

Simulation of flow slides in municipal solid waste dumps using a modified MPS method

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Abstract Flow slides in municipal solid waste (MSW) dumps have caused serious damage to structures and casualties all over the world. Therefore, much attention should be paid to this type of disaster to elucidate the flow mechanisms and fluidization characteristics of MSW, which are essential for the assessment and prevention of flowlike hazards. To bypass the deficiencies of the traditional analysis methods that use the mesh method and are based on a framework of solid mechanics, the moving particle semi-implicit (MPS) method, which is a purely Lagrangian meshless method and proposed for incompressible flow, is introduced to study flow slides in MSW landfills. Considering the no-physical pressure fluctuation that affects the simulation accuracy in the original MPS, the original MPS is revised in three ways: the kernel function, the source term of the Poisson equation and the search for free surface particles. Two benchmark problems, the dam break problem and the static pressure problem, are computed to illustrate the improvement of the pressure stability of the modified MPS. The Bingham constitutive model combined with the Mohr–Coulomb failure criterion is adopted to depict the dynamic features of MSW flow slides, and the equivalent viscosity is employed to bridge the gap between Bingham fluid models and Newtonian fluid models. This method, ultimately, is applied to simulate real flow slides in the Umraniye–Hekimbashi landfill and the Payatas waste dump. The numerical results show good consistency with the field data, indicating that the modified MPS method is capable of capturing the essential dynamic behavior and reproducing the entire process of complicated flow slides in MSW dumps.

Keywords Municipal solid waste · Flow slide · Pressure fluctuation · MPS

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1 Introduction

With economic development and urbanization, the population of and consumption in urban areas increase rapidly, resulting in a growing amount of municipal solid waste (MSW) produced by people's daily life, offices and small industries. Though recycling and reuse of MSW have gained more and more attention in many countries, landfill is still a widely used means of dealing with MSW and will remain so for a long time because of its great advantage in cost-benefit analyses (Blight and Fourie 2005). Taking China as an example: In 2011, there were 677 factories for waste treatment, of which 547 were landfills; 77 % of refuse was disposed of in landfill, while only 19.8 % was dealt with through incineration (National Bureau of Statistics of China 2012).

The stability of landfill has attracted attention in the field of environmental geotechnics. Landfill failure will cause leachates to leak out, which will bring about contamination and other serious environmental problems. Moreover, damage to infrastructure and even vast numbers of casualties may occur. For example, the first reported waste slide happened in Sarajevo in the 1970s, which involved 20,000 m³ of refuse. Two bridges and five houses were destroyed (Gandolla et al. 1979). From then on, similar accidents induced by flow slides have been covered in the technical literature (Brink et al. 1999; Koelsch et al. 2005; Kocasoy and Curi 1995). The disaster that occurred at the Payatas waste dump at Quezon, the Philippines, in 2000 (Merry et al. 2005) led to the deaths of more than 600 people and serious damage to many homes. Therefore, the study of landfill stability has immediate and far-reaching significance in the assessment and prevention of similar hazards.

Though the causes of landfill instability are varied, the buildup of pore pressure resulting from high leachate levels or gas pressure in the refuse is regarded as the key cause. Koerner and Soong (2000) pointed out that an excessive buildup of leachate levels, which can be caused by precipitation, ice formation, addition of liquid waste or leachate injection, was the major reason for failure in ten case histories in the USA. Thiel (1999) found that gas pressure would bring down the effective stress, resulting in landfill instability. The buildup of pore pressure will cause the effective stress to decrease substantially and the deformation to increase rapidly, which will lead to failure. The failure mode of landfills is different from that of an ordinary soil slope because the density of a waste mass is far less than that of soil and the leachate level is always high (Qiu et al. 2011). The failure model can be described as a long run-out waste slide with the liquid phase (e.g., water or leachate) driving the solid phase (e.g., undegraded waste) when the dump becomes unstable. For example, the flow slide at Sarajevo traveled at a distance of more than 1 km. Therefore, analytical investigations of flow slides should be different from those of traditional landslides because of the large deformation and the rheological properties.

Numerical methods are effective tools for stability analysis. Koerner and Soong (2000) employed the CLARA and GEOSLOPE programs, both of which were based on the simplified Janbu method of identifying the translational failure surface, to calculate the factor of safety (FS) of ten unstable dumps in 3D and 2D analysis. Jiang et al. (2010) used the business-compatible software Lizheng to simulate dump failure and reported that the leachate level can affect the landfill stability. Qian et al. (2003) adopted the computer code PCSTABL to analyze translational failure of landfill. All the traditional numerical methods mentioned above, which belong to the mesh method, are based on the framework of solid mechanics and focus on the FS of landfill and the instability conditions. However, research on the characteristics of fluidization of the flow slide after a landfill loses stability is rarely reported in the technical literature. In addition, the mesh method has difficulty in

simulating the large deformation of the flow slide because of numerical diffusion, which is caused by excessive distortion of the mesh when the advection term is discretized (Gotoh et al. 2005). Fortunately, the meshless method based on computational fluid dynamics (CFD) can bypass the numerical diffusion because the advection term is computed by tracking the movements of particles. In other words, the meshless method is advantageous for describing the complicated characteristics of fluidization motion with large deformation in simulations of flow slides.

The moving particle semi-implicit (MPS) method developed by Koshizuka and Oka (1996) and the smoothed particle hydrodynamics (SPH) method proposed by Lucy (1977) are two typical meshless methods. Compared with the original SPH method, the MPS method is a fully incompressible model that is more suitable for describing the MSW materials, and the semi-implicit algorithm in the MPS method makes the results more accurate with an acceptable increase in calculation time. Hence, the MPS is applied in various fields such as nuclear engineering (Heo et al. 2002), bioengineering (Tsubota et al. 2006), microflow analysis (Suzuki et al. 2006) and civil engineering (Gotoh et al. 2007). However, simulations of MSW landfill failure using MPS are rarely reported.

To simulate flow slides in MSW landfills, Huang et al. (2013) introduced the Bingham model combined with the Mohr–Coulomb equation as the constitutive model and achieved some convincing results. In the Mohr–Coulomb equation, the normal stress is represented by pressure (Moriguchi et al. 2005). However, the pressure calculated by the original MPS code suffers from large numerical fluctuations, which will seriously affect the accuracy of simulations of flow slides. Hence, it is very important to keep the pressure stable before introducing the MPS to a flow slide simulation.

The reason for the pressure oscillation is complicated, and previous studies (Sueyoshi and Naito 2002; Hibi and Yabushita 2004; Ataie-Ashtiani and Farhadi 2006; Khayyer and Gotoh 2009; Tanaka and Masunaga 2010; Kondo and Koshizuka 2011; Lee et al. 2011) have mainly focused on one aspect to improve pressure stability. In this paper, the original MPS is modified in three ways (the kernel function, the source term of the Poisson equation and the search for free surface particles), and the improvement of the modified MPS is verified using two examples: the dam break problem and the static pressure problem. Then, the modified MPS with the Bingham constitutive model is used to simulate the failures of the Umraniye–Hekimbashi landfill and the Payatas waste dump. The results for the basic dynamic characteristics of MSW flows, including the post-failure profile and the maximum velocity, were consistent with field survey data.

2 Concept of the MPS method

The MSW is represented by a number of arbitrarily distributed particles that carry the field variables, such as mass, density, pressure and velocity. The interactions of the neighboring particles describe the terms in the governing equation.

2.1 Governing equation

The continuity equation:

$$\frac{D\rho}{Dt} = 0. \quad (1)$$

The Navier–Stokes equation:

$$\frac{D\mathbf{u}}{Dt} + (\mathbf{u} \cdot \nabla)\mathbf{u} = -\frac{1}{\rho}\nabla P + \nu\nabla^2\mathbf{u} + \mathbf{g} \quad (2)$$

in which ρ is the density, t is the time, $\mathbf{u}$ is the velocity vector, ∇ is the gradient, P is the pressure, ν is the kinematic viscosity, ∇^2 is the Laplacian and $\mathbf{g}$ is the gravitational acceleration vector. The right-hand side of Eq. (2) includes a pressure gradient term, a viscous term and a gravity term. To simulate the incompressible flow, all the differential terms should be discretized using the particle interaction model of the MPS method.

2.2 Kernel function

The kernel function is the basis for the particle interaction. The kernel function adopted in the original MPS has a singularity at $r = 0$, which is one of the reasons for the pressure instability. In this study, the following function, which was proposed by Jung et al. (2008), is employed:

$$w(r) = \begin{cases} \left(1 - \frac{r}{r_e}\right)^3 \left(1 + \frac{r}{r_e}\right)^3 & (0 \leq r < r_e) \\ 0 & (r \geq r_e) \end{cases} \quad (3)$$

in which r is the distance between two particles and r_e represents the radius of the particle interaction area, which is 2.1 times the initial particle spacing d_0 .

The particle number density is defined by:

$$n_i = \sum_{j \neq i} w(|\mathbf{r}_j - \mathbf{r}_i|). \quad (4)$$

The incompressible condition is satisfied by keeping the particle number density constant in the original MPS. The constant particle number density is represented by n^0 .

2.3 Gradient and the Laplacian model

The gradient vector at particle i is calculated by the weighted average of these gradient vectors (Koshizuka and Oka 1996):

$$\langle \nabla \phi \rangle_i = \frac{d}{n^0} \sum_{j \neq i} \left[\frac{\phi_j - \hat{\phi}_i}{|\mathbf{r}_i - \mathbf{r}_j|^2} (\mathbf{r}_i - \mathbf{r}_j) w(|\mathbf{r}_j - \mathbf{r}_i|) \right] \quad (5)$$

in which d is the number of space dimensions and $\hat{\phi}_i$ is the minimum value of the effective radius.

The Laplacian is modeled as follows (Koshizuka and Oka 1996):

$$\langle \nabla^2 \phi \rangle_i = \frac{2d}{\lambda n^0} \sum_{j \neq i} [(\phi_j - \phi_i) w(|\mathbf{r}_j - \mathbf{r}_i|)] \quad (6)$$

in which λ is the coefficient by which the variance increase is equal to the analytic solution and is expressed as:

$$\lambda = \frac{\sum_{j \neq i} w(|\mathbf{r}_j - \mathbf{r}_i|) |\mathbf{r}_j - \mathbf{r}_i|^2}{\sum_{j \neq i} w(|\mathbf{r}_j - \mathbf{r}_i|)}. \quad (7)$$

This model is conservative, as the quantity lost by particle i can be obtained by particle j .

2.4 Calculation process

There are two parts of the time integration process. The first part, in which the temporary velocity ($\mathbf{u}_i^*$) and the temporary number density (n_i^*) are calculated, considering the given external force and gravity terms, is an explicit process. Then the temporary position of particle i ($\mathbf{r}_i^*$) can be written using the following:

$$\mathbf{r}_i^* = \mathbf{r}_i^k + \Delta t \mathbf{u}_i^* \quad (8)$$

in which $\mathbf{r}_i^k$ is the coordinate of particle i in k step and Δt is the time increment. As the positions of particles are updated, the mass conservation might not be satisfied: i.e., $n_i^* \neq n^0$.

In the second section, the pressure term, which is not calculated in the first section, is involved and the Poisson equation of pressure is solved implicitly to calculate the pressure, which is used to revise the velocities and positions of particles. The Poisson equation in the original MPS is defined as:

$$\langle \nabla^2 P^{k+1} \rangle_i = \frac{\rho}{\Delta t^2} \frac{n_i^* - n^0}{n^0}. \quad (9)$$

The left-hand side of Eq. (9) can be discretized using the Laplacian model, and the right-hand side of Eq. (9) is to keep the PND constant (i.e., to satisfy the incompressibility) in the simulation. The advantage of the source term in the original MPS is that it avoids density error accumulation in the calculation. However, it leads to high-frequency oscillations in the pressure in both time and space. The other form of the source term is a function of velocity divergence adopted by Khayyer and Gotoh (2009) in the MPS. In this way, the pressure performs better, but the density error accumulates in the calculation. Tanaka and Masunaga (2010) used the mixed formulation of the aforementioned functions. It can relieve the fluctuation, but does not have a definite physical meaning. In other words, the mixed formulation is not obtained from the hydrodynamic equation. In this paper, the source term, which contains one main part and two error-compensating parts and was proposed by Kondo and Koshizuka (2011), is adopted as

$$\frac{1}{\rho} \langle \nabla^2 P^{k+1} \rangle_i = \frac{n_i^* - 2n_i^k + n_i^{k-1}}{n^0 \Delta t^2} + \frac{a}{\Delta t} \frac{n_i^k - n_i^{k-1}}{n^0 \Delta t} + \frac{b}{\Delta t^2} \frac{n_i^k - n^0}{n^0} \quad (10)$$

in which a and b are the dimensionless coefficients for the error-compensating parts and are set to be 0.5 and 0.05, respectively, from performing the proper numerical experiments.

The time increment of each calculation process is used; therefore, the Courant's stability condition and the time resolution 1.0×10^{-3} s must be satisfied (Koshizuka and Oka 1996). The equation is given by

$$\Delta t = \min(\alpha_{dt} d_0 / u_{\max}, 1.0 \times 10^{-3}); u_{\max} = \max\{|\mathbf{u}_i|\} \quad (11)$$

in which α_{dt} is a constant parameter ($=0.2$) and $u_{\max}$ is the maximum velocity value.

2.5 Boundary condition

The wall boundary is composed of one line of wall particles and several lines of dummy particles that are arranged regularly. The number of dummy particles is determined by r_e to avoid a PND deficiency near the boundary. The velocity of the particles in the boundary is set to be zero, and the pressures of the wall particles are calculated to repel the fluid particles from the wall, while the pressures of the dummy particles are not calculated.

As there are no particles out of the free surface, the free surface is judged based on the condition of the PND as follows:

$$n_i^* < \beta n^0 \quad (12)$$

where β is a threshold parameter and $\beta = 0.9$ is selected in this study. The pressure of the particles on the free surface is set to be zero. In the original MPS, the parameter β is set to be 0.97, which results in instability for many inside particles, which may be recognized as free surface particles. The pressure of the misjudged particles is set to be zero, which causes pressure fluctuations in the space.

3 Constitutive model

In this study, the fluidized MSW is modeled as a non-Newtonian fluid, which begins to flow when the shear stress is larger than the threshold value. The Bingham fluid model is one type of non-Newtonian fluid model and has been proven to be valid in the simulation of flow slides in MSW landfill (Huang et al. 2013). Therefore, in this paper, the Bingham model is employed as the constitutive model to depict flow slides of MSW.

The shear stress of the Bingham fluid is given as:

$$\begin{cases} \tau = \eta \dot{\gamma} + \tau_{\min} & (\tau > \tau_{\min}) \\ \dot{\gamma} = 0 & (\tau \leq \tau_{\min}) \end{cases} \quad (13)$$

in which η is the viscosity, $\dot{\gamma}$ is the shear strain rate, and $\tau_{\min}$ is the yield value of the Bingham fluid. In this study, $\tau_{\min}$ is given by the following Mohr–Coulomb equation in which normal stress is represented by pressure. Hence, it is important and necessary to keep the pressure stable to improve the accuracy of the simulation. Equation (13) can be transformed to:

$$\tau = \eta \dot{\gamma} + c + P \tan \phi \quad (14)$$

in which c is cohesion, P is pressure and ϕ is the internal friction angle.

Equation (14) is divided by the shear strain rate $\dot{\gamma}$ to obtain the equivalent viscosity (Moriguchi et al. 2005), which is used to describe the Bingham fluid in the N–S equation that is developed based on the Newtonian fluid. The equivalent viscosity is shown as:

$$\eta' = \eta + \frac{c + P \tan \phi}{|\dot{\gamma}|}. \quad (15)$$

The shear strain rate is expressed as:

$$|\dot{\gamma}| = \sqrt{\frac{1}{2} \left(\frac{\partial \mathbf{u}_i}{\partial x_j} + \frac{\partial \mathbf{u}_j}{\partial x_i} \right) \left(\frac{\partial \mathbf{u}_i}{\partial x_j} + \frac{\partial \mathbf{u}_j}{\partial x_i} \right)} \quad (16)$$

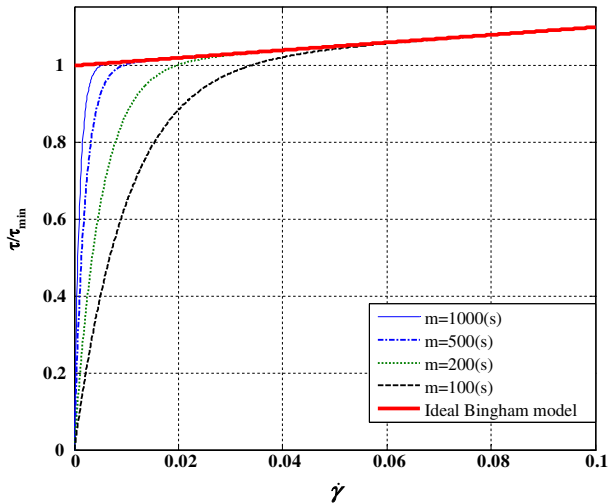


Fig. 1 The relationship between $\tau/\tau_{\min}$ and $\dot{\gamma}$

in which i, j represent different coordinate directions. Because of the discontinuity of Eq. (13) at $\tau = \tau_{\min}$, the approximated formula suggested by Papanastasiou (1987) is employed in this paper and is given as follows:

$$\eta' = \eta + \frac{c + P \tan \phi}{|\dot{\gamma}|} (1 - e^{-m\dot{\gamma}}) \quad (17)$$

in which m is the stress growth coefficient, which has a time dimension. The last part of Eq. (17) is used to approximate the characteristics of the Bingham fluid at a low shear rate. The relationship between $\tau/\tau_{\min}$ and $\dot{\gamma}$ when $\eta/\tau_{\min}$ is set to be one is shown in Fig. 1. It is noted that with a relatively large m , stress can grow quickly at a low strain rate, which shows good agreement with the behavior of the materials before the yield state. Experiment shows that Eq. (17) can describe the responses of red mud suspensions better than Eq. (13) (Dzuy and Boger 1985). As mentioned above, with the buildup of the pore pressure, the effective stress is very low or even zero, which results in the value of shear stress being around zero. In addition, the calculation is simplified by employing Eq. (17). In this paper, $m = 1,000$ s is adopted, as suggested by Otsuka et al. (2009), and η is set to be 1.0 Pa s, which was employed by Uzuoka et al. (1998), in the simulation of the lateral spreading of geomaterials induced by liquefaction. Using the basic concept and the approximated Bingham constitutive model, the MPS code is modified from the sample MPS code of Koshizuka (2005).

4 Verification and validation of the modified MPS method

To verify and validate the improvement of the modified MPS method, two sample problems, the dam break problem and the static pressure problem, were simulated in this paper.

4.1 Dam break problem

The dam break problem, which is a traditional test case for evaluation of the meshless method, was first adopted to investigate comparatively the performance of the original

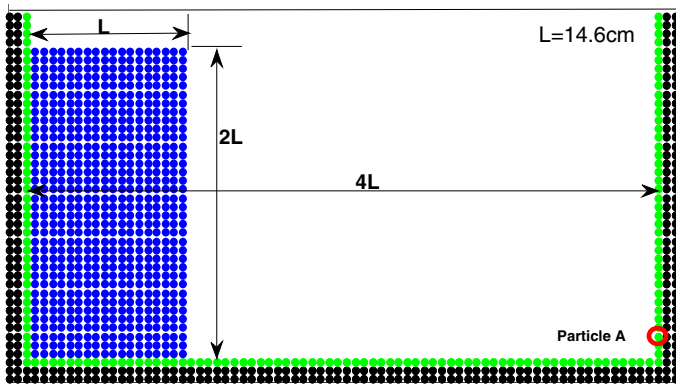


Fig. 2 The model of the dam break problem

MPS and the modified MPS. The initial layout is shown in Fig. 2. The numerical model is composed of 1,122 particles in total, of which 648 are water particles and 474 are boundary particles. The simulation time is 1 s, the initial distance between particles is 0.008 m, and the kinematic viscosity is set to $1 \times 10^{-6} \text{ m}^2/\text{s}$. The water column runs on the bed after collapsing and strikes the right vertical wall at 0.267 s. The position of the leading edge of the water simulated by the modified MPS, the numerical result computed from the original result and the experimental result from Martin and Moyce (1952) are shown in Fig. 3. The trajectory of the front obtained from the modified MPS shows better agreement with the experimental result in comparison with the result from the original MPS, thereby demonstrating the accuracy of the modified MPS method. To compare the pressure, the time histories of the pressure and the density error $(n_A - n^0)/n^0$ at particle A with 0.02 m distance from the bottom are presented in Figs. 4 and 5, respectively. The fluctuations in pressure and the density errors become smaller by employing the modified MPS. Therefore, the modified MPS is not only effective in reducing the pressure fluctuation, but also can improve the macro behavior, such as that of the water front.

4.2 Static pressure problem

The modified MPS method is used to calculate the static pressure in a rectangular tank, the layout of which is shown in Fig. 6. There are in total 960 particles in the simulation: 648 water particles and 312 boundary particles. The simulation time is 1 s, the space between particles is 0.008 m and the viscous effects are ignored. The pressure and density error of particle B at the bottom are computed and compared with the analytic static pressure, shown in Figs. 7 and 8, respectively. In Fig. 7, there is a peak at the beginning. The peak is reasonable, because at the beginning the pressure increases gradually and the vertical velocity of particles moves from acceleration to deceleration until the particles nearly keep motionless. The same phenomenon is also reported by Lee et al. (2011). From the comparison, we can see that the pressure suffers large fluctuations and the density error is considerable in the original MPS simulation, while in the modified MPS calculation, the pressure shows good agreement with the analytic result and the density error is nearly zero. Therefore, the modified MPS has a great advantage in stabilizing the pressure.

Fig. 3 A comparison of the leading edge of the dam break problem

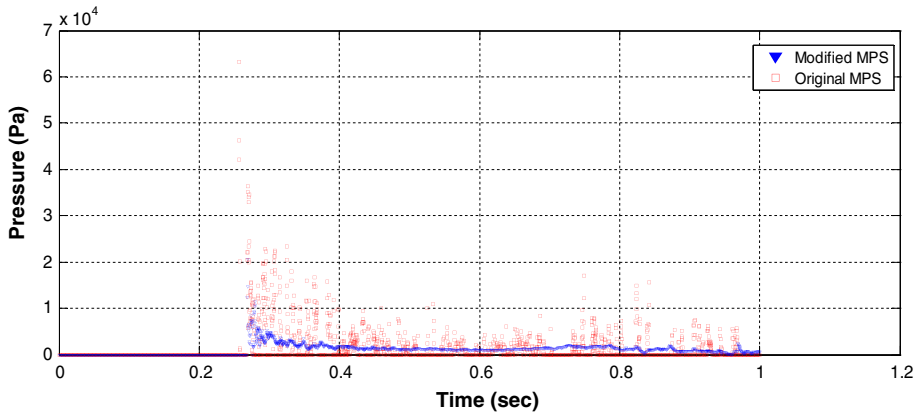
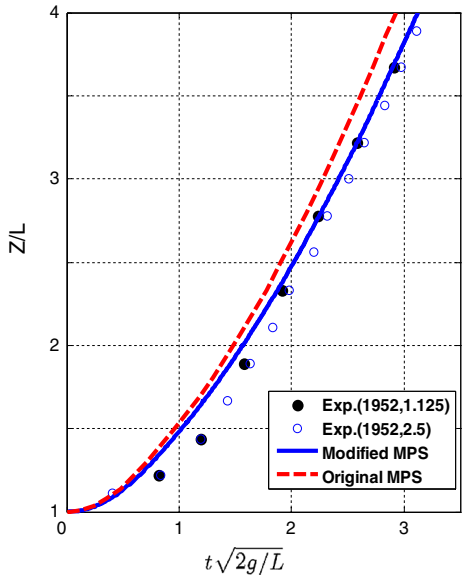


Fig. 4 The time history of the pressure at particle A

5 Modified MPS simulations of flow slide in landfills

The Umraniye–Hekimbashi landfill and the Payatas waste dump failures were two typical flow slides in MSW dumps caused by the liquefaction of MSW. The landfill failures were simulated by the modified MPS to verify the accuracy of the particle method applied in the prediction of the post-failure profile of the disaster.

5.1 The Umraniye–Hekimbashi landfill at Istanbul, Turkey, 1993

The Umraniye–Hekimbashi landfill, which was the second flow slide in a MSW landfill to be reported in the literature, is located in Istanbul, Turkey. In April 1993, a slide happened

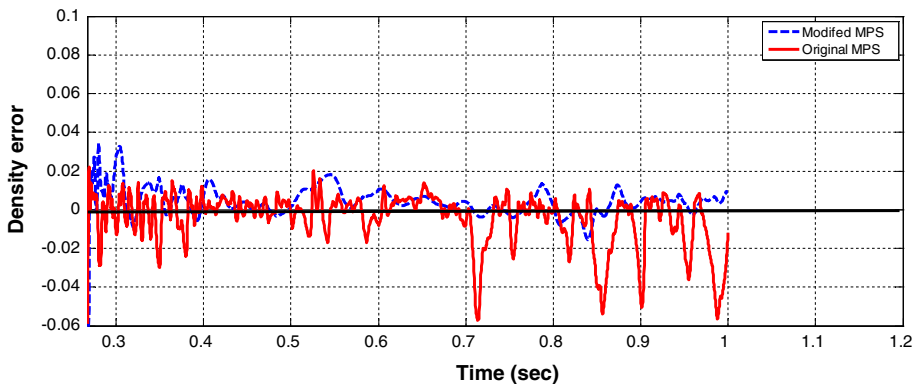


Fig. 5 The time history of the density error at particle A

on the tipping face that carried a 12,000 m³ wedge of liquefied waste, mainly composed of food and garden waste, paper and cardboard waste, ash, dust, sweepings and other waste, down into the valley and a short way up the opposite slope. As a result, 11 informal houses were buried and 39 of their occupants were killed (Kocasoy and Curi 1995; Kanat 2010). The reasons reported in the literature were that an additional disturbing force caused by the covered demolition waste and soil and the winter rain caused liquefaction of the loosened waste. The pre- and post-failure profiles of this landfill are shown in Fig. 9, from which we can see that the angle of the steep hillside dumped waste is about 27°.

A MPS simulation of the flow failure of the Umraniye–Hekimbashi landfill was conducted using the proposed model to capture the whole flow process of the flow slide. There are 1,234 particles, 410 particles for the MSW and 824 for the boundary, with an initial distance between particles of 1 m in the numerical simulation. The shear strength parameters of the MSW are important for the simulation. However, the shear strength for this landfill cannot be found in previous studies. Fortunately, Kavazanjian (2001) suggested values of $c = 24$ kPa, $\phi = 0^\circ$ for the normal stress below 30 kPa and $c = 0$ kPa, $\phi = 33^\circ$ for the normal stress high 30 kPa, respectively, by analyzing data from the failures of American landfills. The parameters used in the simulation are listed in Table 1. It takes almost 20 min to finish the numerical simulation on a personal computer with 2.7 GHz CPU and 2 GB RAM. Figure 10 shows the final profile of the simulation, and Fig. 11 presents simulated surface profiles at different times. As shown in Fig. 10, the MPS-simulated results are in good agreement with the observed geometry.

A simple method has been proposed to estimate the maximum velocity of the landfill slide based on the stagnation height of the MSW on the slope (Blight and Fourie 2005). Using this method, the maximum velocity of the Umraniye–Hekimbashi landfill was about 60 km/h or 16.67 m/s. Figure 12 shows the maximum velocity during the movement simulated using the MPS method. It can be easily obtained from the figure that the liquefied MSW reached the highest flow velocity of 13.74 m/s approximately 4 s after the landfill failure, which was quite close to the estimated velocity.

5.2 The Payatas waste dump at Quezon, Philippines, 2000

A flow slide was triggered by torrential downpours from two consecutive typhoons at the Payatas Landfill in Quezon City, the Philippines, in 2000 (Gaillard and Cadag 2009). The

Fig. 6 The model of the static pressure problem

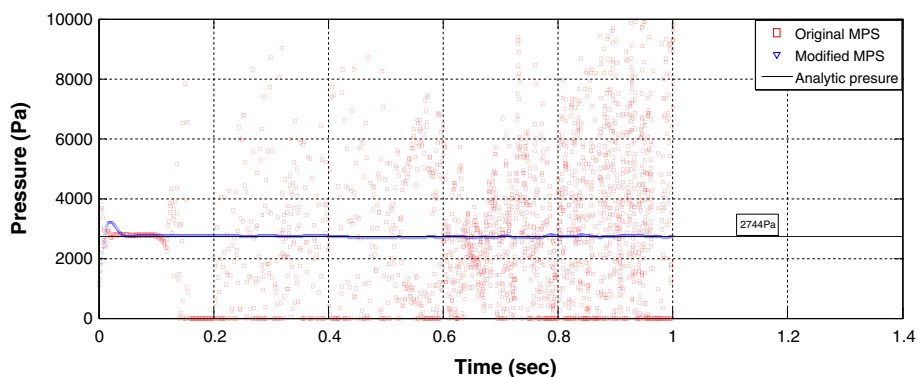
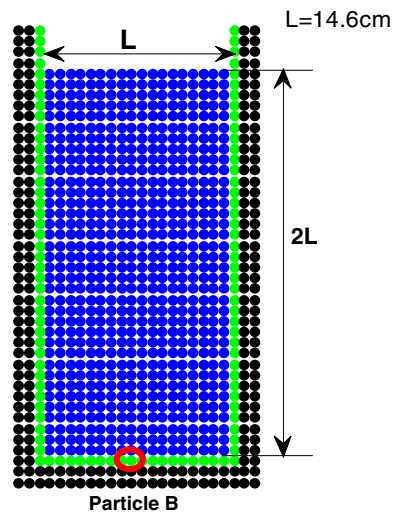


Fig. 7 The time history of the static pressure at particle B

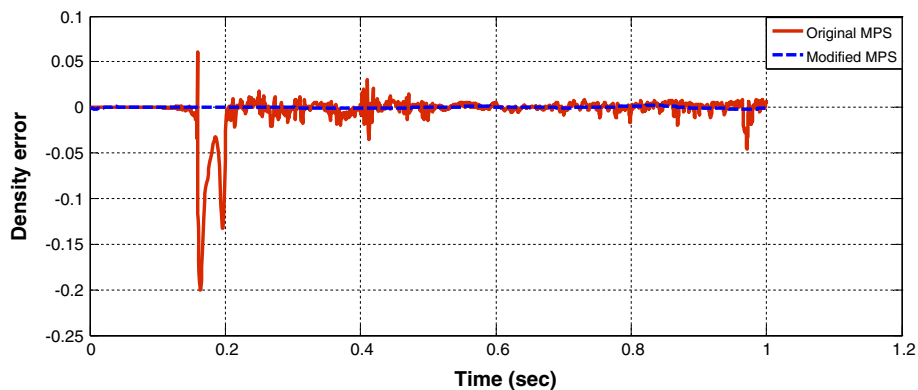


Fig. 8 The time history of the density error at particle B

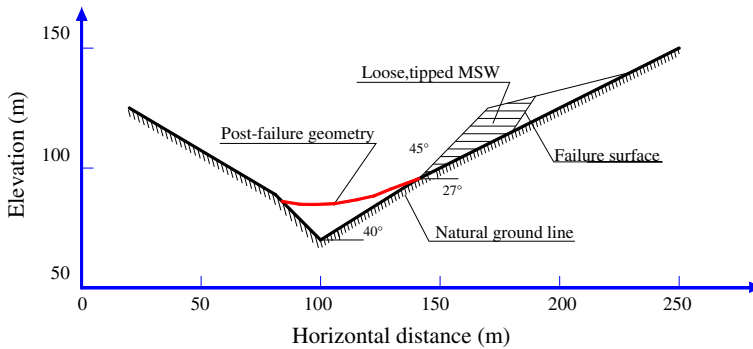


Fig. 9 A section of the MSW flow slide at Istanbul, Turkey, in 1993 (based on Blight 2008)

flow failure began with loud cracking noises coming from the waste body and many cracks leaking water. A large amount of waste, about $15,000 \text{ m}^3$, came down the hillside and slid forward in a mode like a debris flow, destroying all the shack homes in its path and burying approximately 600 people, though the waste only moved forward a relatively short distance, around 20 m. The waste began to burn with a small explosion, the origin of which was sealed. The pre- and post-failure topographies, which were estimated by Blight (2008) based on photographs and limited information, are shown in Fig. 13. The angles of the original landfill and failure surface are 40° and 60° , respectively. It is noted that the failure surface nearly totally traverses the waste mass and goes along the under surface of the landfill.

The parameters used in the simulation were derived from a previous study (Merry et al. 2005) and are listed in Table 2. The total number of particles in the simulation is 2,039, of which 1,284 particles are for the MWS and 755 particles are for the boundary. The calculation takes nearly 50 min on a personal computer with 2.7 GHz CPU and 2 GB RAM.

A comparison of the MPS-simulated profile and the failure configuration is shown in Fig. 14 to check the accuracy of the MPS analysis of the Payatas waste dump. From the comparison, we can see the simulated result is in good agreement with the failure profile provided in the literature except for some errors at both ends. The section of this MSW landfill was reconstructed from photographs because of the absence of a plan or even dimensions for it. Therefore, the deviation between the simulated result and estimated profile is acceptable. The flow process of the failure is presented in Fig. 15.

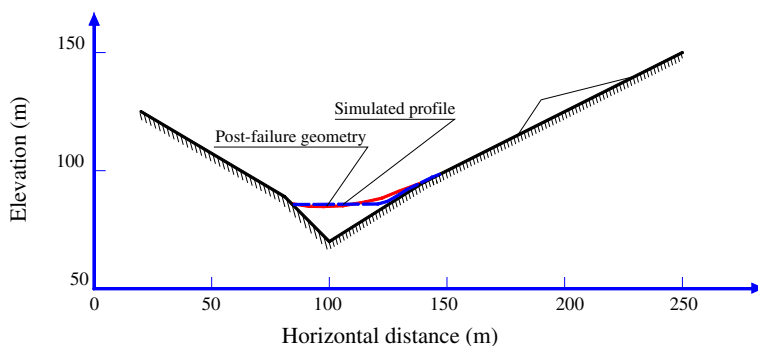
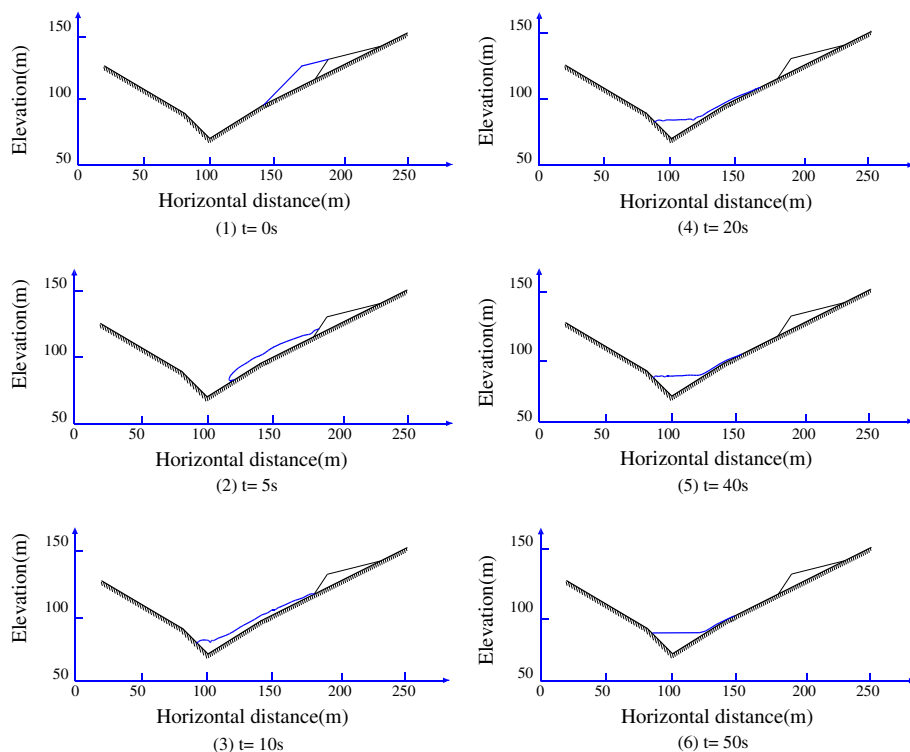
5.3 Analysis of the simulation results

From the comparison of the computed results with the field data on the waste slide configurations for the Umraniye–Hekimbashi landfill and the Payatas waste dump, it is noted that the MPS-simulated post-failure profiles have a high degree of similarity with the surveyed or estimated geometries. Moreover, the simulated maximum velocity in the Umraniye–Hekimbashi landfill shows good agreement with the estimated value. These examples illustrate that the MPS can be applied to simulate flow slides of landfills and reproduce the whole flow process.

Other essential dynamic characteristics can be captured from the MPS simulation, such as the dynamic impact force velocity and even the overtopping volume of waste on the

Table 1 The parameters used in the MPS simulation of the Umraniye–Hekimbashi landfill

Density	ρ (kg/m ³)	1,060
Cohesion	c (kPa)	0
Angle of internal friction	φ (°)	33
Acceleration of gravity	g (m/s ²)	9.8

**Fig. 10** A comparison of the MPS simulation and field data of the Umraniye–Hekimbashi landfill**Fig. 11** The simulated flow process for the flow slide in the Umraniye–Hekimbashi landfill

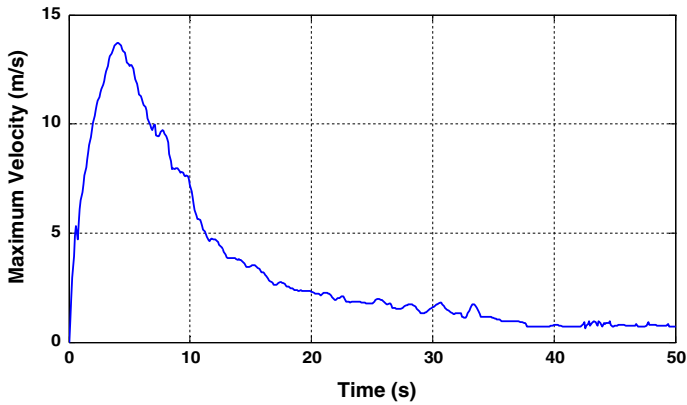


Fig. 12 The time history of the maximum velocity of the flow slide in the Umraniye–Hekimbashi landfill

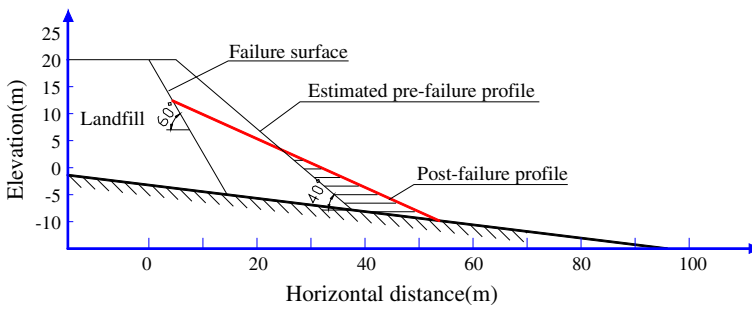


Fig. 13 A section of the MSW flow slide in the Payatas waste dump (based on Blight 2008)

Table 2 The parameters used in the MPS simulation of the Payatas waste dump

Density	ρ (kg/m ³)	1,020
Cohesion	c (kPa)	19
Angle of internal friction	φ (°)	28
Acceleration of gravity	g (m/s ²)	9.8

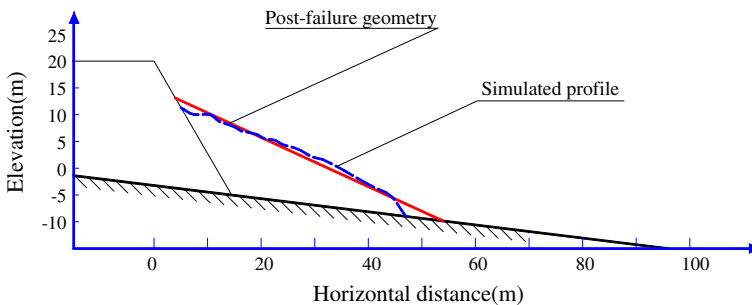
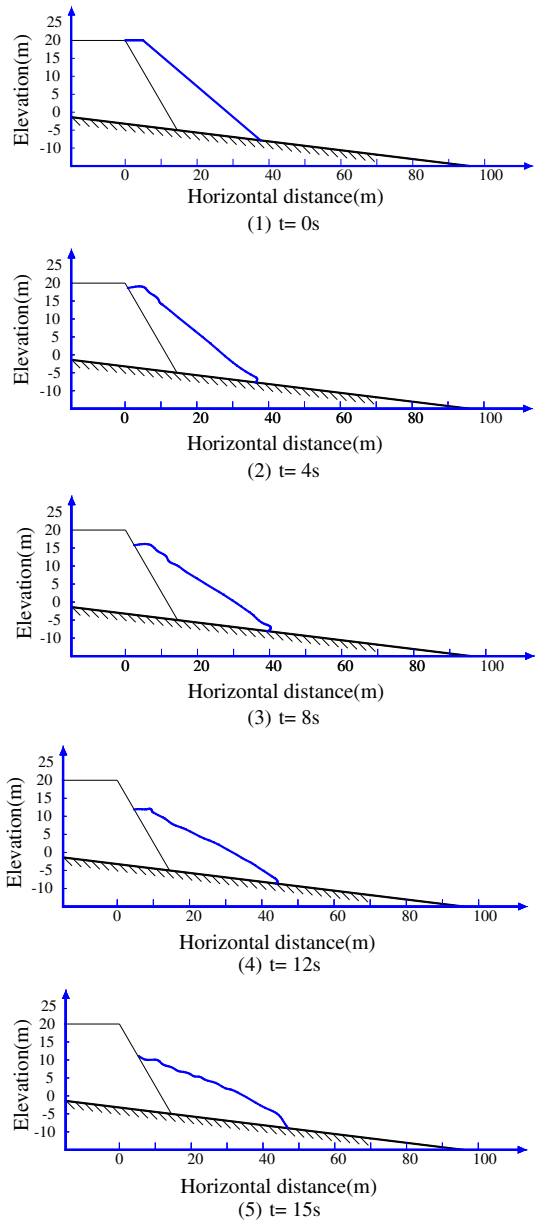


Fig. 14 A comparison of the MPS simulation and field data for the Payatas waste dump

Fig. 15 The simulated flow process for the flow slide in the Payatas waste dump



protection facilities beside the slope configuration. All of the dynamic characteristics are very important for hazard assessment and assist in disaster prevention. However, considering the uncertainties in occurrence and the safety of people, it was nearly impossible to record the dynamic impact force and flow velocity in real time during the disaster, except for the slope configuration surveyed after the hazard. There was also a lack of protection facilities in the early MSW landfills. Hence, in this paper, only the simulation results for

the post-failure profiles and the maximum velocity of the Umraniye–Hekimbashi landfill are compared with the field data.

Further calibration and validation will be needed for the simulation of flow slides in landfills. Additionally, the problem of flow slides in landfills is three-dimensional in reality. However, the modified MPS method in two dimensions is sufficient to research the dynamic features of flow slides and is capable of providing preliminary opinions and suggestions from the comparison of real and computed slope configurations for decision-makers to assess and even prevent similar disasters.

6 Conclusions

Municipal solid waste landfill, the main disposal method for the treatment of MSW in developing countries, is a vitally important part of the public key infrastructure. Many flowlike landfills, which cause enormous destruction and numbers of casualties, have been reported in the literature. Therefore, more attention should be paid to understanding the flow characteristics, which is important for assessment and prevention of similar accidents in other areas. With regard to the difficulty of the traditional mesh method in computing the large deformation: In this paper, the modified MPS method with the Bingham constitutive model based on the Mohr–Coulomb failure criterion is applied to simulate the flowlike MSW landfills, and the simulated results are compared with the field data reported in previous studies.

To bypass the numerical oscillations of pressure calculated from solving the Poisson equation, the original MPS is revised in three ways: the source term of the Poisson equation, the kernel function and the search for free surface particles. It is noted that the source term (which is composed of one main part and two error-compensation parts), the kernel function (which has no singularity when the distance between particles is zero) and the relatively small coefficient (which is used to judge the free surface particles) can effectively reduce the non-physical pressure fluctuations and keep the calculation stable.

Two benchmark cases, the dam break problem and the static pressure problem, have been modeled to verify and validate the improvement of the modified MPS method. For the dam break problem, comparisons of the time histories of the pressure and the density error at particle A between the original MPS and the modified MPS indicate that the modified MPS can reduce the pressure fluctuation and the density error. The position of the leading edge is compared with the experimental result. For the static pressure problem, the time histories of the pressure and the density error were analyzed. In both cases, the comparisons show great improvement in the pressure stability, which verifies the effectiveness of the modified MPS in keeping the pressure stable.

To model the fluidization features of flow slides in landfills, the Bingham constitutive model with the Mohr–Coulomb equation is introduced into the framework of the MPS method and equivalent viscosity is employed to bridge the gap between Bingham fluid models and Newtonian fluid models. The modified MPS method combined with the Bingham model was applied to simulate the real failures of the Umraniye–Hekimbashi landfill and the Payatas waste dump. Some essential dynamic characteristics, including the post-profiles and velocity, can be obtained from the MPS simulation. From the comparison, it is noted that the results of the simulation show good agreement with the field data, which indicates that the modified MPS can reproduce the whole process of the flow slide in MSW landfills.

Although the simulation in this paper is not sufficient, further work will improve the accuracy of simulations of flowlike landfills. The authors firmly believe that the present simulation can still support hazard assessments and risk evaluations, which will ultimately provide preliminary advice to the authorities on preventing similar disasters.

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