wastecon/ISWA World Congress, Charlotte, North Carolina, USA, pp 503–519

Hendron DM, Fernandez G, Prommer PJ, Giroud JP, Orozco LF (1999) Investigation of the cause of the 27 September 1997 slope failure at the Dona Juana landfill. In: 7th International waste management and landfill symposium, Cagliari, Italy, pp 545–554

Huang Y, Dai ZL, Zhang WJ, Huang MS (2013) SPH-based numerical simulations of flow slides in municipal solid waste landfills. Waste Manag Res 31(3):256–264

Hungr O (1995) A model for the runout analysis of rapid flow slides, debris flows, and avalanches. Can Geotech J 32(4):610–623

Jafari NH, Stark TD, Merry S (2013) The July 10 2000 Payatas landfill slope failure. Int J Geoeng Case Hist 2(3):208–228

Kocasoy G, Curi K (1995) The Ümraniye-Hekimbasi open dump accident. Waste Manag Res 13(4):305–314

Koelsch F, Fricke K, Mahler C, Damanhuri E (2005) Stability of landfills-the Bandung dumpsite disaster. In: 10th International waste management and landfill symposium, Sardinia, Cagliari

Komatina D, Jovanovic M (1997) Experimental study of steady and unsteady free surface flows with water-clay mixtures. J Hydraul Res 35(5):579–590

Libersky LD, Petschek AG, Carney TC, Hipp JR, Allahdadi FA (1993) High strain Lagrangian hydrodynamics: a three dimensional SPH code for dynamic material response. J Comput Phys 109(1):67–75

Liu GR, Liu MB (2003) Smoothed particle hydrodynamics: a meshfree particle method. World Scientific Publishing Co. Pte. Ltd., Singapore

Liu MB, Liu GR (2010) Smoothed particle hydrodynamics (SPH): an overview and recent developments. Arch Comput Methods Eng 17(1):25–76

Liu CL, Zhang Y, Zhang F, Zhang S, Yin MY, Ye H, Hou HB, Dong H, Zhang M, Jiang JM, Pei LX (2007) Assessing pollutions of soil and plant by municipal waste dump. Environ Geol 52(4):641–651

Liu ZB, Ma J, Li JM (2009) Stability analysis of the slope of municipal solid waste sanitary landfill. International Symposium on Environmental Science and Technology, Shanghai

Liu XL, Si WJ, Zhu CY, Yu W (2010) Analysis on stability of liner system located in slope of municipal solid waste landfill. In: Proceedings of the 7th international symposium on safety science and technology (ISSST), Hangzhou, China. Science Press, Beijing, China

Lu L, Wang ZJ, Huang XY, Zheng B, Arai K (2014) Dynamic and static combination analysis method of slope stability analysis during earthquake. Math Probl Eng. doi:10.1155/2014/573962

Lucy LB (1977) A numerical approach to the testing of the fission hypothesis. Astron J 82(12):1013–1024

Machado SL, Karimpour-Fard M, Shariatmadari N, Carvalho MF, do Nascimento JCF (2010) Evaluation of the geotechnical properties of MSW in two Brazilian landfills. Waste Manag 30(12):2579–2591

McDougall S, Hungr O (2004) A model for the analysis of rapid landslide motion across three-dimensional terrain. Can Geotech J 41(6):1084–1097

Merry SM, Kavazanjian E, Fritz WU (2005) Reconnaissance of the July 10, 2000 Payatas landfill failure. ASCE J Perform Constr Facil 19(2):100–107

Monaghan JJ (1992) Smoothed particle hydrodynamics. Ann Rev Astron Astrophys 30:543–574

Monaghan JJ (1994) Simulating free surface flows with SPH. J Comput Phys 110(2):399–406

Monaghan JJ (2002) SPH compressible turbulence. Mon Not R Astron Soc 335(3):843–852

Monaghan JJ, Gingold RA (1983) Shock simulation by the particle method SPH. J Comput Phys 52:374–389

Monaghan JJ, Lattanzio JC (1985) A refined particle method for astrophysical problems. Astron Astrophys 149:135–143

Morris JP, Fox PJ, Zhu Y (1997) Modeling low reynolds number incompressible flows using SPH. J Comput Phys 136:214–226

Pastor M, Haddad B, Sorbino G, Cuomo S, Drempetic V (2009) A depth-integrated, coupled SPH model for flow-like landslides and related phenomena. Int J Numer Anal Methods Geomech 33:143–172

Pastor M, Blanc T, Haddad B, Petrone S, Morles MS, Drempetic V, Issler D, Crosta G, Cascini L, Sorbino G (2014) Application of a SPH depth-integrated model to landslide run-out analysis. Landslides 11(5):793–812

Randles PW, Libersky LD (1996) Smoothed particle hydrodynamics: some recent improvements and applications. Comput Methods Appl Mech Eng 139(1):375–408

Reddy KR, Hettiarachchi H, Parakalla NS, Gangathulasi J, Bogner JE (2009) Geotechnical properties of fresh municipal solid waste at Orchard Hills Landfill, USA. Waste Manag 29(2):952–959

Stark TD, Huvaj-Sarihan N, Li GC (2009) Shear strength of municipal solid waste for stability analyses. Environ Geol 57(8):1911–1923

Takeda H, Miyama SM, Sekiya M (1994) Numerical simulation of viscous flow by smoothed particle hydrodynamics. Progress Theor Phys 92(5):939–960

Thusyanthan NI, Madabhushi SPG, Singh S (2006a) Centrifuge modeling of solid waste landfill systems—part 1: development of a model municipal solid waste. Geotech Test J 29(3):217–222

Thusyanthan NI, Madabhushi SPG, Singh S (2006b) Centrifuge modeling of solid waste landfill systems—part 2: centrifuge testing of MSW simulant. Geotech Test J 29(3):223–229

Uzuoka R, Yashima A, Kawakami T, Konrod JM (1998) Fluid dynamics based prediction of liquefaction induced lateral spreading. Comput Geotech 22(3/4):234–282

Zekkos D, Bray JD, Kavazanjian E, Matasovic N, Rathje EM, Riemer MF, Stokoe KH (2006) Unit weight of municipal solid waste. J Geotech Geoenvironment Eng 132(10):1250–1261

Zhan LT, Chen YM, Ling WA (2008) Shear strength characterization of municipal solid waste at the Suzhou landfill, China. Eng Geol 97(3–4):97–111

Zhao H, Song EX (2012) A method for predicting co-seismic displacements of slopes for landslide hazard zonation. Soil Dyn Earthq Eng 40:62–77

Zhu B, Yang CB, Wang L et al (2012) Compounding model MSW and Centrifugal model tests of landfill. In: Proceedings of the 1st China National symposium on coupled phenomena in geomaterials and environmental geotechnics, Hangzhou, pp 425–432 (in Chinese)