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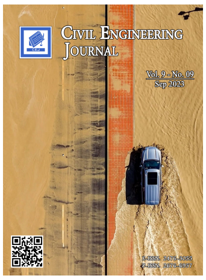
Civil Engineering Journal

(E-ISSN: 2476-3055; ISSN: 2676-6957)

Vol. 9, No. 09, September, 2023



Research on Rainfall Intensity Threshold of Occasional Debris Flow Based on Infiltration

Hanqiang Wang [1], Xiangpeng Ji [1*], Yanping Wang [2*]

[1] *Geological Team of Shandong Province Bureau of Geology and Mineral Resources, Jinan, 255100, China.*

[2] *School of Civil Engineering and Geomatics, Shandong University of Technology, Zibo, 255000, China.*

Received 18 June 2023; Revised 15 August 2023; Accepted 26 August 2023; Published 01 September 2023

Abstract

The rainfall warning method for debris flows usually uses rainfall intensity and duration to establish an I-D relationship internationally and determine the rainfall warning threshold for debris flows. This method requires extensive rainfall data from debris flow events in the study area to establish the I-D relationship. However, some areas with occasional debris flows lack sufficient debris flow events to establish I-D relationships to determine rainfall warning thresholds. Therefore, this study uses the infiltration effect of water flow on gravel soil and establishes a rainfall intensity threshold judgment formula for debris flow initiation based on the limit equilibrium method. Taking the Taiqing debris flow that occurred in Laoshan, China, on June 13, 2018, as an example, the rainfall intensity and characteristics of the debris flow are analyzed. The maximum rainfall intensity during this rainfall process far exceeds the rainfall intensity threshold determined by the judgment formula. Using the judgment formula, it can be determined that the rainfall process will cause debris flow. The judgment result is consistent with the actual situation (where a debris flow occurred during the rainfall process). To further verify the accuracy of the judgment formula, the rainfall process of Typhoon Lichma on August 11, 2019, in the study area was analyzed. The rainfall process has a long history. Still, the rainfall intensity is much lower than the threshold of rainfall intensity for the initiation of debris flow, so this rainfall will not cause the occurrence of debris flow. The judgment result is consistent with the actual situation (no debris flow occurred during rains).

Keywords: Debris Flow; Rainfall Threshold; Monitoring and Early Warning; Geological Hazard.

1. Introduction

A debris flow disaster is a common geological disaster that often brings enormous infrastructure damage and personnel loss. Due to debris flow disasters' sudden and destructive nature, preventing and controlling disasters is very difficult. At present, monitoring and warning of debris flows is one of the essential means to reduce disaster losses.

Rainfall is the main factor inducing debris flow disasters. Therefore, scholars in the field of engineering geology have conducted extensive research on monitoring and warning of debris flow disasters using rainfall as a warning indicator internationally. At present, the early warning value of debris flow rainfall intensity is usually determined through data fitting based on rainfall data to determine the I-D relationship and determine the threshold of debris flow rainfall intensity [1–7]. To improve the warning accuracy of the I-D method for debris flow rainfall threshold, some researchers [4, 8] jointly determine the rainfall intensity warning threshold by adding other influencing factors (such as

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* Corresponding author: jixiangpeng@163.com; wyp@sdut.edu.cn

http://dx.doi.org/10.28991/CEJ-2023-09-09-02

soil moisture content, early precipitation, etc.) to improve the accuracy of debris flow warning. Establishing an I-D-based rainfall intensity warning threshold requires a large number of debris flow events and long-term rainfall monitoring data in the study area [3]. If the amount of data in the study area is too small, the rainfall intensity threshold determined through the I-D method often has lower warning accuracy.

Numerous scholars have also conducted exploratory research on the threshold of rainfall intensity for debris flows in other areas. For example, Martinengo et al. (2023) [9] proposed a validation method for calibrating the rainfall threshold of rocky debris flows using the inverse dynamics method (BDA). The validation results of the study area indicate that this method improves the reliability of the rainfall threshold for debris flow in the study area. Valdes Fernandez et al. (2023) [10] proposed minimum, maximum, and intermediate thresholds based on daily rainfall values and 3-day cumulative rainfall values and applied them to early warning in areas with the highest recurrence rate in Mexico State. Wang et al. (2022) [11] found that different types of rainfall thresholds have significantly different capabilities in distinguishing between rainstorms with positive debris flow response and rainstorms with negative debris flow response, of which the real-time rainfall threshold has the best performance. In addition, research data shows that the mudslides in Beijing are triggered by both rainfall intensity and cumulative precipitation. Debris flow will only occur when the cumulative precipitation and rainfall intensity reach the threshold level simultaneously. Dlabackova & Engel (2022) [12] studied the morphology of debris flows in the Smotna Valley of the West Tatra Mountains and evaluated their formation conditions and previous activities along this path. The research results indicate that the main triggering factor for debris flow is continuous rainfall lasting for 29 hours, resulting in approximately 120–135 mm of rainfall. Exceeding most derived global experience thresholds for debris flow triggering and rainfall thresholds recommended by published research on the western Tatra Mountains.

Chen & Chen (2022) [13] identified three rainfall characteristics caused by landslides and debris flows high rainfall intensity over a short period (<12 hours), high intensity and prolonged rainfall, and high cumulative rainfall over a long period (>36 hours). A landslide warning model combination of cumulative rainfall duration map and rainfall intensity classification, as well as average rainfall intensity duration map and cumulative rainfall classification, has been proposed. Smolikova et al. (2021) [14] conducted a study on the rainfall values triggering mudslides, and the results showed that the cumulative rainfall of 30 days and the rainfall of 1 and 3 days, as well as the development of overall rainfall patterns and rainfall patterns, are more critical for triggering Lemešná mudslides than individual extreme rainfall. Li et al. (2021) [15] constructed the threshold and duration of rainfall intensity based on the mathematical approximation between the critical runoff flow, peak flow, and rainfall intensity during the initiation process of debris flow. Further analysis of the S hydrological hydrograph of rainfall events yields a mathematical approximation and duration of peak flow as a function of rainfall intensity to establish the minimum rainfall required to generate a specific peak flow.

Chang et al. (2021) [16] believe that rainfall patterns can be divided into short-term rainfall patterns, moderate sustained rainfall patterns, and long-term intermittent rainfall patterns in terms of time. The main differences between the three modes of a single precipitation event are rainfall intensity, duration, and cumulative rainfall. Based on this, a rainfall threshold model for debris flow occurrence was established. Liu et al. (2021) [17] compared the rainfall thresholds of de-bris flows before and after earthquakes to evaluate the impact of earthquakes of different intensities. The research results indicate that the post-earthquake threshold is much lower than the pre-earthquake threshold. The above research mainly focuses on cohesive debris flow events in soil, but there is a lot of involvement in the rainfall intensity warning methods for debris flows with gravel as the primary material.

The existing research results indicate that the research on the rainfall threshold of debris flows mainly determines the rainfall threshold of debris flows by establishing an I-D relationship between the rainfall intensity and duration of debris flows that have already occurred. Secondly, the rainfall threshold is determined by analyzing the rainfall process of debris flows that have already occurred. However, it is not possible to collect sufficient debris flow events for establishing I-D relationships to determine the threshold of rainfall intensity for early warning in areas where debris flows occur less frequently. Secondly, current research on debris flows mainly focuses on viscous debris flows containing mud, and there is relatively little research on rainfall intensity for debris flows with gravel as the material. Therefore, this article focuses on debris flows in areas where debris flows occur occasionally, with the primary material being crushed stones. Through mechanical analysis, the initiation conditions of debris flows are determined, and based on this, a method for determining the rainfall threshold for the occurrence of this type of debris flow is established. This method can provide new ideas and technical methods for early warning of debris flow disasters in areas where occasional debris flows occur and debris flow materials are crushed stones. The flowchart of the study is shown in Figure 1.

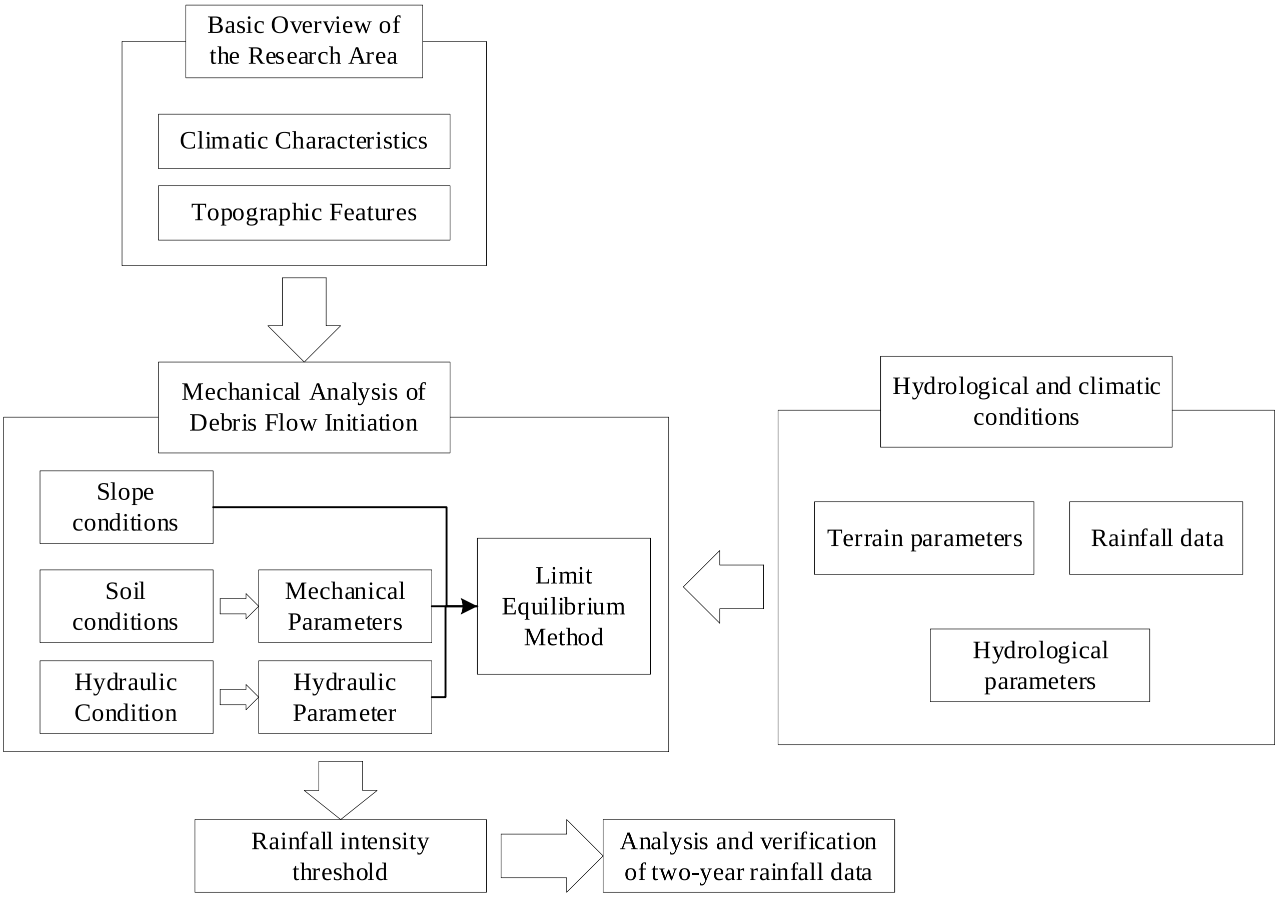

Figure 1. Research methodology flow chart

2. Overview of the Research Area

The debris flow disaster in Taiqing is located on the coastal highway southeast of the Qingdao Peninsula in China (Figure 2-a). The landform of this area belongs to the medium-height mountain erosion landform. The disaster-affected area is shaped like a funnel, with an area of approximately 1.58 hm^2 (Figure 2-a). The development area of debris flow disasters is located within the elevation range of 187~343 m. The overall terrain presents a steep upper and relatively flat lower part. The upper slope has a slope of approximately 70 to 80 °. The slope of the more downward slope is about 30~35 °. The upper slope of-ten experiences collapse and rockfall disasters due to weathering and un-loading, and the collapse materials and rockfall accumulate and stay on the lower slope surface, forming the primary source of debris flow. A gully develops on the slope of the mountain. The cross-section of the valley is in a "V" shape (Figure 3). The average slope on both sides of the valley is 23~25 °, and the local slope can reach 36 °. The middle longitudinal slope of the gully is approximately 32 °. The cross-sectional shape and longitudinal slope of the valleys in the project area provide favourable drainage and drainage conditions for the terrain. Due to the large slope at the bottom of the gully, the collected water will generate a higher water flow velocity during discharge. Due to the transportation of water flow, the collapsed accumulation body is distributed along the length direction of the gully with a thickness of approximately 1~2.5 m of gravel soil layer (Figure 4). On June 13, 2018, a mudslide occurred at this location and destroyed the road, causing road disruption.

The project area has a mild climate in the northern temperate monsoon region. The marine environment directly regulates the temperature in this region. Therefore, the study area is influenced by the southeast monsoon, ocean currents, and water masses from the ocean, which makes the room have significant marine climate characteristics. According to data from the China Meteorological Information Network, the average annual precipitation in Laoshan District is 849.9mm, with a maximum daily rainfall of 269.7mm (September 5, 1956) and a maximum hourly rainfall of 64.1mm. The average relative humidity for many years is 70%. The annual precipitation is mainly concentrated from June to August, accounting for 57%. The rain from December to February of the following year is the least, accounting for 5.4% of the annual precipitation (Figure 5). Over the years, the average number of precipitation days is 84.3, accounting for 23% of the year. Due to terrain conditions, precipitation exhibits significant terrain differences, with higher terrain areas being greater than lower terrain areas.

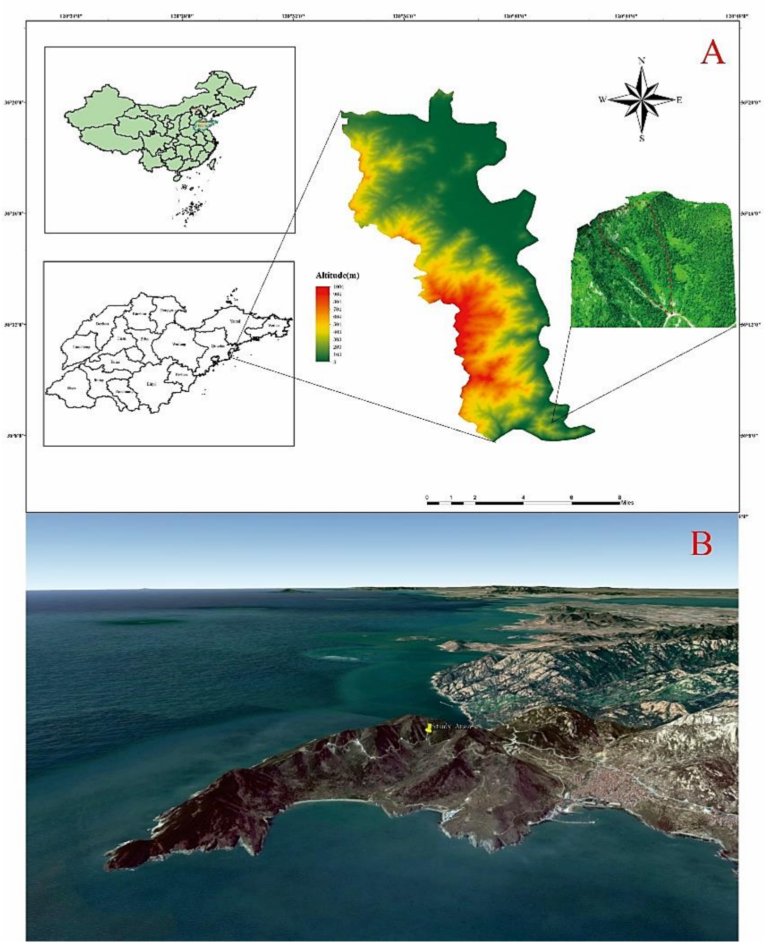

Figure 2. Location Map of the Project Study Area

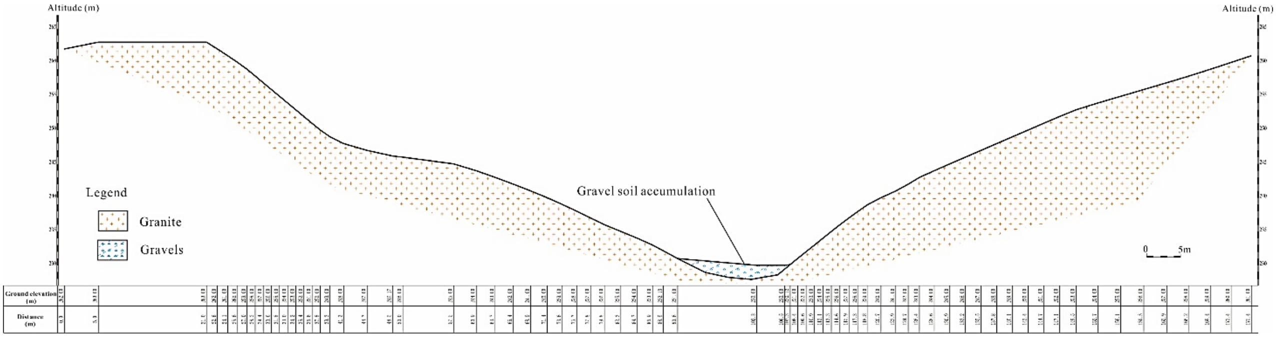

Figure 3. Cross-section shape of the gully

Figure 4. Debris flow Disaster in Taiqing Tourist Area, A. Front photo of the disaster site; B. Gravel at trench bottom

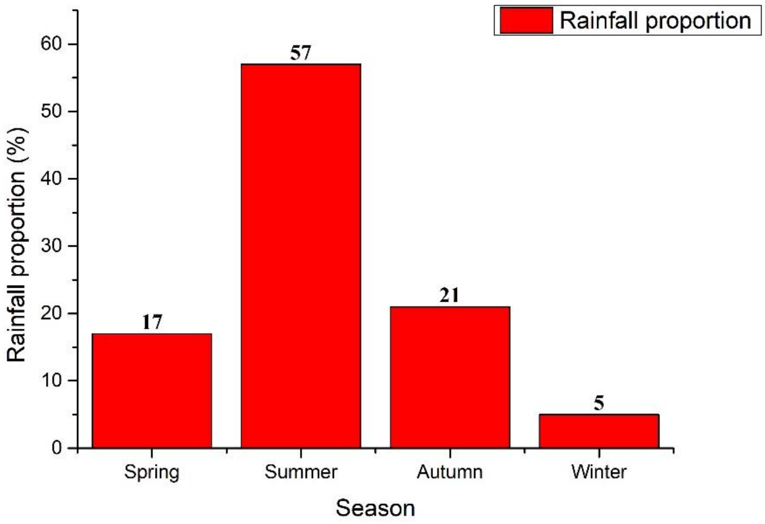

Figure 5. Seasonal distribution of rainfall in LaoShan District (Data from the China Meteorological Administration)

3. Analysis of Rainfall Threshold for Debris Flow Initiation

3.1. Mechanical Analysis of Debris Flow Initiation

The material source of the Taiqing water-rock flow is the collapse deposit, composed of granite blocks and crushed stones with larger particle sizes and a natural angle of repose under natural accumulation conditions. However, the gravel soil in the valley was transported and deposited by floods, and its state is no longer in a natural resting state. The gravel soil layer in the gully is formed by flood transportation and accumulation, and its stability coefficient is related to its internal friction angle and slope shape under natural conditions. Its stability is generally calculated using the following equation.

$$F = \frac{tan\theta}{tana} \tag{1}$$

In the equation, F is the stability coefficient; θ is the internal friction angle of crushed stone soil; *a* is the slope of the ditch bottom.

The occurrence of water-rock flow is the movement of gravel soil under the driving force of water flow. The driving force of water flow is the penetrating force of water flow on the gravel particles. According to the definition of permeability, the hydraulic gradient is used to determine and calculate the permeability. Figure 6 shows that the head difference between the AA' section and the BB’ section is Δh, which is the height difference between point A and point B. The length of the infiltration path is AB, so its hydraulic gradient is:

$$i = \frac{\Delta h}{L_{AB}} = sina \tag{2}$$

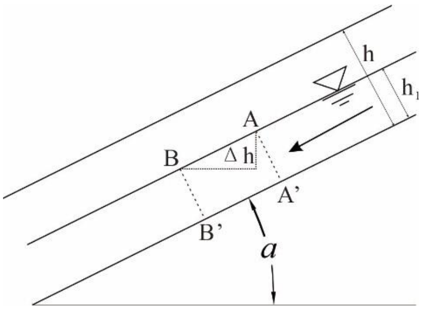

Figure 6. Permeability analysis diagram

In the formula, *i* is the hydraulic gradient; Δh is the head difference; L_{AB} is the distance between points A and B.

So, under the action of seepage, a sliding force (seepage force) is added to the accumulation body, and the stability calculation Equation 1 of the accumulation body will become the following formula (assuming that the water surface is level with the surface of the gravel soil):

$$F = \frac{\gamma' \cdot cosa \cdot tan\theta}{\gamma' \cdot sina + \gamma_w sina} = \frac{\gamma' \cdot tan\theta}{\gamma_{sat} \cdot tana} \tag{3}$$

In the equation, γ' is the effective bulk density of crushed stone soil; γ_{sat} is the saturated bulk density.

According to Equation 3, it can be seen that under the condition of the water, the surface flush with the slope surface, the stability coefficient of crushed stone soil under seepage is much smaller than the stability coefficient of the natural state. Due to the floating bulk density being about half of the saturated bulk density, the stability coefficient under infiltration is almost half of the stability coefficient under natural conditions.

The above analysis is based on the consistency between the water surface and the surface of gravel soil, but what if the water surface is located inside the gravel soil? Assuming the vertical height between the water surface and the ditch bottom is h1 and the thickness of the gravel soil is h (Figure 6). The following equation will calculate the stability calculation equation:

$$F = \frac{w \cdot cosa \cdot tan\theta}{w \cdot sina + \gamma_w sina \cdot h_1} \tag{4}$$

In the formula, w is the effective weight of crushed stone soil per unit width; h1 is the vertical height between the water surface and the bottom of the ditch.

The above equation can derive the conditions for starting the water flow. Assuming a stability coefficient of 1, Equation 4 can be transformed into the following equation:

$$h_1 = \frac{w \cdot cosa \cdot tan\theta - w \cdot sina}{\gamma_w \cdot sina} \tag{5}$$

According to Equation 5, when the water level in the gravel soil in the ditch reaches h1, the gravel soil is in a limit equilibrium state, and the gravel soil begins to slide and lose stability, forming a water-rock flow.

3.2. Determination of Rainfall Threshold

Calculate the rainwater flow rate based on the rainwater design flow calculation formula:

$$Q_s = q \cdot \Psi \cdot F \tag{6}$$

In the equation, Q_s is the rainwater flow rate (L/s); q is the rainstorm intensity L/(s · hm^2); Ψ is the runoff coefficient; F is the catchment area (hm^2).

Assuming that the gully is approximately rectangular and has a width of B, the formula for calculating the drainage capacity of the valley can be calculated by the following equation:

$$Q = Av = h_1 \cdot B \cdot k \cdot i = h_1 \cdot B \cdot k \cdot sina \tag{7}$$

In the formula, k is the permeability coefficient of crushed stone soil; B is the wet circumference width.

Due to Q_s=Q, the combination of Equations 6 and 7 yields the following equation:

$$q = \frac{h_1 \cdot B \cdot k \cdot sina}{\Psi \cdot F} \tag{8}$$

Substitute Equation 5 into Equation 8 to obtain the calculation formula for the rainfall threshold of water-rock flow:

$$q = \frac{(w \cdot cosa \cdot tan\theta - w \cdot sina) \cdot B \cdot k \cdot sina}{\gamma_w \cdot sina \cdot \Psi \cdot F} \tag{9}$$

Equation 9 is the rainfall threshold calculation formula for initiating water-rock flow. When the rainfall intensity exceeds the calculation result of this formula, water-rock flow disasters will occur.

4. Discussion

The previous section analyzed and established a formula for calculating the rainfall intensity threshold to initiate debris flow. However, whether the procedure can be applied to the monitoring and warning of actual debris flow disasters has yet to be directly concluded.

The cross-section of the Taiqing debris flow gully is V-shaped, and the thickness of the gravel soil layer in the ditch is 1-3m, with uneven thickness. The maximum thickness of the gravel soil accumulation in the gutter is located at the lower end of the ditch near the bell mouth of the gully outlet. Select different thicknesses of gravel soil layers to calculate the rainfall intensity threshold. Table 1 shows the basic calculation parameters, and Table 2 shows the calculation results.

Table 1. Basic Calculation Parameters of Taiqing Debris Flow

Unit Weight (kN/m^3)	Gully slope (°)	catchment area (hm^2)	Runoff Coefficient	Permeability coefficient (m/d)	Friction angle θ (°)
20	32	1.58	0.4	50	39

Table 2. Calculation Results of Rainfall Threshold for Gravel Soil with Different Thicknesses

Soil thickness (m)	Sectional area (m^2)	Wet perimeter width B(m)	Rainfall threshold（mm/h）
1	6.64	22.18	7.76
2	19.28	29.34	29.79
2.5	26.8	32.8	46.29
3	35.13	36.34	67.23

From Figure 7, it can be seen that the rainfall threshold increases linearly with the increase of soil layer thickness. When the thickness of the gravel soil layer is 2.5 m, the rainfall threshold is 46.29 mm/h. According to meteorological data from 2018 and 2019 (Figure 8), the maximum rainfall in this area is 59.4 mm/h, which exceeds the rainfall threshold of a 2.5 m thick gravel soil layer. This is consistent with the mudslide event that occurred during the rainfall in 2018.

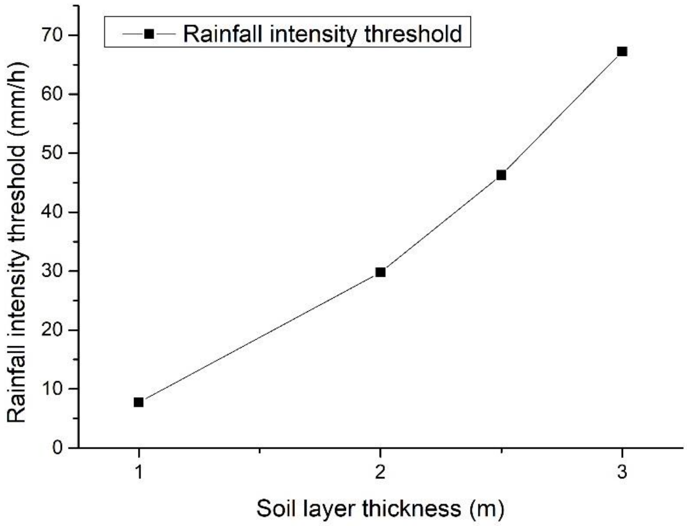

Figure 7. Rainfall intensity thresholds for different thicknesses of gravel soil layers

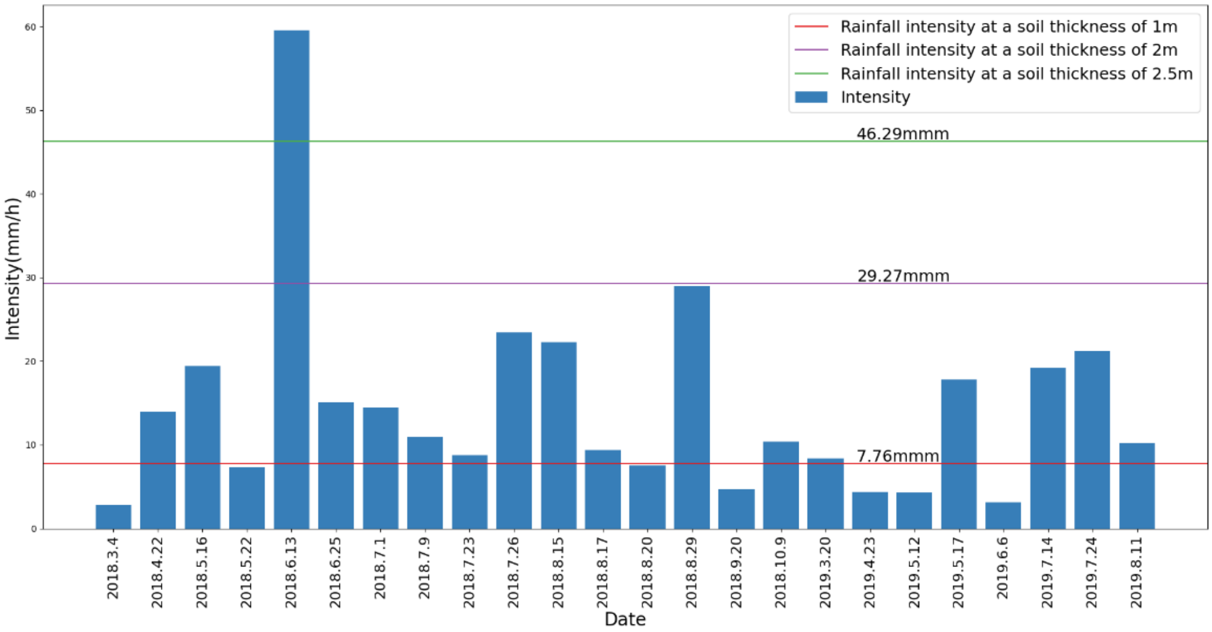

Figure 8. Maximum hourly rainfall intensity in 2018 and 2019

Figure 9 shows the distribution of maximum rainfall events in 2018 and 2019. The three horizontal lines in the figure represent the rainfall thresholds for soil layers with thicknesses of 1, 2, and 2.5 m, respectively. From the graph, it can be seen that the rainfall intensity on June 13, 2018, exceeded the threshold for initiating the debris flow at that location, resulting in a debris flow disaster occurring during the rainfall. The rainfall intensity during other processes in 2018 and 2019 was lower than the rainfall threshold of 2.5m and 2m soil layers. Hence, no debris flow occurred during other rainfall processes, consistent with the actual situation. There were no mudslides even during the rainfall process during the Lichma typhoon in 2019 (Figure 10). Analyzing the rainfall process during Typhoon Lichma in Figure 9, it can be seen that the maximum rainfall intensity during this process is 10.2mm/h, much lower than the rainfall threshold of 46.29mm/h for debris flow initiation. Secondly, the accumulated rainfall of 48.2mm during this rainfall did not cause a debris flow disaster. The reason is that the rainfall period during this rainfall process is 15 hours. Due to the excellent permeability of crushed stone soil, the rainwater collected during such a long rainfall cycle can be discharged promptly in the soil layer, which prevents the formation of a sufficiently high water surface in the soil, resulting in low permeability to drive the movement of the soil layer. Therefore, rainfall cannot cause the occurrence of debris flow disasters.

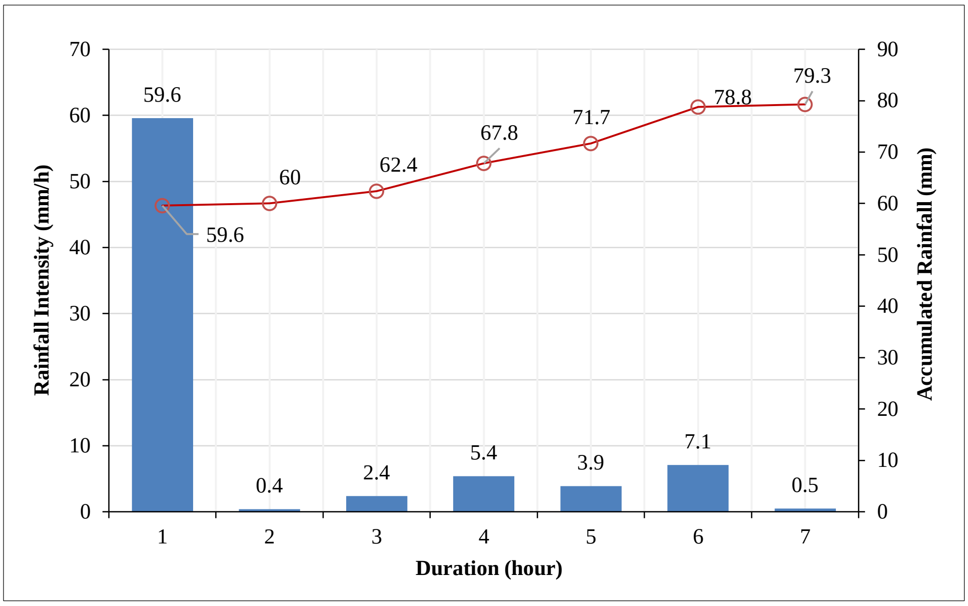

Figure 9. Rainfall on June 13, 2018 (Debris Flow Event)

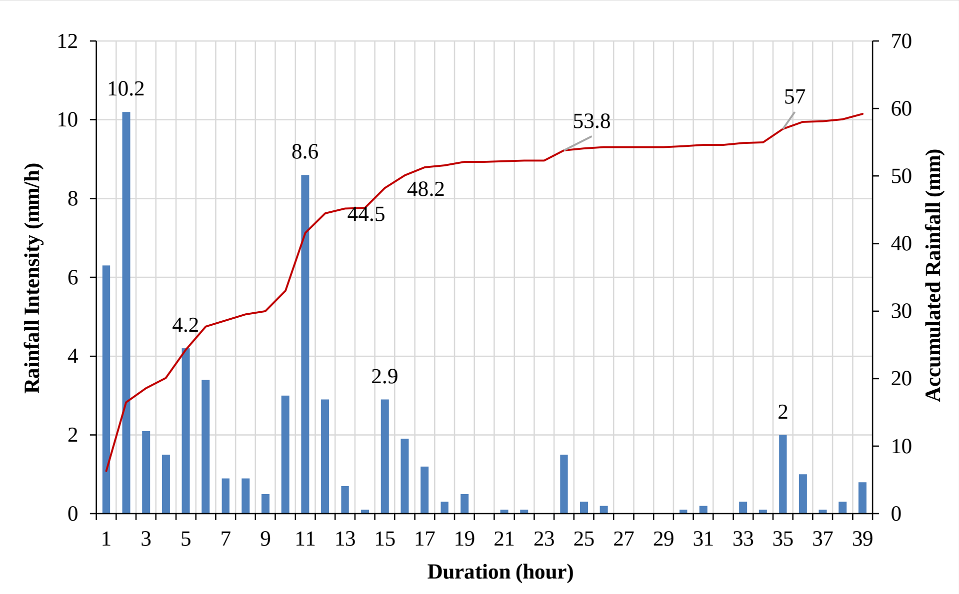

Figure 10. Rainfall on August 11, 2019 (Typhoon Lichma)

The above analysis results show that the thickness of the accumulated soil layer in the Taiqing debris flow is related to the local historical rainfall intensity. This indirectly proves that the formula for determining the threshold of rainfall intensity for initiating debris flow can be well applied to the monitoring and warning of debris flow disasters. However, it should also be noted that the formula for determining the threshold of rainfall intensity for the initiation of debris flow is closely related to the permeability coefficient of the gravel soil at the project's location, terrain, and gully shape. Therefore, using the threshold formula to initiate rainfall intensity for debris flow requires determining the calculation parameters based on the actual engineering situation.

5. Conclusions

From the above analysis, the following conclusions can be drawn:

1) The occurrence of debris flow is closely related to various factors such as topography, climate conditions, and the permeability of gravel soil. The terrain determines the catchment area. According to the parameter relationship of the rainfall intensity threshold judgment in Equation 9, the rainfall intensity threshold is inversely proportional to the catchment area. This indicates that as the catchment area increases, the rainfall intensity threshold will decrease. Secondly, the threshold of rainfall intensity in this formula is directly proportional to the permeability coefficient. The lower the permeability of the soil, the smaller the threshold of rainfall intensity that induces debris flow. According to the permeability characteristics of soil, it can be seen that the smaller the soil particles, the smaller the permeability. Therefore, when the soil in the debris flow area is gravel soil with larger particles, it is often difficult for the area to experience debris flow. If the debris flow in the area is to be induced, it often requires significant rainfall intensity.

2) According to the formula for determining soil stability (3), when the rock and soil are in a limited equilibrium state when the water head height is flush with the surface of the gravel soil, the stability coefficient of the gravel soil is reduced according to the quotient of the floating unit weight and saturated unit weight of the gravel soil. The stability coefficient of the soil layer under seepage conditions is about half of the stability coefficient of the soil layer under non-seepage conditions; The critical head height Equation 5 for inducing soil sliding can be simplified as: $h_1 = \frac{W}{\gamma_w}(ctanatan\theta - 1)$. According to the parameter relationship of this formula, the critical water head height that induces soil instability is directly proportional to the tangent value of the slope angle. The larger the slope inclination angle, the smaller the required critical water head height, and the more likely debris flow will occur. Secondly, the influence of internal friction angle and bulk density of the soil on the critical head is opposite to the influence of slope on the critical head.

3) The main reason for the occurrence of the Taiqing debris flow is short-term, high-intensity rainfall. Long-period rainfall with low rainfall intensity cannot cause the occurrence of debris flow at this location. The main reason is that the source of debris flow at this location is large gravel with high permeability. When the rainfall intensity is low, the gravel soil can quickly discharge rainwater, making it impossible for the water head height inside the gravel soil to reach the critical unstable water head height of the soil, thus preventing the occurrence of debris flow disasters.

6. Declarations

6.1. Author Contributions

Conceptualization, H.W.; methodology, X.J.; investigation, Y.W.; writing—original draft preparation, H.W., X.J., and Y.W.; writing—review and editing, H.W., X.J., and Y.W. All authors have read and agreed to the published version of the manuscript.

6.2. Data Availability Statement

The data presented in this study are available in the article.

6.3. Funding

This research was funded by the Natural Science Foundation of Shandong Province, China, grant number ZR2021MD011.

6.4. Conflicts of Interest

The authors declare no conflict of interest.

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