Engineering Geology 168 (2014) 86–97

Contents lists available at ScienceDirect

Engineering Geology

journal homepage: www.elsevier.com/locate/enggeo

# Large deformation and failure simulations for geo-disasters using smoothed particle hydrodynamics method

Yu Huang [a,b,*], Zili Dai [b]

[a] Key Laboratory of Geotechnical and Underground Engineering of the Ministry of Education, Tongji University, Shanghai 200092, China
[b] Department of Geotechnical Engineering, College of Civil Engineering, Tongji University, Shanghai 200092, China

ARTICLE INFO

*Article history:*
Received 8 November 2012
Received in revised form 22 August 2013
Accepted 23 October 2013
Available online 1 November 2013

*Keywords:*
SPH method
Geo-disasters
Large deformation
Post failure behavior
Application research

ABSTRACT

Geo-disasters result in serious loss of life and property, and prediction and prevention of these disasters is of great importance. The smoothed particle hydrodynamics (SPH) method, a mesh-less hydrodynamics technique, was applied to the modeling of large deformation and post-failure behavior of geomaterials in geo-disasters with some success. The main aim of this paper is to provide a general view of SPH applications for solving a range of large deformation and failure problems, such as dam breaks, slope failure, soil liquefaction, seepage damage, dynamic erosion, underground explosions and rock breakage. Rather than attempting to cover every application found in the technical literature, this review selects some typical examples and describes them in detail.


**Contents**



* Corresponding author at: Key Laboratory of Geotechnical and Underground Engineering of the Ministry of Education, Tongji University, Shanghai 200092, China. Tel.: +86 21 6598 2384; fax: +86 21 6598 5210.
*E-mail address:* yhuang@tongji.edu.cn (Y. Huang).

0013-7952/$ – see front matter 
http://dx.doi.org/10.1016/j.enggeo.2013.10.022

## 1. Introduction

Geo-disasters accompanied by large deformation and failure of geomaterials are a regular occurrence around the world. These include landslides, debris flow, dam breaks, soil liquefaction, seepage damage, and dynamic erosion. Such disasters cause serious damage to infrastructure, resulting in casualties and high economic losses. To reduce the damage, one of the priorities for governments and researchers is to determine the probability of geo-disasters occurring, devise hazard maps, and take protective measures.

Numerical simulation is a powerful tool, playing an increasingly important role in solving complex problems. Grid- or mesh-based numerical methods, such as the finite difference method (FDM) and the finite element method (FEM) have been widely applied to various areas of geomechanics. For example, Crosta et al. (2003, 2004, 2006) used the FEM model to simulate flow-like landslides; Jie et al. (2004) presented an FDM model to analyze steady seepage. All these methods were effective in solving partial differential equations (PDEs), and obtained many interesting results in studies of geo-disaster cases. Despite the success of grid methods, the use of mesh may sometimes lead to numerical difficulties (e.g., severe mesh winding, twisting, and distortion) in predicting geo-disasters accompanied by extremely large deformations, free surfaces, deformable boundaries, moving interfaces, and crack propagation.

To overcome these numerical difficulties, mesh-free methods have been developed. Smoothed particle hydrodynamics (SPH) is a recently-developed mesh-free method based on a pure Lagrangian description. As a mesh-free technique, the main advantage of SPH is that it bypasses the need for a numerical grid, therefore avoiding severe mesh distortions caused by large deformation. Hence, the SPH method has been successfully applied in a range of fields including astrophysics (Monaghan and Lattanzio, 1985; Monaghan, 1992; Curir and Mazzel, 1999; Laibe et al., 2008; Hubber et al., 2011; Valdarnini, 2011), hydrodynamics (Cleary et al., 2006a; Fang et al., 2006; Oger et al., 2006; Tartakovsky and Meakin, 2006; Xiong et al., 2006), hypervelocity impacts and collisions (Johnson et al., 1993; Michel et al., 2006; Sekine et al., 2007; Guida et al., 2011; Marrone et al., 2011), metal manufacturing (Bonet and Kulasegaram, 2000; Cleary et al., 2006b; Prakash et al., 2009), flow slides in landfills (Huang et al., 2013), and mining engineering (Cleary et al., 2006c; Fernandez et al., 2011). More recently, a variety of corrected and improved SPH methods have been developed, including: discontinuous smoothed particle hydrodynamics (DSPH) (Xu et al., 2013), corrected smooth particle hydrodynamics (CSPH) (Rodriguez-Paz and Bonet, 2005), regularized smoothed particle hydrodynamics (RSPH) (Borve et al., 2005), and adaptive smoothed particle hydrodynamics (ASPH) (Attwood et al., 2007; Sigalotti et al., 2009). These methods all enhance the consistency and stability of the SPH method and are widely applied in various research and analysis programs.

In view of the powerful capabilities of the SPH method in large deformation analysis, this method has recently been introduced to geo-disaster prediction and simulation. The objective of this paper is to detail some features associated with SPH simulations for large deformation and post-failure behavior of geomaterials. We first present a brief overview of the basic principles of the SPH method, followed by an overview of SPH applications to geological disaster cases and its related literature, and then conclude by discussing the achievements of the SPH application in geo-disaster prediction and the method's future direction.

## 2. Overview of the SPH method

### 2.1. SPH approximation techniques

The SPH method, first developed for astrophysical applications, is a novel mesh-free particle method based on a pure Lagrangian description (Gingold and Monaghan, 1977; Lucy, 1977). The basic idea behind this method is to provide stable and accurate numerical solutions for PDEs or integral equations using a group of arbitrarily distributed particles carrying field variables, such as mass, density, energy and stress tensors.

The SPH method is based on interpolation theory. The governing equations, in the form of PDEs with field variables, can be transformed into SPH form through two main steps. The first step is to produce continuous forms of functions using integral representations. This is accomplished by applying interpolation functions. This step is usually called the kernel approximation, and the interpolation function is called the smoothing function or smoothing kernel function. For example, a function $f(x)$ at location $x$ could be rewritten in a continuous form:

$$\langle f(x)\rangle = \int_{\Omega} f\left(x'\right) W\left(x - x', h\right) dx', \tag{1}$$

where the angle brackets < > denote a kernel approximation, $x$ represents the location vector of the particle, $\Omega$ is the volume of the integral that contains $x$, and $x'$ is a neighboring particle in the support area. The parameter $h$ defines the size of the kernel support, known as the smoothing length. $W$ denotes the smoothing function.

The second step is to represent the problem domain using a set of discrete particles within the influence area of the particle at $x$, and then to estimate the field variables for those particles. This step is named the particle approximation, and is expressed as follows:

$$\langle f(x)\rangle = \sum_{j=1}^{N} m_j \frac{f\left(x_j\right)}{\rho_j} W\left(x - x_j, h\right), \tag{2}$$

where $N$ is the total number of neighboring particles, $m$ is the mass, and $\rho$ is the density.

The particle approximation states that the value of a function at a particle can be estimated by the average value of all the particles in the support domain. This step makes the SPH method simple without requiring a background mesh for numerical integration.

### 2.2. Special topics

#### 2.2.1. Solid boundary treatment

In most problems of geological engineering, the domain of interest is bounded. The bounding domain, which is usually stationary, might be a rigid body enclosing the fluid or solid matter. A number of techniques have been proposed to treat the solid boundary condition. Free-slip boundaries were used in SPH simulations of free surface flows, with boundary particles that exert strong repulsive forces to prevent SPH particles from penetrating the solid surface (Monaghan, 1994). Those boundary particles do not contribute to the density of the free SPH particles. Libersky et al. (1993) introduced ghost particles with opposite velocity to reflect a symmetrical surface boundary condition and later proposed a more general treatment (Randles and Libersky, 1996); all the ghost particles were assigned the same boundary field variable to calculate the values of the interior particles. Morris et al. (1997) proposed the non-slip boundary condition. In this technique, a tangent plane to the boundary surface is defined, and the velocity on the plane itself is assumed to be zero. Extrapolating the velocity of the fluid particles across the tangent plane, the velocity of each boundary particle would be $V_b = -(d_b/d_f)V_f$, where $d_b$ and $d_f$ are the shortest distances from the boundary particle and the fluid particle to the tangent plane, respectively. The difference between the fluid and boundary particle velocities is then $V_{bf} = (1 + d_b/d_f)V_f$, which can be used to calculate the viscous force. On this basis, a new boundary treatment method was presented, called the multiple boundary tangent (MBT) method for more complex boundary geometries (Yildiz et al., 2009). Fluid particles in the influence domain of the boundary particle were mirrored with respect to the tangent line of the corresponding boundary particle.