Debris Flow Forecast Based on Soil-Water Coupling Mechanism: A Case Study in Aizi Gully Watershed

He Na[1], Niu Haicheng[1], N. Sh. Chen[2], Zhong Wei[2]*,
Tom Cosgrove[3]

1. School of Civil Engineering， Henan Polytechnic University， Jiaozuo， Henan 454000， China ; 2. Key Laboratory of Mountain Hazards and Surface Process, Institute of Mountain Hazards and Environment, Chinese Academy of Sciences and Ministry of Water Resources, Chengdu 610041, China ; 3. Department of Civil Engineering & Materials Science, University of Limerick, Ireland

** Corresponding author at: Institute of Mountain Hazards and Environment, Chinese Academy of Sciences, Chengdu, 610041, PR China;*

e-mail: liutenantz@imde.ac.cn

ABSTRACT

On 28 June 2012, a huge disastrous debris flow occurred in Aizi gully watershed which is situated in Ningnan County, Sichuan Province, China. This debris flow event not only resulted in 40 people being dead or missing, but also seriously affected the construction process of Baihetan Hydropower station. With the aim of reducing the influence of the debris flow on local economy development and people's life, a field investigation and remote sensing interpretation were carried out to explore the whole condition of this area, including the amount of loose deposits, topography conditions and rainfall amount, etc. We concluded that the loose materials, rainfall conditions and topography still satisfied the conditions for debris flow initiation. In the future, under intensive rainfall a large scale debris flow could probably occur in this area, which would pose a grave threat to the safety of the residents. To reduce the risk posed by future debris flows in Aizi gully watershed, a soil-water coupling model was employed to calculate the mixture density, and evaluate the occurrence probability of the debris flow, and assess the corresponding warning grade. On the basis of the results of model calculation, combined with the real-time rainfall condition, timely forecast information can be issued. This in turn can significantly facilitate disaster mitigation and prevention, and the potential disaster of debris flow in Aizi gully can be minimized.

KEYWORDS: Debris flow, forecast, Soil-Water Coupling Model, Aizi gully

INTRODUCTION

The 2008 Wenchuan Earthquake in Sichuan Province, China generated many landslides, which produced a huge amount of loose deposits. These loose deposits have caused a dramatic increase in debris-flow occurrence in subsequent years[1]. Debris flows are recognized as a significant hazard in mountainous areas. Due to its sudden onset, debris flow often causes serious casualties and property loss[2,3]. Their high mobility can cause damage, not only inside and adjacent to the torrent, but also on the alluvial fan. Because many important facilities have been constructed on alluvial fans, the risk related to debris flows has been heightened greatly[4,5]. Furthermore, debris flows have a significant destructive power and usually lead to serious disasters in mountainous areas, particularly due to their high velocity, long run-out distance, large volume and huge capacity for transporting large and heavy items such as trees and rocks[6]. To mitigate the effects of such hazards, numerous methods and techniques have been proposed or tested over a long period[7,8]. However, according to the literature and a generalized consensus among experts, debris flow initiation mechanism have turned out to be very complicated, and a rigorous scientific approach to solving this problem has been needed due to the uncertainties in data collection, as well as in model selection and application [9,10].

Many researchers have focused on prediction of their occurrence[11,12] and estimation of their magnitude and runout distance in order to reduce associated risk. However, as debris flow usually occur in remote mountainous areas, it is difficult to observe them due to their sudden occurrence and rapid development. There is rarely a chance to witness the initiation and movement of natural debris flows even for an expert or a scholar who has been pursuing disaster prevention of debris flow[5,13-15]. As an important means of disaster mitigation, debris flow forecasting has been much studied by researchers. The formation mechanism of debris flow is considered as the theoretical foundation of debris flow forecasting[2,3]. But the formation mechanism of debris flow is incompletely understood due to the complexity of the formation processes. Previous researchers mainly focused on the prediction models for disaster mitigation and prevention, and many models were established, which are almost entirely statistics-based and rely on a vast majority of former debris flow events to determine the rainfall threshold. Due to the variation of regional rainfall data and underlying conditions, the rainfall threshold can be difficult to determine, and the accuracy cannot be guaranteed, and so this approach cannot meet the need of disaster mitigation. A mechanism-based forecast approach is the effective way to reduce the disasters caused by debris flow events[16-20].

STUDY AREA

Aizi gully has a catchment area of 65.55 km^2, and is located on the left bank of Jinsha River within the Baihetan hydropower project area(15 million KW), which is the second largest hydropower station in China. On 28 June 2012, at 5:40am, a sudden catastrophic debris flow destroyed Yanzi village garden, which is located in the outlet of Aizi gully, resulting in 40 people dead or missing. Aizi gully watershed climatically falling into a subtropical monsoon climate zone with a distinct dry and wet season. The study area is composed of three confluence areas: the confluence area of Aizi gully, Gualv gully and Niluohan gully. The west side is higher than the east and the total length of Aizi gully is 21.96km. On both sides of the main gully, the tributary is narrow and deeply cut, and the mean gradient of the main gully is 155‰. In Aizi gully watershed, the maximum altitude is 3646m while the minimum is 604m, giving a maximum relief of 3042m. The vegetation in the watershed is prominently vertically distributed. The main superficial soil includes red soil, mountainous yellow soil, brown soil and meadow soil, among which red soil is the main soil type. The bedrock mainly includes Ordovician dolostone, limestone, sandstone, Cambrian dolomite, sandstone, Sinian system dolomite and Permian basalt.

METHODOLOGY

After the occurrence of the debris flow on the 28 June 2012, a field investigation and remote sensing interpretation were conducted systemically, which allowed us to obtain fundamental data of the study area, which included the distribution of the loose deposits, geological conditions, meteorological conditions, historical rainfall data, seismic activity, and geomorphic characteristics. Subsequently, relevant models were employed to calculate the amount and factor of safety of the loose deposits. Based on the results of model calculations, meteorological conditions and the topography of the study area, preliminary analysis was performed, and we found that the loose deposits, energy and triggering conditions in Aizi gully watershed still easily satisfy debris-flow initiation conditions. Therefore, without engineering countermeasures or early warning systems, the debris flow in Aizi gully watershed will pose a great threat not only to local economic development, but also the safety of the local residents. In addition, Aizi gully is situated in the upper stream of Baihetan hydropower station, from where to the outlet of Aizi gully is only 6.1km. Therefore a debris flow in the watershed can greatly affect the construction process. Furthermore, after the completion of the dam, debris flow material can greatly reduce the capacity of the reservoir, which will reduce the power generation capacity. The main objective of this paper is to forecast the probability of the debris flow in Aizi gully based on water-soil coupling mechanism, to allow early warning information to be released during the rainy season.

Remote sensing interpretation and field investigation

With the aid of remote sensing interpretation, the distribution of loose solid material can be drawn, Fig.1. Generally, the formation of debris flow involves two water-soil coupling phases. First, the coupling of the rainfall and the soil mass of the slope, which leads to the soil mass instability. Subsequently, the coupling of runoff and unstable soil, results in the formation of debris flow. Both are taken as the basic principles for the forecast model of debris flow based on the water-soil coupling at the watershed scale. In the coupling model, rainfall plays a key role in triggering debris flow initiation.

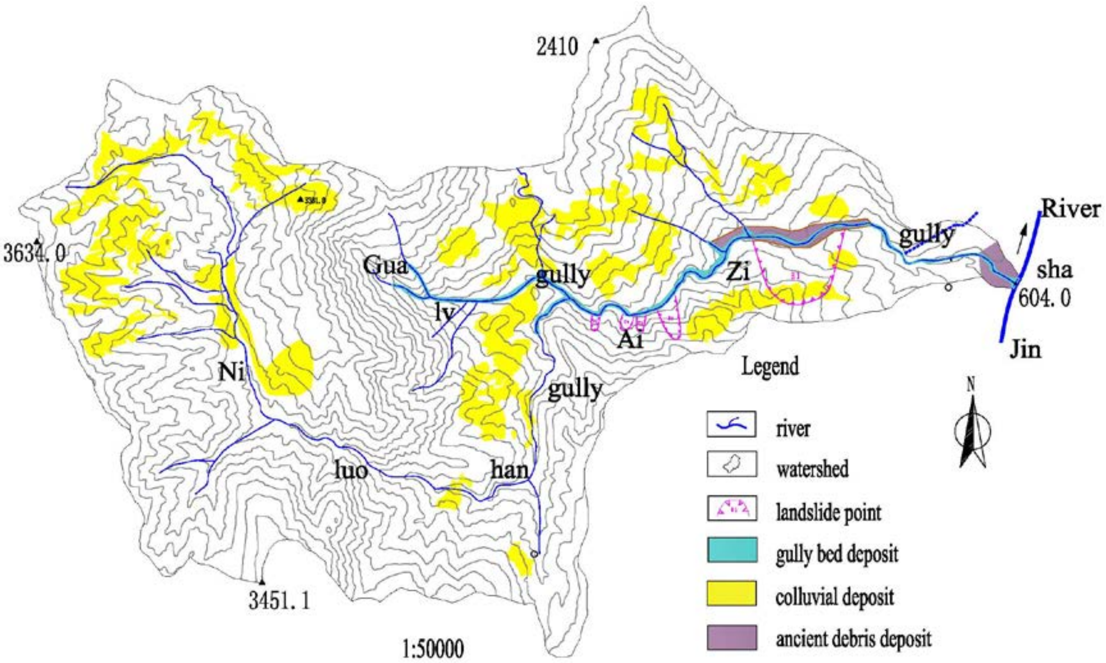

Figure 1: The distribution of loose solid materials in Aizi gullly

Influence of rainfall on the failure of soil mass

The stability of the soil varied as the rainfall lasted. Previous research has confirmed that the depth of the unstable soil varies from 0.5 to 2 metres[2]. Prior to the rainfall infiltration, the soil mass of the slope is mainly unsaturated. Along with the rainfall infiltration, the increase of the soil water content will decrease the matrix suction of the soil mass, which leads to the failure of soil mass. In this study, the slope stability under the action of the rainfall infiltration is analyzed based on the infinite slope model using the factor of safety (F_s). The shallow failure surface governed by the Mohr-Coulomb rule is assumed to be parallel to the slope surface (Fig. 2).

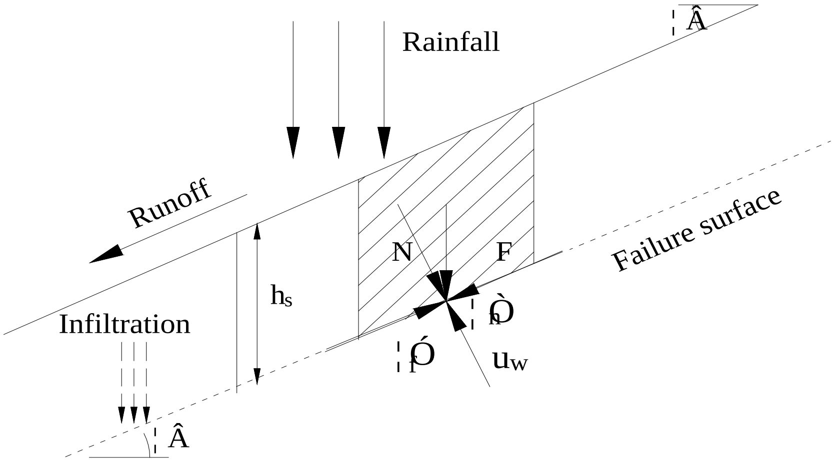

Figure 2: Infinite slope model for analyzing slope stability

The shear strength of the unsaturated soil proposed by Fredlund and Rahardjo is shown as following:

$$\tau_f = c + (\sigma_n - u_a)\tan\varphi + (u_a - u_w)\tan\varphi^b \qquad (1)$$

Therefore, on the basis of Eq.1, the limit equilibrium formula can be expressed as following:

$$F_s = \frac{c + (\sigma - u_a)\tan\varphi + \psi\tan\varphi^b}{F} \qquad (2)$$

The shear force F which induces the slope instability at the shear plane is defined by the downslope parallel component of the soil mass gravity, and it can be expressed as following:

$$F = W\sin\beta = \gamma_t H_s \cos^2\beta \qquad (3)$$

The normal stress at the shear plane can be expressed as following:

$$\sigma_n = W\cos\beta = \gamma_t H_s \cos^2\beta \qquad (4)$$

Compared Eqs. 2, 3 and 4, the final form of the limit equilibrium formula can be derived.

$$F_s = \frac{\tan\varphi}{\tan\beta} + \frac{c + \psi\tan(\eta\varphi)}{\gamma_t H_s \cos\beta\sin\beta} \qquad (5)$$

where c is the soil cohesion force, φ is the internal friction angle, u_a is pore air pressure and equivalent to zero, φ_b is related to matrix suction (It is close to the internal friction angle (φ) in the condition of low matrix suction), H_s is the depth of soil, $\psi = u_a - u_w$ is matrix suction of the soil (it is the function of the soil water content, and is described by Van Genuchten model)[21].

$$S_e = \left[\frac{1}{1 + (\alpha \times \psi)^n}\right]^m \tag{6}$$

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} \tag{7}$$

where S_e is the saturated degree, θ_s is the saturated water content of the soil, θ_r is the residual water content of the soil, θ is the soil water content of the current hour, α , n and m are the parameters of the curve, and $n = 1 - 1/m$.

Amount of the loose deposits in Aizi gully watershed

The loose deposits can be generally subdivided into four categories (Fig.3): residual deposits, colluvial deposits, landslide deposits and ancient debris flow deposits. With the help of field investigations, the distribution of the loose deposits can be identified, and preliminary stability of each slope can be analyzed. To better evaluate the amount of the loose deposits, the calculation model was employed to compute the safety factor, and determine the stability of the slopes. Combining the results of field investigations and model calculation, the total amounts of the loose deposits can be determined, and are shown in Table 1.

a. Residual deposits **b. Colluvial deposits**

c. Landslide deposits **d. Ancient debris flow deposits**

Figure 3: The deposits in Aizi gully watershed

Table 1: The amount of loose deposits in Aizi gully watershed

	Confluence area of Gualv gully ($10^4 m^3$)	Confluence area of Niluo han gully ($10^4 m^3$)	Confluence area of Aizi gully ($10^4 m^3$)	Total amount of the deposits in Aizi gully watershed ($10^4 m^3$)	Amount of loose deposits probably supply to debris flow formation ($10^4 m^3$)
Residual materials	940.18	407.09	1041.54	2388.1	796
Colluvial deposits	6.472	0.162	6.096	1158	579
Landslide deposits		90.1	765	855.1	285
Ancient debris flow deposits			411	411	

Previous research revealed that not all loose deposits can contribute to the formation of debris flow. The probable amount of the loose deposit which participates in debris flow formation mainly depends on the entrainment capability of the runoff during rainfall. To explore the amount of the loose deposits which can participate in debris flow formation, the unstable soil layers on each slope were evaluated meticulously, and the relevant volume was determined. On the basis of the determined amount of the loose deposits, and combined with the prediction model, the conditions for initiation of the debris flow in Aizi gully watershed can be established.

Rainfall condition in Aizi gully watershed

The rainfall data was collected from local meteorological stations, and historical rainfall data was acquired with the help of the local government, which greatly facilitated the following calculation process. The historical maximum rainfall data is shown in Table.2, by which we found that the rainfall in Aizi gully was mainly concentrated in June and July, Fig.4.

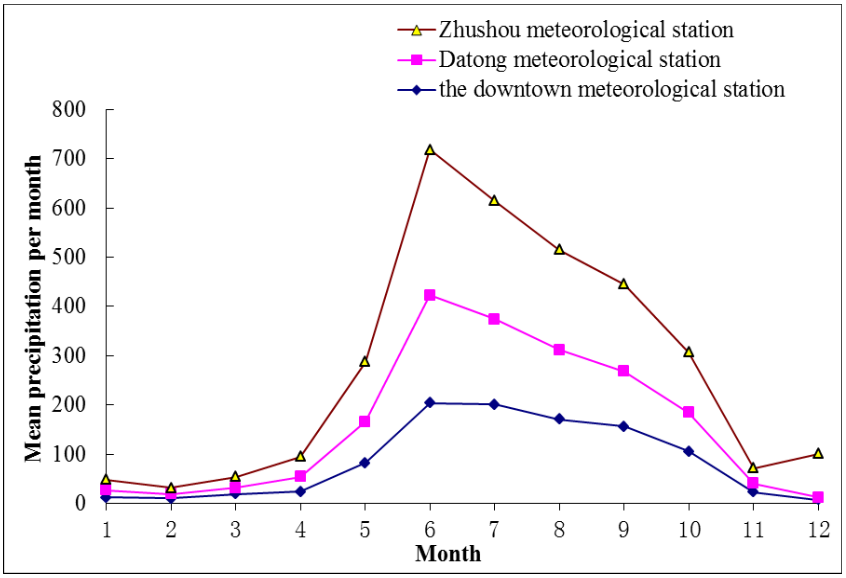

Figure 4: The mean precipitation from 1986 to 2005 in Aizi gully watershed

Table 2: The maximum rainfall of each month in Aizi gully from 1986 to 2005

Month	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Maximum rainfall(mm)	25.7	15.4	34.8	23.4	40.1	138.0	105.7	94.8	63.0	57.7	28.4	15.2
Occurrence in the year	1992	2000	1994	2004	2003	1998	1992	2004	1989	1995	1995	1987
Occurrence in the day	21	27	21	15	28	18	5	23	4	8	2	15

Soil-Water coupling model

The coupling process between the runoff and unstable soil on the slope will result in the formation of debris flow. Due to the complexity of the formation processes, related numerical or physical models are rarely seen at present[22]. From field observation, we found that debris flow is a water-soil mixture with a high density. As a characteristic value of the debris flow, the density is an important index to distinguish the flood, hyper-concentrated flow, dilute debris flow and viscous debris flow, which also represents the proportion of solid material in a debris flow. The density of the mixture reaching a certain value is a necessary condition for debris flow formation, but it is not a sufficient condition. Therefore, the bulk density can be employed to evaluate the probability of debris flow formation, but we cannot determine that debris flow will certainly happen. Apparently, the bigger the bulk density of mixture, the bigger is the formation probability of debris flow, but there is no function available to reveal this relationship. According to Kang[23], the density of debris flow varies from 1.1 to 2.3 $g \cdot cm^{-3}$. If the density of the mixture is divided into a series of reference intervals as in Table 1, the formation probability of debris flow becomes larger from 1st interval to 5th interval of the density[2]. Five grades of debris flow warning are defined according to these density intervals as Table 3.

Table 3: Probability of debris flow formation on the basis of bulk density of water-soil mixture

Standard debris flow density(g/cm^3)	$\rho < 1.2$	$\rho < 1.2-1.5$	$\rho < 1.5-1.8$	$\rho < 1.8-2.0$	$\rho < 2.0-2.3$
Probability of debris flow(%)	0-20	20-40	40-60	60-80	80-100
Grade of early warning	1st	2nd	3rd	4th	5th
Colour of early warning	No Colour	Blue	Yellow	Orange	Red

The bulk density of the mixture is a key factor of this model, which can be estimated from the rainfall runoff and the potential volume of the failure soil mass with the following equation:

$$\rho = \frac{\rho_W V_W + \rho_S V_S}{V_W + V_S} \qquad (8)$$

where ρ is the bulk density of the water-soil mixture, ρ_W is the bulk density of water, ρ_S is the bulk density of solid particle (generally, $\rho_S = 2.7$ g/cm^3), V_W is the volume of the runoff and V_S is the volume of failure soil mass.

RESULTS AND DISCUSSION

Having analyzed the amount of the loose deposits, meteorological condition and topography, we found that Aizi gully still has the potential to form large debris flows. Therefore, without engineering countermeasures or an early warning system, a catastrophic disaster can be caused by a debris flow in this watershed. With the aim of reducing the risk and improving the development of the local economy, and guaranteeing the security of the residents in this area, timely and accurate forecast information is the efficient way to achieve this goal. Therefore, the density of the mixture is employed as a prediction index in this paper. The results of the calculation may be compared with Table.3 to determine the warning grade.

In terms of the water-soil coupling Eq. 8, with the aim of using the mixture density ρ for issuing the prediction information of the debris flow in Aizi gully watershed, the total amount of the unstable soil mass V_S and runoff V_W due to rainfall process should be estimated in real-time. The two key parameters are closely related with the variation of soil water content, matrix suction and runoff under the action of the rainfall. Therefore the hydrological process in Aizi gully watershed should be simulated to get these hydrological parameters[24,25].

In section 3.2.1, we identified that the rainfall mainly concentrates in June and July. Therefore, we use the cumulative rainfall data in these two months to calculate the bulk density of the water-soil mixture. Comparing the results of calculation with Table.3, the Probability of debris flow occurrence can be estimated. With the aim of reducing disasters caused by the debris flow in Aizi gully watershed, an early warning system can be established[26]. Forecast information can be issued in a timely manner with the help of local meteorological stations.

Combining the field investigation with the soil-water coupling model, the critical rainfall for each interval can be identified. In this paper, we used 10mins rainfall, 1hour rainfall and 24hours rainfall as the forecast indices to predict the occurrence of debris flow. Through calculation, we found that without antecedent rainfall, as the cumulative rainfall in 24hours reached 30mm, the density of the mixture was in the interval corresponding to the 4th grade of debris flow warning. Moreover, if the antecedent cumulative rainfall within the five days prior to the rainfall event reached 18mm, the 24hours cumulative rainfall less than 30mm would probably trigger the occurrence of debris flow in Aizi gully watershed. In terms of 10mins rainfall, as the rainfall amount in 10mins reached 4.48mm, the density of the mixture was in the interval corresponding to the 3rd grade of debris flow warning. Furthermore, when 1hour rainfall was employed as the index to forecast the occurrence of debris flow in the watershed, by computation we found that as the 1hour rainfall reached 7.88mm, the density of the mixture is falling into the 3rd warning grade. As the cumulative rainfall increased, the probability and scale of the occurrence of the debris flow in Aizi gully increased. To better fulfill the demands of disaster mitigation and prevention, an early warning system based on critical rainfall can be established in this watershed, which can greatly beneficial to debris flow forecast.

CONCLUSIONS

Having analyzed the formation mechanism of the debris flow in Aizi gully, we found that the debris flow formation process can be described as follows: the run-off generated by rainfall entrained a huge amount of loose material as it flowed down the slope. This caused shallow slides, and transforming the process into debris flow in a second stage. After this initial phase, the debris flow volume increased rapidly by a chain of subsequent cascading processes starting with collapses of the sidewalls of the banks, damming and breaching, leading to a rapid widening of the erosion channel. In terms of erosion amount, the subsequent mechanisms were much more important than the initial one. The damming and breaching were found to be the main reasons for the huge magnitude of the debris flows in Aizi gully watershed.

With the help of field investigation and remote sensing interpretation, we found that the loose deposits, rainfall condition and topography condition still satisfied the demands of debris flow initiation conditions. Therefore, the debris flow in Aizi gully watershed can pose a great threat to local economic development and the security of the residents. In order to reduce the risk posed by the debris flow in this area, we used the soil-water coupling model to calculate the density of the mixture, and took this as the index to forecast the probability of the occurrence of the debris flow. We used the cumulative rainfall amount in 10mins, 1hour and 24hour periods to compute the mixture density, and compared the calculated results with Table.3, so that the warning grade can be identified. The critical rainfall for 10mins, 1hour and 24hours are 4.28mm, 7.78mm and 30mm, respectively. As the amount of rainfall increased, the probability of the occurrence of debris flow increased, and the warning grade becomes higher. Base on the above analysis, with the aid of local meteorological station data, the real-time rainfall data can be acquired and the forecast information can be issued in a timely way. This in turn can greatly benefit disaster mitigation and prevention, which can facilitate the development of the local economy and enhance people’s safety.

ACKNOWLEDGEMENTS

This work was financially supported by Doctoral fund at Henan Polytechnic University (Grant No. B2015-58), CRSRI Open Research Program (Program SN: CKWV2015205/KY), and the National Natural Science Foundation of China (41302284).

REFERENCES

[1] Hu W, Dong XJ, Xu Q, et al. Initiation processes for run-off generated debris flows in the Wenchuan earthquake area of China[J]. Geomorphology. 2016, 253: 468-477.

[2] Zhang S, Yang H, Wei F, et al. A model of debris flow forecast based on the water-soil coupling mechanism[J]. Journal of Earth Science. 2014, 25: 757-763.

[3] Chen N-s, Tanoli JI, Hu G-S, et al. Outlining a stepwise, multi-parameter debris flow monitoring and warning system: an example of application in Aizi Valley, China[J]. Journal of Mountain Science， 2016, 13(9): 1527-1543.

[4] Hürlimann M, Copons R, Altimir J. Detailed debris flow hazard assessment in Andorra: a multidisciplinary approach[J]. Geomorphology. 2006, 78(3): 359-372.

[5] Sättele M, Bründl M, Straub D. Quantifying the effectiveness of early warning systems for natural hazards[J]. Nat Hazards Earth Syst Sci. 2016, 16(1): 149-166.

[6] Sepúlveda SA, Rebolledo S, Vargas G. Recent catastrophic debris flows in Chile: Geological hazard, climatic relationships and human response[J]. Quaternary International. 2006, 158(1): 83-95.

[7] Park DW, Lee SR, Vasu NN, et al. Coupled model for simulation of landslides and debris flows at local scale[J]. Natural Hazards. 2016: 1-30.

[8] Wei L-W, Lin H-H, Chi C-C. The establishment of rainfall thresholds for debris slide in Taiwan-with the combination of multivariate analysis and the IR index[J]. Japanese Geotechnical Society Special Publication. 2016, 2(29): 1069-1074.

[9] Guzzetti F, Carrara A, Cardinali M, et al. Landslide hazard evaluation: a review of current techniques and their application in a multi-scale study, Central Italy[J]. Geomorphology, 1999, 31(1): 181-216 %@ 0169-0555X.

[10] Liu D, Zhang S, Yang H, et al. Application and analysis of debris-flow early warning system in Wenchuan earthquake-affected area[J]. Natural Hazards and Earth System Sciences， 2016， 16(2): 483-496.

[11] Bathurst JC, Burton A, Ward TJ. Debris flow run-out and landslide sediment delivery model tests[J]. Journal of Hydraulic Engineering, 1997, 123(5): 410-419.

[12] Giannecchini R, Naldini D, Avanzi GDA, et al. Modelling of the initiation of rainfall-induced debris flows in the Cardoso basin (Apuan Alps, Italy)[J]. Quaternary International, 2007, 171: 108-117.

[13] Ni H-Y. Experimental study on initiation of gully-type debris flow based on artificial rainfall and channel runoff[J]. Environmental Earth Sciences, 2014,73: 6213-6227.

[14] SHIMA J, MORIYAMA H, KOKURYO H, et al. Prevention and Mitigation of Debris Flow Hazards by Using Steel Open-Type Sabo Dams[J]. International Journal of Erosion Control Engineering, 2016， 9(3): 135-144.

[15] Sun G, Cheng S, Jiang W, et al. A global procedure for stability analysis of slopes based on the Morgenstern-Price assumption and its applications[J]. Computers and Geotechnics, 2016, 80: 97-106.

[16] Chen NS, Zhou W, Yang CL, et al. The processes and mechanism of failure and debris flow initiation for gravel soil with different clay content[J]. Geomorphology, 2010, 121(3-4): 222-230.

[17] Klubertanz G, Laloui L, Vulliet L. Identification of mechanisms for landslide type initiation of debris flows[J]. Engineering Geology, 2009, 109(1): 114-123.

[18] Ni HY, Zheng WM, Tie YB, et al. Formation and characteristics of post-earthquake debris flow: a case study from Wenjia gully in Mianzhu, Sichuan, SW China[J]. Natural Hazards, 2011, 61: 317-335.

[19] Sun G, Huang Y, Li C, et al. Formation mechanism, deformation characteristics and stability analysis of Wujiang landslide near Centianhe reservoir dam[J]. Engineering Geology, 2016, 211: 27-38.

[20] Yu B, Zhu Y, Wang T, et al. A prediction model for debris flows triggered by a runoff-induced mechanism[J]. Natural Hazards, 2014, 74: 1141-1161.

[21] Van Genuchten MT. A closed-form equation for predicting the hydraulic conductivity of unsaturated soils[J]. Soil Science Society of America Journal, 1980, 44(5): 892-898.

[22] Zhou W, Tang C, Asch TWJ, et al. Rainfall-triggering response patterns of post-seismic debris flows in the Wenchuan earthquake area[J]. Natural Hazards, 2013, 70: 1417-1435.

[23] Kang Z, Lee C, Law K, et al. Debris flow research in China[M]. 2004.

[24] Cong Z, Yang D, Gao B, et al. Hydrological trend analysis in the Yellow River basin using a distributed hydrological model[J]. Water Resources Research, 2009, 45(7): 1-13.

[25] Yang D, Herath S, Musiake K. A hillslope-based hydrological model using catchment area and width functions[J]. Hydrological Sciences Journal, 2002, 47(1): 49-65.

[26] Papa M, Medina V, Ciervo F, et al. Derivation of critical rainfall thresholds for shallow landslides as a tool for debris flow early warning systems[J]. Hydrology and Earth System Sciences, 2013,17(10): 4095-4107.

Other papers on Debris Flow in EJGE:

[1] He Na, N.S. Chen, Zeng Mei, Chen Rong: “Runout Prediction of Aizi Gully Debris Flow Based on Model Calculation” *Electronic Journal of Geotechnical Engineering*, 2014: (19/Z4) pp 17039-17051. Available at ejge.com.

[2] Wu Hengbin, He Zeping, Mao Haitao, Zhou Tingqiang: “On the Motion of Debris Flow Based on the Energy Conservation Law” *Electronic Journal of Geotechnical Engineering*, 2014: (19/s) pp 4555-4573. Available at ejge.com.

[3] Dapeng Zhu, Qiduo He, and Shier Dong: “Inversion Analysis on Critical Moisture and Flow Velocity Formula of Debris Flow Based on Physical Simulation Test” *Electronic Journal of Geotechnical Engineering*, 2012: (17/X) pp 3371-3377. Available at ejge.com.

[4] Liu Daxiang: “Basic Characteristics and Proneness Evaluation about Debris Flow in Zhangmu Gully of Tibet” *Electronic Journal of Geotechnical Engineering*, 2017 (22.07), pp 2675-2688. Available at ejge.com.

[5] Dr. Muhammad Syukri, Dr. Rosli Saad, Dr. M.M. Nordiana, and I. N. Azwin: “Preliminary Study of Sumatera Fault Using 2-D Resistivity Imaging Method” *Electronic Journal of Geotechnical Engineering*, 2014: (19/D) pp 971-979. Available at ejge.com.

[6] Abdoullah Namdar: “Tsunami and Liquefaction Resistance of Subsoil” *Electronic Journal of Geotechnical Engineering*, 2013: (18/Y) pp 5907-5919. Available at ejge.com.

[7] Marwan & Asrillah: “Determining and Characterizing Bedrocks Using Geo-electrical and Geotechnical Method at Belawan-North Sumatra” *Electronic Journal of Geotechnical Engineering*, 2015: (20.3) pp 1075-1085. Available at ejge.com.

[8] Tang DeLan and Xiao QiaoLin: “Mechanical Properties Research Base on Porous Basalt” *Electronic Journal of Geotechnical Engineering*, 2014: (19.X) pp 8295-8304. Available at ejge.com.

* * *

Editor’s note.
This paper may be referred to, in other articles, as:

He Na, Niu Haicheng, N. Sh. Chen, Zhong Wei, and Tom Cosgrove: “Debris Flow Forecast Based on Soil-Water Coupling Mechanism: A Case Study in Aizi Gully Watershed” *Electronic Journal of Geotechnical Engineering*, 2017 (22.14), pp 5465-5478. Available at ejge.com.