Fluvial Fan Process due to Swing Phenomena

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To analyze the fan formation process due to swing phenomena of the debris flow, the authors performed a numerical simulation of debris flow by means of depth integrated two dimensional governing equations of solid-water mixture and the bed shear stress formula characterized by yield and the fluid type shear stress. In this research, the debris flow phenomena and fan formation processes are studied as the test case applied in the Chacaito Creek located in the metropolitan urban area of Caracas city, Venezuela. The results of 2-D numerical simulations confirmed the influences of swing phenomena in the temporal variations of the morphology of debris fan. Likewise, the research demonstrates that fan formation processes in successive numerical simulations have variations in the spatial distribution of the sediment deposition due to changes in the debris flow directions caused by the topographic conditions at the fan head and the swing phenomena.

Key words: swing phenomena, fan morphology, debris flow, numerical simulation

1. INTRODUCTION

Fan morphology caused by debris flow has unique geomorphologic characteristics, which originate from a single point as a fan head and creates a cone shape due to sedimentation [Lecce, 1990]. Debris flow from a single event may not be so large; however, the fan may widely spread due to many events. For example, Fig. 1 shows the fan morphology of the Illgraben catchment in Switzerland. In this figure, the red curve shows the upper part of the catchment, which is mostly area where debris flow takes place; the yellow curve delimits the geomorphology of debris fan; the brown curves represent the geomorphology contours; and the blue curve indicates the current flow. The figure shows a cone type geometry, with a fan head. Despite the current debris flow path is about 30m, actual size of the debris fan is about few kilometers. This figure as well as field studies suggests that a swing of debris flow path causes the creation of the fan morphology. Despite accumulated knowledge on fan morphology and swing phenomena from field surveys, there is limited research from numerical studies.

To study the swing of the debris flow, we conducted the depth integrated two dimensional numerical simulation, applying the model originally

Fig. 1 Fluvial fan of Illgraben catchment, Switzerland (Red curve indicates the border of upper of catchment, blue curve specifies current river, yellow curve shows the geomorphology of debris fan and brown curves the geometry of contours). Originally document Wyss, C. 2013 and edited by authors.
developed by Miyamoto [2010]. The model which focused basically on landslide movements is based on continuity and momentum equations of solid-water mixture flow. The bed shear stress in this model is formulated in terms of static inter-granular contacts, particle-to-particle collisions, and an interstitial liquid phase, which are originally proposed by Egashira et al. [1997]. In this study, debris flow supplying to the fan head is specified assuming the uniform flow formed in an artificial, prismatic, and steep open channel. For this purposes, we selected Chacaito basin located in Caracas city, Venezuela, which has steep slope in mountain region and has mild slope in the metropolitan area.

This paper describes the debris flow phenomena and fan formation processes based on successive numerical simulations.

2. NUMERICAL MODEL

The debris flow behaviors can be predicted by means of a numerical model based on the depth integrated two dimensional equations for the mass and momentum conservation of the debris flow body as well as on the mass conservation equation of bed sediment, using a bed shear stress formula and an erosion rate one [Egashira, 2011]. The numerical model composed of full equations, which may be complex, can evaluate not only the developing and decreasing processes of debris flow along a torrent reach, but also flooding processes over a debris fan. However, a simplified model will be recommended when we predict a behavior of soil block due to a landslide, because sediment concentration of the flow body does not change in its run-out process. Miyamoto [2010] proposed the simplified model to evaluate a two dimensional behavior of sediment mass released by landslides, assuming that the both of total sediment volume and sediment concentration do not change in the run-out process.

With applying Miyamoto’s model, this study mainly aims to investigate depositional processes of debris flow, especially how the flow course change related to the local geometry. Therefore, the depositional process is evaluated in terms of deformation of the flow body, and the sediment erosion can be neglected in this treatment.

2.1 Governing equations

The mass conservation equation is written as

\[
\frac{\partial h}{\partial t} + \frac{\partial uh}{\partial x} + \frac{\partial vh}{\partial y} = 0
\]  

where \(t\) is the time, \(x\) and \(y\) are Cartesian coordinates along the flow/traverse direction, \(h\) is the flow depth, and \(u\) and \(v\) are \(x\)- and \(y\)-components of velocity.

The momentum conservation equations are written as

\[
\frac{\partial uh}{\partial t} + \frac{\partial \beta uuh}{\partial x} + \frac{\partial \beta vuh}{\partial y} = -gh \frac{\partial H}{\partial x} - \frac{\tau_{bx}}{\rho_m} \tag{2}
\]

\[
\frac{\partial vh}{\partial t} + \frac{\partial \beta uuh}{\partial x} + \frac{\partial \beta vuh}{\partial y} = -gh \frac{\partial H}{\partial y} - \frac{\tau_{by}}{\rho_m} \tag{3}
\]

where \(\beta\) is the momentum correction factor, \(H\) is the free surface elevation, \(\tau_{bx}, \tau_{by}\) are \(x\)- and \(y\)-components of the bed shear stress defined by

\[
\tau_{bx} = \tau_b \frac{u}{\sqrt{u^2 + v^2}} \tag{4}
\]

\[
\tau_{by} = \tau_b \frac{v}{\sqrt{u^2 + v^2}} \tag{5}
\]

\(\tau_b\) is the bed shear stress which is described in section 2.2. \(\rho_m\) is the mass density of the debris flow body, which is explained as

\[
\rho_m = (\sigma - \rho) \tau + \rho \tag{6}
\]

where \(\sigma\) is the mass density of sediment, \(\rho\) is the mass density of the fluid phase, and \(\tau\) is the volumetric concentration of the coarse sediment. The fluid phase is composed of water and fine sediment.

2.2 Formula of bed shear stress

To simulate the debris fan process more appropriately, the formula of Coulomb and fluid type shear stress is employed, which is proposed by Egashira et al. [1997]. This is formulated as,

\[
\tau_b = \tau_s + \frac{f_b (u^2 + v^2)}{c_r} \tag{7}
\]

where \(\tau_s\) is Coulomb type shear stress, \(f_b\) is the friction factor related to the fluid motion.

Coulomb type shear stress is

\[
\tau_s = \left(\frac{\tau}{c_r}\right)^{\frac{1}{2}} (\sigma - \rho) \tau h \tan \theta \tan \phi \tag{8}
\]

where \(c_r\) is the sediment concentration at the stationary sediment layer, \(\theta\) is the bed slope, and \(\phi\) is the inter-particle friction angle of sediment particle. \(f_b\) is derived as follows,

\[
f_b = \frac{25}{4} \left(\frac{f_d + f_f}{d}\right) (\frac{h}{d})^2 \tag{9}
\]

where \(d\) is sediment diameter, and \(f_d, f_f\) are defined as

\[
f_d = k_d \left(\frac{\sigma'}{\rho}\right) \left(1 - e^2\right) \tau^{\frac{1}{2}} \tag{10}
\]

and

\[
f_f = k_f \frac{(1 - e^2)^{\frac{3}{2}}}{\tau^{\frac{1}{2}}} \tag{11}
\]

respectively, where \(k_d = 0.0828, k_f = 0.16,\) and \(e\) is...
restitution coefficient $e = 0.85$.

In this model, the free surface of deposited debris flow is the bed surface for the next event. Therefore, we do not need the mass conservation equation of bed sediment, bed elevation equation.

### 2.3 Calculation condition

To investigate debris flow phenomena numerically in the field, the Chacaito creek was selected. The Chacaito creek is located at the northern part of the Caracas city in Venezuela, as seen in Area A of Fig. 2. The mountains in Chacaito creek reach an altitude of 2,700m, while the metropolitan area reaches 900m.

In the area, altitude differences as well as steep slopes which trigger debris flows and cause large hazards. Among several small creeks located in this region, the Chacaito creek is one of the largest basin. Fig. 3 is a closer look of Chacaito creek. The upper basin, as the mountainous area, has an average slope of about 12 degree, an area of 8.43 km$^2$, and a length of 7.89 km. On the other hand, the lower basin, the urban area of part of the Caracas city, has an average slope of 2 degree. As indicated in Fig. 2 and 3, the border between the mountainous and the metropolitan area can be identified. Based on this understanding, it is assumed that the debris flow generates at the upper basin, and discharges to the lower basin.

Figure 4 shows the geometry around the fan head as well as the upper part of the debris fan and the position of cross sectional profile at $Y=1,950$m. There are six different local ridges namely R1 to R6, as well as seven local valley namely V1 to V7. The debris flow discharges from the V1 to the fan head.

Figure 5 is the cross sectional profile of the geometry at $Y=1,950$m illustrated in Fig. 4. As shown in Fig. 4, R4 is located at 998m and shows the highest altitude; while V2 is the lowest point among those valleys and it is located at 981m. Among those ridges and valleys, roughly 5 to 11m difference can be recognized.

The total amount of the debris flow volume, $\overline{V}$ for a single event is set up as 750,000m$^3$, including pore water and sediment. The absolute sediment volume is 390,000m$^3$ which is composed of coarse and fine sediment. Fine sediment volume which behaves as fluid is 78,000m$^3$ resulted
from \( p_f c \varphi (p_f = 0.2) \), in which \( p_f \) is the composition rate of fine sediment. Boundary condition at the fan head located at \( x=1,000 \text{m} \) and \( y=1,500 \text{m} \), is determined automatically by means of the following way: debris flow is fed through an artificial open channel attached at the fan head. The channel is 100m with, 150m long, 50m deep and bed slope 12 degree. The supplied debris flow is produced by releasing sediment stored in this channel. The physical parameters employed in present simulation are as follows: \( \phi_s = 34.0 \) degree, \( \sigma = 2,650 \text{ kg/m}^3 \), \( \rho = 1,300 \text{ kg/m}^3 \), \( d = 0.1 \text{m} \), \( c_s = 0.52 \), \( \bar{c} = 0.416 \). The momentum correction factor is assumed to be \( \beta = 1.0 \). Regarding the spatial and temporal grid sizes, \( \Delta x = 5.0 \text{m} \), \( \Delta y = 5.0 \text{m} \), and \( \Delta t = 0.0005 \text{s} \), are applied.

To investigate fan formation processes, a series of eleven successive 2-D numerical simulations, from Case 1 to Case 11, are performed. In each case, we employ the same supply condition of debris flow. In present treatment, the calculated free surface for deposited debris flow gives the bed surface morphology for the next debris flow. Therefore, one of the successive simulations employs the initial geometric condition which is simulated by the previous result. For example, in Case 1, the currently observed DEM data is applied in the numerical simulation; thereafter, in Case 2 the topographic condition of bed surface is constructed by the final result of the Case 1. Likewise, eleven successive cases are conducted.

The DEM data was issued by Venezuelan Foundation Institute of Engineering for Research and Technology Development and Civil Protection and Environment Institute Chacao Municipality in 2012. This DEM was extracted with the application of a sub-scene on one sensor of the image GeoEye-1 at GEO level. The GEO level applies radiometric and geometric processes to the GeoEye-1 Image to obtain the tools for the creation of orthoimage with high precision. The tools are constituted by coefficients for polynomial rational functions, geographic and cartographic parameters, a DEM and a specialized software. The obtained DEM in GEO level was fused, orthorectified and corrected with the cartography of Cartocentro Project, 1997 Scale 1:25,000, cartographic parameters given by Geographic Institute of Venezuela Simon Bolivar and control points in the field. The DEM has as spatial resolution of 0.5 m with cartographic parameters of Datum WGS84. The GeoEye-1 Image was given by Integral Solution GIS Company (SIGIS), Sanchez, J. 2012.

3. RESULTS AND DISCUSSION

3.1 Single debris flow process

Results of the 2-D numerical simulation for the debris flow process are shown in Fig. 6(a)-(d). This shows sediment deposition areas at the time of 42.5, 80.0, 105.0, and 135.0 seconds. The initial topography is illustrated with the black and white contour for geometry ranging between 960m and 1,210m, and the debris flow depth is described by colored contour ranging between 0 and 10m. As shown in Fig. 6(a), the first debris flow starts from V1 and moves toward V4 with riding on the R2 and R4. At this moment, the width of the debris flow is about 230m. Thereafter as seen in the Fig. 6(b) at the time of 80.0 second, the debris on the V1 slightly changes the direction to the V3. In addition, it spreads to two directions, such as towards V3, and keeping moving further in between R2 and V4. As indicated in Fig. 6(c) at the time of the 105.0 seconds, the debris flow does not go further compared with Fig. 6(b); instead, more sediment deposition occurs in the V6, and the V3 including

![Fig.5 Cross sectional profile of the geometry at Y=1950m.](image-url)
the climbing up to the R1. As consequence, the maximum reaches at the left side of this figure extended till at X=660m at this time. Finally at the time of 135.0 seconds as shown in the Fig. 6(d), the debris flow moves along the R4 and reached to V6 is extends till to X=1,150 m at the end.

We understand the spreading process of the debris fan as shown in Fig. 6 as the swing phenomena. Results suggest that initially the debris flow moves straight and then the swing phenomena occur due to topographic angulation. Most of the sediment deposition occurred in the valley though few deposition takes place on the ridge.

Regarding the morphological changes due to debris flow, it is observed that a single branch which is about 200m wide formed in early stage illustrated in (a) of Fig. 6. The branch is extended laterally to 460m in (d) of Fig. 6. In addition, the formation of three branches is recognized in final stage. Such fan formation processes can be seen in the study performed by Takahashi et al. [1988].

3.2 Fan formation process

It is recognized that debris flow morphology has a convex geometry which is observed in the example of fluvial fan of Illgraben catchment shown in Fig. 1, and that swing phenomena play an important role on such a fan formation process. Figure 7 shows the result for Case 11 which is the final result of successive numerical simulations. The figure illustrates changes in the debris fan morphology which are perceived in the variations
Fig. 7 Topography obtained from computation for Case 11. It is a final form of the debris fan.

Fig. 8 Changes of the sediment deposition occurred during each specified period.

of contour lines when they are compared with the initial condition, Fig. 4. According with this comparison, the contour lines have four important changes: 1) the convex morphology of debris fan is more marked; 2) the contour lines has a radial increase until a distance of Y=2,300m due to the progradation of the debris flow; 3) the contour lines located on the fan head (X=1,000m) are less dense as consequence of successive sediment depositions and changes in the bed slope; and 4) the valleys V1, V5, V6 and ridge R5 which were observed in the Fig. 4 disappear due to sediment deposition, and four valleys: V2’, V3’, V4’ and V7’, and four ridges: R1’, R2’, R4’ and R6’ are still remained. Three ridges, R1’, R2’ and R4’, tend to be straighten due to the radial development of the fan.

To investigate the fan formation process clearly, we focused on the thickness of sediment deposition during a period among several event such as from Case 1 to Case 3, Case 3 to Case 6, Case 6 to Case 9 and Case 9 to Case 11. Fig. 8 shows the areas resulted from sediment deposition deeper than 5m during each specified period illustrated in the bottom of the figure. We can see the deposition area changes often largely.

Case 1-3 shows the debris flow moves south-east and its spatial distribution is located between X=630m and X=1,150m. For Case 3-6, debris flow directs from fan head in same direction of the previous case but at Y=1,700m, the flow bifurcates in two directions; one is inclined to south-east direction and another to south-west direction. This bifurcation occurs by means of swing phenomena. In Case 6-9, sediment deposition takes place straightforward in south-southwest direction. Finally, in Case 9-11 the debris flow does not move long distances as Cases 3-6 and 6-9.

Additionally, Fig. 9 shows the cross sectional profiles for the cases 1, 3, 6, 9 and 11. The results show that the cross-sectional shape develops macroscopically keeping a convex shape and that the previously formed valleys disappear gradually through the fan formation process. The processes of cross sectional formation as well as the valley disappearance can be found in the results illustrated in Fig. 7 and 8.

4. CONCLUSIONS

To understand a fan formation process due to debris flow events, the depth integrated two dimensional numerical simulations about water and sediment mixture flow are conducted. The simulations were conducted assuming no erosion and no changes of the sediment concentration.

The results obtained from the present study are summarized as follows:

1) The results of a single debris flow event on the actual debris-fan, which has local ridge and valleys, show that three branches of the debris flow are formed and the width of the three branches is about two times bigger than that of the single branch.

2) The results of fan formation processes demonstrate that swing phenomena play an important role in the fan formation process and the topographic condition at the fan head is also responsible to the fan process.

3) A debris fan with the cross section of a convex shape is reproduced by means of numerical simulations.

In future research, it is important to investigate the relation of swing phenomena and erosion processes using governing equations with full terms.
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