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Jet and Mixing Characteristics in Single Raindrop Splash Problem

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Abstract: *The raindrop impact is very important in soil erosion problems on hill slopes, while the splash characteristics (especially the jet and mixing) are crucial in raindrop impact processes. Focusing on the jet and mixing features in this process, a series of numerical experiments and discussion are conducted in this study. The meshless Smoothed Particle Hydrodynamics (SPH) method is employed and validated with the theoretical solution and experimental data. Two groups of numerical experiments, focusing on the jet around the rigid surface and the mixing between the drop and different underlain water layers respectively, are carried out. In the first group of numerical experiments, the effect of incidence angle of the drop is discussed. A high speed jet strip is found near the rigid surface and varied with incidence angle of the raindrop. In the second group of numerical experiments, it is found that full mixing between drop and water layer only happened in a very close range around the impact zone while the outer zone is just simply driven away. Two kinds of mechanism on jet occurrence and mixing are proposed and explained based on the simulated results.*

Key Words: erosion, drop impact, splash, SPH, mixing, inclined impact, jet stripe.

1. Introduction

Raindrop splash (RS) process plays an important role in overland flow and soil erosion on hill slopes. It could even dominate the flow and erosion in many situations, especially in the initial period of rainstorm or at the top of slopes (Kinnell, 2005). In a typical RS process, a raindrop of which diameter is around 2~5mm impacts on a shallow underlain water layer (of which depth is generally below 15mm) with a velocity about 4~9m/s, such a high speed impact will cause strong jet and mixing of fluid around the crater which are believed related with local soil erosion. Thus study on this jet and mixing processes could provide more information on the understanding of hillslope scale soil erosion.

RS process is a typical drop impact problem which has been studied for decades. Levin & Hobbs (1971) first noticed the splash phenomena, Thoroddsen (2002) studied the ejecta sheet in drop impact problems with different fluid and impact characteristics, Yarin (2006) systematically summarized previous studies on drop impact problem. However, it should be noted that the most of previous studies (often with a background on printing technology etc.) mainly focused on impact pattern features instead of the jet and mixing characteristics in drop impact process. The reason could partly address to the difficulties on studying them with neither common experimental technology nor classical numerical methods. Thus in this paper, we will try to employ a Lagrange based meshfree numerical method, which might be more convenience confronting those difficulties, to study jet and mixing characteristics in ideal single raindrop splash problem.

2. Theory and Assumptions

The kernel processes of RS on overland shallow water are the impact of a raindrop on underlain water layer with limited depth (see Figure 1).

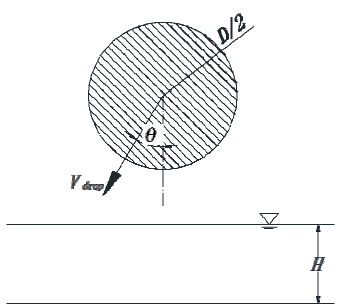


Figure 1. Illustration of a typical single raindrop splash problem

In this large deformed transient process, the raindrop size D, the impact speed V_{drop}, the incidence angle of the drop θ and the water layer depth H are key factors. The impact speed V_{drop} could be calculated using the following empirical equation:

$$V_{drop} = (17.2 - 0.844\ D)\ \sqrt{0.1D} \qquad (1)$$

With these factors, three dimensionless coefficients could be defined – Weber number, Bond number and Ohnesorge number. In the common RS problems, only Weber number is important. While for the problem in which raindrop size exceeds 2.1mm, the Weber number is greater than 400 (see Figure 2), which means the effect of surface tension could also be neglected. As jet and mixing effects are of concern for bigger raindrop size rather than smaller size, the minimum raindrop size is set as 3.0mm in this study, and thus only the effects of inertia force are take into account.

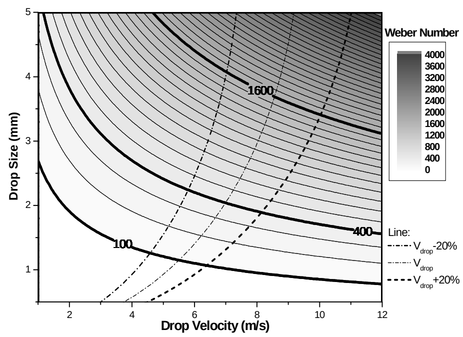


Figure 2. Weber number vs. drop size and impact velocity in typical raindrop splash problems

3. Numerical Methods

The Smoothed Particle Hydrodynamics (SPH) method is employed to simulate the splash process. The SPH method is a meshfree Lagrange based method which is very suitable for large deformation problem like RS. The SPH method uses particles to express the discrete Navier-Stokes equation, which is as following:

$$\frac{d\rho_a}{dt} = \sum_b m_b \vec{\boldsymbol{v}}_{\boldsymbol{ab}} \nabla_a W_{ab} \qquad (2)$$

$$\frac{d\vec{\boldsymbol{v}}_{\boldsymbol{a}}}{dt} = -\sum_b m_b \left(\frac{P_b}{\rho_b^2} + \frac{P_a}{\rho_a^2} \right) \nabla_a W_{ab} + \vec{\boldsymbol{g}} + \sum_b m_b \left(\frac{4\upsilon \vec{\boldsymbol{r}}_{\boldsymbol{ab}} \nabla_a W_{ab}}{(\rho_a + \rho_b)\left|\vec{\boldsymbol{r}}_{\boldsymbol{ab}}\right|^2} \right) \vec{\boldsymbol{v}}_{\boldsymbol{ab}} \qquad (3)$$

In which ρ is density, m is mass of particle, v is velocity, W is kernel function, P is pressure, υ is kinematic viscous and r is the distance of two particles.

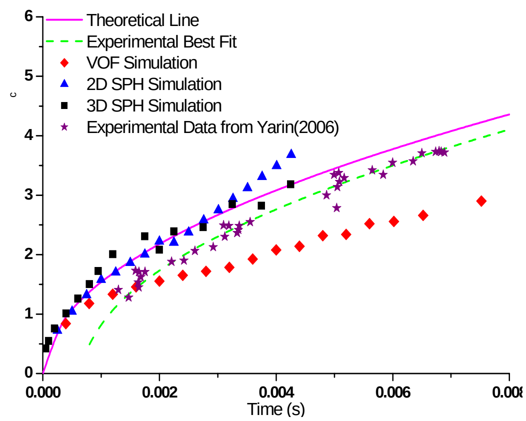


Figure 3. Comparison of SPH simulated crown size evolution with theoretical value, experimental data and VOF simulated results.

We carried out a series of tests to check the validity of the SPH method applying in RS problems. Taking the geometrical feature evolution of splash crown as reference variable, the SPH simulated results are compared with theoretical value, experimental data (Yarin, 2006) and VOF simulated results. Good agreements with experimental data are observed for both 2D and 3D SPH simulation (see Figure 3).

4. Numerical Experiments

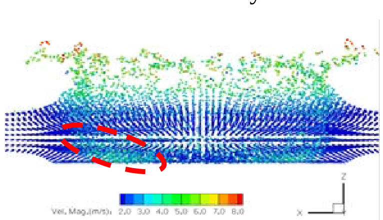
Two groups of numerical experiments, focusing on the jet around the rigid surface and the mixing between the drop and different underlain water layers respectively, are carried out.

4.1. Jet characteristics experiments

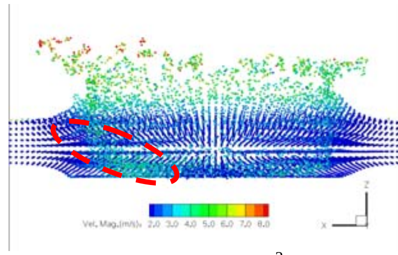
In this group of experiments, we discuss what the distinctness in different drop incidence situation is and how it could influence the local soil erosion. In fact, the different drop incidence could correspond to two situations, a horizontal underlain surface and an inclined one, which are different when gravity is important. In this section, only the horizontal underlain surface situation is discussed as the inertial force, instead of gravity, dominates the initial stage which we are talking about. And for the same reason, the laminar model is employed to model the viscous term.

In this group of simulation, the raindrop diameter is set to 4mm (thus its impact speed is 8.8m/s according to Equation 1) and the underlain water depth is 2mm, which is a typical shallow splash impact in rainstorm. The incidence of the drop varies from 5^o to 30^o with an interval of 5^o. The splash process is simulated with SPH method in three dimensional condition using around 1,120,000 particles. The cubic spline kernel function is employed, the boundary condition is applied by exerting a repulsive force on related particles, and the prediction-correction method is applied for time step marching.

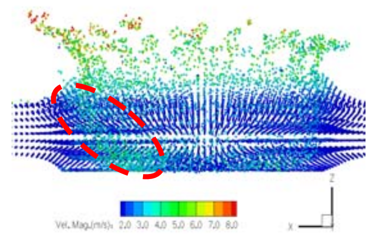
Part of typical simulated results is shown in Figure 4. Four graphs show the velocity distribution at the moment of 1.0×10^{-3}s after impact for different incidence angle respectively. Each point in graphs is one particle and the color of the point represents the velocity magnitude of the particle. It is easy to notice that the incidence angle will cause asymmetry of the splash ejecta, but at the initial stage of the splash process, this asymmetry of crown shape just change slightly when incidence angle increases from 5^o to 30^o, even the velocity distribution does not vary too much too. However, the situation in underlain layer is quite different. We could notice one obvious high speed jet stripe exists in each graph (draw in red dash line), which is very different from each other. In the 5^o case, the jet stripe only exists near the bottom layer and is sharp, while in the 30^o case, the jet stripe is as large as underlain layer depth, which means it is no more a local jet but push the whole underlain layer forward.



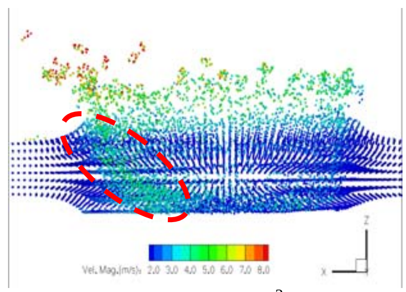
5^o , T=1.0×10^{-3}s



15^o , T=1.0×10^{-3}s



20^o , T=1.0×10^{-3}s



30^o , T=1.0×10^{-3}s

Figure 4. The effect of incidence angle (the dashed lines illustrate the jet zone near the rigid surface)

4.2. Mixing characteristics experiments

In this group of experiments, we discuss how ejecta forms, what its constitution is and when the drop and underlain layer mix with each other. Studying on mixing characteristics needs Lagrange based information of the fluid, which is trivial for both experimental technology and Euler based numerical method like VOF or Level-Set, while SPH method do not need to confront these difficulties as we know exactly where one particle come from. So in this section, we discriminate the drop material from the underlain material on propose. Considering the three-dimensional effects in mixing processes are not strong and two-dimensional simulation results are easier to analyze, we use the latter in this group of numerical experiments.

Specifically, we set up cases like this, the raindrop diameter is set to 3mm (thus its impact speed is 8.2m/s), the incidence of the drop is zero and the underlain water depth varies from 1 to 6mm(1, 2, 3, 6mm). The splash process is simulated with SPH method in two dimensional condition using around 50,000 particles. The cubic spline kernel function, the repulsive force boundary condition and the prediction-correction method are employed too.

Due to limitation on space, Figure 5 only shows the case of 3mm drop impact on 1mm underlain layer. The grey particles represent the drop material and the colored particles represent the underlain layer material. The color is configured according to the relative position of particles before impact and will not change through the splash process. The red color means the particles are on the top of underlain layer before impact, and so on. Thus the color gives us a reference to discuss the mixing of particles. Three snapshots are taken at 2.0×10^{-4}s, 7.0×10^{-4}s and 2.5×10^{-3}s respectively. Those snapshots show that only a small region of underlain layer could experience a strong mixing either inter-layers or between drop and layers at the initial stage of RS, the most of underlain layer is just driven away with the basic configuration intact. The ejecta of a splash crown are mainly constituted of underlain layer materials, and are pushed forward by drop induced jet stripe from the bottom of the layer.

5. Discussion

Based on two groups of numerical experiments, the jet and mixing characteristics of the single raindrop splash problem are studied. From the simulated results, it is clear to see that the jet stripe plays a very important role in raindrop splash problems. For different incidence angle, the ejecta shapes are similar while the jet stripes are very different. Further study finds that the jet stripes are also related with underlain layer depth, even in the vertical impact situation.

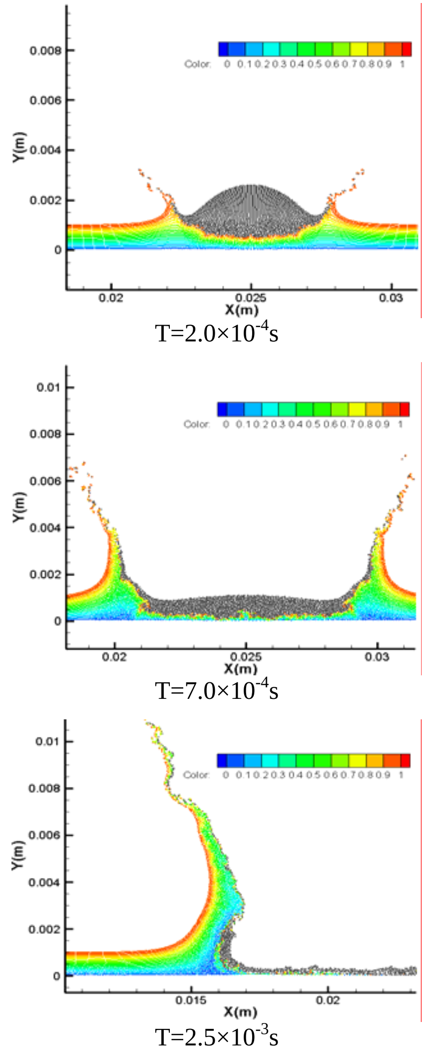


Figure 5. The mixing process in RS problem (the depth of water layer is 1mm while the drop size is 3mm)

According to those result, we believe that there are two kinds of mechanism on jet occurrence existing in RS problem. The first kind is that jets go along with the interface between drops and underlain layers, which generate the top structures of the crown. As the jet is generated at the surface, the top structures of the crown for different underlain layer depth are similar at the initial stage of RS. Such a mechanism will not cause notable mixing between underlain layers at all, and this part of ejecta is generally constituted of both drop and underlain materials. The second kind of mechanism is the jet stripe near the bottom of the underlain layer, which contributes to the formation of crown base. This jet stripe is mainly generated by interaction between the deformed drop and the solid surface. That is why it cannot be observed in the large underlain layer depth cases (like 3mm drop impact on 6mm layer). On contrast, in the shallow impact problems, this jet stripe actually dominates the flow near the solid surface. When the underlain layer is relative shallow or the drop velocity is large, the jet stripe is sharp and stay close to the solid surface, thus might cause strong shear on the bottom and induce serious local denudation and erosion. When the underlain layer is relative deep or the drop velocity is not large enough or drop impacts with a large incidence angle, the jet stripe just pushes the underlain layers aside and transports the underlain materials. That is one reason why raindrop splash erosion is severe only at the beginning of the rainstorm.

Conclusion

Focusing on the jet and mixing features in RS process, a series of numerical experiments and discussion are conducted in this study. The meshless smoothed particle hydrodynamics (SPH) method is employed and validated with the theoretical solution and experimental data. Two groups of numerical experiments, focusing on the jet around the rigid surface and the mixing between the drop and different underlain water layers respectively, are carried out. The effect of incidence angle of the drop is discussed. We found a high speed jet strip near the rigid surface, and the strip size and shape varied with incidence angle of the raindrop. Such a high speed strip would be possible to cause serious denudation on the ground and sediment transport, which may contribute to local erosion. In the second group of numerical experiments, we found that full mixing between drop and water layer only happened in a very close range around the impact zone which could be only several times of drop diameter, while the outer zone is just simply driven away by drop induced jet stripe. That means the underlain materials might be in the majority in ejecta of RS process. Based on the simulation data, two kinds of mechanism on jet occurrence and mixing are proposed and explained.

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