Research Article

Dimensionless Assessment Method of Landslide Dam Formation Caused by Tributary Debris Flow Events

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Received 27 July 2018; Revised 27 October 2018; Accepted 22 November 2018; Published 22 January 2019

Academic Editor: Lionel Esteban

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In this study, we develop a dimensionless assessment method to evaluate landslide dam formation by considering the relationship between the run-out distance of a tributary debris flow and the width of the main stream, deposition thickness of the tributary debris flow, and the water depth of the main stream. Based on the theory of debris flow run-out distance and fan formation, landslide dam formation may result from a tributary debris flow as a result of two concurrent formation processes: (1) the run-out distance of the tributary debris flow must be greater than the width of the main stream, and (2) the minimum deposition thickness of the tributary debris flow must be higher than the in situ water depth of the main stream. At the confluence, one of four types of depositional scenarios may result: (1) the tributary debris flow enters into the main stream and forms a landslide dam; (2) the tributary debris flow enters into the main stream but overflow occurs, thus preventing complete blockage of the main stream; (3) the tributary debris flow enters into the main stream, does not reach the far bank, and sediment remains partially above the water elevation of the main stream; or (4) the tributary debris flow enters into the main stream, does not reach the far bank, and sediment is fully submerged in the main stream. This method was applied to the analysis of 11 tributary debris flow events during Typhoon Morakot, and the results indicate that the dimensionless assessment method can be used to estimate potential areas of landslide dam formation caused by tributary debris flows. Based on this method, government authorities can determine potential areas of landslide dam formation caused by debris flows and mitigate possible disasters accordingly through a properly prepared response plan, especially for early identification.

1. Introduction

Blockage of a main stream by tributary debris flow events in mountainous areas is a natural phenomenon of river evolution between the confluence of a tributary and the main stream. A significant amount of solid material can be rapidly delivered to the main stream by the inflow of a tributary debris flow. If the volume of the tributary debris flow is high with respect to the transport capacity of the river flow discharge, solid materials of the tributary debris flow deposited in the main stream cannot be washed downstream immediately, allowing for formation of a landslide dam [1].

Landslide dams formed by large-scale soil and rock mass movement through a tributary into a mainstream have been recognized as a serious global natural hazard. The failure of a landslide dam results in a flooding disaster in the downstream catchment, especially during the rainy season. Tributary debris flows are considerably destructive and affect a large area, with devastating floods capable of moving large volumes of debris that may greatly threaten the lives and property of populations downstream of the event. The period from landslide dam formation to failure usually occurs over a short time, resulting in considerable challenges to emergency work [2–8]. Therefore, it is extremely important to determine if a tributary debris flow can block its main stream and form a dam.

In considering the formation of a landslide dam caused by a tributary debris flow, numerous studies have focused
on confirming the following criteria: (1) the depositional volume of the tributary debris flow that crosses the river is larger than the minimum river-blocking volume, (2) the depositional thickness is greater than the water depth of the main stream, and (3) the amount of sediment supplied by the tributary debris flow exceeds the amount of erosion by the river flow [9, 10]. However, two important issues were not considered in these studies, namely, (1) whether the tributary debris flow can reach the far bank of the main stream and (2) whether the minimum deposition thickness of the tributary debris flow is higher than the water depth of the main stream. Recently, consideration of the run-out distance of a tributary debris flow and its minimum deposition thickness was evaluated to establish a more accurate assessment method of landslide dam formation caused by tributary debris flows [6, 11–14]. Although the results of these studies satisfy the formation conditions of a dam, additional characteristics, such as the hydraulic interaction between the arriving debris flow and the receiving main river, which causes additional resistances to debris-flow propagation, have not been considered. The run-out distance and the deposition thickness of a tributary debris flow will be influenced by the flow of the main stream and differences in rainfall intensities over various recurrence periods.

This study presents the application of a dimensionless assessment method to tributary debris flow dam formation in an attempt to identify the areas that may be affected by failure of such dams, especially for early identification. In our study, we developed a dimensionless assessment method to evaluate the potential of river-blocking phenomena. We define a classification scheme that describes four potential scenarios at the confluence between a tributary debris flow and a main stream. With the application of nondimensional analysis, we can establish the relationships between the run-out distance of the tributary debris flow and the width of the main stream and the deposition thickness of a tributary debris flow and the water depth of the main stream. In addition, we improved the theory of run-out distance of the tributary debris flow by considering flow resistance, buoyancy effects, and deflection angle. The objectives of this study are to better understand the potential of river-blocking phenomena when the tributary debris flow enters into the main stream and to establish a method of early identification. This method was applied and verified through a case study of 11 tributary debris flow events during Typhoon Morakot (Taiwan). This study provides a method that can identify high-risk areas for potential areas of landslide dam formation caused by debris flows, which in turn will allow the government authorities to create suitable disaster early warning plans that minimize or eliminate loss of life and property.

2. Data Selection of Tributary Debris Flow Events

On August 8, 2009, Typhoon Morakot struck the central and southern mountainous areas of Taiwan. The typhoon created floods throughout the watershed areas because of the extended time, high intensity, and considerable accumulation of rainfall. The maximum hourly rainfall and cumulative rainfall were recorded as 121 mm (Mintzu rainfall station) and 1748 mm (Jiashian #2 rainfall station), respectively. A single-type disaster develops into a compound disaster under extreme continuous rainfall conditions. Compound disasters with a concentrated distribution in central and southern areas of Taiwan included landslides, debris flows, and floods [15–17].

A number of tributary debris flow events during Typhoon Morakot were found to have blocked the main stream and formed a landslide dam. Most of the landslide dams have already disappeared due to dam collapse or sediment infilling of the established barrier lake. Here, we focus on 11 cases of debris flow events during Typhoon Morakot, which include six that resulted in landslide dam formation and five that did not. These six landslide dams are distributed in the mountainous areas of the central and southern regions of Taiwan and include the Namasha, Yi, Putunpunas, Heshe, Koushe, and Houju River landslide dams. Several studies have been done on the formation mechanisms, hazards, and monitoring and risk for formation at these sites [14, 18–21]. Five remnant debris flow deposits that did not form fans are distributed in the mountainous areas of the southern regions of Taiwan, including Namasha DF008, Taoyaun DF001, Taoyaun DF006, Liugui DF009, and Liugui DF014 [22]. Figure 1 and Table 1 show the locations and characteristics of the 11 debris flow events, respectively.

In this study, the required model information was obtained through the above cited literature as well as through the interpretation of satellite images, topographical maps (1/25000), a 5 m resolution digital terrain model (DTM), and on-site sampling and investigations. Discharge data of the main streams during Typhoon Morakot were extracted from a report published by the Taiwan Water Resources Agency [23]. This information provides the basis for our analysis of landslide dam formation caused by tributary debris flow events.

3. Methodology

3.1. Classification of Deposition at the Confluence of a Tributary Debris Flow and Main Stream. The formation of a landslide dam caused by a tributary debris flow occurs when two conditions are met: (1) the run-out distance of the tributary debris flow is greater than the width of the main stream, and (2) the minimum deposition thickness of the tributary debris flow is higher than the in situ water depth of the main stream [6, 11–14]. If the above two processes have not occurred simultaneously, we define any alteration to the course of the impacted river as a river change phenomenon. The likely relationship between the tributary debris flow and river flow was considered to improve debris flow theory on the run-out distance and deposition thickness. When the tributary debris flow enters the main stream, the applied force of the debris flow in the water must be considered. We modified the theory of run-out distance of the tributary debris flow under consideration of the hydraulic interaction between the arriving debris flow and the receiving main river. Therefore, we define the modified result can be described as the revised run-out distance of the tributary
debris flow, $L_{df}'$. In addition, the direction of the run-out distance of the tributary debris flow will be affected considerably by the angle of confluence and the flow force and indirectly affects whether or not the main stream becomes blocked [24, 25]. Therefore, we modified the blocked width of the main stream at the tributary site and define the modified result can be described as the revised width of the main stream at the tributary site, $B_w'$. 

Based on the above definition, a dimensionless assessment method can be established based on the relationship between the revised run-out distance of the tributary debris flow, $L_{df}'$, and the revised width of the main stream at the tributary site, $B_w'$, and the deposition thickness of the tributary debris flow, $Z$ ($Z_{\text{max}}$ or $Z_{\text{min}}$), and the water depth of the main stream at the tributary site, $h_w$. When $L_{df}' > B_w'$ and $Z_{\text{min}} > h_w$, the landslide dam formation conditions can be satisfied.

The depositional outcome of a tributary debris flow entering into a main stream can be classified into one of the four scenarios: (type 1) the tributary debris flow enters into the main stream and forms a landslide dam; (type 2) the tributary debris flow enters into the main stream but overflow occurs across the main stream at the junction, thus preventing blockage of the main stream; (type 3) the tributary debris flow enters into the main stream, does not reach the far bank, and sediment remains partially above the water table of the main stream; (type 4) the tributary debris flow enters into the main stream, does not reach the far bank, and sediment is fully submerged in the main stream. Only the first type can be defined as a landslide dam created by a tributary debris flow. Figure 2 illustrates the four types of depositional states following the entrance of a tributary debris flow into a main stream and their dimensionless parameters.

3.2. The Run-out Distance of the Tributary Debris Flow. To establish if the first condition of landslide dam formation by debris flow can be fulfilled, evaluation of the run-out distance of the tributary debris flow at the confluence is necessary. A debris-flow fan can result if the run-out distance of the tributary debris flow is longer than the width of the main stream. The run-out distance theory of debris flows was developed by Takahashi [26] as follows (Figure 3):

$$\frac{d}{dt} \left[ \frac{1}{2} (h + h_{fr}) x \rho_{df} u \right] = \frac{1}{2} (h + h_{fr}) x \rho_{df} g \sin \theta_d + \rho_{df} q_{df} u_{df} \cos (\theta_u - \theta_d) + \frac{1}{2} (\sigma - \rho) C_{df} K_a + \rho \right] \frac{g h_{df}^2}{2 \cos \theta_u - \theta_d} - \frac{1}{2} (\sigma - \rho) g (h + h_{fr}) x C_{df} \tan \phi_k \cos \theta_d,$$

where $t$ is time; $h$ is the height of the tributary debris flow head; $h_{fr}$ is the height of the debris-flow front; $x$ is the movement distance of the tributary debris flow; $\rho_{df} = (\sigma - \rho) C_{df} + \rho$ is the density of the tributary debris flow (σ: the

Figure 1: Locations and images of 6 landslide dam cases and 5 uniformed landslide dams in this study (FORMOSAT-2 Image, Aug. 2009).
Table 1: Main characteristics of 11 tributary debris flow events during the Typhoon Morakot.

| No. | Name                  | Latitude, longitude | Watershed area $A_{wj} \ (10^4 \text{ m}^2)$ | Tributary stream length $l_m \ (\text{m})$ | Highest elevation $H_u \ (\text{m})$ | Lowest elevation $H_l \ (\text{m})$ | Upstream slope $\theta_u \ (\degree)$ | Downstream slope $\theta_d \ (\degree)$ | Mean width at the tributary site $B_w \ (\text{m})$ | Upstream watershed area at the tributary site $A_{wu} \ (10^4 \text{ m}^2)$ | Mean slope at the tributary site $\theta_w \ (\degree)$ | Mean width at the tributary site $B_w \ (\text{m})$ | Maximum 1-h rainfall intensity during Typhoon Morakot $I \ (\text{mm/h})$ | Blocking or not |
|-----|-----------------------|---------------------|---------------------------------------------|------------------------------------------|----------------------------------|--------------------------------|----------------------------------|----------------------------------|--------------------------------------------|---------------------------------------------|-----------------------------------------------|---------------------------------------------|------------------------------------------------|------------------------|
| 1   | Namasha landslide dam | N23.321 E120.746    | 670                                         | 4650                                     | 2278                            | 736                             | 17.8                             | 0.6                              | 10                                         | 21200                                       | 1.1                                           | 40                                           | 94.5                                         | Y                       |
| 2   | Yi River landslide dam| N23.294 E120.729    | 940                                         | 4502                                     | 2260                            | 659                             | 16.8                             | 0.8                              | 15                                         | 24010                                       | 1.0                                           | 45                                           | 121.0                                        | Y                       |
| 3   | Putunpunas River landslide dam | N23.194 E120.790 | 579                                         | 5122                                     | 2141                            | 602                             | 17.7                             | 0.9                              | 12                                         | 51888                                       | 0.7                                           | 80                                           | 115.5                                        | Y                       |
| 4   | Heshe River landslide dam | N23.568 E120.873 | 442                                         | 4196                                     | 2283                            | 861                             | 17.2                             | 0.6                              | 10                                         | 8242                                        | 2.1                                           | 80                                           | 85.5                                         | Y                       |
| 5   | Koushe River landslide dam | N22.818 E120.700 | 481                                         | 3543                                     | 1863                            | 415                             | 20.3                             | 1.6                              | 15                                         | 5200                                        | 1.4                                           | 60                                           | 119.0                                        | Y                       |
| 6   | Houjue River landslide dam | N23.192 E120.618 | 181                                         | 2028                                     | 951                             | 291                             | 17.0                             | 0.3                              | 10                                         | 1107                                        | 1.1                                           | 35                                           | 55.0                                         | Y                       |
| 7   | Namasha DF008          | N23.230 E120.694    | 125                                         | 2037                                     | 1089                            | 564                             | 16.6                             | 1.2                              | 10                                         | 27785                                       | 2.0                                           | 75                                           | 121.0                                        | N                       |
| 8   | Taoyaun DF001          | N23.168 E120.774    | 411                                         | 4328                                     | 2003                            | 532                             | 17.0                             | 0.6                              | 15                                         | 55210                                       | 1.0                                           | 60                                           | 115.5                                        | N                       |
| 9   | Taoyaun DF006          | N23.263 E120.820    | 157                                         | 1777                                     | 1667                            | 741                             | 19.2                             | 3.5                              | 10                                         | 39784                                       | 1.2                                           | 50                                           | 98.0                                         | N                       |
| 10  | Liugui DF009           | N23.014 E120.664    | 456                                         | 4347                                     | 1275                            | 258                             | 17.9                             | 2.2                              | 15                                         | 84048                                       | 0.9                                           | 80                                           | 91.5                                         | N                       |
| 11  | Liugui DF014           | N23.066 E120.681    | 549                                         | 4218                                     | 1352                            | 324                             | 15.9                             | 0.2                              | 15                                         | 79173                                       | 0.5                                           | 300                                          | 103.0                                        | N                       |
density of a particle (usually determined as 2650 kg/m$^3$), $\rho$: the density of the fluid (usually determined as 1000 kg/m$^3$), $C_{df}$: the volume concentration of the tributary debris flow during flow); $u$ is the mean velocity of the tributary debris flow during the deposition process; $g$ is the acceleration due to the gravity (usually set at 9.81 m/s$^2$); $\theta_d$ is the downstream slope of the tributary; $q_{df}$ is the discharge of the tributary debris flow per unit width; $u_{df}$ is the mean velocity of the tributary debris flow during the movement process; $\theta_u$ is the upstream slope of the tributary; $K_a = \tan^2(45 - \phi_{df}/2)$ is the coefficient of active earth pressure ($\phi_{df}$: internal friction angle of the tributary debris flow, where Tsai [27] proposes $\phi_{df} = 37^\circ$); $h_{df}$ is the mean depth of the tributary debris flow; and $\phi_k$ is the kinematic friction angle of the tributary debris flow (Tsai [27] proposes $\phi_k = 31^\circ$).
Takahashi [26] proposed an equation based on equilibrium concentration, $C_{dfco}$, to represent the volume concentration of the tributary debris flow during flow, $C_{df}$, written as

$$C_{dfco} = C_{df} = \frac{\rho \tan \theta_u}{(\sigma - \rho) \left(\tan \phi_u - \tan \theta_u\right)}.$$  \hfill (2)

The volume concentration of the tributary debris flow during flow, $C_{df}$, is always less than about $0.9C_*$ [26]. $C_*$ is the volume concentration of the tributary debris flow at deposition (the volume concentration of the tributary debris flow at deposition means that the maximum possible concentration when a tributary debris flow stopped and formed a debris-flow fan). The change of this value can be significantly affected by different materials of debris flow. Therefore, this value is usually obtained through field investigation. The values are mainly between 0.6 and 0.7 by field investigations for debris-flow cases in Taiwan [22, 27, 28]. Here, Tsai [27] proposes that $C_*$ is 0.67.

By the conservation of mass:

$$\frac{1}{2} \left( h + h_{fi} \right) x = q_{df} t. \hfill (3)$$

Substituting equation 3 into equation 1 one obtains

$$\frac{du}{dt} + \frac{u}{t} = \frac{U}{t} - G, \hfill (4)$$

where

$$U = u_{df} \cos (\theta_u - \theta_d) \left(1 + \frac{[(\sigma - \rho)C_{df}K_u + \rho] \cos \theta_u gh_{df}}{2[(\sigma - \rho)C_{df} + \rho]u_{df}^2}\right), \hfill (5)$$

$$G = \frac{(\sigma - \rho)gh_{df} \cos \theta_u \tan \phi_k}{(\sigma - \rho)C_{df} + \rho} - g \sin \theta_d. \hfill (6)$$

The solution of equation 4 under initial conditions is

$$t = 0, \quad u = U, \hfill (7)$$

$$u = U - \frac{1}{2} Gt. \hfill (8)$$

Integrating equation 8 from 0 to $t$, $x$ is given as follows:

$$x = Ut - \frac{1}{4} Gt^2. \hfill (9)$$

When $u = 0$, $t = 2U/G$; $x$ will equate to the run-out distance of the tributary debris flow $L_{df}$:

$$L_{df} = \frac{U^2}{G}. \hfill (10)$$

In addition to flow resistance (drag force, $F_D$, and hydrostatic force, $F_W$) [11], the buoyancy effect, $F_B$, must also be considered [29–31] when the tributary debris flow enters into the main stream (Figure 3):

$$F_D = \frac{1}{2} \rho_u C_D [u_{df} \cos (\theta_u - \theta_d)]^2 h_w \cos \theta_d, \hfill (11)$$

$$F_W = \frac{1}{2} \rho_u g h_w^2 \cos \theta_d,$$

$$F_B = V_w \rho_u g \sin \theta_d = h_w x \rho_u g \sin \theta_d.$$

where $\rho_u$ is the density of the water, $C_D$ is the resistance coefficient (it can be used to quantify the resistance of the tributary debris flow that enters into the main stream, smaller value indicates a less water resistance). Here, De Blasio et al., and Ilstad et al. [29, 30] propose $C_D = 0.003$ for the field case of submarine debris flows), and $V_w$ is the submersed volume of the tributary debris flow.

Therefore, we modified the momentum conservation of the debris flow (equation 1), written as

$$\frac{d}{dt} \left[ \frac{1}{2} (h + h_{fi}) x \rho u_{df} \right] = \frac{1}{2} (h + h_{fi}) x \rho u_{df} g \sin \theta_d + \rho u_{df} q_{df} u_{df} \cos (\theta_u - \theta_d) + \frac{1}{2} \left[ (\sigma - \rho) C_{df} K_u + \rho \right] gh_{df}^2 \cos \theta_u \cos (\theta_u - \theta_d) - \frac{1}{2} (\sigma - \rho) g (h + h_{fi}) x C_{df} \tan \phi_k \cos \theta_d - F_D - F_W - F_B, \hfill (12)$$

and subsequently equation 5 can be modified and shown as

$$U = u_{df} \cos (\theta_u - \theta_d) \left(1 + \frac{[(\sigma - \rho)C_{df}K_u + \rho] \cos \theta_u gh_{df}}{2[(\sigma - \rho)C_{df} + \rho]u_{df}^2}\right),$$

$$- \rho_u C_D u_{df} \cos^2 (\theta_u - \theta_d) h_w - \frac{\rho_u g \cos \theta_d}{2[(\sigma - \rho)C_{df} + \rho]} h_w^2 - \frac{\rho_u x g \sin \theta_d}{[(\sigma - \rho)C_{df} + \rho]} u_{df} h_{df}.$$  \hfill (13)

According to the law of mass conservation, the discharge of the tributary debris flow, $Q_{df}$, can be calculated by

$$Q_{df} = B_u q_{df} = B_u h_{df} u_{df}, \hfill (14)$$

where $B_u$ is the mean width of the tributary.

Tsai et al. [28] proposed an equation to represent the relationship between the discharge of the tributary debris flow.
flow, \( Q_{df} \), and the maximum 1 h rainfall intensity, \( I \), shown
in the following equation

\[
Q_{df} = \frac{1}{360} C_R C_* C_{df} I A_{df},
\]

where \( C_R \) is runoff coefficient (the runoff coefficient is the ratio of the peak rate of direct runoff to the average intensity of rainfall in a storm, it can also be defined to be the ratio of runoff to rainfall over a given time period. A higher value indicates a relatively high runoff [32]. Here, Taiwan Soil and Water Conservation Bureau [33] propose the runoff coefficients are between 0.7 and 0.9 for mountainous area of Taiwan; an average value (0.8) was used in this study), and \( A_{df} \) is the watershed area of the tributary (10^4 m^2).

The mean velocity of the tributary debris flow during the movement process, \( u_{df} \), was derived from Takahashi [34] and written as

\[
u_{df} = \frac{2}{5d_{50}} \left( \frac{g \sin \theta_u}{a \sin \phi_k} \left[ C_{df} + (1 - C_{df}) \frac{\rho}{\sigma} \right] \right)^{1/2} \cdot \left[ \left( \frac{C_f}{C_{df}} \right)^{1/3} - 1 \right] h_{df}^{3/2},
\]

where \( d_{50} \) is the mean diameter of a particle and \( a \) is the Bagnoism number equal to 0.042 [35]. The mean diameter of a particle, \( d_{50} \), can be estimated by field investigations and photographic techniques [36].

The mean depth of the tributary debris flow, \( h_{df} \), can be estimated through substituting equations 15 and 16 into equation 14.

A potential change in direction of a tributary debris flow is strongly influenced by the river flow and angle of confluence when the tributary debris flow enters the main stream. This not only governs the movement and deposition process of the tributary debris flow but also indirectly affects whether or not the main stream becomes blocked [24, 25]. We define the angle of deflection, \( \beta \), to describe the direction change of a tributary debris flow with the angle of confluence, \( \alpha \). Assuming that all parts of the tributary debris flow volume are not removed by erosion by the main stream, the resultant force direction of the river flow momentum and the tributary debris flow momentum determines the deflection direction of the debris flow. The deflection direction can be estimated by the sine rule (Figure 4):

\[
\frac{Q_w u_w \sin \beta}{\sin \alpha} = \frac{Q_{df} u_{df} \sin \alpha - \beta}{\sin (\alpha - \beta)},
\]

where \( Q_w \) is the discharge of the main stream and \( u_w \) is the mean velocity of the main stream at the tributary site.

The momentum ratio is defined as \( R \):

\[
R = \frac{Q_w u_w}{Q_{df} u_{df}}.
\]

The angle of deflection, \( \beta \), can be modified to

\[
\beta = \tan^{-1} \left( \frac{R \sin \alpha}{1 + R \cos \alpha} \right),
\]

Through the relationship between the angle of confluence, \( \alpha \), and the angle of deflection, \( \beta \), the run-out distance of the tributary debris flow, \( L_{df} \), and the mean width of the main stream at the tributary site, \( B_w \), can be modified as follows:

\[
L_{df} = L_{df} \frac{\sin (180^\circ - \alpha)}{\sin (\alpha - \beta)},
\]

\[
B_w = \frac{B_w}{\sin (\alpha - \beta)}.
\]
When \( L_{df}^{'} > B_{w}^{'} \), the first formation condition can be satisfied.

### 3.3. The Deposition Thickness of the Tributary Debris Flow

For the fulfillment of the second condition of formation of a landslide dam caused by debris flow, evaluation of the necessary deposition thickness of the tributary debris flow at the confluence is required. When a tributary debris flow enters the main stream the minimum deposition thickness of the tributary debris flow is measured on the far bank of the main stream, whereas the maximum deposition thickness of the tributary debris flow occurs on the tributary side (type 1 and 2 of Figure 2). If the tributary debris flow cannot reach the far bank of the main stream, we will not consider that the minimum observed depositional thickness of the tributary debris flow is found on the far side of the main stream (type 3 and 4 of Figure 2).

When a debris flow from a tributary forms a debris-flow fans, the maximum deposition thickness of the tributary debris flow, \( Z_{\text{max}} \), and the minimum deposition thickness of the tributary debris flow, \( Z_{\text{min}} \), can be approximated via a Gaussian curve with an empirical coefficient, \( C_L \), represented by [37]

\[
Z_{\text{min}} = Z_{\text{max}} e^{-\left(2c_{z,-2}\right)^{-1} \left(\theta_{df}^{'} / \theta_{d}\right)^2}, \tag{21}
\]

where Tsai [37] proposes \( C_{L} = 0.41 \) in the field case.

The maximum deposition thickness of the tributary debris flow, \( Z_{\text{max}} \), can be estimated by the geometric relationship of the revised run-out distance of the tributary debris flow, \( L_{df}^{'} \), and the deposition slope of the tributary debris flow, \( \tan \theta_{df} \) [28];

\[
Z_{\text{max}} = L_{df}^{'} \tan (\theta_{df}^{'} - \theta_{d}). \tag{22}
\]

Tsai et al. [28] modified the formula of the deposition slope of the tributary debris flow, \( \tan \theta_{df} \) [26], considering the relationship between mean deposition slope along the longitudinal axis, \( \theta_{df} \), the discharge of the tributary debris flow per unit width, \( q_{df} \), the volume concentration of the tributary debris flow during emplacement, \( C_{df} \), and the mean particle diameter, \( d_{50} \). Consequently, the deposition slope of the tributary debris flow, \( \tan \theta_{df} \), can be calculated from the following equation

\[
\tan \theta_{df} = \frac{C_{df} \left( \sigma - \rho \right)}{C_{df} \left( \sigma - \rho \right) + \rho \left[ 1 + 4.5 \times 10^{-4} C_{df}^{-6} \left( q_{df}^{1 / 2} / g d_{50}^{3} \right)^{1 / 2} \right]} \tag{23}
\]

In order to obtain the water depth of the main stream at the tributary site, \( h_{w} \), the discharge of the main stream at the tributary site, \( Q_{w} \), must be estimated. The area ratio method can be used to estimate the discharge:

\[
Q_{w} = A_{w}^{'} Q_{w1}, \tag{24}
\]

where \( A_{w}^{'} \) is the upstream watershed area at the tributary site, \( A_{w1} \) is the upstream watershed area at the downstream gauging station, and \( Q_{w1} \) is the discharge of the main stream at the downstream gauging station.

Substituting the discharge of the main stream at the tributary site \( Q_{w} \) into Manning’s formula, the water depth of the main stream at the tributary site, \( h_{w} \), can be obtained from

\[
Q_{w} = a_{w} u_{w} = a_{w} \left( R_{w}^{2} / 3 \right) \tan \theta_{w}^{1 / 2} = \frac{1}{n} \left( B_{w}^{1 / 3} h_{w}^{2 / 3} \right) \tan \theta_{w}^{1 / 2}, \tag{25}
\]

where \( a_{w} \) is the cross-sectional area of river flow at the tributary site, \( n \) is the Manning coefficient, \( R_{w} \) is the hydraulic radius, and \( \tan \theta_{w} \) is the mean slope of the main stream at the tributary site. The range of Manning coefficients, \( n \), is between 0.03 and 0.04 for the mountain streams in Taiwan [38–40]. Here, an average value (0.035) was used in this study.

When \( Z_{\text{min}} > h_{w} \), the second formation condition can be satisfied.

### 4. Results and Discussion

#### 4.1. Application of the Dimensionless Assessment Method

The methods for assessing landslide dam formation described in Section 3 of this paper were applied to 11 tributary debris flow events during Typhoon Morakot. Based on the landslide dam formation conditions, the dimensionless assessment method can be used to discriminate the formation of a landslide dam from other depositional scenarios at the confluence of a tributary and its main stream. Tables 2 and 3 list the calculated results of related parameters for the discrimination of landslide dam formation caused by tributary debris flow. Considering Tables 2 and 3, the related results are explained as follows:

1. River blocking and dam formation are constantly changing under different river flow conditions and tributary debris flow momentum, especially for variable rainfall intensities over varying recurrence periods. In our study, the assessed results of 11 tributary debris flow cases are consistent with actual field situations and have definite physical meaning. In addition, the maximum 1 h rainfall intensity, \( I \), and the discharge of the main stream at the tributary site, \( Q_{w} \), can be considered to evaluate landslide dam formation caused by tributary debris flow under different conditions of rainfall recurrence periods.

2. Based on the dimensionless assessment method, the classification of the confluence between tributary debris flow and main stream can be precisely differentiated. The results of this study were verified through a case study on six landslide dam cases, in
## Table 2: Parameters of the tributary debris flow for 11 tributary debris flow events.

| No. | name                     | Mean diameter of particle $d_{50}$ (m) | Volume concentration $C_{df}$ | Density $\rho_{df}$ (kg/m$^3$) | Discharge $Q_{df}$ (m$^3$/s) | Mean velocity $u_{df}$ (m/s) | Mean depth $h_{df}$ (m) | Run-out distance $L_{df}$ (m) | Revised run-out distance $L_{df}'$ (m) | Deposition slope $\theta_{df}$ (°) | Maximum deposition thickness $Z_{\text{max}}$ (m) | Minimum deposition thickness $Z_{\text{min}}$ (m) |
|-----|--------------------------|----------------------------------------|-------------------------------|--------------------------------|-------------------------------|-----------------------------|-------------------------|-------------------------------|-----------------------------------------------|---------------------------------|------------------------------------------|------------------------------------------|
| 1   | Namasha landslide dam    | 0.02                                    | 0.45                          | 1.74                          | 431                           | 35.7                        | 1.21                    | 31.46                         | 2.41                           | 410                             | 606                                      | 2.7                                      | 22.6                                    | 21.9                                    |
| 2   | Yi River landslide dam   | 0.02                                    | 0.40                          | 1.66                          | 635                           | 38.5                        | 1.10                    | 33.8                          | 2.21                           | 516                             | 710                                      | 1.5                                      | 8.1                                      | 8.0                                      |
| 3   | Putunpunas landslide dam | 0.01                                    | 0.44                          | 1.73                          | 442                           | 43.4                        | 0.85                    | 34.66                         | 2.33                           | 515                             | 1335                                     | 1.5                                      | 12.7                                    | 11.8                                    |
| 4   | Heshe River landslide dam| 0.02                                    | 0.42                          | 1.69                          | 226                           | 25.6                        | 0.88                    | 23.91                         | 2.31                           | 247                             | 378                                      | 2.8                                      | 14.3                                    | 9.4                                      |
| 5   | Koushe River landslide dam | 0.01                                   | 0.58                          | 1.96                          | 961                           | 40.9                        | 1.57                    | 38.47                         | 2.61                           | 567                             | 571                                      | 4.4                                      | 27.7                                    | 26.8                                    |
| 6   | Houjue River landslide dam | 0.01                                  | 0.41                          | 1.68                          | 58                            | 15.1                        | 0.38                    | 11.74                         | 2.35                           | 59                              | 134                                      | 3.1                                      | 6.5                                     | 2.3                                     |
| 7   | Namasha DF008            | 0.02                                    | 0.40                          | 1.66                          | 83                            | 14.6                        | 0.57                    | 8.79                          | 2.13                           | 36                              | 779                                      | 3.7                                      | 33.9                                    | 0.0                                      |
| 8   | Taoyaun DF001            | 0.01*                                   | 0.41                          | 1.68                          | 276                           | 30.3                        | 0.61                    | 13.74                         | 2.29                           | 83                              | 634                                      | 1.5                                      | 10.0                                    | 2.1                                      |
| 9   | Taoyaun DF006            | 0.01*                                   | 0.52                          | 1.86                          | 156                           | 21.6                        | 0.72                    | 6.40                          | 2.12                           | 19                              | 234                                      | 5.6                                      | 8.3                                     | 0.0                                      |
| 10  | Liugui DF009             | 0.01*                                   | 0.45                          | 1.75                          | 287                           | 28.8                        | 0.66                    | 8.33                          | 2.14                           | 32                              | 371                                      | 2.5                                      | 1.6                                     | 0.0                                      |
| 11  | Liugui DF014             | 0.01*                                   | 0.37                          | 1.61                          | 280                           | 32.8                        | 0.57                    | 25.60                         | 2.20                           | 298                             | 1654                                     | 0.8                                      | 16.8                                    | 0.8                                      |

* An assumed value because of no field investigation data.
Table 3: Parameters of the main stream and dimensionless indices for 11 tributary debris flow events.

| No. | Name                        | Discharge of the main stream at the downstream gauging station $Q_w$ (m$^3$/s) | Upstream watershed area at the downstream gauging station $A_w$ (10$^4$ m$^2$) | Discharge $Q_w$ (m$^3$/s) | Mean velocity $u_w$ (m/s) | Mean depth $h_w$ (m) | Angle of confluence $\alpha$ (°) | Angle of deflection $\beta$ (°) | Revised width $B_w$ (m) | $L_{df} / B_w$ | $Z_{max} / h_w$ | $Z_{min} / h_w$ | Classification |
|-----|-----------------------------|---------------------------------------------------------------------------------|-------------------------------------------------------------------------------|---------------------------|-------------------------|-------------------------|-------------------------------|-------------------------------|---------------------|----------------|----------------|----------------|----------------|
| 1   | Namasha landslide dam       | 9308                                                                             | 75077                                                                         | 9308                       | 2628                    | 11.1                    | 90                           | 47                           | 59                  | 10.27         | —              | 3.70           | Type 1          |
| 2   | Yi River landslide dam      | 9308                                                                             | 75077                                                                         | 9308                       | 2977                    | 10.8                    | 90                           | 53                           | 63                  | 11.27         | —              | 1.30           | Type 1          |
| 3   | Putunpunas landslide dam    | 12106                                                                            | 1340                                                                          | 12106                      | 7180                    | 11.1                    | 90                           | 67                           | 207                 | 6.45          | —              | 1.46           | Type 1          |
| 4   | Heshe River landslide dam   | 5426                                                                             | 44814                                                                         | 5426                       | 998                     | 7.5                     | 90                           | 59                           | 141                 | 2.68          | —              | 5.63           | Type 1          |
| 5   | Koushe River landslide dam  | 8657                                                                             | 62330                                                                         | 8657                       | 722                     | 14.1                    | 95                           | 3.4                          | 61                  | 9.36          | —              | 14.26          | Type 1          |
| 6   | Houjue River landslide dam  | 7001                                                                             | 16100                                                                         | 7001                       | 481                     | 6.3                     | 90                           | 64                           | 80                  | 1.68          | —              | 1.05           | Type 1          |
| 7   | Namasha DF008               | 9308                                                                             | 75077                                                                         | 9308                       | 3445                    | 12.2                    | 65                           | 63                           | 1778                | 0.44          | 8.99           | —              | Type 3          |
| 8   | Taoyuan DF001               | 12106                                                                            | 1340                                                                          | 12106                      | 7639                    | 14.0                    | 90                           | 83                           | 460                 | 1.38          | —              | 0.23           | Type 2          |
| 9   | Taoyuan DF006               | 12106                                                                            | 1340                                                                          | 12106                      | 87492                   | 13.6                    | 80                           | 75                           | 614                 | 0.36          | 1.02           | —              | Type 3          |
| 10  | Liugui DF009                | 12106                                                                            | 1340                                                                          | 12106                      | 11630                   | 14.2                    | 90                           | 85                           | 917                 | 0.40          | 0.16           | —              | Type 4          |
| 11  | Liugui DF014                | 12106                                                                            | 1340                                                                          | 12106                      | 87492                   | 10955                   | 90                           | 80                           | 1663                | 0.99          | —              | 0.16           | Type 4          |
which $L_{df}/B_w$ and $Z_{min}/h_w$ were effectively used to determine the occurrence of landslide dams (Figure 5), thereby confirming the viability of this line research.

(3) As landslide dams resulting from tributary debris flow typically occur in remote mountain areas, parameters are difficult to measure under the conditions of severe weather combined with traffic delays. Therefore, we obtained topographic parameters through GIS with topographical maps (1/25000), 5 m resolution DTM, and satellite images. These topography parameters can provide variables for calculation of the assessment method. In addition, some parameters cannot be obtained from the literature, such as the internal friction angle of the tributary debris flow, $\phi_{df}$, the kinematic friction angle of the tributary debris flow, $\phi_k$, the volume concentration of the tributary debris flow at deposition, $C_v$, and the mean particle diameter, $d_{50}$ (Table 2); thus, the appropriate assumptions are necessary. For accurate assessment of landslide dam formation, the parameter of the internal friction angle of the tributary debris flow, $\phi_{df}$, needs to be used cautiously, as it is the most sensitive parameter for our method [14].

(4) It is necessary to be able to assess the potential site of debris flows before using the dimensionless assessment method. The potential site of debris flows can be determined preliminarily by the critical slope for the debris-flow initiation. Takahashi [26] proposed an equation to represent the critical slope for the debris-flow initiation, $\theta_{\text{critical}}$, shown in the following equation:

$$\tan \theta_{\text{critical}} = \frac{C_v(\sigma - \rho)}{C_v(\sigma - \rho) + \rho(1 + k^{-1})} \tan \phi. \quad (26)$$

In this study, the critical slope for the debris-flow initiation, $\theta_{\text{critical}}$, can be calculated under the conditions $C_v = 0.67$, $\sigma = 2650\text{kg/m}^3$, $\rho = 1000\text{kg/m}^3$, $\phi = 37^\circ$, and $k = 1$ ($k$ is Kármán constant, Takahashi [26] proposes $k = 1$). According to equation 26, the critical slope for the debris-flow initiation, $\theta_{\text{critical}}$, was $15^\circ$. This means that the debris flow may be triggered on a tributary stream when a critical slope for the debris-flow initiation is larger than $15^\circ$.

4.2. Applicability and Limitations of the Dimensionless Assessment Method. The dimensionless assessment method was applied and verified based on 11 tributary debris flow events during Typhoon Morakot. Due to the frequent occurrence of typhoons and earthquakes, more than 1700 potential sites for debris flow events in Taiwan can be identified [41]. It is necessary to be able to predict and assess the potential for landslide dam formation resulting from debris flows in order to reduce loss of life and property from such disasters. The site information of potential debris flows, rainfall intensities, and the discharge of the appropriate main streams at varying recurrence periods have been established in Taiwan. This information is useful to establish the location of possible river-blocking sites with the dimensionless assessment method. Relevant emergency rescue measures needed following the emplacement of a landslide dam can therefore be documented in advance by using the method. In this study, the following limitations in our methodology are noteworthy:

(1) During Typhoon Morakot, river height, width, and cross-section may have undergone quite drastic changes due to the influence of cascading tributary debris flow or multiple debris flows. Therefore, topographical maps (1/25000) and 5 m resolution DTM of predisaster conditions may not necessarily be accurate for postdisaster assessment.

(2) The Rational Method Equation was used to calculate the discharge of the tributary debris flow, $Q_{df}$, but it is only suitable for application in small-scale watersheds of area less than $10\text{km}^2$ in Taiwan. Applicability to large-scale watersheds $>10\text{km}^2$ or other watershed scales requires further testing and clarification.

(3) The results of this study are suitable for a single event of a tributary debris flow. Because of the impact of the extended time, high intensity, and considerable accumulation of rainfall, debris flow could have occurred several times in the same tributary or cascading tributary during Typhoon Morakot. The

Figure 5: Assessment results of the tributary debris flow entering the main stream for 11 tributary debris flow events during Typhoon Morakot.

| Type | $Z_{max}$ | $Z_{min}$ |
|------|------------|------------|
| Type 1 | Dam formed | Dam unformed |
| Type 2 | Dam formed | Dam unformed |
| Type 3 | Dam formed | Dam unformed |
| Type 4 | Dam formed | Dam unformed |

11 cases of the debris flow events during Typhoon Morakot

1. Dam formed
2. Dam unformed

![Figure 5: Assessment results of the tributary debris flow entering the main stream for 11 tributary debris flow events during Typhoon Morakot.](image-url)
The river cross-section types and Manning coefficient, $n$, affect the estimation of water depth of the main stream at the tributary site, $h_w$, especially for mountain streams. Manning’s formula is derived based on the assumption that the frictional resistance forces (the boundary shear forces) are balanced by the gravitational forces. Although the Manning coefficient is defined empirically, Manning’s formula is grounded on a well-defined theoretical basis, although with clear physical limitations in real applications. However, it is true that in practical applications in the fields of Hydrology and Fluvial Hydraulics the validity conditions of this equation are not always respected, especially for high-gradient streams, because the objectives of this study are to establish a method of early identification for the potential of river-blocking phenomena when the tributary debris flow enters into the main stream, therefore simplified the irregular cross-section to be rectangular, and use an average value of Manning coefficient to estimate the water depth of the main stream at the tributary site. Actually, the Manning coefficient should be determined by field investigation and measurement, especially for high-gradient streams (mountain streams) [42, 43]. However, using experience value may be allowed when Manning coefficient cannot be obtained and should be applied carefully in practical usage to avoid large errors.

When flash floods caused by heavy rainfall in mountain streams occur, the volume concentration of the main stream will be changed due to a mixture of water and sediment and further develop hyperconcentrated flow. Here, the effects of the volume concentration of the main stream are ignored when the tributary debris flow enters into the main stream. Because the objectives of this study are to establish a method of early identification for the potential of river-blocking phenomena when the tributary debris flow enters into the main stream, therefore we do not analyze the volume concentration of the main stream change and to be assumed as a clear water condition.

The dimensionless assessment method aims to provide a methodology of the early identification for possible river-blocking sites. The application of this methodology should be limited to early warning disaster prevention and emergency response for river-blocking hazards and not for the purpose of deep and definitive interventions/works in the river system. For this, proper planning should be done, and a more realistic physical theory should be used, probably with the support of physical and numerical modelling. However, in favor of the proposed methodology, it is also true that due to the complexity of the debris-flow process, numerical simulation models of debris flows are still limited with regard to practical applications.

5. Conclusions

This research proposed a dimensionless assessment method to discriminate landslide dam formation caused by tributary debris flow events, especially for early identification. In addition, a classification of the resultant deposits once a tributary debris flow enters into a main stream was proposed and includes four types based on the relationship between the revised run-out distance of the tributary debris flow, $L_{df}$, and the revised width of the main stream at the tributary site, $B_{m}′$, in addition to the deposition thickness of the tributary debris flow, $Z (Z_{\text{max}}$ or $Z_{\text{min}}$), and the water depth of the main stream at a tributary site, $h_w$. We revised the theory of run-out distance of the tributary debris flow after considering flow resistance, buoyancy effects, and deflection angle. Based on the results of the preliminary study of 11 tributary debris flow events during Typhoon Morakot, it was determined that the method can be used for early warning disaster prevention and emergency response for landslide dam hazards caused by tributary debris flow events under fluctuating rainfall intensities at varying recurrence periods. However, the actual situation may be significantly affected by the erosion velocity of river flow, the volume concentration of the main stream (hyperconcentrated flow), the composition structure of particles, cascading debris flow, multiple debris flows, the volume available for obstruction, and the volume of the debris-flow fan. In subsequent research, these effects must depend on the support of physical and numerical modelling due to limitations of this methodology.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

Acknowledgments

We thank two anonymous reviewers for their constructive comments on an earlier version of this manuscript. This research was supported by the National Natural Science Foundation of China (Grant Nos. 41501012 and 41661144028), CAS “Light of West China” Program, and the Chinese Academy of Science and Technology Service Network Planning (Grant No. KFJ-STS-ZDTP-015).

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