Hazard Prediction Method of Landslide Damming and Analysis of a Typical Application

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\textbf{Abstract.} Landslide damming occurs frequently, affects a wide range of areas, and is difficult to predict, thus threatening the safety of human life, properties, and engineering structures. However, the studies on early identification remain at an early stage. This paper proposes a hazard prediction method for landslide damming, which includes prediction models of river blockage, landslide dam geometry, landslide dam stability, and dam breach time. On this basis, the landslide damming hazard can be predicted via ten parameters: the repose angle of the landslide mass, the landslide volume, the landslide discharge, the river discharge, the reservoir capacity of the barrier lake, the bottom width of the valley, two slope angles on both sides of the valley, the valley bed inclination, and the sliding surface dip-angle. The proposed method was examined in relation to a typical case, namely, the Baige landslide damming that occurred in 2018 in China, with the application process presented integrally. The results indicated that the river blockage model predicted that the Baige landslide could form a huge landslide dam, which was fully in line with the actual situation. The landslide dam geometry model provided the predicted value of the height, width, and length, as well as the downstream and upstream angles, of the Baige landslide dam, with the maximum relative error between the predicted values and the true values less than 20%. The prediction results of the landslide dam stability model indicated that when the reservoir capacity of the barrier lake is 280 million m\textsuperscript{3}, the dam could breach. In fact, the dam breach time model predicted that the dam could breach within 38 h after the landslide dam formation, which was 11\% less than the actual breach time of the Baige landslide dam. The current study provides a useful theoretical reference and technical support for the early identification, prediction, and warning of the disaster chain of landslide-induced river blocking.

\textbf{Keywords:} Disaster Chain, Landslide Dam, River Blocking, Hazard Prediction Method

1. Introduction
A landslide dam forms when the landslide obstructs a narrow and steep valley in a mountainous area [1]. Due to the loose structure of the deposits, the landslide dam may collapse in a short period of time, causing further serious disasters in downstream areas. Many countries have regularly been faced with landslide dam disasters, including Canada, China, Japan, Italy, New Zealand, and the United States [2]. Thus, there is an urgent need to address the safety problems caused by landslide dam geological disasters. In fact, the early identification of such disasters has received a great deal of attention in recent years.

Landslide damming disasters generally involve a clear chain effect, with the entire evolution of the disaster chain including the process of the landslide, river blocking, and dam breaches. Previous studies [3-5] have mainly been focused on the evolution of the dam breach and the flooding and debris flow induced by the breach, while there exists no systematic study on the process of dam formation. Furthermore, research results pertaining to a hazard prediction method for landslide damming have not, as yet, been reported.

This paper was thus aimed at addressing this gap in presenting such a hazard prediction method. The method incorporates four models: a new dimensionless river blockage criterion, a prediction model for landslide dam geometry, a stability evaluation model for landslide dams, and a prediction model for the time duration of river blockages. The application process of the proposed method is examined in terms of a typical case, namely, the Baige landslide damming that occurred in 2018 in China.

2. The Baige Landslide Dam

2.1. Overview of the Baige landslide

At 22:06 on October 10, 2018, a massive landslide occurred on the right bank of Jinsha River at a point located at Baige village, the junction of Tibet and Sichuan Province (31°4’56.41” N, 98°42’17.98” E). The main channel of Jinsha River was blocked by the Baige landslide, forming a huge landslide dam. Following the blockage of the river for 43 h, the dammed lake held $2.9 \times 10^8$ m$^3$ of water. At 17:15 on October 12, the Baige barrier lake began to flow naturally [6] and by 14:30 on October 13, the barrier lake had essentially retreated to the base flow, and the danger was eased. However, on November 03, 2018, the rock mass at the back edge of the slip source area of the first landslide again collapsed and Jinsha River was blocked for a second time.

2.2. Basic characteristics of the Baige landslide dam

Since the second Baige landslide occurred at the same location as the first, the formation process of the dam was greatly influenced by the initial landslide dam. In addition, the discharge process of the second landslide dam involved artificial intervention. As such, the method presented in this study was not applicable and the application analysis of this case was thus carried out on the first “10.10” Baige landslide.

![Fig. 1. River blockage and landslide dam on the Jinsha River (modified from [7]). (a) Parameters of the Baige landslide, (b) parameters of the Baige landslide dam.](image-url)
The Baige landslide, which may have been due to the weathering and creep deformation over a long period of time, occurred on the right bank of Jinsha River. As shown in Fig. 1a, the elevation of the river surface and the landslide trailing edge was approximately 2,880 and 3,680 m, respectively, while the landslide area was approximately 76.7 × 10⁴ m². Meanwhile, as shown in Fig. 1b, the longitudinal length of the landslide was approximately 1,300 m, while the transverse width was approximately 470–720 m, with the average width around 600 m. In the direction along Jinsha River, the middle part of the landslide mass was thicker than the lower and upper parts, with the average thickness approximately 31 m. The landslide mass began to collapse under the action of gravity, undergoing collision and erosion before ultimately entering Jinsha River at a velocity of approximately 11.7 m/s [8]. According to the average thickness, width, and velocity of the landslide mass, the average discharge of the mass was approximately 217,620 m³/s. Meanwhile, the volume of the mass that entered the river to form a landslide dam was approximately 27.95 × 10⁶ m³. The maximum height of the landslide dam was 81.4–130 m, the width was 500–700 m, and the top and bottom lengths were 270–320 m and 962–1,330 m, respectively. The main parameters of the Baige landslide dam are listed in Table 1.

**Table 1. Geometry parameters of the Baige landslide dam.**

| Parameter                  | Value          |
|----------------------------|----------------|
| Dam height, H (m)          | 81.4-130       |
| Dam top length, L₁ (m)     | 270-320        |
| Dam bottom length, L₂ (m)  | 962-1330       |
| Dam width, B (m)           | 500-700        |

The valley bed angle of Jinsha River was approximately 2.34°, with the river channel presenting a “U” shape with a bottom width of 150 m and slope angles of 35° and 23° on the left and right banks, respectively. The average sliding slope angle of the Baige landslide was around 34°, while the repose angle of the landslide mass was approximately 34°. During the 43-h period from the formation of the landslide dam to its overtopping, the discharge of the river was approximately 800 m³/s. Table 2 presents the main parameters of the river-blocking event.

**Table 2. The main parameters of the Baige river-blocking event.**

| Parameter                  | Value          | Parameter                  | Value          |
|----------------------------|----------------|----------------------------|----------------|
| Landslide volume of entering the river, V (m³) | 27.95×10⁶ | Discharge of Jinsha River, Qw (m³/s) | 800 |
| Repose angle of landslide mass, φ (°)             | 34             | Riverbed inclination, θ (°) | 2.34          |
| Sliding surface dip-angle, α (°)                  | 34             | Right riverbank slope, φi (°) | 34             |
| Landslide discharge, Ql (m³/s)                    | 217620         | Left riverbank slope, φr (°) | 23             |
| Reservoir capacity of barrier lake, V_b (m³)      | 2.9×10⁸        | Bottom width of river, b (m) | 150            |

3. Prediction of Landslide Dam Formation

The quantitative prediction of landslide damming disasters involves four main steps. First, it is necessary to assess whether a potential landslide could block a river. Second, if a landslide could block the river to form a landslide dam, the geometry of the dam must be predicted. Third, based on the prediction results for the landslide dam geometry, the stability of the dam must be evaluated. Finally,
if the landslide dam is deemed to be unstable, the failure time of the dam must be predicted. As such, four models were proposed to predict the landslide damming hazard.

3.1. Discriminant criterion for landslide dam formation
A landslide dam could form when the landslide and river parameters reach a critical point that would allow for a moving landslide to block the flowing river. A total of 29 experiments were carried out in our previous study [9], and based on these experiments, a new dimensionless river blockage criterion (RBC) was proposed to predict the formation of a landslide dam. The RBC is given by the following equation:

\[ RBC = \frac{Q_l}{Q_w} \]  

where \( Q_l \) is the landslide discharge (\( \times 10^{-3} \) m\(^3\)/s) and \( Q_w \) is the water flow rate of the river valley (L/s).

The critical conditions for landslide dam formation were derived based on our previous study [9] as follows: a landslide completely blocks the river and a landslide dam will form when the landslide discharge is 1.5 times or larger than that of the river; when the landslide discharge is less than 1.5 times that of the river, a landslide dam cannot form.

3.2. Prediction model for landslide dam geometry
The geometry of a landslide dam is highly influenced by the landslide dam formation conditions. A series of experiments were thus designed to systematically investigate the formation process and the 3D geometry of landslide dams under different combinations of valley bed inclinations and sliding surface dip-angles [10]. A prediction model for the landslide dam geometry was established based on the experimental results:

\[
\begin{align*}
H &= \kappa_1 \sqrt{\frac{V}{W}} \\
L_b &= \kappa_2 \sqrt{\frac{V}{W}} \\
L_t &= \kappa_3 \sqrt{\frac{V}{W}} \\
W &= \frac{1}{2} \left( 2w + \frac{h}{\tan \phi_l} + \frac{h}{\tan \phi_r} \right)
\end{align*}
\]

where \( V \) is the landslide mass volume (m\(^3\)), \( H \) is the landslide dam height (m), \( L_b \) is the bottom width of the landslide dam (m), \( L_t \) is the top width of the landslide dam (m), \( W \) is the equivalent valley width (m), \( w \) is the valley bottom width (m), \( \phi_l \) and \( \phi_r \) are the right and left riverbank slope angles (°), respectively, and \( \kappa_1, \kappa_2, \) and \( \kappa_3 \) are the morphological parameters, which can be expressed by the following formulas:

\[
\begin{align*}
\kappa_1 &= \sqrt{\frac{2 \lambda \tan \beta_d \tan \beta_u}{2 \tan \beta_d - \lambda (\tan \beta_d + \tan \beta_u)}} \\
\kappa_2 &= \sqrt{\frac{2 \tan \beta_u}{2 \lambda \tan \beta_d \tan \beta_u - \lambda^2 \tan \beta_d (\tan \beta_d + \tan \beta_u)}} \\
\kappa_3 &= \frac{1}{\kappa_1} - \kappa_1 \frac{\tan \beta_d + \tan \beta_u}{\tan \beta_d \tan \beta_u}
\end{align*}
\]
where $\beta_d$ and $\beta_u$ are the downstream and upstream slopes ($^\circ$), respectively, and $\lambda$ denotes the relationship between the relative angles of the downstream and upstream slopes. The attendant parameters can be expressed by the following formulas:

\[
\begin{align*}
\beta_d &= \chi \phi - \theta \\
\beta_u &= \chi \phi + \theta \\
\lambda &= 0.37 + 1.1 \tan \theta \\
\chi &= 0.57 + 0.51(1 + e^{(\alpha - 34)/10.5})^{-1}
\end{align*}
\] (4)

where $\theta$ is the riverbed inclination ($^\circ$), $\alpha$ is the sliding surface dip-angle ($^\circ$), and $\phi$ is the repose angle of the landslide mass ($^\circ$).

3.3. Stability evaluation model for landslide dams

The stability of a landslide dam is mainly determined by the critical condition of the reservoir capacity of the upstream barrier lake and the geometry of the landslide dam. Based on this understanding, the stability of a landslide dam could be rapidly predicted in terms of its geometry. In our previous study [11], a database containing 1,328 cases of landslide dams was collected and, based on this, a stability evaluation model for landslide dams was proposed. The model is given by the following equation:

\[I_e = -1.554 + 2.317 \log(V_L) - 2.828 \log(B_{du}) - 2.336 \log(L_h)\] (5)

where $V_L$ is the reservoir capacity of the barrier lake ($m^3$), $B_{du}$ is the dam width (m), and $L_h$ is the dam length (m).

Again, the criterion of landslide dam stability was determined based on our previous study as follows: when $I_e \geq 0$, the landslide dam is unstable; when $I_e < 0$, the landslide dam is stable.

3.4. Prediction model for the time duration of river blockage

According to Peng and Zhang [12], without channelized spillways or other protected outlets, landslide dams commonly fail due to overtopping. Based on this understanding, a method for predicting the duration of a given river blockage was proposed in our previous study [9]. The duration of a river blockage can be expressed in the following terms:

\[t = \kappa_1 V/(2Q_w \tan \theta)\] (6)

where $t$ is the duration of the river blockage (s), while $\kappa_1$, $V$, $Q_w$ and $\theta$ are defined as above.

4. Case Study Results

4.1. Results

Here, Eq.1 was used to assess the Baige landslide dam formation. The Jinsha River discharge and the Baige landslide discharge are detailed in Table 2. Using Eq. 1, the RBC was found to be 272, which was far higher than the critical condition for landslide dam formation. Therefore, it could be predicted that the Baige landslide could form a large landslide dam, which was consistent with the facts.

Meanwhile, Eqs. 2, 3, and 4 were used to predict the geometry of the Baige landslide dam, with the seven parameters listed in Table 2 used as input parameters for calculating the geometric parameters of the dam. The calculated results were then compared with the actual parameters, which are listed in Table 3. Here, there was a relative error of around 20% with the calculated results for the height and length of the landslide dam in relation to the actual values. Despite this slight error, the calculated results could be used to provide the conditions for the next step in hazard prediction.
Table 3. Calculated values and actual values of the geometric parameters of the Baige landslide dam.

|            |   |   |   |   |   |
|------------|---|---|---|---|---|
|            | $H$ (m) | $L_t$ (m) | $L_b$ (m) | $B_{de}$ (m) | $\beta_i$ (°) | $\beta_d$ (°) |
| Calculated values | 145 | 189 | 774 | 698 | 30.39 | 25.71 |
| Actual values    | 81.4-130 | 270-320 | 962-1330 | 500-700 | / | / |

Following this, Eq. 5 was used to predict the stability of the Baige landslide dam. The reservoir capacity of the barrier lake was presented in Table 2, while the width and length of the landslide dam were calculated in the previous step. Using Eq. 5, it was found that $I_e = 3.4$. Therefore, according to the criterion, the Baige landslide dam is unstable.

Using the geometric parameters of the landslide dam (Table 3) and Eq. (6), the duration of the Baige river-blocking event was calculated to be approximately 38 h. In fact, Jinsha River underwent a natural discharge 43 h after the landslide. As such, the calculated duration was approximately 11% less than the actual duration. The calculated results in this study can thus be regarded as satisfactory and acceptable.

4.2. Discussion

The proposed prediction method incorporates ten input parameters: the repose angle of the landslide mass ($\phi$), the landslide volume ($V$), the landslide discharge ($Q$), the river discharge ($Q_r$), the reservoir capacity of the barrier lake ($V_{ol}$), the bottom width of the valley ($w$), two slope angles on both sides of the valley ($\phi_1$ and $\phi_2$), the valley bed inclination ($\theta$), and the sliding surface dip-angle ($\alpha$).

Among them, the repose angle of the landslide mass, the bottom width of the valley, the two slope angles on both sides of the valley, the river discharge, and the valley bed inclination can be easily obtained from a geological survey. Meanwhile, a number of previous studies have proposed useful methods for predicting the landslide volume, the sliding surface dip-angle, and the landslide discharge, and these methods could be adopted for further investigations. Disaster chains, which can involve landslide debris, flow-river blocking, dam failure, flooding, and debris flow, often occur in the southwest of China. The current study provides a useful theoretical reference and technical support for the early identification, prediction, and warning of such disaster chains.

5. Conclusions

This paper presented a hazard prediction method for landslide damming. The application process of the method was then fully demonstrated using the case of the Baige landslide dam. The following conclusions can be drawn:

(1) The hazard prediction method incorporates four models: a new dimensionless RBC, a prediction model for landslide dam geometry, a stability evaluation model for landslide dams, and a prediction model for the duration of river blockages.

(2) The proposed method also includes ten input parameters: the repose angle of the landslide mass, the landslide volume, the landslide discharge, the river discharge, the reservoir capacity of the barrier lake, the bottom width of the valley, two slope angles on both sides of the valley, the valley bed inclination, and the sliding surface dip-angle.

(3) The prediction results of the proposed method were in good agreement with the actual situation of the Baige landslide damming event. The calculated parameters of the height and length of the landslide dam were 20% different from the actual values, while the predicted stability of the Baige landslide dam was in line with the actual situation. The predicted duration of the Baige river-blocking event was approximately 11% less than the actual duration.

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