A Preliminary Test Study on Debris Flows in a Contracted Drainage Channel at Mawan Valley, Chongqing

Huo Miao^{1,a,*}, Wang Xu^{2,b}, He Chuankai^{3,c}, Liang Yufeng^{4,d}, Zhao Jiangtao^{1,e}, Qi Lijian^{1,f}, Jiang Chenjie^{1,g}

¹College of Water Conservancy and Hydropower Engineering, Sichuan Agricultural University, Ya'an City, 625014, China
²Ocean College, Zhejiang University, Zhoushan, 316021, China
³China Datang Corporation, Chengdu University, Chengdu, 610031, China
⁴Research Design and Research Institute of Sichuan University, Chengdu, 610065, China
^ahuomiao@sicau.edu.cn, ^b1203045@zju.edu.cn, ^c812980876@qq.com, ^d371289809@qq.com,
^e14709@sicau.edu.cn, ^f171282346@qq.com, ^g1959364329@qq.com
*Corresponding author

Abstract: A drainage channel is an efficient debris flow countermeasure, but defects in practical function exist due to the non-peer exchange between post-geological hazard investigation and flow dynamics estimation. Especially in a drainage channel with a contracted entrance, the structural design depends on the peak discharge, the velocity of a debris flow, and the interaction between sediment and structure. This paper mainly explores debris flows interacting with a contracted channel before the drainage part through flume model tests. Results are illustrated as follows: i) In and after the contracted section, overflow and silting of debris flow are coexistent. Overflow grows with the increasing entrance inclination and the total debris flow volume. The silting efficiency keeps in higher quantity and drops roughly with increasing the total debris flow volume. Overflow and silting are both controlled when contraction angle β is reduced. ii) The debris flow in the entrance exceeds lateral wall height instantly when the contraction angle β is equal to 21.23° but falls down when β is smaller (equal to 19.14°). The deflection angle of the shock wave front φ varies in a small range with β . The normalization of maximum wave thickness in the entrance has a positive parabola correlation with the Froude coefficient Fr while decreasing β can reduce the normalized thickness. iii) The impact load of a debris flow on the lateral walls shows a hydrodynamic pattern analogy. The peak load has a positive linear relationship with Fr. Furthermore, the coefficient indicating the normalization of peak loadaneeds to be corrected according to the deflection angle of the shock wave front φ .

Keywords: Debris flow, Contracted drainage channel, Overflow and silting, Impact load

1. Introduction

Debris flows are a frequent transport of sediment with broad content of fluid and solid, which can threaten the safety of residents and infrastructures nearby ^[1-2]. Based on the assessments of triggering and flowing modes, many countermeasures are designed to preserve people or reinforce the buildings from debris flows ^[3-4]. As a type of countermeasures in the alluvial areas, the drainage channel can reset the flow path to secured sites ^[5]. In mountainous regions of China, where debris flows frequently run out and deposit, drainage channel plays a dominant role in related prevention plans ^[6]. Lateral wall height, longitudinal gradient, and section, which quantify the dimension and efficiency of a drainage structure, are mainly designed according to the peak discharge and the momentum of a debris flow ^[7-8]. Moreover, a drainage channel with narrowed cross-sections and variable longitudinal gradients is often designed due to the restriction of topographies and the intention of increasing flush velocity ^[9-10]. One typical example is a contracted transition entrance aiming to guide debris flows into the drainage structure and accelerate sediment transport while disturbing the flows under insufficient structure size if any. Furthermore, prediction models of debris flows may not account for the interaction of fluids and solid granular in natural cases ^[11]. A rational design needs to investigate variant movements of debris flow in the contracted entrance of a drainage channel through comprehensive methods.

Some studies have discussed the superthickness of a debris flow in a curved channel, indicating that bending superthickness could affect flow profile and velocity concerning lateral wall height and structure ^[12-14]. Wang ^[15] suggested that a debris flow in a bending channel could be divided into two parts: the mud flow superthickness along the tangent direction and the other is the moving in radial direction generating overflow along the lateral wall. Moreover, Parameshwari ^[16] dynamics. However, contractions in natural or artificial debris-flow channels where overflow and blockage can be visible in engineering practice are rarely reckoned. Liu ^[17] evaluated a waste disposal yard of a hydropower station, which shrinks the flow path of a debris flow-prone tributary gully. They stressed that debris flows in the contracted channel could impact the stability of the different bank. A contraction reduces not only the debris flow discharge rate but also a channel's space volume; thus, redundant sediments may overflow. Kean ^[18] introduced a factor of a natural channel, namely a sediment capacitor, to evaluate the propagation of a debris flow, which is related to longitudinal gradient and impact intermittent dynamics. This capacitor provides a new thought to understand the spatial discharge of a debris flow in a channel. However, a lack of knowledge on contraction impact hinders the accuracy of engineering design strategy.

To understand the overflow and blockage mechanism of a debris flow in a contracted entrance, this study simulates and analyses multiple sediment movements in a model channel with a contracted entrance according to an actual engineering design plan, and several typical patterns of debris flows are preliminarily discussed.

2. Study Site

The study site is located at the exit of Mawan valley (E108°0'16.31", N29°32'3.74", a debris flow gully in Houping Township, Wulong District, Chongqing, China), where a hydropower station is built. On June 21st, 2019, a long duration of heavy rainfall (105 mm in three hours) induced debris flows. In the event, 15,000 m³ of sediments washed out (the solid fraction is approximately 0.7), and about 4800 m³ of sediment jammed the box culvert (3.0 m×2.8 m) of the hydropower station that is designed to discharge flash floods. The depth of the debris flow ranged from 1 to 3 m, and the grain size distribution of the sediment is from 0.002 mm to 800 mm. Eventually, the first floor of the main powerhouse and the whole backside area were submerged by the debris flow, and most generator sets and frontal roads were damaged (Fig. 1).



Figure 1: The impact area of the debris flow on June 21st., 2019, Mawan valley: (a) the hydropower station, (b) the initiation area of the debris flow, and (c) the debris alluviation behind the powerhouse.

Afterward, a drainage channel is designed to make sediments and fluids bypass the powerhouse, and the cross-section of the channel is narrowed through a symmetric contraction due to the limitation of local geomorphology (Fig. 2). Cross section and longitudinal gradient of the channel structure are determined by the peak discharge and velocity, which are derived from post-field surveys on mud cracks of the latest event based on technical guidelines related to debris flow prevention and control engineering (Ministry of Land and Resources of the People's Republic of China 2018)^[19]. However, the dynamical effects of the contracted segment, namely a transition entrance of the channel, are neglected initially. Approximately 31,900 m³ of loose sediments lies in the upstream channel and can be easily entrained by runoff on rainy days, indicating that a subsequent debris flow is prone to occur, and the

discharge capacity of the designed drainage channel would be challenged. Since the dynamics of debris flow in this non-uniform channel remain uncertain, it is integral to study the possible impacts of the contraction. We only accept papers written in English and without orthographic errors.



Figure 2: Initial design drawing of the drainage channel: (a) layout plan, (b) longitudinal profile (the elevation system is set up according to Yellow Sea Height Datum), and (c) cross-section of the channel.

3. Methods

A series of small scale flume model tests is conducted to investigate the interaction between flow dynamics and the contracted entrance in the drainage channel design. The flume facility (4.5 m long) mainly consists of a descending part and a drainage part. The flume is divided into two steel-framed transparent broadsides and one steel bottom, and the cross-section of the flume is constantly rectangular (sized 0.4×0.4 m).

The longitudinal gradient is adjustable by a novel pulley block located at the top of the flume (Fig. 3a). The drainage part mainly consists of the contracted entrance and subsequent channel segment. Rigid cystosepiments with a length of 0.36 m are shaped and glued to broadsides, forming the sidewall model, like a cone-shaped entrance of the model drainage channel to simulate the contracted part, the contraction angle or the width of which is adjustable (Fig. 3b). The initiation of model debris flow complies with an efficient way, i.e., water run-off ^[20]. Solid sediments are piled near the top of the device where water can flush out from an overflow weir. The water supply through the overflow weir can provide approximately a discharge rate of 15 liter per second, which as pretested successfully mobilizes the sediments (Fig.3c). The paved thickness of the solid sediments for debris-flow initiation is 0.05 m, and two lengths are employed- 0.80 m and 1.50 m, respectively, to generate debris flows with two kinds of volumes.

According to the open-channel and the gravity-driven features of debris flow, the principle of similarity in model tests refers to the geomorphology of the prototype and the proximity of the gravity acceleration g and the Froude number $Fr^{[21-22]}$. Related dimension scale without centrifuge is ruled in Table 1 and Table 2. Solid sediments are gathered from field debris depositions with clay, sand and gravel and are primarily angular. The maximum sieving diameter of sediments is 16 mm according to the dimension scale, and the diameter size under 0.1 mm stays with the prototype (Fig. 3d). Twenty cases, including parallel subsets with equivalent conditions, comprise varied initiations and

compositions of debris flows, longitudinal descending gradients, and contraction angles of the entrance, and control variables are listed in Table 3.

Dimension	Unit	Scale value
Bulk density ρ_P / ρ_M	kg/m ³	1
Gravity acceleration g_P/g_M	m/s ²	1
Froude coefficient F_{rP}/F_{rM}	-	1
Size L_P/L_M	m	50
Volume V_P/V_M	m ³	50 ³
Discharge Q_P/Q_M	m ³ /s	50 ^{5/2}
Velocity U_P/U_M	m/s	501/2
Time T_P/T_M	S	501/2
Load stress P_P/P_M	Pa	50

Table 1: Scale set of debris flow model.

Notice: Subscript *P* and *M* are abbreviations of prototype and model.

Physical parameters	Prototype	Model
Bulk volume of solid sediment (m ³)	-	0.027/0.013
Volume of water (m ³)	-	0.011/0.006
Solid fraction	0.7	0.7
Total volume of debris flow(m ³)	4800/2400	0.038/0.019
Developing zone length (m)	75	1.5
Bulk density of debris flow (10 ³ kg/m ³)	1.82	1.82±0.05
Maximum particle diameter (m)	0.80	0.016
Length of gully before entrance (m)	122.00	2.44
Width of gully before entrance B_0 (m)	20.00	0.40
Longitudinal gradient of the entrance θ (°)	11.6	9/12/15
Sidewall height of drainage channel (m)	4.00	0.08
Net width of drainage channel $B_1(m)$	6.00/7.50(broadening)	0.12/0.15(broadening)
Longitudinal gradient of drainage channel (°)	2.3	2.3

Table 2: Distinction between prototype and model.

Notice: Broadening means the increasing of the net width.

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Case	Total volume (m ³)	Flume inclination (°)	Contraction angle β (°)
1		9	
2		9	
3	0.029	12	
4	0.038	12	
5		15	21.22
6		15	21.25
7		12	
8	0.019	12	
9		15	
10		15	
11		12	
12	0.029	12	10.14
13	0.038	15	19.14
14		15	

A high-speed camera (serial number is N4, shooting at 200 frames per second) and a digital camera are employed to monitor the performance of the debris flow along the model channel simultaneously. The velocity and the thickness of model debris flow along the contracted channel, are both tracked and back-calculated by analytical video frames. Two ultrasonic distance detection sensors are planted before the entrance to produce a backup calculation of the debris flow thickness for the back-calculated values (Fig. 3e).



Figure 3: Experimental model configurations: (a) profile and size dimension of flume facility, (b) vertical view of the contracted entrance model and (c) layout, (d) grain size distribution of sediments for the debris flow initiation and (e) two ultrasonic sensors for the measurement of the flow thickness before the entrance.

The overflow and silting efficiencies are both defined as a mass ratio of sediment to that of the debris flow, respectively. Sediment mass is collected and measured in the cone-shaped spot, and overflow mass can be retrieved at the top of the sidewall model after each surge test. An earth load cell that only receives normal impact stress is planted on the left sidewall of the entrance, so the thrust of a debris flow can be quantified.

4. Results

4.1. Post Static Measurements

Measurements after model debris flow in the entrance show that the narrowed effect before the drainage channel induces both overflows and silting of sediments in all cases with the contraction angle β of 21.23° or the net channel width B_1 of 0.12 m. However, considerable gaps in efficiencies between overflows and silting due to different experimental setups. The overflow efficiency is low (below 0.13) and increases with the increasing of the descending gradient θ and the total debris flow volume V_0 (Fig. 4a and 4b). Moreover, as shown in Fig. 4c, the silting efficiency exceeds 0.55 but shows a disproportionate trend with θ . The silting efficiency drops when the volume of debris flows is doubled (Fig. 4d). As the contraction angle reduces to 19.14°(B_1 is broadening to 0.15 m), both overflow and silting decline sharply (Fig. 4e). Post measurements in the channel model indicate that in the contracted part, the overflow state is generally slight and is relevant with β and θ of the channel and V0 of a debris flow. On the other hand, the silting state is more evident and is relevant with β and V_0 .



Figure 4: Overflow and silting that vary with multiple configurations of model drainage channel: (a) overflow that varies with descending gradient θ , (b) overflow that varies with total volume, (c) silting that varies with descending gradient θ , (d) silting that varies with total volume V0 and (e) overflow and silting efficiency under the variation of β .

4.2. Debris Flow Dynamics in the Entrance

Despite the low overflow gauge, the instant thickness of debris flow that exceeds the lateral wall height may not be practically allowed for its high impact on the infrastructures. Besides, postmeasurements dominated by saturated solid sediments also lower the efficiencies of the overflow and silting due to a significant loss of water from sediments. Therefore, to improve the evaluation of instant overflow, movements of the water-solid mixture are analyzed through synchronous video frames of frontal and lateral shootings. Instantaneous motion capture shows that the maximum thickness of debris flow h_1 mostly occurs at the entrance of the drainage channel, and all exceeded the lateral wall height (80 mm) (Fig. 5a-f). The velocity and the thickness of the incoming debris flow U_0 and h_0 are computed after the analysis of frame by frame with an identical time interval of 0.02 seconds using the tracking module in the Image-pro Plus Program (abbreviated as IPP) (Fig. 5g). Here we employ the average of the IPP track measurements and data output by the two ultrasonic distance detection sensors to verify the ultimate thickness before the entrance.



Figure 5: Moving profiles of debris flows in the contracted entrance: (a) $9^{\circ}(\theta)$ - 0.019 m³ (V₀), (b) $12^{\circ}(\theta)$ -0.019 m³(V₀), (c) $15^{\circ}(\theta)$ -0.019 m³(V₀), (d) $9^{\circ}(\theta)$ -0.038 m³(V₀), (e) $12^{\circ}(\theta)$ -0.038 m³(V₀), and (f) $15^{\circ}(\theta)$ -0.038 m³(V₀), and (g) tracking process of velocity and thickness using the snap shot sequence.

Table A. Dynamical	variables in t	he wave	thickness	analysis	lincluding	narallal	cases)
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Fr	B_1/B_0	Wave deflection angle $\varphi(^{\circ})$	h1/h0
2.652		42	4.539
2.417		39	4.404
2.435		41	3.470
3.258		43	5.130
4.527		45	6.735
3.247		44	5.018
3.673	0.3	45	6.063
4.847		43	7.764
4.464		42	6.347
3.118		45	4.546
2.540		43	3.512
2.384		41	3.889
2.839		42	4.030
3.022		38	3.196
2.807		40	3.106
2.839		40	4.146
3.022		39	4.160
2.807		39	4.545
3.945	0.375	42	4.539
4.651		39	4.404
4.401		41	3.470



Figure 6: Display of patterns of overflow and silting in one typical case (θ : 15°-V₀: 0.019 m³): (a) top view and (c) profile view of overflow at the early stage, and (b) top view and (d) profile view of overflow and silting at the later stage.

A shock wave front is also monitored under the contraction angle deflection of the lateral walls through the top camera view. The transverse blockage effect contributes to the increasing of h_1 . The pattern of overflow is roughly divided into two stages of debris flow surge: i) the first surge parallel to the adjacent lateral wall develops into the run-up flow mode and silts up (Fig. 6a and 6c), and ii) the subsequent partial wave normal to the adjacent lateral wall overrides the sedimentation and flows over the lateral walls (Fig. 6b and 6d). The incoming debris flow undergoes thickness jumping (from h_0 to h_1) in the entrance. According to Ippen ^[23] and Zhou ^[24], the normalization of maximum thickness $h1/h_0$ is related to Froude coefficient before the contraction Fr, the angle between the edge of wave-front, the adjacent lateral wall axis, i.e., wave deflection angle φ and transverse blockage effect that is defined by the ratio of B_1 to B_0 . Test cases indicate that φ fluctuates in a small range with β (38° and 40° under β =19.14°, 39° and 45° under β =21.23°) (Table 4). The h_1/h_0 has positive correlation with Fr, and the best appropriate fitting curve of the scatter data is the parabola. In addition, h_1/h_0 under $B_1/B_0 = 0.375$ is smaller than the one under $B_1/B_0 = 0.300$, meaning the increasing of B_1/B_0 can enhance the unblocked effect of the entrance (Fig. 7).



Figure 7: The normalization of maximum thickness of debris flow h_1/h_0 varying with the Fr and the blockage B_1/B_0 , noting that B_1 and B_2 in tables are parameters of fitting-curve expressions.

4.3. Surge Impact on the Lateral Wall

In each test case, the debris-flow impact load on the left sidewall of the entrance increases abruptly to the peak value in the early period of a debris flow. It then shows load attenuation with a small range

of fluctuation (Fig. 8a), the tendency of which is analogous to one on the rigid debris-flow barrier ^[25]. The decline and stabilization of the load data after the peak value can be interpreted as volume loss of sediment and deposition. Figure 8b shows that the peak load Pm has a positive linear relationship with *Fr* (the fitting formula is P_m =3.79*Fr*, and the correlation coefficient R^2 =0.996); however, the dimension of both hands of the fitting formula is not equivalent. As inspired by Cui ^[26] and Jiang and Towhata ^[27], an empirical impact coefficient α is employed in the dimension analysis of the impact mechanism:

$$\alpha = \frac{P_m}{\rho U_0^2} \tag{1}$$

where ρ is the bulk density of debris flow. α , in this case, ranges from 1.90 to 3.01 and approximately decreases with *Fr*, which, however, exceeds the value calculated by the model proposed by Cui ^[26] (Fig. 8c).



Figure 8: Impact surge effect on the left lateral wall of the contracted entrance: (a) impact load versus time, (b) impact load versus Fr, (c) the empirical coefficient and correction of impact load varying with Fr, and (d) diagrammatic sketch of flow velocity direction under the impact of the shock wave in the contraction.

5. Discussion

This study aims at overflow and silting behaviors of debris flow surges in a drainage channel with a symmetrically contracted entrance. Though rough boundary conditions and the similarity of the experimental flume model can't meet the similarity of dynamics perfectly, some technical insights on the incoming flow inside the entrance are underlined. In terms of the facilitation of channel slope and volume of a debris-flow surge ^[28-29], both the *Fr* and V_0 of a debris flow and the contraction angle β should be taken into account, which may provide a new trend to improve the flow efficiency of the channel structure in practice. Lessening the contraction angle or broadening the channel width is a good way to address the issues of overflow and silting. The *Fr* and B_1/B_0 are highly sensitive to the maximum thickness normalization of overflow wave h_1 .

For the specious fluid feature of a debris flow, bilateral contraction and top free surface of the entrance induce pressure differences in the debris flows and squeeze partial slurry out, while the narrowing of the channel space increases particle contact probability, resulting in evident sedimentation. Thorough discussions on the flow states, particle frictions and collisions, clogging of large particles, and washing effects of post-water flow should be considered in further study ^[30-31]. The prediction of

the maximum wave thickness should be a momentum approach that integrates shock wave, longitudinal height jump, and transverse blocking effect, which is linked with the hypothesis of the shock wave before a slit dam and/or a wall-like obstacle ^[32-33]. Theoretical deduction is not performed here due to a lack of understanding of the fluid pressure differences and experimental limitations. Therefore, the further study will stress solid-fluid interaction, focus on the dynamic pressure difference and extend the interaction between sediment and the contracted entrance to evaluate thickness jump more precisely.

The impact load here is a preliminary parameter for evaluating the thrust on the sidewalls under nondestructive circumstances. The higher gauge of the coefficient α in our experiments than that in the model proposed by Cui^[26] indicates not only the *Fr* but also the deflection angle of shock wave front φ . The normal impact should be related to the normal component of the velocity that is perpendicular to the shock wave front U_{1n} (Fig. 8d). Based on the geometry relationship, U_{1n} can be given:

$$\begin{cases} U_{1n} = U_{1s} \tan(\varphi - \beta) \\ U_0 \cos \varphi = U_{1s} \end{cases}$$
(2)

where U_{1n} is the velocity that is perpendicular to the shock wave front and U_{1s} is the velocity that is parallel to the shock wave front. An additional coefficient ξ is introduced to correct the impact coefficient as follow:

$$\begin{cases} a_{1n} = \frac{P}{\rho U_{1n}^2} = \xi \alpha \\ \xi = \cos^2 \varphi \cdot \tan^2 (\varphi - \beta) \end{cases}$$
(3)

As shown in Fig. 8, ξ can be calibrated by the values of φ and β , which in some extent explains the difference with the calculation by the model proposed by Cui^[26].

In practice, the effects of impact energy, deformation, tensile strength, and failure mode should be quantified as integrated with the load effects ^[33]. As suggested by Ng ^[34], the fluctuations of the peak load here are inferred as a concentrated load exerted by several boulders in the model debris flows (the maximum grain diameter of which is16 mm). The peak value P_m after scaling up to the prototype reaches 0.82 MPa, which is below the compressive strength of a concrete structure, but there is no direct proof of the structure's safety. In the subsequent study, the impact load and the velocity and pressure changes behind the wave front will be considered to establish a dynamical thickness prediction model.

The above-mentioned discussion emphasizes the interaction between the dynamics of a debris flow and the contracted entrance in controlling overflow and silting, and technical issues about this mechanism are imperative to be resolved. Moreover, this study has been carried out for two years since 2020, and the final construction plan of the drainage channel adopted our suggestion about increasing the net width and reducing the contraction angle as well as increasing the sidewall height (Fig. 9). The follow-up survey on the engineering project is conducted in 2022, and no overflow has been detected since the channel was built in 2020.



Figure 9: Eventual construction of the drainage channel (units: m): (a) the downstream view (taken in 2022), (b) the upstream view (taken in 2022), (c) the final cross-section, and (d) the originally designed cross-section of the channel.

ISSN 2616-5872 Vol.6, Issue 1: 7-18, DOI: 10.25236/AJEE.2024.060102

6. Conclusions

Flume model tests are employed based on a specific engineering project to explore the interaction between debris flows and a contracted drainage channel. With high-speed visual analyzing and angular processing of debris flows, this study covers several key factors, i.e., overflow and silting efficiencies, the maximum wave thickness, and impact load on the left lateral wall of the entrance. The major findings are listed as follows:

a) The overflow efficiency and maximum wave thickness in the contracted entrance grow with the increase of the longitudinal gradient and total debris flow volume. The silting efficiency is much greater than the overflow efficiency, and it roughly drops with the increase in the total volume. An efficient way to control overflow is decreasing the contraction angle and/or the net width broadening of the entrance within the drainage channel, which can also reduce silting efficiency.

b) The debris flow in the contracted entrance exceeds lateral wall height through a large contraction angle β . Under the same transverse blockage, the maximum thickness normalization of overflow wave h_1/h_0 has a positive parabola correlation with the Froude coefficient *Fr*. And the increasing of B_1/B_0 or the decreasing of β can reduce the thickness jump effect in the entrance.

c) The peak impact load of debris flow on the lateral wall of the contracted entrance have positive correlations with Fr. The deflection angle of the shock wave front φ should be added to the evaluation of the peak load after deflection of the wall axis.

Acknowledgements

This study is funded by Natural Science Foundation of Sichuan Province (2022NSFSC1123).

References

[1] Takahashi T. Debris flow [J]. Annual review of fluid mechanics, 1981, 13(1): 57-77.

[2] Wu H H, Yang Z Y, Liu H, et al. Formation conditions and mechanical characteristics of debris flows in Zoumaling Gully of PR China [J]. Electronic Journal of Geotechnical Engineering, 2014, 19: 1917-1930.

[3] Rickenmann D. Empirical relationships for debris flows [J]. Natural hazards, 1999, 19(1): 47-77.

[4] Wang T, Ye GL, Hu JZ, Tan YJ. Discover the characteristics of debris flow and countermeasures of Zhou qu [J]. Northern Environment, 2011, 5: 29-31.

[5] Mizuyama T. Structural countermeasures for debris flow disasters [J]. International Journal of Erosion Control Engineering, 2008, 1(2): 38-43.

[6] Chen J, Chen X, Zhao W, et al. Experimental study on the characteristics of a debris-flow drainage channel with an energy dissipation structure [J]. Bulletin of Engineering Geology and the Environment, 2017, 76(1): 341-351.

[7] Chen H, Tang H. Theory and application of high-speed drainage structure in controlling debris flow [J]. Chin J Geol Hazard Control, 2004, 15(1): 11-16.

[8] Gao Q, Chen X, Zhao W. A review: design of debris flow drainage canal [J]. Chinese Journal of Geological Hazard and Control, 2010, 21(2): 1-7.

[9] Chen J G, Chen X Q, Wang T, et al. Types and causes of debris flow damage to drainage channels in the Wenchuan earthquake area [J]. Journal of Mountain Science, 2014, 11(6): 1406-1419.

[10] Xu T, Ma Y, Wang Y, et al. Application progress of scour-abrasion resistant materials of hydraulic concrete; proceedings of the IOP Conference Series: Earth and Environmental Science, F, 2020 [C]. IOP Publishing.

[11] Bouchut F, Fernández-nieto E D, MANGENEY A, et al. A two-phase two-layer model for fluidized granular flows with dilatancy effects [J]. Journal of Fluid Mechanics, 2016, 801: 166-221.

[12] Procter C. Debris flow dynamics: A flume study of velocity and superelevation [D]; Durham University, 2012.

[13] Liu Q H, Tang C, Yu B. Delineation of debris flow inundation range based on flow depth and curve superthickness [J]. Journal of Mountain Science, 2018, 36(4): 581-588.

[14] Scheidl C, Mcardell B W, Rickenmann D. Debris-flow velocities and superelevation in a curved laboratory channel [J]. Canadian Geotechnical Journal, 2015, 52(3): 305-317.

[15] Wang Z, You Y, Zhang G, et al. Superelevation analysis of the debris flow curve in Xiedi gully, China [J]. Bulletin of Engineering Geology and the Environment, 2021, 80: 967-978.

ISSN 2616-5872 Vol.6, Issue 1: 7-18, DOI: 10.25236/AJEE.2024.060102

[16] Kattel P, Kafle J, FischerI J T, et al. Interaction of two-phase debris flow with obstacles [J]. Engineering Geology, 2018, 242: 197-217.

[17] Liu Z W, Han Z Y, Han H L. Stability evaluation and potential mud-stone flow impact prediction of waste disposal yard in a hydropower station [J]. Railway Investigation and Surveying, 2011, 37(6): 79-82.

[18] Kean J W, Mccoy S W, Tucker G E, et al. Runoff-generated debris flows: Observations and modeling of surge initiation, magnitude, and frequency [J]. Journal of Geophysical Research: Earth Surface, 2013, 118(4): 2190-2207.

[19] Land M O, China R O T P S R O. Specification of geological investigation for debris flow stabilization [Z]. Standards Press of China Beijing, China. 2018.

[20] Xiangang J, Peng C, Huayong C, et al. Formation conditions of outburst debris flow triggered by overtopped natural dam failure [J]. Landslides, 2017, 14(3): 821-831.

[21] Iverson R M. Scaling and design of landslide and debris-flow experiments [J]. Geomorphology, 2015, 244: 9-20.

[22] Vagnon F, Segalini A. Debris flow impact estimation on a rigid barrier [J]. Natural Hazards and Earth System Sciences, 2016, 16(7): 1691-1697.

[23] Ippen A T. Gas-wave analogies in open channel flow; proceedings of the Proceedings 2nd Hydraulics conference, F, 1943 [C]. University of Iowa.

[24] Zhou G G, Du J, Song D, et al. Numerical study of granular debris flow run-up against slit dams by discrete element method [J]. Landslides, 2020, 17(3): 585-595.

[25] Shibuya H, Katsuki S, Kokuryo H, et al. Experimental study of load for steel frame check dam caused by debris flow with woody debris [J]. Journal of the Japan Society of Erosion Control Engineering, 2012, 65(1): 54-61.

[26] Cui P, Zeng C, Lei Y. Experimental analysis on the impact force of viscous debris flow [J]. Earth Surface Processes and Landforms, 2015, 40(12): 1644-1655.

[27] Jiang Y J, Towhata I. Experimental study of dry granular flow and impact behavior against a rigid retaining wall [J]. Rock Mechanics and Rock Engineering, 2013, 46(4): 713-729.

[28] Hürlimann M, Rickenmann D, Medina V, et al. Evaluation of approaches to calculate debris-flow parameters for hazard assessment [J]. Engineering Geology, 2008, 102(3-4): 152-163.

[29] Prochaska A B, Santi P M, Higgins J D, et al. A study of methods to estimate debris flow velocity [J]. 2008, 5(4): 431-444.

[30] Choi C E, Ng C W W, Liu H, et al. Interaction between dry granular flow and rigid barrier with basal clearance: analytical and physical modelling [J]. Canadian Geotechnical Journal, 2020, 57(2): 236-245.

[31] Yang D, You Y, Zhao W, et al. Abrasion behavior and anti-wear measures of debris flow drainage channel with large gradient [J]. Water, 2020, 12(7): 1868.

[32] Zhang K, Lu T. Study on scouring and deposition laws of debris flow drainage trough [J]. Research of Soil and Water Conservation, 2002, 9(4): 61-63

[33] Wu Y, Wang D, Li P, et al. Experimental investigation of dry granular flows down an inclined channel against a wall-like obstacle of limited width [J]. Acta Geotechnica, 2023, 18(4): 2141-2154.

[34] Ng C W, Liu H, Choi C E, et al. Impact dynamics of boulder-enriched debris flow on a rigid barrier [J]. Journal of Geotechnical and Geoenvironmental Engineering, 2021, 147(3): 04021004.