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Research on runout scale of gully type rainstorm debris flow based on numerical simulation

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Abstract. The occurrence of gully type rainstorm debris flow will pose a serious threat to people's lives and properties. The runout scale of debris flow is an important parameter to estimate disaster losses, so it is necessary to research the runout scale of gully type rainstorm debris flow. The numerical simulation method can be used to reproduce debris flow events. In order to simulate the runout process of gully type rainstorm debris flow after the earthquake and estimate the runout scale, the "8.14" catastrophic debris flow event occurred in Hongchun Gully, Yingxiu Town was taken as the research object, and the event was simulated with the R. Avaflow model to analyze the runout process of debris flow, and a contrastive analysis was conducted between the simulation results and the measured data of the debris flow accumulation fan. The simulation results showed that the maximum erosion depth of the "8.14" catastrophic debris flow in the Hongchun Gully was 1.27 m, which occurred at the corner of the main gully, and the total amount of debris flow was 780,000 m^3. The simulation results are close to the measured data. R. Avaflow model has good applicability and accuracy, and can be used to simulate and estimate the runout scale of rainstorm debris flow. The research results can provide an important reference for risk evaluation of rainstorm debris flow.

Keywords. Runout scale, rainstorm debris flow, R. Avaflow model, earthquake area.

Debris flow is a common natural disaster, and its components are mainly mud, sand, stone and water, with great destructive power [1]. After the "5.12" Wenchuan earthquake, the geological environment of the earthquake-stricken area is seriously damaged, and a large number of loose deposits are produced, which provide a rich material source for the outbreak of debris flow and threaten the safety of life and property in the disaster area at all times [2].

The runout scale of debris flow is a hot topic in debris flow research. At present, the researches on runout scale of debris flow are mostly based on statistical model and numerical simulation, which analyze the single variable in the runout process of debris flow. The statistical model is established by multiple historical samples to predict the runout volume of debris flow, but this method cannot effectively predict the areas with missing historical data. The numerical simulation method is of low cost and good operability, and is a feasible tool to realize disaster recurrence [3]. In the past researches, many scholars used numerical simulation to solve the problem of debris flow [4], such as FLO-2D [5], Massflow-2D [6], RAMMS [7], RASH3D [8]. These models are single runout simulation, and ignore the initiation process of debris flow or consider the initiation of debris flow in a simple way. This is obviously different from the actual situation. Other models, such as Flow-R [9], consider the initiation point of debris flow, but only calculate according to the terrain slope, without considering the impact of material sources on the initiation of debris flow, which is also obviously different from the actual situation. The research on the runout scale of debris flow is of great significance in disaster prevention and mitigation, and accurate prediction models can reduce the loss of life and property in disaster areas.

R. Avaflow model [10] is a dynamic two-phase flow model. It adopts Pudasaini algorithm, contains many basic physical phenomena, proposes a new generalized resistance, and considers the interaction between solids and liquids in debris flow fluid, which can reproduce the results of most previous simple models. It can be used to simulate the erosion of debris flow on gullies in the movement process, and can also reflect the changes in various parameters (kinetic energy, thickness, velocity, pressure) of debris flow. The R. Avaflow model is used to simulate the runout process of gully type rainstorm debris flow. Taking the "8.14" debris flow in Hongchun Gully, Yingxiu Town, Wenchuan County, Sichuan Province as an example, the flow process and accumulation process of debris flow in Hongchun Gully as well as the final accumulation volume of debris flow were estimated. The results can provide some reference for the relevant research on the runout scale of gully type rainstorm debris flow.

1. Overview of the Research Area

Located in the northeast of Yingxiu Town, Wenchuan County, Hongchun Gully is a primary branch gully on the left bank of Minjiang River, the drainage basin is fan shaped (Figure 1), and the terrain belongs to deep cut structure eroding low mountains and middle mountains. The drainage area of Hongchun Gully is 5.24 km^2, the total length of the main gully is 3.6 km, and the longitudinal gradient is 35.8%; in the upstream branch gullies, the Xindianzi Gully has relatively large longitudinal slope, and the longitudinal slope of the lower gully section is slightly gentle, showing the characteristics of alternating steep and gentle slopes (Figure 2). Affected by the Wenchuan earthquake, the rock mass fractures are developed, which are mostly cut into gravels and block stones, providing favorable conditions for the development of collapse and landslide.

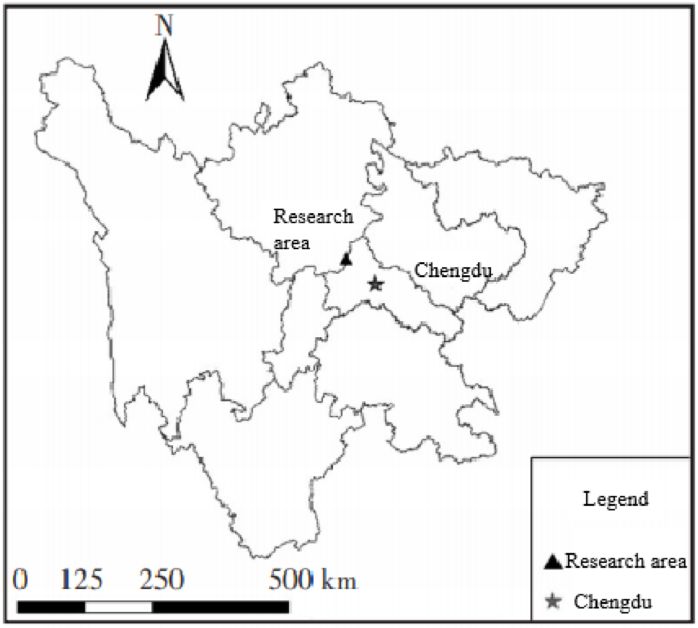

Figure 1. Geographical location of the research area

Yingxiu Town belongs to the subtropical humid monsoon climate zone at the edge of Sichuan Basin, and is the rainy center of western Sichuan. It is one of the areas with frequent heavy rain, and has four distinct seasons and a mild climate. The average annual precipitation is 1,253.1 mm, the maximum annual precipitation is 1,688 mm (1964), and the minimum annual precipitation is 836.7 mm (1974). In summer, the heavy rain is frequent, short in duration, and strong in intensity. The precipitation from June to September accounts for 60%~70% of the annual precipitation.

At about 3:00 a.m. on August 14, 2010, debris flow broke out simultaneously in the upstream of Hongchun Gully and three of its branch gullies, Ganxipu, Dashuigou and Xindianzi, which ended at around 5:00 a.m. ("8.14" debris flow for short) [11]. This debris flow not only destroyed and silted the Dujiangyan-Wenchuan Expressway and G213 national highway under construction, but also blocked the Minjiang River. The accumulation fan formed by debris flow has a total length of 470 m, a maximum width of 350 m, and a total area of 96,500 m^2. About 711,000 m^3 of debris flow sediments were accumulated at the mouth of the gully, 400,000 m^3 of solid materials rushed into the Minjiang River [12], silting up the river channel of the Minjiang River, which is about 150 m wide. The water level of the river rose, and the right bank was diverted to form a 20~30 m wide spillway, resulting in 32 deaths and more than 8,000 residents being forced to evacuate [13].

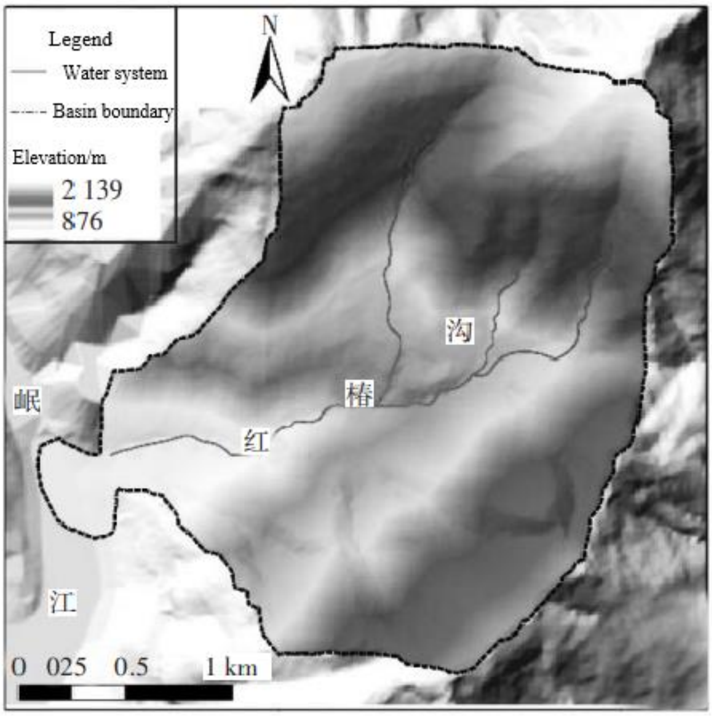

Figure 2. Elevation distribution in the research area

2. Runout scale of rainstorm debris flow based on numerical simulation

2.1. Control equation

R. Avaflow is a two-phase flow model, which mainly uses the mass conservation and momentum equations to calculate the fluid motion law. The solid phase and liquid phase of the fluid have different physical properties. The properties of liquid phase include liquid depth (h), liquid viscosity (η_f), liquid density (ρ_f) and isotropic stress distribution. For solid phase, the internal friction angle(ϕ), material density (ρ_s), base friction angle (δ), volume fraction of solid (α_s, $\alpha_f = 1-\alpha_s$ is the volume fraction of liquid) and anisotropic stress (k_x and k_y are used to represent the coefficient of lateral earth pressure in x and y directions respectively) are the unique properties of solid phase. For the velocity components $u_f = (u_f, v_f)$ and $u_s = (u_s, v_s)$ of the liquid and solid phases at the same depth, they are both the functions of their time and space.

The mass conservation equations are:

$$\frac{\partial}{\partial_t}(\alpha_f h) + \frac{\partial}{\partial_x}(\alpha_f u_f h) + \frac{\partial}{\partial_x}(\alpha_f v_f h) = 0 \tag{1}$$

$$\frac{\partial}{\partial_t}(\alpha_s h) + \frac{\partial}{\partial_x}(\alpha_s u_s h) + \frac{\partial}{\partial_x}(\alpha_s v_s h) = 0 \tag{2}$$

The momentum equations are:

$$\frac{\partial}{\partial_t}\left[\alpha_f h\left(u_f + \frac{\partial_s}{\partial_f}C(u_f - u_s)\right)\right] + \frac{\partial}{\partial_x}\left[\alpha_f h\left(u_f^2 + \frac{\partial_s}{\partial_f}C(u_f^2 - u_s^2) + \frac{\beta_{xf}h}{2}\right)\right] + \frac{\partial}{\partial_y}\left[\alpha_f h\left(u_f v_f + \frac{\partial_s}{\partial_f}C(u_f v_f - u_s v_s)\right)\right] = hs_{xf} \tag{3}$$

$$\frac{\partial}{\partial_t}\left[\alpha_f h\left(v_f + \frac{\partial_s}{\partial_f}C(v_f - v_s)\right)\right] + \frac{\partial}{\partial_x}\left[\alpha_f h\left(u_f v_f + \frac{\partial_s}{\partial_f}C(u_f v_f - u_s v_s) + \frac{\beta_{xf}h}{2}\right)\right] + \frac{\partial}{\partial_y}\left[\alpha_f h\left(v_f^2 + \frac{\partial_s}{\partial_f}C(v_f^2 - v_s^2) + \frac{\beta_{yf}h}{2}\right)\right] = hs_{yf} \tag{4}$$

$$\frac{\partial}{\partial_t}\left[\alpha_s h\left(u_s - \gamma C(u_f - u_s)\right)\right] + \frac{\partial}{\partial_x}\left[\alpha_s h\left(u_s^2 + \gamma C(u_f^2 - u_s^2) + \frac{\beta_{xs}h}{2}\right)\right] + \frac{\partial}{\partial_y}\left[\alpha_s h\left(u_s v_s - \gamma C(u_f v_f - u_s v_s)\right)\right] = hs_{xs} \tag{5}$$

$$\frac{\partial}{\partial_t}\left[\alpha_s h\left(v_s - \gamma C(v_f - v_s)\right)\right] + \frac{\partial}{\partial_x}\left[\alpha_s h\left(u_s v_s - \gamma C(u_f v_f - u_s v_s)\right)\right] + \frac{\partial}{\partial_y}\left[\alpha_s h(v_s^2 - \gamma C(v_f^2 - v_s^2) + \frac{\beta_{ys}h}{2}\right] = hs_{ys} \tag{6}$$

Where: $\beta_{xs} = \varepsilon k_x p_{bs}$, $\beta_{ys} = \varepsilon k_y p_{bs}$, $\beta_{xf} = \beta_{yf} = \varepsilon p_{bf}$, $p_{bf} = -g^z$, $p_{bs} = (1-\gamma)p_{bf}$, $\varepsilon = H/L$. L and H are the length and width of the fluid; C is the virtual mass coefficient; γ is the density ratio; s_{xf} and s_{yf} represent the displacement of liquid part in x direction and y direction respectively; s_{xs} and s_{ys} represent the displacement of the solid part in the x direction and in the y direction respectively.

2.2. Runout scale of rainstorm debris flow

R. Avaflow is a two-phase flow model simulating debris flow movement, including solid and liquid phases. The digital elevation model (DEM) is input, all the landslides triggered by rainfall are regarded as the initiation point of debris flow, and various parameters of the initiation point are input, mainly the fluid motion parameters, including solid volume weight, liquid volume weight, base friction angle, Reynolds coefficient, minimum fluid motion depth, etc. The solid volume weight and liquid volume weight are the basic parameters of debris flow mixed fluid, and the Reynolds coefficient is a dimensionless parameter characterizing fluid flow in the model. The material source of debris flow is released from the initiation position, moves along the gully, and finally accumulates in the accumulation area; erosion is considered in the whole movement process. When the fluid finally stops moving, the parameter limiting the termination of simulation is the minimum fluid motion depth, thus completing the simulation of the movement and accumulation process of debris flow.

The runout scale of debris flow is the volume of solid materials from the debris flow in a short time [14]. In the simulated movement process of debris flow, after the landslide triggered by rainfall starts, the volumes of solid and liquid phases change, the fluid thickness changes accordingly, and finally the fluid stops moving and accumulates in the accumulation area. Based on the mathematical geometric method, the simulation will predict the debris flow runout range and the debris flow accumulation thickness in the accumulation area, and the debris flow runout scale can be obtained by multiplying the accumulation area by the debris flow accumulation thickness in the accumulation area.

2.3. Model performance evaluation method

The model is mainly evaluated from two aspects: first, the discrimination of the model, or prediction accuracy. The evaluation indicators include AUC, C index, NRI, etc.; second, goodness of fit, or degree of calibration. The evaluation indicators include AIC, BIC, R^2, Brier score, etc. According to the actual problems, the degree of attention to these two aspects is different. Generally, most scenarios pay more attention to discrimination, that is, the model should first possess higher discrimination ability, and then its performance of calibration will be evaluated.

Scheidl accuracy evaluation model based on simulated accumulation area and measured runout range was adopted [15]. This model gives consideration to both accumulation area and accumulation volume, and defines two positive accuracy coefficients α, ε and two negative precision coefficients β, γ. The evaluation coefficient Ω was calculated with these four coefficients according to the calculation formula below:

$$\alpha = \frac{X}{X+Z}, \beta = \frac{Y}{Y+Z}, \gamma = \frac{Z}{X+Z} = 1 - \alpha, \varepsilon = \frac{V}{V_{\mathrm{observed}}} \tag{7}$$

$$\Omega = \alpha - \beta - \gamma + \varepsilon \tag{8}$$

When $\Omega = 2$, it means that the simulated accumulation is completely consistent with the actual accumulation; when $\Omega = -2$, it means that the simulated accumulation is completely inconsistent with the actual accumulation. The model performance evaluation is shown in Figure 3, which explains the definition of sub intervals X, Y and Z.

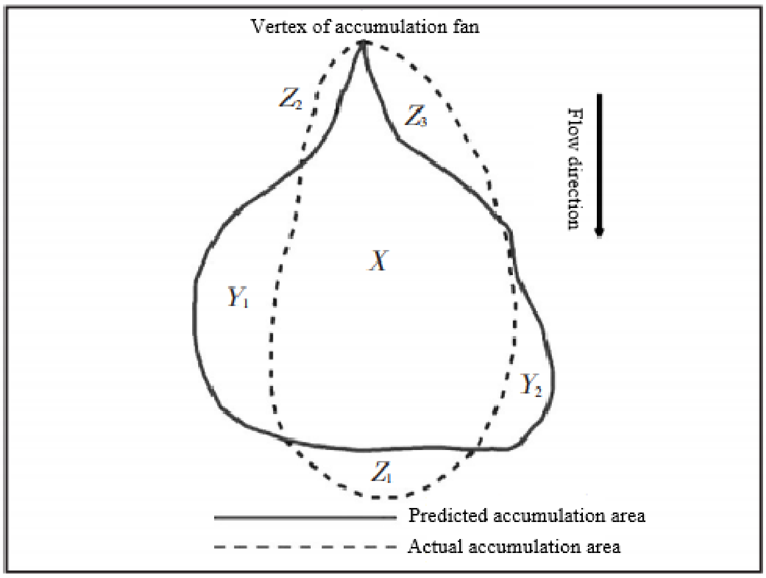

Figure 3. Comparison of measured and predicted accumulation ranges

In Figure 3, X is the right judgment zone, Y and Y_1 are the false judgment zones, and Z_1, Z_2 and Z_3 are the missing judgment zones. The zoning (X, Y, Z) compares the predicted hazard area with the actual hazard area of debris flow accumulation fan.

3. Results

3.1. Data source and parameter selection

(1) Data source

DEM accuracy for simulation is 25 m × 25 m, and the vegetation adopts the data extracted from Landsat 7 satellite image on February 22, 2010. The threshold value of NDVI is defined as 0.5, that is, NDVI ≥ 0.5 means there is vegetation, and NDVI < 0.5 means there is no vegetation. The rainfall data is the hourly rainfall from 17:00 on August 12 to 5:00 on August 14, 2010.

(2) Simulation parameters

The soil cohesive force used for the simulation parameters is C_{soil} = 2,710 Pa. According to the research results of Peter Lehmann, the tensile and shear strength provided by the vegetation used in the research area is τ_{root} = 1,500 Pa, but the vegetation in the research area of this paper is obviously more luxuriant, so the simulation uses τ_{root} = 1,600 Pa. The results proved that the parameter setting conforms to the actual situation. The initial saturation θ_0 = 0.75, and the internal friction angle of soil ϕ = 35°.

In the R. Avaflow simulation of the movement process of debris flow, the initial release height of the liquid has an obvious impact on the simulation results. The accuracy of this parameter determines whether the simulation effect is consistent with the actual situation. Assuming that the solid and liquid are evenly distributed in the material source of debris flow, the initial release height of liquid can be calculated inversely by using the solid liquid volume ratio $k=v_s/v_f$. The k value successfully links the initial solid release volume calculated by the initiation model to the initial liquid release volume required by the motion model. See Table 1 for basic parameters of R. Avaflow simulation.

Table 1. Basic parameters used for R. Avaflow simulation

ρ_s /(kg/m^3)	ρ_f /(kg/m^3)	ϕ / (°)	δ / (°)	C /kN	T /s	t /s	CFL	h_{min} /m
2 700	1 000	35	16	0.5	700	10	0.25	0.001

3.2. Simulation results

In the simulation, the soil depth was used as a function of the slope, which represents the lower boundary of the topsoil. The soil depth data was plotted and interpolated along different locations of the basin, most of the soil layer thickness was calculated based on empirical formulas, which was only applicable to a certain area. The landslide hydrodynamic triggering (LHT) model [16] can solve this problem well. The landslide hydrodynamic triggering (LHT) model is a model in which the soil mass is gradually destroyed under rainfall conditions, and finally becomes unstable as a whole. It connects the hydrological state and mechanical state of soil mass through physical model, and maintains the stability of slope soil mass with friction, cohesion, capillary force and plant root strength. On this basis, calculating the initiation part with the landslide hydrodynamic triggering (LHT) model solves the problem that the initiation position and initiation volume cannot be accurately predicted when R. Avaflow is used to simulate rainstorm debris flow. Researches have shown that the thickness of soil layer in most areas is less than 10m, so 10m is taken as the threshold of soil layer thickness.

The rainfall landslide distribution map (Figure 4) and the soil layer thickness map (Figure 5) calculated according to the LHT model were intersected to assign a value to the simulated landslide thickness. The landslide with thickness attribute was used as the initiation point of debris flow and was imported into R. Avaflow model software for simulation.

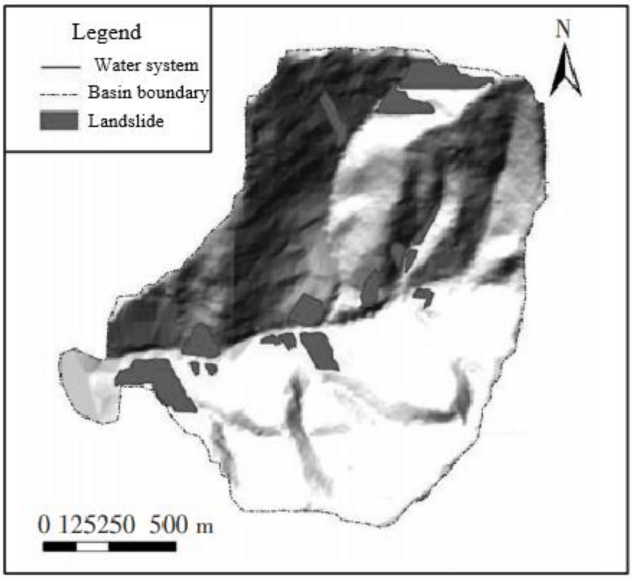

Figure 4. Distribution of rainfall landslide in the research area

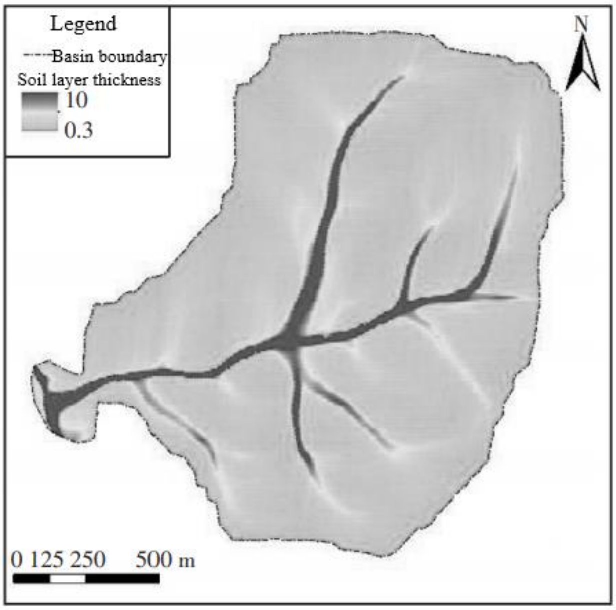

Figure 5. Distribution of soil layer thickness in the research area

The simulation results showed that the debris flow stopped at 230 s. Although the total simulation time in the parameter setting T=500 s, the debris flow stopped when the fluid velocity and flow depth reached the set thresholds (h_{min}). The maximum erosion depth of debris flow was 1.27 m, which occurred at the corner of the main gully. This location was consistent with the actual survey results, but the depth was less than the actual erosion results, because the simulated gully strength was uniform, while the actual gully strength was non-uniform, indicating that the non-uniformity of gully strength had a great impact on debris flow erosion. According to the depth of the debris flow (Figure 6), the shape and thickness of the debris flow varied greatly in the first 60s due to the huge energy contained in the debris flow. After 100 s, with the consumption of fluid kinetic energy, the debris flow started to change slowly and tended to deposit. The simulation results showed that during the whole movement process of debris flow, about 200,000 m^3 of solid materials in the gully were initiated, which, together with the solid materials initiated on the slope, formed a huge debris flow in Hongchun Gully with a total volume of 780,000 m^3. The runout volume was slightly larger than the measured result, because the simulation considered that all landslides caused by rainfall would participate in the movement of subsequent debris flow, and considered the hazard of debris flow in the most dangerous situation, which was not the actual condition. Therefore, it is reasonable. Finally, some deposits were washed into the Minjiang River and deposited in the river channel, which is consistent with the actual survey results.

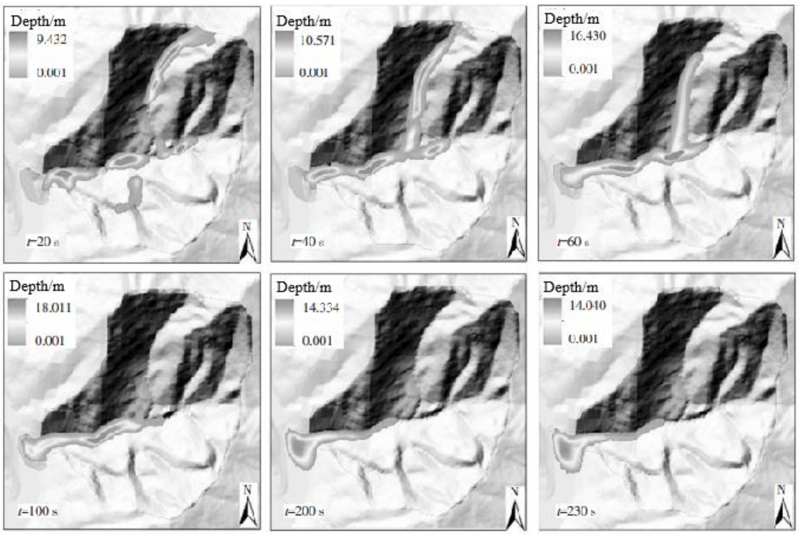

Figure 6. Movement process of debris flow

3.3. Model performance evaluation

The main purpose of this paper is to reproduce the runout process and estimate the runout scale of the "8.14" catastrophic debris flow in Hongchun Gully. Therefore, it is necessary to verify the simulation results of debris flow. Scheidl accuracy evaluation model based on simulated accumulation area and measured runout range was adopted. When t = 230 s, the debris flow stopped. Therefore, the range of accumulation at this time was selected as the simulated accumulation area. The comparison diagram between the simulation results and the actual accumulation (Figure 7) showed that the area of the right judgment area was X = 165,000 m^2, the area of the false judgment area was Y = 56,000 m^2, and the area of the missing judgment area was Z=16,000 m^2. The actual accumulation volume ($V_{observed}$) in the formula was measured on the site according to the method in Reference [16], which was 711,000 m^3. The calculation result Ω = 1.6, indicating good simulation effect.

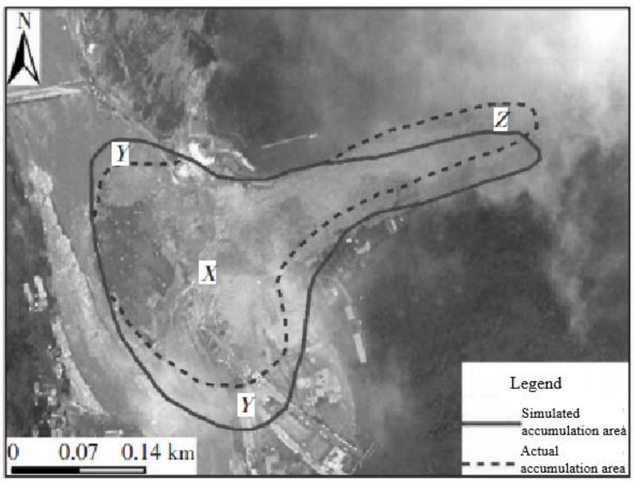

Figure 7. Verification comparison

4. Conclusion

After the Wenchuan earthquake, the geological environment in the earthquake area is seriously damaged, Gully type rainstorm debris flows occur from time to time, posing a serious threat to people's lives and properties. Therefore, it is necessary to research the runout scale of gully type rainstorm debris flows. The numerical simulation research in this paper adopts R. Avaflow model to simulate the runout process and estimate the runout scale of debris flow, and draws the following conclusions.

(1) R. Avaflow model is a two-phase flow model that simulates the movement of debris flow, and it simulates the material movement of the whole runout process of debris flow under rainfall conditions. The difference between the simulated accumulation area and the measured runout range is small, and the runout volume is slightly larger than the actual volume, which is acceptable because the model assumes that all landslides are involved in the initiation of debris flow. This model is more practical than simple single-phase flow model and two-phase flow model without considering erosion, and can better reflect the volume changes of solids and liquids in the movement process of debris flow.

(2) The debris flow in Hongchun Gully is not caused only by extreme weather, nor is it determined by a single factor such as vegetation or terrain. Instead, under the combined action of multiple factors, the slope underwent unstable damage, the rain scoured loose deposits, and water and soil mixture gathered, which finally formed the debris flow. The debris flow on the accumulation fan buried a large number of houses, and the debris flow rushing into the Minjiang River blocked the river channel and led to flooding, which brought terrible disasters to the residents of Yingxiu Town.

References

[1] Tang Hai, Tang Chuan, Chen Ming, et al. Numerical simulation analysis of the effect of debris flow prevention and control projects in highly seismic regions [J]. Bulletin of Soil and Water Conservation, 2019,39(4):196-201.

[2] Luo Yuting, Tang Chuan, Xiong Jiang, et al. Analysis of causes of "8.20" debris flow in Xiazhuang Gully, Wenchuan County, Sichuan Province and the prediction of river blocking range [J]. Bulletin of Soil and Water Conservation, 2020,40(6):193-199.

[3] Peng Zhangqiang, Zou Hong. Research on initiation of debris flow in Hongchun Gully based on LHT model [J]. Gansu Water Resources and Hydropower Technology, 2021,57(2):31-34.

[4] Wang J, Yan Yu, Qinghua Gong, Shaoxiong Yuan. Debris flow disaster risk analysis and modeling via numerical simulation and land use assessment [J]. Arabian Journal of Geosciences, 2020,13(19):979.

[5] O'Brien J S, Julien P Y, Fullerton W T. Two-dimensional water flood and mudflow simulation [J]. Journal of hydraulic engineering, 1993,119(2):244-261.

[6] Ouyang C, He S, Xu Q, et al. A MacCormack-TVD finite difference method to simulate the mass flow in mountainous terrain with variable computational domain [J]. Computers & Geosciences, 2013,52:1-10.

[7] Christen M, Kowalski J, Bartelt P.RAMMS: Numerical simulation of dense snow avalanches in three-dimensional terrain [J]. Cold Regions Science and Technology, 2010,63(1-2):1-14.

[8] Vagnon F, Pirulli M, Yague A, et al. Comparison of two depth-averaged numerical models for debris flow runout estimation [J]. Canadian Geotechnical Journal, 2018:56(1):89-101.

[9] Horton P, Jaboyedoff M, Rudaz B, et al. Flow-R, a model for susceptibility mapping of debris flows and other gravitational hazards at a regional scale [J]. Natural hazards and earth system sciences, 2013,13(4):869-885.

[10] Pudasaini S P. A general two-phase debris flow model [J]. Journal of Geophysical Research: Earth Surface, 2012,117(3):1-28.

[11] Jiang Zhilin, Zhu Jing, Chang Ming, et al. Dynamic evolution characteristics of material source amount formed by debris flow in Hongchun Gully in Wenchuan earthquake area [J]. Mountain Research, 2014,32(1):81-88.

[12] Li Dehua, Xu Xiangning, Ji Feng, et al. Engineering prevention and control of catastrophic debris flow in Hongchun Gully, Yingxiu Town, Wenchuan County and preliminary effect analysis [J]. Journal of Engineering Geology, 2013,21(2):260-268.

[13] Tang C, Zhu J, Ding J, et al. Catastrophic debris flows triggered by a 14 August 2010 rainfall at the epicenter of the Wenchuan earthquake [J]. Landslides, 2011,8(4):485-497.

[14] D'Agostino V, Marchi L. Debris flow magnitude in the eastern Italian alps: data collection and analysis [J]. Physics and Chemistry of the Earth. Part C, 2001,26(9):657-663.

[15] Scheidl C, Rickenmann D. Empirical prediction of debris flow mobility and deposition on fans [J]. Earth Surface Processes and Landforms: The Journal of the British Geomorphological Research Group, 2010,35(2):157-173.

[16] Lehmann P, Or D. Hydromechanical triggering of landslides: From progressive local failures to mass release [J]. Water Resources Research, 2012,48(3):1-24.

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