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GIS-based numerical simulation of debris flow

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ABSTRACT

Debris flow is the rapid flow which can lead to serve damages. It is important to study the movements of debris flow. Since during a debris flow, the erosion and deposition processes are important, the conventional fixed bed assumption is not acceptable. In this study, firstly we considered the debris flow as a solid-fluid mixed continuum and adopted the depth-averaged govern equations to simulate the propagation and evolution of river bed. Secondly, the set of partial differential equations was solved numerically by means of explicit staggered leap-frog scheme that is accurate in space and time. The grid of difference scheme was derived from GIS raster data. Then the simulation results can be displayed by GIS and easily used to form the hazard maps. Finally, a real-case application shows not only propagation but also erosion and deposition process of debris flow can be well simulated by the proposed method. Comparing with field investigation and the method which is not considered the erosion and deposition, it shows that the present results are more reasonable.

Key words: debris flow; numerical simulation; GIS; propagation; erosion; deposition

1. INTRODUCTION

Debris flow is a rapid flow which could lead to severe flooding with catastrophic consequences such as damage to properties and loss of human lives. For example, in the 'Minamarta debris flow disaster' in 2003, 21 people were killed by the debris flow. 240 houses, many office buildings and the Hakata-eki subway station were inundated with muddy water (Roy 2004). More recently, a giant debris flow burst on Aug. 8th, 2010 in Zhouqu City in China, 1765 people were killed. More than 5500 houses were inundated and the total economic losses reached to 212 million RMB (Tang 2011).

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Therefore, debris flow disasters have been recognized as a critical problem facing the world today and increasing attention has been focused on the study of debris flows.

Debris flow can be considered of sediment and water mixture in a manner as if it was a flow of continuous fluid driven by gravity, and it attains large mobility from the enlarged void space saturated with water or slurry. Associated with debris flow movement there is often significant erosion and deposition that can dramatically change the channel bed. At the end of an alluvial fan, where the slope of the bed decreases significantly, debris flow slows significantly, depositing large amounts of sediments (Aronne 2009).

Due to the complexity of the debris flow process, a number of models were developed to simulate the flow behavior. These models can be classified as: single-phase models (Hungr 1995, 1997; Naef 1999; Rickenmann 1997; Coussot 1994; Whipple 1997), and two-phase models (Brufau 2000; Nakagawa 1997, 2000; Shieh 1996; Takahashi 1991, 1992; Zanre 1996; Lai 1991; Morris 1996). Single-phase models are often used in situation with no significant morphological changes. The resulting integrated models present only the volume conservation equation and the momentum equation. It has the advantage to obtain the parameters from existed debris flows. However, it cannot simulate the important erosion and deposition process. Thus Two-phase models which treat the solid and fluid separately are introduced. The resulting integrated model presents only one momentum equation, derived for a fluid with the bulk density. The equations, which describe the flow, are completed by a mass conservation equation for each of the two phases (Fraccarollo 2000). Two-phase models permit a non-homogeneous treatment of the mixture. It is able to simulate the erosion and deposition processes through the movable channel bed, and, therefore, is suitable to face problems where the morphological evolution is to be determined. In this study, we adopted the most favorite Takahashi's model which incorporated the possibility of erosion and deposition.

For hazard mapping and risk assessment, the geographic information system (GIS) has been recognized as a useful tool to process spatial data and to display results. The GIS-based approaches in assessing debris flow hazards were reported in recent years (Lin 1995; Cheng 1997; Lin 1998, 2000). Numerical simulation by incorporating GIS is important prediction and analysis tools. One significant advantage of numerical simulation coupled with GIS is that the grid networks for simulation can be extracted from GIS raster data and all the calculated results can be displayed in GIS and used to the hazard mapping directly.

In this study, following adoption of the flow dynamics model from Takahashi (1992) (referred as T-model hereafter), we developed a debris flow simulation program incorporating with GIS by deriving the computation networks form GIS raster data. This coupled model was used to simulate a well-documented Yohutagawa debris flow in Japan. Comparing the results with the detailed field investigation and fixed bed model simulated results, it shows that the present coupled model is rational and effective.

2. GOVERNING EQUATIONS

Debris flow is treated as two-phase mixture flow of solid and fluid in T-model. An important feature of this model lies in considering the dynamics of the mixture and the morphological evolution of the river bed. The depth-averaged partial differential equations of T-model are derived from the conservation balances of mass (solid and mixture) and of momentum (mixture) in a coordinate system (Fig. 1). The governing equations describing the process of debris flow may be described as following:

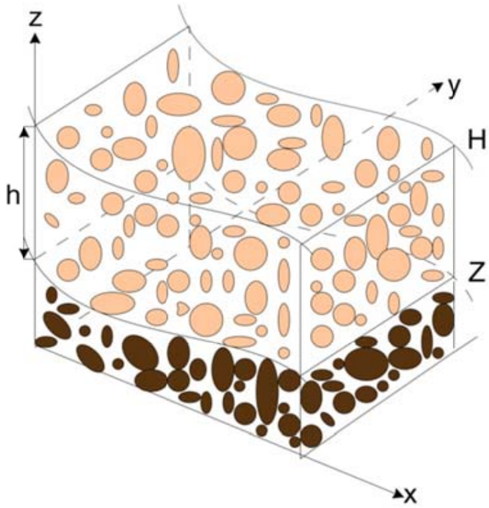

Fig.1. Definition of coordinate system for two dimensional governing equations

The depth averaged momentum conservation equations in $x-$ and $y-$ directions are respectively given as follows:

$$\frac{\partial M}{\partial t}+\beta\frac{\partial (uM)}{\partial x}+\beta\frac{\partial (vM)}{\partial y}=-\frac{\tau_{bx}}{\rho_m}-gh\frac{\partial H}{\partial x}$$

(1)

$$\frac{\partial N}{\partial t}+\beta\frac{\partial (uN)}{\partial x}+\beta\frac{\partial (vN)}{\partial y}=-\frac{\tau_{by}}{\rho_m}-gh\frac{\partial H}{\partial y}$$

(2)

The continuity equation of debris flow mixture is:

$$\frac{\partial h}{\partial t}+\frac{\partial M}{\partial x}+\frac{\partial N}{\partial y}=i$$

(3)

The continuity equation of the solid fraction is:

$$\frac{\partial (Ch)}{\partial t}+\frac{\partial (CM)}{\partial x}+\frac{\partial (CN)}{\partial y}=iC_b$$

(4)

The equation for the change of river bed elevation is:

$$\frac{\partial Z_b}{\partial t} + i = 0$$

(5)

Where $M = uh$ and $N = vh$ are the flow flux components in $x -$and $y -$directions, respectively; u and v are the depth-averaged velocity components in $x -$ and $y -$ directions, respectively; h is the flow depth; $H = Z_b + h$ is the elevation of the free surface; Z_b is the vertical bottom coordinate of the channel bed; β is the quadratic correcting coefficient taking into account the shape of the velocity profile; ρ_m is the debris flow mixture density, and $\rho_m = C(\sigma - \rho) + \rho$, σ and ρ are the solid density and fluid density, respectively; C and C_b are the volume concentrations of solids fraction in the flow and on the bed, respectively; g is the gravitational acceleration; i is the erosion or deposition velocity; τ_{bx} and τ_{by} are the bottom resistance on the river bed in $x -$and $y -$directions, respectively.

To complete the up five equations, two closure equations are needed for computing the velocity of erosion or deposition and the bottom resistance. According to the empirical equations of Takahashi (2007), the velocity of erosion or deposition in Eq. (3) (4) and (5) can be written as follows:

When erosion ($C_e \geq C$):

$$i = \delta_e \frac{C_e - C}{C_b - C_e} \frac{\sqrt{M^2 + N^2}}{d}$$

(6)

When deposition ($C_e < C$):

$$i = \delta_d \frac{C_e - C}{C_b} \frac{\sqrt{M^2 + N^2}}{h}$$

(7)

Where δ_e and δ_d are the erosion and deposition coefficient, respectively; d is the represent diameter. C_e is the equilibrium concentration and can be represented as (Takahashi, 2007):

$$C_e = \frac{\rho tan\theta}{(\sigma - \rho)(tan\emptyset - tan\theta)}$$

(8)

Where θ is the slope angle; $\emptyset$ is the Coulomb or basal friction angle.
The bottom resistance τ_{bx} and τ_{by} in Eq. (1) and (2) are described as follows:
For stony-type debris flow ($C \geq 0.4 * C_b$):

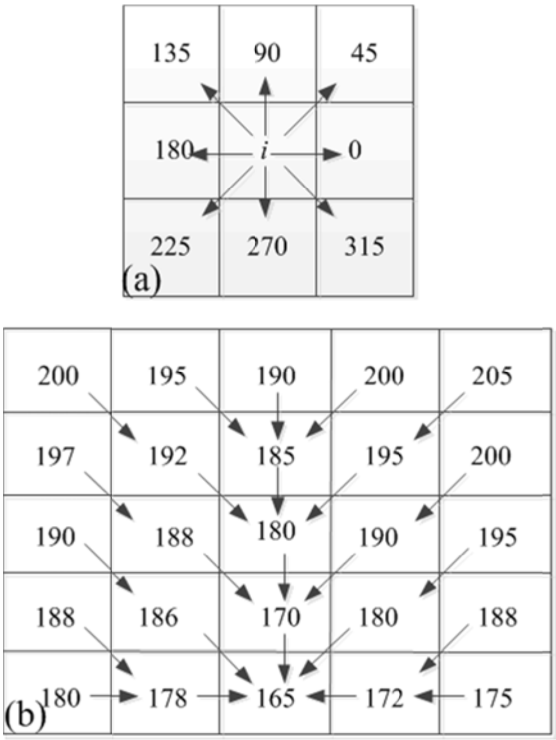

Fig.2. (a) Possible flow direction in a cell; (b) Flow direction in a DEM.

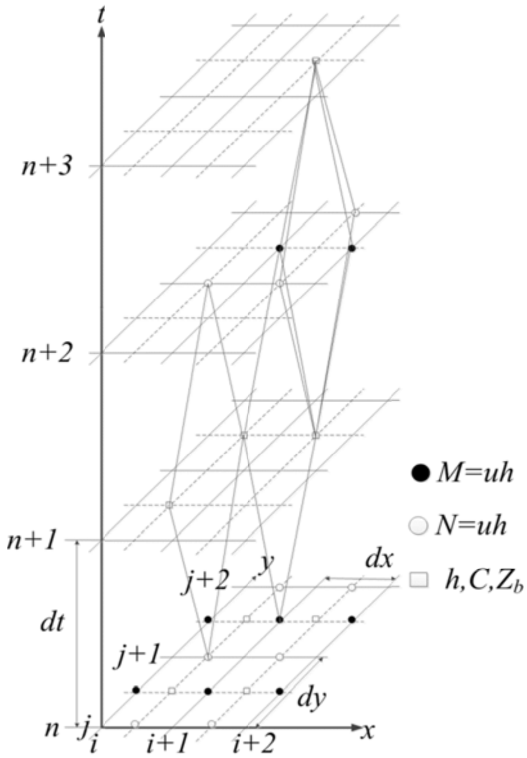

Fig.3. Grids and flow for debris flow computation

$$\tau_{bx} = \frac{\sigma}{8}\left(\frac{d}{h^2}\right)^2 \frac{1}{[(C_b/C)^{1/3} - 1]^2} M\sqrt{M^2 + N^2}$$

(9)

$$\tau_{by} = \frac{\sigma}{8}\left(\frac{d}{h^2}\right)^2 \frac{1}{[(C_b/C)^{1/3} - 1]^2} N\sqrt{M^2 + N^2}$$

(10)

For immature debris flow ($0.01 \leq C < 0.4 * C_b$):

$$\tau_{bx} = \frac{\rho_m}{0.49}\left(\frac{d}{h^2}\right)^2 M\sqrt{M^2 + N^2}$$

(11)

$$\tau_{by} = \frac{\rho_m}{0.49}\left(\frac{d}{h^2}\right)^2 N\sqrt{M^2 + N^2}$$

(12)

For bed load transportation ($C \leq 0.01$):

$$\tau_{bx} = \frac{\rho g {n_m}^2}{h^{7/3}} M \sqrt{M^2 + N^2}$$
(13)

$$\tau_{by} = \frac{\rho g {n_m}^2}{h^{7/3}} N \sqrt{M^2 + N^2}$$
(14)

here n_m is pseudo-Manning's coefficient which accounts for both turbulent boundary friction and internal collisional stresses.

3. NUMERICAL SIMULATION COUPLED WITH GIS

In this section, we will present how to produce numerical simulation incorporating GIS technology.

3.1 Generation of DEM for simulation

In order to generate the topographical data required for the simulation using T-model, a GIS-based digital is first converted to a Digital Elevation Model (DEM) (shown in Fig. 2(b)).The resolution of the DEM is 2.5 m×2.5 m and is saved as raster in GIS. This raster-based DEM is then converted to a grid data file format readable by the T-model for the computer simulation. Each data point contains elevation and coordinates (Fig. 2(b)), and this data set forms our topographical model.

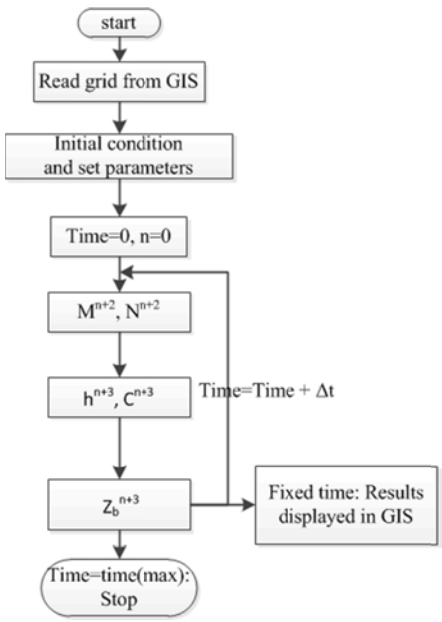

Fig. 4. The simple flow chart of the numerical simulation coupled with GIS.

3.2 Source identification and upstream boundary setting

Next step is to identify the potential source zone. After field trip work in the area and after studying the available aerial photographs, potential source zone is identified in Fig. 2(b) in shaded area. According to field observation, the total volume of soil and source zone boulder that may be available in GIS. So the average thickness of slide discharge in source zone is estimated from volume divide area, also that we can set the initial concentration for source zone. This average thickness and initial concentration are used as the upstream boundary of simulation.

Fig. 5. Photograph of Yohutagawa debris flow (modified from KKG's photograph)

3.3. Numerical solution and results display

Numerical models are organized on a grid cell basis. Each cell has eight possible flow directions (left, right, up, down and the four diagonals) (see Fig. 2.(a)), but in fact that a cell overland flow is only routed along one flow direction which is the maximum down-slope direction (Fig. 2.(b)). The numerical solution of the above Eq. (1) to (5) is based on a leap-frog difference scheme that is accurate in space and time, the linear terms use forward difference scheme, and the nonlinear terms use central difference scheme. As denoted in Fig. 3, the flow depth, concentration or elevation of the debris flow mass in each grid is arranged at the midpoint, and the flux M and N are arranged at the boundary central point of the grid. The specific difference equations were derived by means of explicit staggered leap-frog scheme proposed by Yoshiaki (1988). Finally, these five equations have been coded by C++ language, the simple flow chart of the numerical simulation coupled with GIS is shown in Fig. 4. Through all the calculated results displayed in GIS we can get the hazard maps for debris flow.

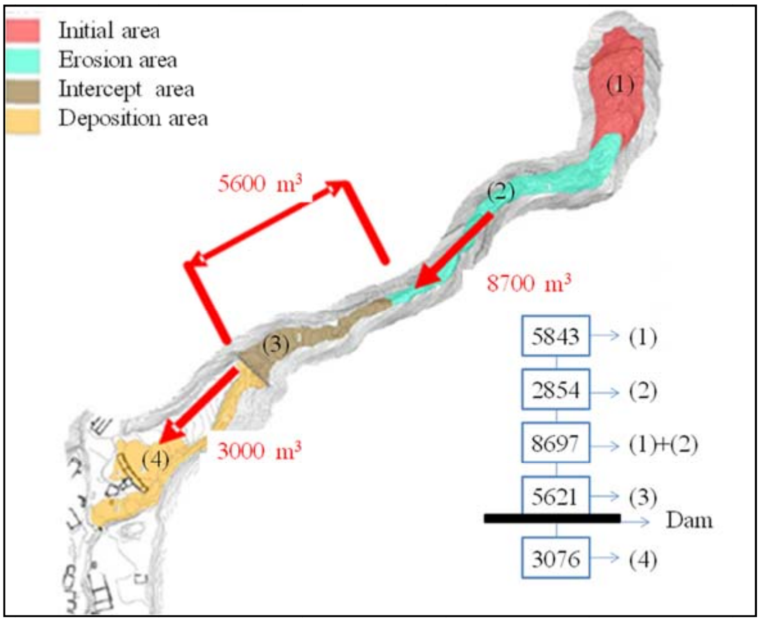

Fig.6. The actual movement of soil and sand (modified from KKG's photograph)

4. APPLICATION TO A REAL DEBRIS FLOW

In this section some applications of the model are presented, the model was applied to a real debris flow occurred in Japan. On Oct. 20th, 2010, a debris flow induced by landslide happened in Yohutagawa in Amamishi city. Although this debris flow only destroyed one building and one house, however there are kindergarten and a primary school in its path (Fig. 5). According to the investigation of Kokusai Kogyo Group (KKG), the volume of sediment discharge in source zone is estimated to be 5843 m^3 and the source zone area is 3895 m^2, so the average thickness of discharge is about 1.5 m. In this simulation, the average thickness 1.5m and the concentration 0.44 were used in the initial simulation. In addition, other material properties and rheological parameters well-documented by KKG for simulation are listed in Table. 1. The actual move ment of soil and sand is shown in Fig. 6, we can see that the total volume in initial and erosion area is approximately 8700 m^3 , the volume in intercept area by dam is about 5900 m^3, and the volume rush out of the dam in deposition area is about 3000 m^3. The specific location of each area is also shown in Fig. 6.

Table.1. The material properties and rheological parameters for simulation

$\sigma(kg/m^3)$	$\rho(kg/m^3)$	C_b	$d(m)$	$g(m/s^2)$	δ_e
2550	1180	0.60	0.03	9.8	0.0007
δ_d	ϕ	n_m	$\Delta t(s)$	$\Delta x(m)$	$\Delta y(m)$
0.05	28°	0.04	0.001	2.5	2.5

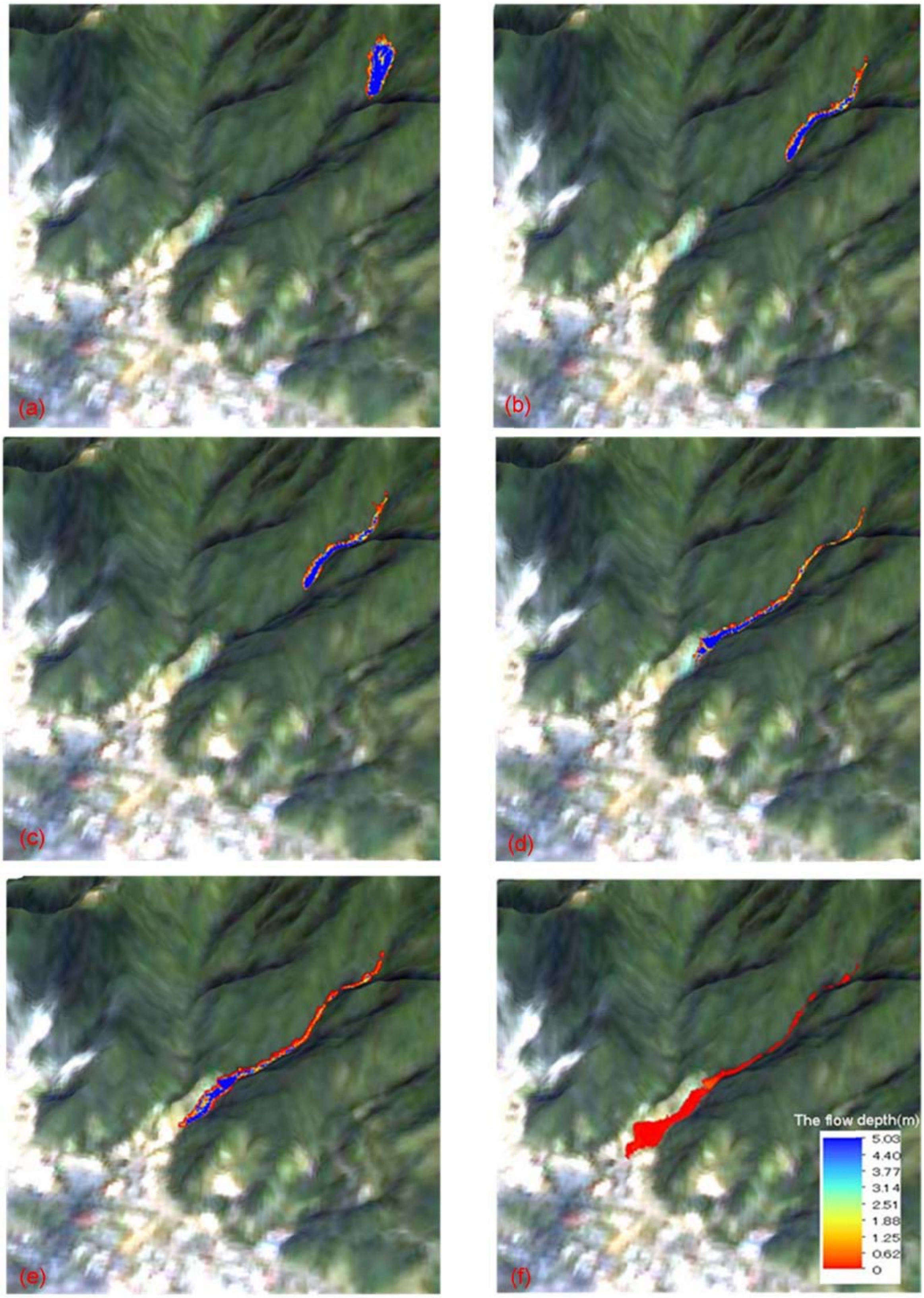

Fig. 7. The propagation and affected regions in different times ((a) 2s, (b) 40s, (c) 94s, (d) 110s, (e)150s, (f) 220s).

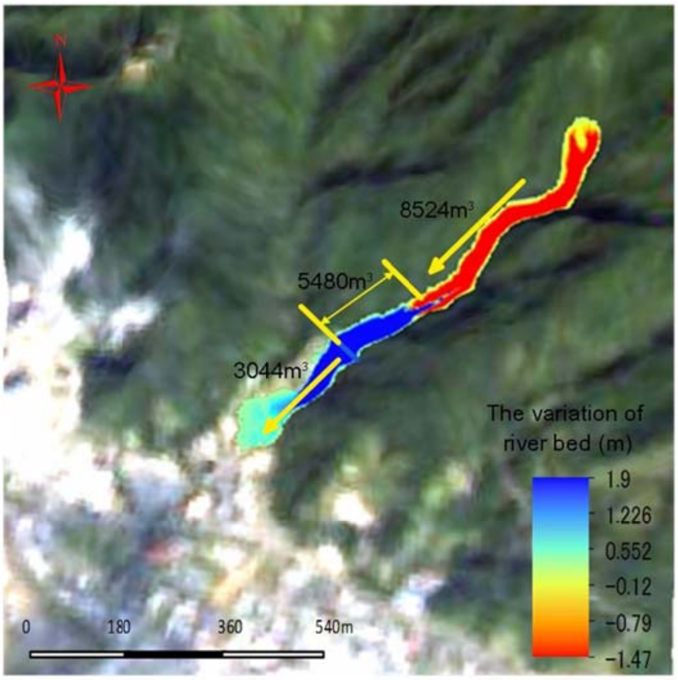

Fig. 8. The variation of river bed by mobile-bed model (T-model).

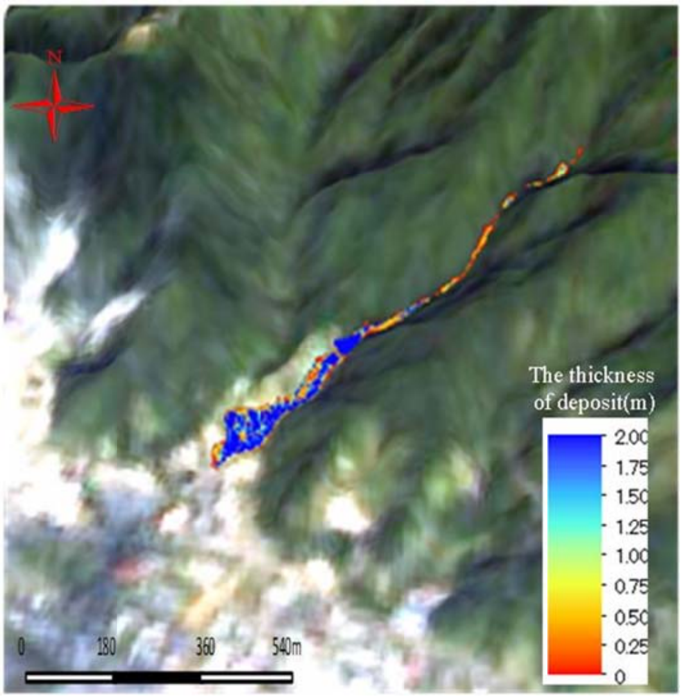

Fig.9. The thickness of deposit by fixed bed model

A time-lapse simulation of the dynamic propagation and affected regions of debris flow over the three-dimensional complexity terrain is illustrated in Fig. 7. Fig. 8 shows the variation of river bed evaluated between the initial condition and the current time step. By comparing with actual investigation (Fig. 6), we can see that the volumes and river bed variations in each area (erosion area, intercept area and rush out area of dam) have good agreements. If using fixed bed model which does not consider the erosion and deposition (Fig. 9), it only can simulate the thickness of deposit in one time step, but can't simulate the morphological variations, so its result have not agreement with the actual situation.

CONCLUSIONS

We have presented an approach to estimate the potential hazard of debris flow by incorporating the results of numerical simulation and GIS technology. A GIS environment provides a good platform for coupling a numerical model of a debris flow. As rater grid networks of digital elevation model in GIS can be used as the finite difference mesh, the governing equations are solved numerically using Leap-frog difference scheme. All the input and output data are processed in GIS. As a real case study, the model achieved reasonable results in comparison with field investigation. Comparing with fixed bed model, this model not only reproduced the propagation, but also simulated erosion and deposition of debris flow across the complex topography. The advantages of numerical simulation coupled with GIS are that the preprocessing routine in which the computation data are prepared, the post-computation visualization, the results analysis, and providing an effective tool for risk analysis and hazard map.

REFERENCES

Aronne, A., Luigi, F. and Giorgio, R. (2009). "Two-dimensional simulation of debris flows in erodible channels", *Computers & Geosciences*. **35**, 993-1006.

Brufau, P., Garcia-Navarro, P., Ghilardi, P., Natale, L. and Savi, F. (2000). "1D mathematical modelling of debris flow", *J. Hydraul. Res.* **38**(6), 435-446.

Cheng, K.Y., Lin, L.K. and Chang, S.Y. (1997). "The field investigation and GIS application in a potential hazardous area of debris flow". *Debris-Flow Hazards Mitigation: Mechanics, Prediction, and Assessment, Proceedings of the First International Conference. ASCE, New York,* 83–92.

Coussot, P. (1994). " Some considerations on debris flow rheology". *in Dynamics and Geomorphology of Mountain Rivers, P. Ergenzinger and K.H. Schmidt (Eds.), Lectures Notes in Earth Sciences*, **52**, 315-326, Springer-Verlag, Berlin.

Fraccarollo, L. and Papa, M.. (2000). "Numerical simulation of real debris-flow events", *Phys. Chem. Earth, Part B* **25**(9), 757-763.

Hungr O. (1995). "A model for the runout analysis of rapid flow slides, debris flows, and avalanches", *Can. Geotech. J.*, **32**, 610-623.

Hungr O. and Evans S.G. (1997). "A dynamic model for landslides with changing mass", *in: Proc. Engineering geology and the environment, Athens, Greece,* 719-724.

Lin, M.L. and Jeng, S.S. (1995). "A preliminary study of risk assessment of debris flow using GIS". *Journal of the Chinese Institute of Civil and Hydraulic Engineering* **7**(4), 475–486.

Lin, J.Y., Yang, M.D. and Lin, P.S. (1998). "An evaluation on the applications of remote sensing and GIS in the estimation system on potential debris flow". *Annual Conference*

of Chinese Geographic Information Society(CD edition).
Lin, P.S., Lin, J.Y., Hung, J.C. and Yang, M.D. (2000). "Risk assessment of potential debris flows using GIS", *Proceedings of the Second International Conference on Debris-Flow. Balkema*, 431–440.
Lai, C. (1991). "Modelling alluvial channel flow by multimode characteristic method", *J. Hydr. Engng* **117**,32-53.
Morris, P.H., and Williams, D.J. (1996). "Relative celerities of mobile bed flows with finite solid concentration". *J. Hydr. Engng* **122**, 311-315.
Nakagawa, H. and Takahashi, T. (1997). "Estimation of a debris flow hydrograph and hazard area", *in: Debris-Flow Hazards Mitigation: Mechanics, Prediction, and Assessment, Proc. 1st International DFHM Conference, ed. C.L. Chen (San Francisco, CA, USA),* 64-73.
Nakagawa H., Takahashi, T. and Satofuka, Y. (2000). "A debris-flow disaster on the fan of the Harihara River", *Japan, in: Debris-Flow Hazards Mitigation: Mechanics, Prediction, and Assessment, Proc. 2nd International DFHM Conference, eds. G.F. Wieczorek and N.D. Naeser (Taipei, Taiwan)*,193-201.
Naef, D., Rickenmann, D., Rutschmann, P. and McArdell, B.W.. "Comparison of friction relations for debris flows using a one dimensional finite element simulation model", *Natural Hazards and Earth System Sciences*(in press).
Roy C.S. (2004), "Landslides and debris flows strike Kyushu", Japan.
Rickenmann, D. and Koch, T. (1997). "Comparison of debris flow modelling approaches", *in: Debris-Flow Hazards Mitigation: Mechanics, Prediction, and Assessment, Proc. 1st International DFHM Conference, ed. C.L. Chen (San Francisco, CA, USA),* 576-585.
Shieh, C.L., Jan, C.D. and Tsai, Y.F. (1996). "A numerical simulation of debris flow and its applications", *Nat. Hazards* **13**, 39-54.
Tang C. (2011). "Triggering conditions and depositional characteristics of a disastrous debris flow event in Zhouqu city, Gansu Province, northwestern China", *Nat. Hazards Earth Syst. Sci.,* **11**, 2903-2912.
Takahashi, T. (1991). Debris Flow (IAHR Monograph Series, Balkema, Rotterdam, The Netherlands),165 pp.
Takahashi T., Nakagawa H., Harada T. and Yamashiki Y. (1992). "Routing debris flows with particle segregation", *J. Hydraul. Eng.***118**(11),1490-1507.
Takahashi T. (2007). Debris Flow: Mechanics, Prediction and Countermeasures. *Balkema-proceedings and monographs in engineering, water and earth sciences.* 448 pp.
Whipple, K.X. (1997). "Open channel flow of Bingham Fluids: applications on debris flow research", *Journal of. Geology*, **105**, 243-262.
Yoshiaki, I. and Akihide, T. (1978). "Numerical simulations of flows and dispersive behaviours in southern part of lake Biwa", *Annuals, Disas. Prev. Res. Inst., Kyoto Univ.*, No. 31 B-2.
Zanre, D.D.L., and Needham, D.J. (1996). "On simple waves and weak shock theory for the equations of alluvial river hydraulics". *Philos. Trans. Roy. Sot. A* **354**, 2993-3054.