Article

Modeling Flood Peak Discharge Caused by Overtopping Failure of a Landslide Dam

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Abstract: Overtopping failure often occurs in landslide dams, resulting in the formation of strong destructive floods. As an important hydraulic parameter to describe floods, the peak discharge often determines the downstream disaster degree. Based on 67 groups of landslide dam overtopping failure cases all over the world, this paper constructs the calculation model for peak discharge of landslide dam failure. The model considers the influence of dam erodibility, breach shape, dam shape and reservoir capacity on the peak discharge. Finally, the model is compared with the existing models. The results show that the new model has a higher accuracy than the existing models and the simulation accuracy of the two outburst peak discharges of Baige dammed lake in Jinsha River (10 October 2018 and 3 November 2018) is higher (the relative error is 0.73% and 6.68%, respectively), because the model in this study considers more parameters (the breach shape, the landslide dam erodibility) than the existing models. The research results can provide an important reference for formulating accurate and effective disaster prevention and mitigation measures for such disasters.

Keywords: peak discharge prediction; landslide dams; floods; overtopping failure; calculation model

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1. Introduction

Landslide is a common mountain hazard, which is widely distributed in the steep mountain gorge area [1,2]; it often has the characteristics of high location, high speed, long distance of movement [3]. In particular, the frequency of large-scale landslides is higher under the action of heavy rainfall or high-intensity earthquake [1]. When there are rivers in the direction of landslide movement, the landslide is easy to accumulate into the river and form a dam to block up the upstream water level. Once a dam failure occurs, it will also cause a huge flood disaster in the downstream and enlarge the scope and scale of the hazard [2,4–11]. For example, in 1786, a strong $M = 7.75$ earthquake in Luding-Kangding area, Sichuan Province, southwestern China, formed a landslide dam and the flood caused by the landslide dam failure killed more than 100,000 people [12]. In addition, Yigong Landslide dammed lake (9 April 2000) [13], Tangjiashan landslide dammed lake (12 May 2008) [14] and Baige landslide dammed lake (10 October 2018 and 3 November 2018) [15] occurred in recent years, which caused serious life and property losses of upstream reservoir inundation and downstream extraordinary outburst flood.

Landslide dam is a kind of natural earth rock dam without special design and specific spillway. Its geometry, material composition and internal structure are significantly different from those of artificial earth rock dam [16] and its failure probability is much higher than that of artificial earth rock dam [17–19]. According to statistical data [19], the service life of landslide dams ranges from a few minutes to thousands of years, with 87%, 83%, 71%, 51% and 34% of them less than one year, half a year, one month, one week and one

day, respectively. Most of the cases (91%) were overtopping and only a few landslide dams were piping failure (8%) and slope instability. This kind of “short life, multiple overtopping failure” nature creates the high risk of a landslide dam, which is closely related to the shape, material composition, internal structure, main river shape and hydraulic characteristics of a landslide dam [2,8,10,19]. Therefore, the failure mechanism of landslide dams has become an important scientific problem.

Several numerical models of overtopping dam break based on physical processes have been proposed, such as DAMBRK model [20], BREACH model [21], BEED model [22], BRES model [23], Tingsanchali and Chinnarasri’s model [24], HR-BREACH [25], SIMBA model [26,27], Wang and Bowles’s model [28], BRES-Zhu model [29], Faeh’s model [30], Wu and Wang’s model [31] and Gradual dam breaches model [32]. However, the above model is almost for artificial earth rock dam and it is difficult to be applied to landslide dam with complex natures. In addition, Zhong et al. [8] established a water soil coupling mathematical model to simulate the overtopping failure process of Tangjiashan dam. Chang and Zhang [33] proposed a landslide dam overtopping failure model based on physical process to simulate the effect of soil erodibility changing with depth on the erosion process. Shen et al. [2] considered not only the change of soil erodibility with depth, but also the erosion mode (unilateral dam failure and bilateral dam failure) and different material composition of landslide dam. Cao et al. [34] also established a two-dimensional model of landslide dam failure based on the traditional shallow water dynamic equation. Even so, the computational efficiency is greatly reduced and the reliability of the results is low due to the difficulties in obtaining the parameters required by the model, controlling the boundary conditions and over simplification of the model. Therefore, a rapid dam failure risk assessment method is needed.

As one of the most important parameters in the process of dam failure, the peak discharge of dam failure often determines the downstream disaster degree and the reliability of its prediction results determines the accuracy and effectiveness of disaster prevention and mitigation measures [35]. The simulation of flood peak discharge has been studied as early as the 1980s. At present, a large number of simulation models have emerged, such as Kirkpatrick’s model [36], Macdonald and Langridge-Monopolis’ model [37], Singh and Snorrason’s model [38], Costa’s model [39], Costa and Schuster’s model [17], Froehlich’s model [40], Webby’s model [41], Walder and O’Connor’s model [42], Pierce et al. model [43], Peng and Zhang’s model [19] and Hakimzadeh et al. model [44]. Among them, most of the models are only applicable to earth rock dams and most of the formulas are single independent variables, so the calculation results are uncertain and the existing models do not consider the impact of the breach shape on the peak discharge. In addition, because the breach flow is a strong unsteady flow when the dam failure, the upstream water level is complex and difficult to describe quantitatively, the height of water level drop (d) and the potential energy of the water body in the process of dam break (PE) is difficult to be measured, so the formula containing this parameter still has strong limitations. In fact, the breach shape determines the cross-section area of the outburst flood; the dam erodibility determines the duration of the outburst flood [45,46], so these two parameters still have an important impact on the peak discharge of the dam break flood.

The purpose of this study is to solve the shortcomings of the existing researches, such as the low simulation accuracy of the peak discharge of landslide dam failure and the incomplete consideration of the parameters. According to 67 groups of historical landslide dam failure cases with relatively complete data, the calculation model of the peak discharge of landslide dam failure is constructed on the basis of considering the final breach shape, dam body shape, dam erodibility and reservoir capacity and compared with the existing models. The Baige dammed lake (98°41′52.15″ E, 31°4′54.91″ N) outburst event in 2018 is used to further verify it. The model can provide reference for disaster prevention and mitigation of landslide dam failure.

2. Materials and Methods

2.1. Landslide Dam Failure Data

Based on the extensive collection of relevant literature, this paper obtains 67 groups of historical landslide dam failure data all over the world (Appendix A Table A1), including 45 groups of historical landslide dam failure data summarized in Peng et al. [19]. In Table A1, dam erodibility indicates the resistance of dam materials to the erosion action of water flow. Briaud (2008) [47] proposed six erosion categories (very high, high, medium, low, very low and non-erosive) according to erosion rate and breach velocity or flow shear stress. The higher the dam erodibility is, the greater the peak discharge is. However, the data of erosion rate, velocity and shear stress cannot be obtained before the dam break. Therefore, this paper refers to Zhang et al. (2019) [9] and Cui et al. (2008) [48] and divides the dam erodibility into three categories (high, medium, low) according to the particle composition of the landslide dam. The classification criteria are: when the landslide dam is dominated by large stones, it is low erodibility (*L*); when the landslide dam is dominated by soil, it is high erodibility (*H*); when the landslide dam contains a large number of stones and soil, it is medium erodibility (*M*). The meanings of other parameters are shown in Figure 1.

Figure 1. Schematic diagram of dam shape.

2.2. Modeling Dam-Break Peak Discharge

2.2.1. Calculation of Breach Size

Previous studies have shown that the width of the breach is most closely related to the storage capacity of the barrier lake [49–51]. Therefore, this study assumes that the width of the breach bottom is proportional to the 1/3 power of the storage capacity and then the expression of the final width of the breach (W_b) with the same dimension can be obtained:

$$W_b = \lambda V_l^{1/3} \quad (1)$$

where λ is a parameter determined by the erodibility of landslide dam; V_l is the capacity of barrier lake.

Secondly, Peng et al. [19] pointed out that the breach depth is closely related to the height of the barrier dam and the capacity of the barrier lake. Therefore, this paper uses the formula given by Peng et al. [19] for reference and assumes that the breach depth can be expressed as:

$$\frac{h_b}{H_r} = \xi \left(\frac{H_d}{H_r} \right)^\alpha \left(\frac{V_l^{1/3}}{H_d} \right)^\beta \quad (2)$$

where, ξ , α and β are parameters determined by the erodibility of landslide dam, which reflects the influence of the erodibility of landslide dam on the depth of breach; $H_r = 1$ m; V_l is barrier lake capacity; h_b is breach depth; H_d is landslide dam height.

A total of 67 groups data of landslide dam failure in Table A1 are fitted manually in a graph and analyzed by using Formulas (1) and (2) and the corresponding λ , ξ , α and β of

three kinds of landslide dam erodibility are obtained, as shown in Table 1. In the future, new landslide cases should be added to further modify these parameters.

Table 1. Calculation parameters of peak discharge of landslide dam with different erodibility. “H” refers to the high erodibility of the landslide dam, “M” refers to the moderate erodibility of the landslide dam, “L” refers to the low erodibility of the landslide dam.

Dam Erodibility	λ	ξ	α	β
H	0.27	4.554	0.283	0.433
M	0.15	5.641	0.047	0.532
L	0.07	0.7247	0.404	0.612

2.2.2. Calculation of Peak Discharge of Dam Failure

In order to consider the impact of breach shape on the peak discharge, this paper uses the semi analytical model proposed by Wang et al. [52] for reference. In this model, the cross-section shape of the breach is generalized as a trapezoid (Figure 1b) and then combinative parameter of the cross section is calculated according to Equation (3).

$$q = \frac{W_b}{M_l + M_r} \quad (3)$$

where q is combinative parameter of the cross section of breach, which is a parameter reflecting the shape of the breach. W_b is the bottom width of landslide dam breach. M_l and M_r are the slope ratio of left and right side of the breach, respectively; when landslide dam is overtopping failure, $M_l = M_r = 1.0$.

Then, the characteristic parameter (W_u) of final breach water depth is calculated by Equation (4).

$$W_u = \sqrt{\frac{h_b}{2q}} \quad (4)$$

Then, according to Equation (5), the characteristic parameter (W) of the breach water depth is calculated.

$$\frac{W}{W_u} = \frac{G(W_u) - x^*}{G(W) + \left(\frac{2W^2+1}{W^2+1}\right)^{-1/2}} \quad (5)$$

where $G(W_u)$ and $G(W)$ are two functions of W_u and W , respectively. x^* is the dimensionless distance, $x^* = 0$ at the breach.

The expressions of $G(W_u)$ and $G(W)$ are as follows:

$$G(W_u) = 2\sqrt{2} \left[1 - \frac{275}{2^{10}} \frac{\arctan W_u}{W_u} - \frac{19}{2^{10}} \left(\frac{1}{W_u^2 + 1} \right) - \frac{1}{2^9} \left(\frac{1}{W_u^2 + 1} \right)^2 \right] \quad (6)$$

$$G(W) = 2\sqrt{2} \left[1 - \frac{275}{2^{10}} \frac{\arctan W}{W} - \frac{19}{2^{10}} \left(\frac{1}{W + 1} \right) - \frac{1}{2^9} \left(\frac{1}{W + 1} \right)^2 \right] \quad (7)$$

According to Equations (4)–(7), the characteristic parameter (W) of breach water depth can be obtained, but the solution process needs to be obtained by trial calculation method, so the implicit expression of characteristic parameter (W) of breach water depth is transformed into approximate explicit expression (Equation (8)).

$$\begin{cases} W = 0.6339W_u^{0.9809} \exp(0.1551W_u) - 0.00036 & 0.02 \leq W_u \leq 0.45 \\ W = 0.7513W_u^{1.1650} \exp(-0.0475W_u) + 0.01960 & 0.45 < W_u \leq 3.00 \end{cases} \quad (8)$$

In order to illustrate the accuracy and rationality of Formula (8), a point is taken every 0.01 interval in the interval $W_u \in [0.02, 3.00]$ and then Formulas (4)–(7) and Formula (8)

are used to calculate the characteristic parameter (W) of breach water depth and then the calculation error of Formula (8) is compared. The results show that the average relative error is 0.067% and the maximum relative error is only 0.259%. In addition, Formula (8) is used to calculate 67 groups of landslide dam failure cases in Table A1. The minimum value of initial breach water depth characteristic parameter W_u is 0.28 and the maximum value is 1.53, which is far less than the calculation interval in Formula (8), so Formula (8) can meet the actual demand.

Finally, according to Formula (9), the peak discharge (Q_p) of landslide dam failure is calculated.

$$Q_p = 1.64 \sqrt{2gq^5} (M_l + M_r) W^3 \sqrt{\frac{(W^2 + 1)^3}{2W^2 + 1}} \quad (9)$$

where Q_p is the peak discharge of landslide dam failure, m^3/s ; g is the acceleration of gravity, m/s^2 .

3. Results and Discussions

3.1. Model Verification and Comparison

As the height of water level drop (d) and the potential energy (PE) of water are difficult to be measured in the process of dam failure, the calculated formula of peak discharge of landslide dam failure in Table 2 is selected for comparison with the model of this paper. The calculated results of each calculated model are shown in Figure 2.

Table 2. Empirical formula for peak discharge of landslide dam burst flood.

Empirical Formula	Note	References
$Q_p = 6.3 \cdot (H_d)^{1.59}$	H_d : Dam height (m).	Costa (1985) [39]
$Q_p = 672 \cdot (V_1)^{0.56}$	V_1 : Volume of dammed lake (m^3).	Costa (1985) [39]
$Q_p = 181 \cdot (V_1 H_d)^{0.43}$	H_d : Dam height (m). V_1 : Volume of dammed lake (m^3).	Costa (1985) [39]
$Q_p = 1.60 \cdot (V_0)^{0.46}$	V_1 : Volume of dammed lake (m^3).	Walder and O'Connor (1997) [42]
$Q_p = g^{\frac{1}{2}} H_d^{\frac{5}{2}} \left(\frac{H_d}{H_r} \right)^{-1.371} \cdot \left(\frac{V_1^{1/3}}{H_d} \right)^{1.536} \cdot e^a$	g : The acceleration of gravity (m/s^2). H_d : Dam height (m). $H_r = 1$ m; V_1 : Volume of dammed lake (m^3). a : Erodibility coefficient. When the dam erodibility is high, medium and low, a is 1.236, -0.380 and -1.615 respectively.	Peng and Zhang (2012) [19]

It can be seen from Figure 2 that the reliability of the model proposed in this study and the model proposed by Peng et al. [19] is significantly higher than that of other models; compared with the model proposed by Peng et al. [19], when the measured peak discharge of landslide dam failure is less than $10,000 \text{ m}^3/\text{s}$, the calculated peak discharge of this study model is similar to that of Peng et al. [19]. When the measured peak discharge of landslide dam failure is greater than $10,000 \text{ m}^3/\text{s}$, the calculated peak discharge of this study model is closer to the optimal line than that of Peng et al. [19].

The mean relative error (MRE), root mean square error ($RMSE$) and coefficient of determination (R^2) of the calculated peak discharge are further used to illustrate the calculated effect of the above model. The MRE reflects the average reliability or the average error rate of the calculated value. The $RMSE$ reflects the precision of the calculated value because it is particularly sensitive to maximum and minimum values. The R^2 reflects the correlation between the calculated value and the measured value. The simulation will be more accurate with smaller MRE and $RMSE$ and larger R^2 . MRE , $RMSE$ and R^2 are as follows:

$$MRE = \frac{1}{N} \sum_{i=1}^N \frac{|Q_{cal,i} - Q_{obs,i}|}{Q_{obs,i}} \quad (10)$$

$$RMSE = \sqrt{\frac{1}{N} \sum_{i=1}^N (Q_{cal,i} - Q_{obs,i})^2} \quad (11)$$

$$R^2 = 1 - \frac{\sum_{i=1}^N (Q_{cal,i} - Q_{obs,i})^2}{\sum_{i=1}^N (Q_{obs,i} - Q_{obsm})^2} \quad (12)$$

$$Q_{obsm} = \frac{1}{N} \sum_{i=1}^N Q_{obs,i} \quad (13)$$

where $Q_{cal,i}$ is the simulation peak discharge of the i th landslide dam failure case ($i = 1, 2, 3$); $Q_{obs,i}$ is the measured peak discharge of the i th landslide dam failure case ($i = 1, 2, 3, \dots$), $N = 67$ in this paper; Q_{obsm} is the mean of the measured peak discharges. According to the calculated results (Table 3), MRE , $RMSE$ and R^2 of this model are smaller than those of other models, indicating that the calculated effect of this model is the best.

Figure 2. Comparison of calculated results of different models. (a,b) are separated from the same figure, because if all models are put into the same graph with too many data points, it is difficult to distinguish the calculation accuracy of each model.

Table 3. Comparison of calculated effects of flood peak discharge calculation model.

Model	References	MRE	RMSE (m ³ /s)	R ²
This study	-	0.48	4387	0.995
$Q_p = g^{\frac{1}{2}} H_d^{\frac{5}{2}} \left(\frac{H_d}{H_r} \right)^{-1.371} \cdot \left(\frac{V_1^{1/3}}{H_d} \right)^{1.536} \cdot e^a$	Peng and Zhang (2012) [19]	0.50	12,227	0.963
$Q_p = 181 \cdot (V_1 H_d)^{0.43}$	Costa (1985) [39]	1.49	44,479	0.510
$Q_p = 672 \cdot (V_1)^{0.56}$	Costa (1985) [39]	1.34	29,943	0.778
$Q_p = 6.3 \cdot (H_d)^{1.59}$	Costa (1985) [39]	3.12	62,412	0.035
$Q_p = 1.60 \cdot (V_1)^{0.46}$	Walder and O'Connor (1997) [42]	1.32	48,278	0.423

3.2. Example Application

On 10 October 2018 and 3 November 2010, a large-scale landslide occurred in Baige (98°41′52.15″ E, 31°4′54.91″ N) within the boundaries of Jiangda County in Tibet and Baiyu County in Sichuan Province, blocking the main stream of Jinsha River and forming a barrier lake (Figure 3). After that, overtopping failure occurred (Figure 4), causing serious threat and loss to the upstream and downstream affected areas. Zhang et al. [9] investigated the two dam failure events of Baige landslide and obtained detailed dam failure data (Table 4).

Figure 3. Location of Baige landslide. The figure comes from Zhang et al. (2019) [9]. **Figure 4.** Baige landslide blocking the river on October 10, 2010. (a) is the panorama before the landslide dam break, and (b) is the top view of the dam crest when the landslide dam break.

Table 4. Parameters of Baige landslide dam on Jinsha River in 2018.

Dam Failure Events	Dam Erodibility	Dam Height h_d (m)	Volume of Dammed Lake V_l ($\times 10^6$ m ³)	Data Sources
10 October 2018	M	61	49	Zhang et al. [9]
3 November 2018	M-H	81	494	

This study model and models in Table 2 are used to simulate the peak discharge of two landslide dams. The simulated results are shown in Table 5. It can be seen from Table 5 that the simulated values of the peak discharge of this study model and Peng et al. [19] are more reasonable, but the simulated effect of this study model is still significantly better than that of Peng et al. [19], while there is a large gap between the simulated results of other models and the measured peak discharge, especially for the landslide dam failure event on 3 November, the simulated relative error is more than 90%.

Table 5. Simulated results of peak discharge of two dam breaks in Baige of Jinsha River in 2018.

Prediction Model	Peak Discharge (m ³ /s)		Relative Error (%)	
	10 October 2018	3 November 2018	10 October 2018	3 November 2018
This study	9927	31,634	0.73	6.68
$Q_p = g^{\frac{1}{2}} H_d^{\frac{5}{2}} \left(\frac{H_d}{H_r} \right)^{-1.371} \cdot \left(\frac{V_l^{1/3}}{H_d} \right)^{1.536} \cdot e^a$	7999	30,528	20.01	9.95
$Q_p = 181 \cdot (V_l H_d)^{0.43}$	11,369	17,244	13.69	94.91
$Q_p = 672 \cdot (V_l)^{0.56}$	14,765	21,670	47.65	93.61
$Q_p = 6.3 \cdot (H_d)^{1.59}$	4345	6821	56.55	97.99
$Q_p = 1.60 \cdot (V_l)^{0.46}$	11,651	15,967	16.51	95.29
Measured peak discharge	10,000	33,900	–	–

In addition, there are already some empirical simple models and physical or numerical complex models in landslide dam-failure [2,8,10,15,18,21,24,33,39,50,52–55], while our proposed model is halfway, representing a promising compromise that needs to be further tested to new case studies.

4. Conclusions

The purpose of this study is to obtain the calculated model for peak discharge of landslide dam failure based on 67 historical landslide dam failure cases all over the world. The key conclusions are:

- (1) The calculated model for peak discharge of landslide dam failure is proposed, which can consider the dam erodibility, the final shape of the breach, the shape of the dam, the lake volume and other parameters at the same time.
- (2) Compared with other models, the calculated peak discharge of this model are more close to measured peak discharge. In addition, the model needs 12 parameters to calculate the breach depth, breach bottom width, breach top width and breach peak discharge, whereas the model proposed by Peng et al. needs 17 parameters.
- (3) The model proposed in this paper is used to simulate the peak discharge of two dam failure events of Baige landslide in Jinsha River (10 October 2018 and 3 November 2018). The relative error of peak discharge simulation of the two events is 0.73% and 6.68%, respectively, which is obviously better than other models, indicating that the simulated effect of the model is reasonable.

Finally, new cases of landslide dam failure should be added in the future study to further modify the model. This study can provide an important theoretical reference for disaster prevention and mitigation of landslide dam.

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Abbreviations

H_d	Dam height
V_1	Volume of dammed lake
W_d	Dam width
V_d	Volume of landslide dam
h_b	Breach depth
W_t	Breach top width
W_b	Breach bottom width
Q_p	Peak discharge of landslide dam failure
PE	Potential energy of water
d	Height at which the water level drops during a dam outbreak
g	Acceleration of gravity
a	Erodibility coefficient of landslide dam
H	High erodibility of the landslide dam
M	Moderate erodibility of the landslide dam
L	Low erodibility of the landslide dam
H_r	Unit length, $H_r = 1$ m
q	Combinative parameter of the cross section of breach
M_l	Slope ratio of left side of the breach
M_r	Slope ratio of right side of the breach
W_u	Characteristic parameter of initial breach water depth
W	Characteristic parameter of the breach water depth
λ	Parameter determined by the erodibility of landslide dam
ξ	Parameter determined by the erodibility of landslide dam
α	Parameter determined by the erodibility of landslide dam
β	Parameter determined by the erodibility of landslide dam
MRE	Mean relative error
$RMSE$	Standard deviation
R^2	Coefficient of determination

Appendix A

Table A1. Historical case data of landslide dam failure. “H” refers to the high erodibility of the landslide dam, “M” refers to the moderate erodibility of the landslide dam, “L” refers to the low erodibility of the landslide dam.

No.	Name	Location	Data of Formation	Dam Height H_d (m)	Dam Width W_d (m)	Dam Volume V_d ($\times 10^6$ m ³)	Lake Volume V_l ($\times 10^6$ m ³)	Dam Erodibility	Breach Depth h_b (m)	Breach Top Width W_t (m)	Breach Bottom Width W_b (m)	Peak Discharge Q_p (m ³ /s)	References
1	Tsatichhu	Bhutan	10 September 2003	110	700	5	1.5	H	-	-	-	6900	[56]
2	Arida River, Hanazono Village	Papua New Guinea	11 November 1985	200	3000	200	50	H	70	-	-	8000	[57]
3	Bireh-Ganga River	India	22 September 1983	274	2750	286	460	H	97.5	-	-	56,650	[39,42]
4	Mantaro River	Peru	16 August 1945	133	580	3.5	301	H	56	-	-	35,400	[58]
5	Mt Adams	New Zealand	6 October 1999	90	700	12.5	6	H	45	125	45	2500	[59,60]
6	Nishi River, Totsugawa Village	Japan	20 August 1889	20	120	0.63	0.4	H	-	-	-	1100	[18,61]
7	Tanggudong	China	8 June 1967	175	3000	68	680	H	-	-	55	53,000	[62]
8	Tegermach River	USSR	1853	120	60	20	6.6	H	-	310	55	4960	[39,63]
9	Totsu River, Daito Village	Japan	20 August 1889	18	450	0.036	0.78	H	-	-	-	3400	[18,61]
10	Totsu River, Daito Village	Japan	20 August 1889	10	380	0.23	0.93	H	-	-	-	3500	[18,61]
11	Totsu River, Nakatotsugawa Village	Japan	20 August 1889	7	250	0.073	0.65	H	-	-	-	6900	[18,61]
12	Arida River, Hanazono Village	Japan	18 July 1953	10	150	0.18	0.047	H	-	-	-	890	[18,61]
13	Yigong	China	9 April 2000	80	2350	300	3000	H	58.39	-	128	124,000	[64]
14	Tanggudong	China	8 June 1967	175	3000	68	680	H	-	-	-	53,000	[12]
15	Lantianwang	China	10 June 1786	70	1400	40	50	H	-	-	-	37,345	[12,65]
16	Cordillera de Santa Cruz	Argentina	November 2005	15	355	12	0.0041	H	-	-	-	1000	[66]
17	Ambon Island	Indonesia	July 2012	140	1660	170	25	H	-	-	-	17,000	[67]
18	Indus valley near the Nanga Parbat	Pakistan	December 1840	150	30,000	-	30,000–50,000	H	-	-	-	509,000	[68]
19	Donghekou	China	12 May 2008	20	750	12	6	M	10	25	15	1000	[69]
20	East Fork Hood River	America	25 December 1980	10.7	225	0.085	0.105	M	-	-	-	850	[18,39]
21	Hime River	Japan	9 August 1911	60	500	1.9	16	M	-	-	-	1800	[18,61]
22	Hongshihe	China	12 May 2008	50	500	18	4	M	10	-	9	500	[69]
23	Iketsu River	Japan	19 August 1889	140	180	3.4	26	M	-	-	-	480	[18,61]
24	Kaminirau River	America	26 July 1788	50	500	2	2.2	M	-	-	-	440	[18,61]
25	Kano River, Kitatotsugawa Village	Japan	20 August 1889	15	130	0.094	1.3	M	-	-	-	1600	[18,61]
26	Kano River, Totsugawa Village	Japan	20 August 1889	20	120	0.1	0.6	M	-	-	-	1300	[18,61]
27	La Josefina	Ecuador	29 March 1993	100	1100	20	200	M	43	-	-	10,000	[42,70]
28	Mantaro River	Peru	25 April 1974	175	3800	1300	670	M	107	243	-	10,000	[71]
29	Naka River, Kaminaka Town	Japan	25 July 1892	80	330	3.3	75	M	-	-	-	5600	[18,61]
30	Nishi River, Totsugawa Village	Japan	20 August 1889	20	200	0.6	1.3	M	-	-	-	980	[18,61]
31	Nishi River, Totsugawa Village	Japan	20 August 1889	25	250	0.63	1.8	M	-	-	-	1200	[18,61]
32	Pilsque River	Ecuador	2 January 1990	58	450	1	2.5	M	30	50	-	700	[42,72]
33	Ram Creek	New Zealand	24 May 1968	40	1200	2.8	1.1	M	30	-	30	1000	[73]
34	Rio Paute	Ecuador	29 March 1993	112	800	25	210	M	-	-	-	8250	[74]
35	Rio Toro River	Costa Rica	13 June 1992	85	600	3	0.5	M	40	60	-	400	[75]
36	Susobana River	Japan	24 March 1847	54	250	1.2	16	M	-	-	-	510	[18,61]
37	Tangjashan	China	12 May 2008	82	611.8	20.37	246.6	M	30	190	90	6500	[4,76]
38	Totsu River, Amakawa Village	Japan	20 August 1889	80	350	2.5	17	M	-	-	-	2400	[18,61]

Table A1. Cont.

No.	Name	Location	Data of Formation	Dam Height H_d (m)	Dam Width W_d (m)	Dam Volume V_d ($\times 10^6$ m ³)	Lake Volume V_l ($\times 10^6$ m ³)	Dam Erodibility	Breach Depth h_b (m)	Breach Top Width W_t (m)	Breach Bottom Width W_b (m)	Peak Discharge Q_p (m ³ /s)	References
39	Totsu River, Daito Village	Japan	21 August 1889	80	750	13	40	M	-	-	-	2000	[18,61]
40	Totsu River, Kitatotsugawa Village	Japan	20 August 1889	110	690	3.1	42	M	-	-	-	4800	[18,61]
41	Unawaea Landslide Dam	New Zealand	17 August 1991	70	550	4	0.9	M	-	-	-	250	[42]
42	Upstream Xiaogangjian	China	12 May 2008	95	300	2	12	M	30	80	-	3950	[77]
43	Xiaojiqiao	China	12 May 2008	62	200	2.42	20	M	37.3	131.6	8	1000	[78]
44	Zepozhu, Dong River	China	27 October 1965	51	650	29	2.7	M	-	-	-	560	[39,62]
45	Hongshiyuan	China	3 August 2014	83~96	262	12	260	M	-	-	-	7420	[7]
46	Sunkoshi landslide dam	Nepal	2 August 2014	52	300	2	11.1	M	-	-	-	6346	[79]
47	Hsiaolin village	China	9 August 2009	44	1500	15.4	9.9	M	-	-	-	2974	[5]
48	Tsao-Ling	China	21 September 1999	50	150	120	46	M	-	-	-	7422	[80]
49	Xuelongnang	China	Ancient	84	680	-	310	M	33	-	-	10,168~16,091	[53]
50	Wenjaiba	China	12 May 2008	50	700	6	5	M	-	-	-	2300	[81]
51	Yibadao	China	12 May 2008	25	100	0.15	3.79	M	-	-	-	2153/2355	[82]
52	Laoyingyan	China	12 May 2008	100	500	4.7	5	M	-	-	-	1700	[83]
53	Qingyandong	China	21 June 2005	30		0.3	1.5	M	6.5	-	30	500	[84]
54	Downstream Xiaogangjian	China	12 May 2008	30	150	3.5	7	M	-	34.6	-	3900	[85]
55	Hattian Bala Landslide Dam	Pakistan	8 October 2005	130	1587	65	62	M	-	-	-	5500	[6,86]
56	Baige 1	China	10 October 2018	61	1500	-	249	M	-	-	-	10,000	[9]
57	Baige 2	China	3 November 2018	81	1000	-	494	M-L	-	-	-	33,900	[9]
58	Arida River, Hanazono Village	Japan	20 July 1953	60	500	2.6	17	L	-	-	-	750	[18,61]
59	Jackson Creek Lake	America	18 May 1980	4.5	302.5	0.77	2.47	L	-	-	-	477	[18]
60	Ojika River	Japan	1 August 1683	70	400	3.8	64	L	-	-	-	620	[18,61]
61	Sai River	Japan	24 March 1847	82.5	1000	21	350	L	-	-	-	3700	[18,61]
62	Shiratani River, Totsugawa Village	Japan	21 August 1889	190	500	10	38	L	-	-	-	580	[18,61]
63	Sho River	Japan	29 November 1586	100	600	19	150	L	-	-	-	1900	[18,61]
64	Tangjiawang	China	12 May 2008	35	800	4	7/15.2	L	-	-	-	974	[87]
65	Suya	China	17 July 2012	4.3	300	0.6	4.1	L	-	-	-	338	[88]
66	Kuitun River	China	15 July 1978	10	150	0.75	1.67	L	-	-	-	917	[89]
67	Paree Chu	India	26 June 2005	40	1100	-	64	L	-	-	-	2000	[90]

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