Development of Hydro-Debris 2D Model

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Abstract. The principal aim of a vertical two-dimensional numerical model development is for estimating the particle tracing and mechanism of 10mm and 2.5mm particles. The model development in this study is based on a model developed by Yamashiki et al. (1997). The particle tracing movement can be visually analyzed by using HSVC. A numerical model was developed using the Marker and Cell (MAC) method, which involves a SGS (Subgrid-Scale) model and the PSI-Cell (Particle Source in Cell) Method. The transportation processes of debris and air bubble were simulated in Lagrangian form by introducing air bubble and debris markers.

1. Principle Background of Hd2dm

Air bubble movement characteristics were simulated by this numerical model. The staggered Marker and Cell (MAC) grid was first publish by Harlow and Welch, 1965 which has become one of the most popular ways to simulate fluid flow in computer graphics. The MAC grid method discritizes space into cubical cells with width h. Each cell has pressure p, defined at its center. It also has a velocity, u=(ux, uy, uz), but the component of the velocity are placed at the centers of three of the cell faces, ux, on the x-min face, uy, on the y-min face and uz on the z-min face as shown in Figure 1. Staggered position of the velocity in this manner tends to produce more stable simulations than storing the velocity at the cell centers. In addition to spatial grid cells, set of marker particles (point in space) is used to represent the fluid volume. As the simulation progresses, the marker particles are moved through the velocity field and then used to determine which cells contain fluid.

The Marker and Cell method was modified, combining SGS model and PSI-CELL method (Gotoh, 1992 and Crowe et al., 1977). A lagrangian solution for the air bubble transport was determined by surrounding water pressure with assumption of initially uniform air bubbles diameters. The mechanism of picking up and transport process of bed material in macro turbulence zone was simulated using the lagrangian model based on Tchen’s equation (Tchen, 1947 and Gotoh, 1992), assuming that bed materials is uniform. The computer code was written in C language, using reference “103 Y0/VIFMAC” of the computer library of Kyoto University, created by Takemoto (Takemoto et al., 1983) and developed by Tetsuro Sakai et al. (1987). The systems of governing equations are the grid-filtered time-dependent three-dimensional compressible (with low Mach number) mixed flow Navier-Stokes, liquid phase continuity equations. SGS (Sub Grid Scale) model for only liquid phase is introduced. The effect of
Lagrangian sediment particle into liquid phase is being considered using PSI-CELL (Particle Source in Cell) method (Gotoh, 1992 and Crowe et al., 1977).

Figure 1: A MAC grid cell. Velocity components $u_x$, $u_y$, and $u_z$ are stored on the minimal faces of the cell. Pressure, $p$ is stored at the cell center.

1.1. The Lagrangian model
Models of sediment transport in turbulent flow are determined with another aspect. The model of van Rijn can be classified as a deterministic model and Eulerian. There is another aspect of the modeling of sediment transport, the model probabilistic and, sometimes, Lagrangian. The fundamentals of this model were made by using the Einstein (1950) parameters pick up rate and step length. More sophisticated model was developed by Nakagawa and Tsujimoto (1980) that explains about the mechanism step length using a probabilistic function. This model was known as a Eulerian model. The model of Nakagawa and Tsujimoto is very sensitive especially in term of changing the input and favorable in explaining the phenomenon. The mechanisms of the sediment pulling up and transport of saltation and rolling had been searched. Gotoh clarified the mechanism of transport based on the model of Nakagawa and Tsujimoto. Lagrangian model was used in this study with following reasons 1) Allows the simulation of motion of each particle of the sediment and 2) Unifies the phenomenon of sediment transport.

The first reason was used because the existences of coarse sediment near the downstream area. The Lagrangian model has its advantage when the diameter of the material is large. The second reason was it easily explained about transition of the sediment transport phenomenon. When a particle of sediment is pulled up and picked up by runoff, it will be transported by the macro turbulence. The equation of motion of the particle in the flow, according to Newton's second law can be written as:

$$ M \ddot{a}_s = \overrightarrow{F}_D + \overrightarrow{F}_L + \overrightarrow{F}_g \tag{1} $$

where

$ M $ : virtual mass of sediment particle

$ \ddot{a}_s $ : sediment particle acceleration

$ \overrightarrow{F}_D $ : drag force hydrodynamic

$ \overrightarrow{F}_L $ : ascending hydrodynamic forces

$ \overrightarrow{F}_g $ : force of gravity
Assumed that the particle is a sphere, the quantities above are:

\[ M = \rho \left( \frac{\sigma}{\rho} + C_M \right) A s d^3 \]  

\[ \vec{F}_s = \rho \left( \frac{\sigma}{\rho} + C_M \right) g A s d^3 \]  

\[ F_D = -\frac{1}{2} C_D \rho A_s d^2 \left| \vec{u}_s \right|^2 \left[ \vec{u}_s + \rho \left( 1 + C_M \right) A_s d^3 \frac{D\vec{u}_f}{Dt} \right] \]  

where

\[ \vec{u}_s = \vec{u}_p - \vec{u}_f \]: relative velocity of the particle

According to the work of Van Rijn (1984), the hydrodynamic forces in turbulent flow and upward:

\[ \vec{F}_L = -\alpha_L \rho n^{1/2} d^2 \left( \frac{d\vec{u}}{dn} \right) \]  

where

\[ n \]: vector perpendicular to the vector \( \vec{u}_s \)

\[ \alpha_L \]: ancestry coefficient, varying according to the number

1.2. Particle equation

In the present study was performed using particle tracking equations which is lagrangian equation. Basic equations are as follows:

\[ \rho \left( \frac{\sigma}{\rho} + C_M \right) A s d^3 \frac{d\vec{u}_s}{dt} = \epsilon \left( -\frac{1}{2} C_D \rho \left| \vec{u}_s \right| A_s d^2 + \rho \left( 1 + C_M \right) A_s d^3 \frac{D\vec{u}_f}{Dt} \right) + \rho \left( \frac{\sigma}{\rho} - 1 \right) A_s d^3 \left( g_s - \mu_f g_f \right) \]  

\[ C_D = 0.4 + \frac{24}{R_e} ; R_e = \frac{\left| \vec{u} - \vec{u}_f \right| d}{v} \]  

In which \( C_D \): drag coefficient, \( \vec{u}_p \): velocity vector of sediment particle (for each diameter), \( \vec{u}_f \): water phase velocity vector \( \vec{u}_f = \vec{u}_p - \vec{u}_f \), \( A_s = \pi / 4 \), \( A_s = \pi / 6 \), \( d \): diameter of the sediment \( C_M \): virtual mass coefficient (0.2, 0.35 and 0.5), \( s \): density of sediment particle, \( \rho \): water density. \( \epsilon \): shading coefficient determined only when sediment is in the bed and shaded by other sediment. \( \mu_f \) friction coefficient only works when sediment is at the bottom. This term was determined according to Nakagawa et al. (1978) for the simulation of successive saltation movement as followed Gotoh method. The lagrangian air bubble transport equation is introduced similarly as:

\[ \rho \beta A_s a^3 \frac{d\vec{u}_a}{dt} = -\frac{1}{2} C_{Da} \rho \left| \vec{u}_a \right| A_s a^2 + \rho \beta A_s a^3 \frac{D\vec{u}_f}{Dt} - \rho g A_s a^3 \epsilon \]  

where \( \beta \) is virtual mass, given as 0.5, \( \rho \) is water density, \( a \) is a air bubble diameter, \( C_{Da} \): friction coefficient of air bubble, as given as 2.6. The Adam-Bashforth method was used for time integration.

The air entrainment process was treated as follows: The entrainment from the water surface was treated by distributing air bubble marker particles in the sub-cells of the surface cells with no water marker cell. These distributed air bubble marker particles are transported according to the surface air drag coefficient which is assumed to 1.0. The air entrainment by the air bubble capitation is simulated by distributing the air bubble marker particles in the inner air cells. The air bubble pairing and dividing cannot be simulated in this study.
1.3. Preliminary numerical simulation results by HD2DM

Figure 2 shows the simulation results by HD2DM. The flume length is 5m with 20cm height and width respectively. The composed of mixed material (grain size 2.5mm and 10mm) is shaped near the upper part of the channel. For the purpose of numerical simulation investigation, only 25° slope angle is considered. In this case, those mixed materials were set as follows (a) The ratio between small particles (2.5mm) to big particles (10mm), 9:1 and (b) The ratio between small particles (2.5mm) to big particles (10mm), 4:1.

During preliminary study of particle segregation, the HSVC was placed near the downstream of the flume channel. After a good understanding of particle routing characteristics at this part, the HSVC was moved near the upstream (erodible bed) of the flume channel. The 25° slope angle is fixed and the water flow (discharge) from upstream was set to be 150cm/s for all simulations case. The preliminary results can be divided into two groups which are (a) and (b). Result of (a) shows the gradual collapse process of mixed grains material by the stream water. The simulation results of composed material movement characteristics were shown in (b). In order to reproduce the experiment condition, numerical simulations were introduced with a stopper which was set at the tip of the mixed material. Simulations shows the collapse which did not start from the tip of the material and the stopper did not move during the simulation. The water stream which flows around the stopper and the bubble entrainment is reproduced clearly. For preliminary results, we can declare that simulation results and high-speed camera pictures are in fairly good agreement. The ratio between small particles (2.5mm) to big particles (10mm) is 9:1. From the results, the ratio of the particles shows a good routing mechanism. For that reason, the ratio of small particle is high; therefore, the numbers of small particles are many as comparison to big particles.
2. Conclusions
A two-dimensional numerical model was developed for computing the characteristics of the particle routing of debris flow to simulate the classification effects by applying the particle tracking method which is the most suitable for qualitative simulation of the two-phase flow. Lagrangian suspended load momentum equations was considered to be applicable. A numerical model was developed using the Marker and Cell (MAC) Method, which involves a SGS (Subgrid-Scale) model and the PSI-Cell (Particle Source in Cell) Method. The transportation processes of debris and air bubble were simulated in Lagrangian form by introducing air bubble and debris markers. Air bubble movement characteristics were simulated by this numerical model. The flow condition of the low fluid content rate and low porosities was omitted for the simulation based on reasons above.

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