# Accuracy Evaluation of Landslide Simulation using Depth Integrated Particle Method

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DIPM (depth-integrated particle method) is an effective numerical method suitable for sediment-related disaster simulation of a very wide area with detailed topographic information. The model considers the flowing mass as a combination of soil columns. The equations of motion of such soil columns are solved as two-dimensional discrete 'particles' traveling through the surface terrain. The particles are susceptible to bottom shear friction computed by modified Manning's formula with yield stress and column-to-column interaction based on their hydraulic gradient. Consequently, the flow behavior is governed by only two material parameters: the Manning's coefficient $n$ and the critical deposition angle $i_{cr}$ related to the yield stress. Flow simulations were conducted by considering the slope failures at the Tomisato and Horonai district of Atsuma town during Hokkaido Eastern Iburi Earthquake (2018) as case study areas. The topographic data were extracted from national data widely available for Japan using GIS. The difference in geological conditions, vegetation and water content of the case study areas had some influence while identifying the material parameters through flow simulation. The average value for $n$ and $i_{cr}$ are 0.1 and 6°, respectively, with an average accuracy of 66%.

## 1. Introduction

The Hokkaido Eastern Iburi earthquake struck at 3:07 on September 6, 2018, at the southern part of Hokkaido, Japan, causing thousands of slope failures spread over hilly regions within approximately 400 km$^2$ in Atsuma, Abira, and Mukawa town. In the current study, slope failure that occurred in the north of Atsuma town at Tomisato and Horonai district was analyzed as case studies. The slope of this area is covered mostly by layers of volcanic ash soil. The slope failure type was categorized as earth flow type. Slip surface was described as the Ta-d pumice layer from the Tarumae volcano 9,000 years ago and the En-a layer from the Eniwa volcano nearly 200,000 years ago (Kawamura et al.,2018[1]).

The topographic information of the study areas, which is about 2000 km by 2000 km for Tomisato and 3000 km by 3000 km for Horonai District (Fig. 1), was extracted from the Digital elevation model (DEM), composed of 10 m mesh using ArcGIS software. The initial failure locations were set from the slope failure distribution map by GSI using ArcGIS (GSI[2]; Kita,2018[3]).

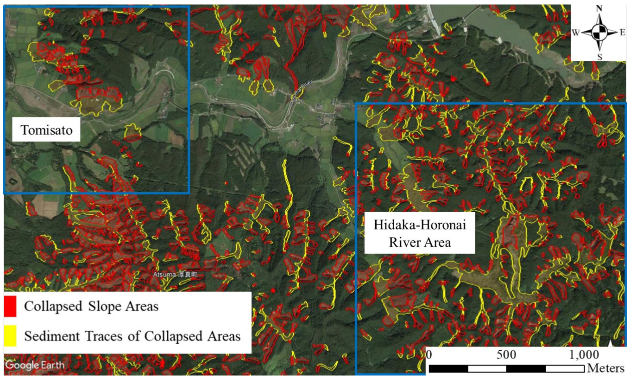


Figure 1: Slope failure locations at the Tomisato area.

The study adopts a depth-integrated particle method (DIPM) with a simple constitutive model that can simulate landslides' phenomena in a wide area with detailed topographic information (Hoang et al.,2009[4]; Zhang and Matsushima,2014[5]). The model deals with the flowing mass as a combination of soil columns. The equations of motion of such soil columns are derived as 2D discrete 'particles' moving along the surface terrain. A linear interaction model describes the interaction between two neighboring particles based on their hydraulic gradient. The model mainly comprises two governing parameters describing debris flow: Manning's coefficient and critical deposition angle. Because of such a simplified structure similar to the Discrete Element Method, DIPM is a very efficient and stable flow simulation method compared to other methods based on the finite difference method (Ouyang et al., 2013[6]) or Smooth Particle Hydrodynamics (Pastor et al., 2009[7]). In this paper, we evaluate the accuracy of DIPM through the simulation of landslides at the Tomisato and Horonai district of Atsuma town during Hokkaido Eastern Iburi Earthquake and discuss the appropriate parameters in this region.

## 2. Depth Integrated Particle Method (DIPM)

The depth-integrated balanced equation (or the shallow water equation) can be written as the following

$$\frac{\partial \bar{v}_x}{\partial t} + \bar{v}_x \frac{\partial \bar{v}_x}{\partial x} + \bar{v}_y \frac{\partial \bar{v}_x}{\partial y} = -g_x \frac{\partial p}{\partial x}(h_0 + h) - \frac{(\tau_b)_x}{\rho_h}$$
$$\frac{\partial \bar{v}_y}{\partial t} + \bar{v}_x \frac{\partial \bar{v}_y}{\partial x} + \bar{v}_y \frac{\partial \bar{v}_y}{\partial y} = -g_y \frac{\partial p}{\partial y}(h_0 + h) - \frac{(\tau_b)_y}{\rho_h} \quad (1)$$

where, $v = (v_x,\ v_y)$ is a depth-integrated flow velocity vector; $(g_x, g_y)$ is the gravitational acceleration component parallel to the base slope; $h_0$ and $h$ are the base ground and water surface height, respectively; $\tau_b = (\tau_{bx},\ \tau_{by})$ is the bottom shear-stress vector; $\rho$ is the debris flow density, and $p$ is denoted as the hydraulic pressure.

The hydraulic pressure gradient is modelled by the interaction force between the two soil columns particles. Assuming 2D closed hexagonal packing, the non-dimensional interaction force between the columns, that is, the force divided by the column weight is defined as eq. (2). A linear relationship between normalized particle distance and pair-wise relationship is considered in the simulation and given by eq. (3)

$$f = \frac{1}{3} K_0 \cdot \frac{h_0}{d_0} \left(\frac{d_0}{d}\right)^3 \quad (2)$$

$$f = \frac{\alpha}{3} K_0 \cdot \frac{h_0}{d_0} \frac{d_{lim} - d}{d_0} \quad (3)$$

Where $K_0$ is the static earth pressure, $h_0$ is the initial height of the soil column, $d_0$ and $d$ are the initial and current particle spacings, respectively, and $d_{lim}$ is the maximum spacing where repulsion force is acting on. It is important to note that the total pressure acting on a column becomes nonlinear even though the pair-wise interaction (eq. (3)) is linear because not only the closest neighbor particles but also the other particles within $d_{lim}$ spacing contributes to the total pressure. Fig. 2 shows that $d_{lim}/d_0 = 2.0$ and $\alpha = 0.6$ for pair-wise interaction gives the consistent total interaction force with the theoretical curve (eq. (2)). Note that the total interaction is computed by assuming the hexagonal packing and slightly differs in different orientations.

The bottom shear stress is an opposing force to the fluid movement, reducing the flow. The bottom shear stress as a smoothened Birmingham-type was computed using (eq. (4)).

$$\tau_b = \left( \tau_{cr} \|\bar{v}\|^m + \rho g \frac{n^2}{R_h{}^{1/3}} \|\bar{v}\|^2 \right) \frac{\bar{v}}{\|\bar{v}\|} \quad (4)$$

Where, $\tau_{cr} = \rho g R_h \tan i_{cr}$, $n$ is the Manning coefficient, $R_h$ is the hydraulic radius, and $i_{cr}$ is the critical deposition angle.

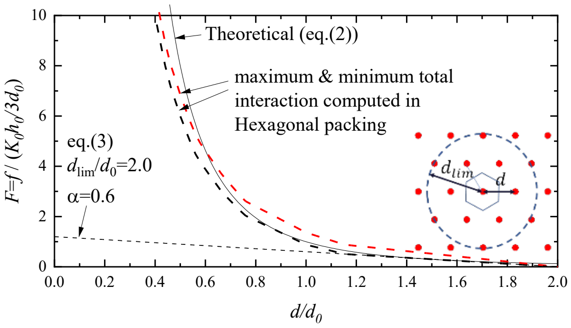


Figure 2: Relationship between normalized interparticle distance and non-dimensional interaction force.

## 3. Flow Simulation Results

In this study, the simulation accuracy is checked based on the affected area (both collapsed and inundated area) due to slope failure. The analyzing meshes were divided into four categories as per Table 1, and the accuracy index is calculated as per eq. (5).

Table 1: Summary of the indexes

| Simulated Affected Area | | Actual Affected Area | |
|---|---|---|---|
| | | True | False |
| | True | TP | FP |
| | False | FN | TN |

$$\text{Accuracy}, \alpha = \frac{TP}{TP + FP + FN} * 100 \quad (5)$$

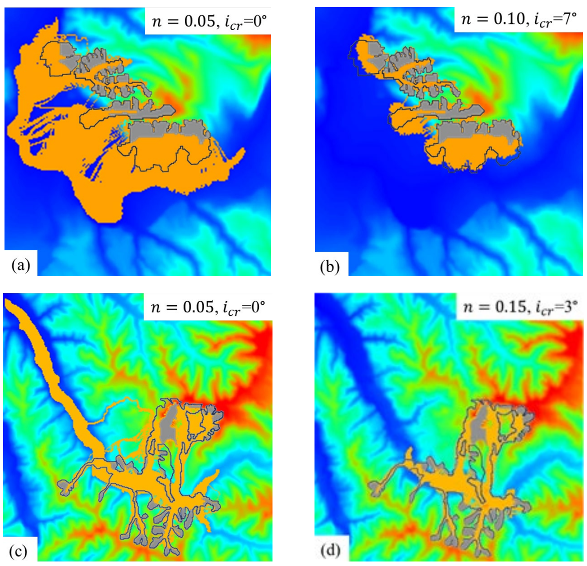


Figure 3: Flow simulations with a different set of $n$ and $i_{cr}$

Fig. 3 shows the actual collapsed area in the grey, simulated inundated area in orange and the actual inundated area with the black outline for various sets of $n$ and $i_{cr}$. When we compared the simulated inundated area with the actual one, it shows that for smaller $n$ and $i_{cr}$ causes an excess flow acceleration and results in a large deviation, as shown in Fig. 3(a, c). The inundated area becomes smaller and narrower as $i_{cr}$ increases. Considering the debris flow stopped within the black outline boundary, the minimum and maximum values of $n$ and $i_{cr}$ were identified, and one of the best simulation results are shown in Fig. 3(b, d).

Fig. 4(a, b) shows the correlation between the accuracy index of the simulation for different sets of $n$ and $i_{cr}$. For Tomisato area the value of $n$ is between 0.05 to 0.15 and $i_{cr}$ is between 5° to 10° with the most suitable accuracy ranging from 63% to 69%. On the other hand, the for Horonai area at the Hidaka-Horonai river blockage, the value of $n$ is between 0.75 to 0.15 and $i_{cr}$ is between 3° to 7° with the most suitable accuracy ranging from 63% to 66%. In the case of the Hidaka-Horonai river blockage, since the flowing mass reached the river, it might have increased the water content. With a higher content of water, the critical deposition angle is reduced, which explains the lower $i_{cr}$ value in case of Hidaka-Horonai river blockage area. In addition, $n$ increases with the vegetation density, which resulted in higher values of $n$ in this area compared to Tomisato area.

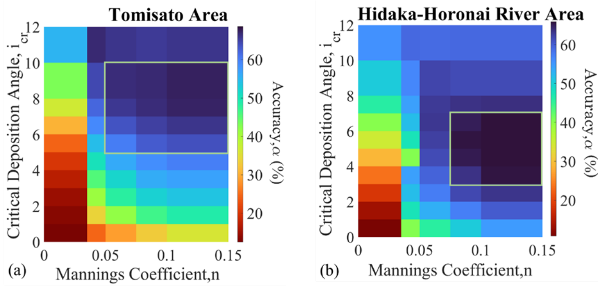


Figure 4: Co-relation between the accuracy index and material parameter (**$n$** and **$i_{cr}$**)

## 4. Conclusion

Depending on the existing research and reports from field investigation, the landslides from the Tomisato and Horonai districts were analyzed in this study. The outcome of this study shows that DIPM can simulate sediment-related disasters such as slope failure and subsequent debris flow/mudflow for a wide area with detailed topography. By setting the initial failure location, the model detected the inundated area with an average accuracy of 66%. The different range of parameter values is due to differences in the vegetation density and water content in the flowing mass of the study areas. Therefore, the average value of the material parameter is $n$= 0.1 and $i_{cr}$= 6°, respectively.

## References

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