Smoothed Particle Hydrodynamics Simulation for Debris Flow: A Review

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Abstract. Debris flow is a kind of geological disasters occurred in a mountainous area and can cause serious impacts on human lives, infrastructure and houses. Therefore, the potential exposure to this hazard may occur in the surrounding area. This paper assesses some recent noncommercial Smoothed Particle Hydrodynamic (SPH) package for debris flow. SPH as a Lagrangian method, in recent decade SPH showed to be effective in solving in engineering problems involving numerical formulation. The paper considers the features and capabilities can be offer from the non-commercial SPH package that are available and accessible for researcher related to debris flow, solid fluid interaction and so on. Finally, researcher may consider the SPH package based on the suitability of the study as well as the accuracy of the experimental test that have been compared with SPH package.

1. Introduction

A meshless numerical smoothed particle hydrodynamic (SPH) was originally used in astrophysics [1,2] and Monaghan, (1994) [3] has been introduced and applied to free surface flows. SPH has been recognized as one of the numerical and predictive tools across industries and disciplines. Furthermore, several SPH codes have become part of numerical research and development laboratories and academic institutions due to fact that the results obtained are good in term of consistency and accuracy.

Regardless of the fact that SPH the effectiveness of its use, there are deficiencies that make SPH less popular, is its extremely high computational requirements and time consuming to engineering problems when it was first introduce. Especially the case when complex moving boundaries are present and involves 3D multi-phase flows [4,5].

As SPH known as being computationally demanding. Graphic processing unit (GPU) implementation has become one of big improvement into SPH code and rapidly increase a popularity. This make it potential to use SPH codes to study complex 3-D flows at real-life scales, while computational times can be manageable [6]. Moreover, multi-processors on a GPU enables speed-ups close to two orders of magnitude compared to an optimized single-thread CPU code [7].

In recent years, GPUs have been explored to accelerate the SPH model and substantially improved against their CPU counterparts in terms of computational efficiency [8]. Thus, many researchers, academic and industrial from various discipline and field have developed SPH package to suit their needs in numerical simulation. This paper structured as follows: In section 2, is covering SPH
formulation. Then, reviewed covering the features in non-commercial or open source framework and some validation of their SPH package that available free.

2. Debris Flow
Debris flows commonly consists mixture of soil, rocks and water. These flows are frequently initiated by landslides, bank failure or hills lope failures related to high rainfall and/or large runoff [9-12]. There are many definitions and terms given by researchers to define this phenomenon, as well as the various basis in different literatures and characteristics presented. According to Dine [13], the general term “debris flow” can be generally separated into “open slope debris flow” and “channellized debris flow” and defined as “a type of mass movement that involves water-charged, predominantly coarse-grained inorganic and organic material flowing rapidly down a steep confined, pre-existing channel. This phenomenon consists of processes including initiation, flow, and deposition [11]. A debris flow, occasionally referred to as a mudslide, is a flowing mixture ranging from watery mud to thick, rocky mud that can transport large items such as boulders, trees, and other debris. Debris flows travel rapidly downslope along drainage channels or stream valleys, often transporting and depositing a large volume of material in areas where the gradient flattens, such as roadways [14]. Rickenmann stated debris flow is termed “torrents” in European Alpine countries and steep streams are prone to debris-flow occurrence [15].

Earle mentioned if the material involved is gravel sized or larger, it is recognized as a debris flow [16]. Since it takes more gravitational energy to move larger particles, a debris flow typically forms in an area with steeper slopes and more water than does a mudflow. In many cases, a debris flow takes place within a steep stream channel, and is triggered by the collapse of bank material into the stream.

According to Plummer et al., a debris flow is flow involving soil in which coarse material (gravel, boulders) is predominant [17]. A debris flow can be like an earthflow and travel relatively short distances to the base of a slope or, if there is a lot of water, a debris flow can act like a mudflow and flow rapidly, traveling considerable distance in a channel. Rapidly moving debris flows can be extremely devastating.

Haddad et al. mentioned debris flow most commonly term in Indonesian is lahar [18]. Originating from a volcano also can be called transitional flow, or hyperconcentrated flow [19]. The complex dynamic systems involved can mobilize large volumes of sediment, travel big distances along narrow gorge channels, and deposit volcanic debris on alluvial fans at gorge outlets.

3. SPH Formulation
Based on the SPH method, the fluid and continuum media are treated as a set of discretized particles. The integration of the equations to describe the motion of fluid is solved in the Lagrangian formalization. Any physical variables (e.g., pressure, density, velocity, position) of a particle can be approximated by the values of the nearby particles with a kernel function. It is the kernel approximation and particle discretization that make SPH method to be greatly capable to tackle the problem with free surface flow and large deformation but without grids [20].

The basic principle of the SPH formulation is the integral representation of a function $f$ which may represent a numerical of interest at a point $r$. The approximation according to (Gingold and Monaghan, 1977) [21] written as:

$$ f(r) = \int f(r') W(r - r', h) dr' $$

where $r$ is integral variable, $W$ defined as kernel function and $h$ as smoothing length. The performance of SPH model depends greatly on the selection of the smoothing kernel in term of computational accuracy and stability [2, 22, 23].

Where the subscript denotes an individual particle, the integrals are approximated numerically by a summation of contributions from the surrounding particles in the domain:
\[ f(r_a) = \sum_b f(r_a)W(r_a - r_b, h)\Delta v_b \]  

where \( \Delta v_b \) = volume of a neighbouring particle (b), \( \Delta v_b = \frac{m_b}{\rho_b} \) = mass and \( \rho \) = density. There is two basic and normally used in as kernel in SPH package; which is cubic spline kernel and Quintic kernel. Further, many new kernel was proposed by researchers to gain the higher computational accuracy and stability of the SPH method. For instance, [2] proposed double cosine kernel function is sufficiently smooth, and is associated with an adjustable support domain. It also has smaller second order momentum, and therefore it can have better accuracy in terms of kernel approximation.

4. SPH Solver
An open-source codes developed and redistributed under the terms of the GNU General Public License as published by the Free Software Foundation. Along with the source code, documentation that describes the compilation and execution of the source files is also distributed. This encourage other researchers to try SPH. Most downloads to date have been registered by researchers and students that have conducted their research on fluid dynamics using Smoothed Particle Hydrodynamics models. Moreover, the code has been downloaded not only by students and researchers from universities and institutes but also by companies with industrial interests.[24] (Crespo et al., 2015). The increasing interest in SPH is indicated by the appearance of other important SPH solvers such as the open source DualSPHysics [23], JOSEPHINE [25], GPUSPH [26], AQUAgpusph [27], ISPH [28], GADGET [29], pysph [30] and many other close-source.

5. SPH Model and Case Study

5.1 2010 Yohutagawa Case Study
Researcher have been conducting modeling to analyze the hazard design and mitigation design of the Yohutagawa torrent (28°240N, 129°320E) located in the Amami Oshima Island, southwest Japan has a catchment area of about 0.24 km² and elevation varying from 20 to 250 m [20]. The region are mainly composted by mudstone and sandstone. In October 2010, an intensive rainfall accompanying with Typhoon Meji triggered the debris-flow event.

In this case, the Navier–Stokes equations incorporating the rheological model of non-Newtonian fluid behavior to solve the dynamic motion of the flow-type landslides. Implemented into the DualSPHysics code [23] as a SPH package and the governing equations incorporating the modified rheological model were numerically solved in the SPH framework, which is quite robust in 3D performance.

Researcher created a 3D model with complicated terrain corresponding to the in-situ situation to verify the reliability and accuracy of the model. The field observations in terms of debris volume and deposition area were compared and in good agreements.

This can conclude that under the complex topography SPH able to accurately modeling the debris flow movement. As well, features such as the front velocity and section discharge of the debris-flow were also well analyzed, which will contribute to the design work of mitigation or countermeasures and provide evidences for the hazard assessment. Figure 1 shows 2010 Yohutagawa debris flow, Amani city, Japan and Figure 2 shows the debris flow motion in this study.
Figure 1. 2010 Yohutagawa debris flow, Amani city, Japan [20].

Figure 2. Debris flow motion in this study [20].
5.2 The Sham Tseng San Tsuen debris flow, Hong Kong

On the 23rd of August 1999, the debris flow event was happened in Sham Tseng San Tsuen, Hong Kong. Intense rainfall about 479mm 24 hours before the event to be the cause of the debris flow [31].

A data provided by Hong Kong Geotechnical Office were used to create 2D model to describe debris flows where the difference of velocities between solid grains and fluid is important. The 2D model were simulated by Lagrangian model (SPH) and a double set of nodes (solid and fluid) which can move relatively to each other are used in this study. The drag depends on the relative velocity between phases. It is possible to find situations where the fluid abandons the body of the mixture using 2 set of nodes.

In the article, triaxial tests on the soils involved (loose to medium dense colluvium containing boulders and cobbles) and the completely decomposed granite CDG soils, it was concluded that cohesion was zero and the friction angle ranged from 37° to 38°, for which we find \( \tan \phi' = 0.75 \) - 0.78. Researcher has notice that, according to the report, [32] the distal end of the debris deposition had a travel angle of about 24° much smaller than the friction angle found in laboratory tests. Furthermore, in many models, it was proposed to use effective friction angles with \( \tan \phi' = 0.35 \), much smaller than that measured in laboratory.

In researcher analysis, have assumed that friction angle is 31°. This value has been chosen as the one providing results close to those observed in the field. It is important to notice that propagation is a dynamic process, for which the triaxial results—valid for much lower strain rates—are not well known. Densities of soil particles, pore fluid, and mixture were taken as 2400 kg/m³, 1000 kg/m³, and 2000 kg/m³. The drag law selected is the same described in the previous examples, with \( VT = 3.0e^{-2} m/s^{-1} \) \( m=1 \). Based on the results, researcher conclude real debris flows can be simulated with the proposed model, obtaining reasonable results. Figure 3 shows terrain topography and path of debris flow showing profiles at times 10 and 120 seconds. Figure 4 shows terrain topography and path of debris flow showing profiles at times 10 and 120 seconds.

**Figure 3.** General view of the location [31].
5.3 Wenjia Gully and Hongchun Gully Debris Flow

In this article, researcher has conducted research at two location near the epicenter of the Wenchuan earthquake triggered in 2008 where the first location is Wenjia gully located north of Qingding, Mianzhu, and in Sichuan Province [34]. The second location is Hongchun gully located opposite newly reconstructed Yingxiu in Sichuan Province. Their engineering geology and hydrologic geology conditions are similar due to close by.

A 2D SPH model for Wenjia Gully was established with 4126 particles were used for the debris flow source and 3836 particles for the boundary. SPH simulated to investigate the impact forces they undertake.

A 3D SPH model for Hongchun Gully was established with 7280 particles were used for the 3D terrain and 1405 for the material source, with a space between the particles of 8 m. Three check dams with a height of 16 m are set in the gully to investigate the impact force of the Hongchun gully debris flow.

In this SPH simulation, viscosity coefficients $68 (0.5 \eta)$ and $272 \text{ Pa s} (2 \eta)$ are used. From the results, stated that the simulated peak impact force and the force evolution under different slope angles were in good agreement with test data. Researcher therefore conclude that the SPH model was able to accurately estimate the impact force. Figure 5 shows the simulated propagation for Wenjia gully and Figure 6 shows SPH model for the Hongchun gully.

![Figure 4. Terrain topography and path of debris flow showing profiles at times 10 and 120 seconds [31].](image-url)
Figure 5. The simulated propagation for Wenjia gully [34].

Figure 6. SPH model for the Hongchun gully [34].
5.4 Debris Flow of Alvera

Researcher [35] simulated extends debris flow event from Mount Cristallo to the village of Alvera – Cortina d’Ampezzo and and it has been built by means several orthophotos and the Regional Technical Charter, while the bottom elevation has been assigned through the lidar surveys available from the Civil Engineering Department of Belluno. Three simulation have been carried out for this study, first simulation only considered water, the second only boulder alone and lastly mixture of water and boulder.

The phenomena were simulated by Lagrangian SPH method using DualSPHysics [23] framework to study the dynamics of a debris flow.

From the researcher observation, interesting results and features have been obtained that would not have been visible with a traditional Eulerian approach. In specific, the simulations have shown that the thrust of water greatly affects the problem, since the boulder stops earlier when it is no longer dragged by the flow. Furthermore, in all the examined cases, the boulder stops when it finds natural narrowing in the riverbed along its path. This result suggests possible interventions along the riverbed, such as the construction of artificial bottlenecks in appropriate sections, with the aim to mitigate the risk that the boulders reach the downstream inhabited areas. Nevertheless, researcher suggest to study more in depth to develop optimum protection approaches. Figure 7 shows the orthophoto view and SPH simulation view. Figure 8 shows the results after respectively 5, 20 and 40 s.

Figure 7. (a) Orthophoto of the domain area. (b) Alvera’s debris flow simulation domain [35].

Figure 8. Results after: (a) 5 s; (b) 20 s; (c) 40 s. In red the boulder with water, in yellow the boulder alone [35].
6. Conclusions
In the review, SPH model are using Lagrangian method to simulate. The SPH model application cases which are representative in fluid-structure interactions in debris flow. The applications are depending on: hydrodynamic problems and interaction problems, which are based on different equations of state and have obviously different features. The various cases show the potential of SPH method to be further extended and applied in the fluid-structure interactions in debris flow. For now, SPH method are considerable, reliable and able to satisfactorily to reproduce debris flow case at field scales.

Future developments such validation on various parameters, equipment in the experimental to improve the accuracy of the numerical model performance.

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