A geotechnical index for landslide dam stability assessment

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ABSTRACT
Effective disaster countermeasures of landslide dams hinge on the stability prediction in the emergency and mid-long-term stages. Variable morphological characteristics and multiple geomorphic indices as well as complicated geotechnical parameters pose significant challenges to a quick stability assessment. A particle size distribution (PSD) database was established based on 83 landslide deposits, including damming and non-damming landslides from around the world. Characteristic parameter $K$ for quantitatively measuring landslide dam material properties were suggested on the basis of statistical analysis of deposit PSDs. Here we proposed a geotechnical index $MMI$ (morphometry & material index) including dam volume, height and width, as well as characteristic parameter $K$, grain size $d_{90}$ and lake volume that helps to estimate landslide dam stability. Besides, landslide dams in our inventory were divided into four levels based on their material composition, longevity and spillway form. With this we achieved the stability classification criterion according to the relation between these historical cases stability levels and $MMI$ values. This study underlines the need to include geotechnical aspects such as grain size distribution for assessing dam stability, because the impact of material conditions on landslide dam evolution cannot be ignored.

1. Introduction

Natural river-damming events induced by landslides have occurred in all mountain environments on the globe (Delaney and Evans 2015; Do et al. 2016). The potential outburst flood from landslide dam failure often poses a major hazard to society and environment downstream, making dam stability assessment necessary (Chen et al. 1992; Glancy and Bell 2000; Hewitt 2006; Davies and Korup 2007; Evans et al. 2011a,
Examples include the landslide dam formed on Dadu River China in 1786, which might have resulted in the largest number of casualties in the human history ($\approx 1 \times 10^5$) (Dai et al. 2005). More recently, the Baige landslide dams impounding both the Jinsha River China in 2018 had caused evacuation of more than $1 \times 10^5$ people and extensive damage to infrastructure in the valley involved (Ministry of Emergency Management, PRC). Previous research and our investigations have indicated that there are also longer-lived dams which are preserved until today. Some of those dams provide opportunities for power generation and tourism (Weidinger et al. 2002; Duman 2009; Hermanns et al. 2009; Wang et al. 2012; Korup and Wang 2015; Delgado et al. 2020; Zhang et al. 2021). Examples include the Waikaremoana lake in New Zealand, which is a holiday destination and waterhead supply for a power station (Schuster and Alford 2004). And the 2014 Hongshiyan landslide dam in China that is also used for hydroelectricity generation after being stabilized by building concrete cut-off wall and headrace tunnel after emergency treatment (He et al. 2021). Thus, it is critical to increase our understanding of landslide dam stability assessment.

Apart from natural collapse, the failure of a multiple landslide dams was initiated artificially in the early stage of their existence in order to prevent an uncontrolled dam breach (Zhong et al. 2020). Thus, the natural longevity of these dams with human intervention is unknown. Therefore, both emergency and mid-long-term stability assessments play an important part in hazard mitigation and risk management (Korup and Tweed 2007; Crosta et al. 2011; Dufresne et al. 2018). However, such assessments are still challenging due to the diverse factors influencing in varying degrees on dam stability (Zheng et al. 2021). Efficient tools have to be developed to better address landslide dam hazards (Dong et al. 2011b; Yang et al. 2013; Fan et al. 2019).

Studies on landslide dam behavior in the past have gained a considerable significance for predicting the dam evolution for future dams (Tacconi Stefanelli et al. 2015; Zhang et al. 2016; Fan et al. 2020). Various morphological stability indices, including Blockage Index ($BI$) (Canuti et al. 1998; Casagli and Ermini 1999), Impoundment Index ($II$) (Casagli and Ermini 1999; Korup 2004), Dimensionless Blockage Index ($DBI$) (Ermini and Casagli 2003), Backstow Index ($IS$), Basin Index ($BI$), and Relief Index ($RI$) (Korup 2004), Hydromorphic Dam Stability Index ($HDSI$) (Tacconi Stefanelli et al. 2016, 2018), have been proposed for rapid assessment (all abbreviations of this paper are summarized in the attached table A1). However, regional geological and climatic differences and landslide types may have a larger impact on dam stability than these geomorphic indices (Ermini and Casagli 2003; Korup 2004; Weidinger 2011; Hermanns et al. 2011a; Oppikofer et al. 2020; Tacconi Stefanelli et al., 2018). A lack of data on landslide dam that did not pose a risk to society and the uncertainty of how dam volumes calculated might also impact the assessment results. Besides, these indices pay only attention to morphological parameters, although the three-dimensional distribution of landslide material also influences dam stability (Schuster 1986; Korup 2002; Weidinger 2011; Hermanns et al. 2011b; Korup and Wang 2015; Wang et al. 2016). Furthermore, some indices may not be
appropriate in assessing successive landslide dams which occur at the same site (Liao et al. 2020). For example, $BI$ is the ratio dam volume $V_d / \text{catchment area } A_C$, and a larger ratio means a more stable dam. Thus, successive landslide dams with the same volume and different height would have the similar assessment result because their $A_C$ is a constant. However, it is likely to be improper because a higher dam usually has a lower stability as suggested by most other indices. Similar problem also exists for the $HDSI$ index. Additionally, the altitude difference of a catchment is difficultly available for most cases, which hampers the use of $RI$ index. Thus, sometimes these indices are not reliable if they are used in the emergency situation to make a good decision.

In fact, the inner structure and material composition also control the landslide dam stability (Costa and Schuster 1988; Fread 1988; Casagli et al. 2003; Ermini et al. 2006; Weidinger 2011; Chen et al. 2017; Kumar et al. 2019). However, the effort on better understanding the geotechnical aspects of landslide dam stability have been more restricted compared to the aspects of geomorphological constrains. A rapid prediction method of landslide dam stability that considers both morphological characteristics and dam composition is developed by using logistic regression analysis (Shen et al., 2020), but more available testing tools are needed to validate this model. Other assessment methods including dam material mainly rely on the qualitative evaluation of the type of the landslide, which is in a way a geotechnical assessment as landslides are classified based on materials (Weidinger 2011). Data deficiency of landslide dam material causes a lot of difficulties in quantitative characterization of dam geotechnical property (Casagli et al. 2003).

Within this contribution, we try to present a new geotechnical index for landslide dam stability assessments by considering dam geometry, grain size, and properties of the impounded water body. For this purpose, a PSD database was established based on 83 documented historical landslide deposits, including 60 damming and 23 non-damming landslides from around the word. Two empirical functions were applied to analyze the PSDs and search for characteristic parameters that can be used in a stability assessment of a landslide dam. At last, a geotechnical index $MMI$ with limits of different stability levels was proposed based on existing indices and an inventory of 42 landslide dams.

2. Material and methods

2.1. Inventory and distribution analysis of landslide deposit PSDs

Material composition exerts a significant influence on the short and mid-long-term landslide dam stability (Alexander 2010; Weidinger 2011; Fan et al. 2020). Dams with fine particles tend to erode rapidly, but those with imbricated coarse grains may have a slower erosion process (Wang et al. 2012; Miller et al. 2018). The PSD is one of the most important material properties of a landslide deposit, which affects its inner texture and permeability (Visher 1969; Meyer et al. 1994; Gabet and Mudd 2006; Donato et al. 2009; Dunning and Armitage 2011; Zhou et al. 2019). Therefore, we developed a parameter for characterizing material property based on 83 landslide deposit PSDs (supplementary material, Table S1).
Here landslide dam was regarded simply as a landslide deposit. PSDs of landslide dams in Italy were extracted as number values from the literature, while data from all other sites by extracting values from grain size distribution curves. All the grain size distributions are between 0.0005 mm ($d_5$) and 27120 mm ($d_{95}$), this wide grain size distributions range accords with the landslide dam grain characteristic reported earlier (Casagli et al. 2003; Dunning and Armitage 2011; Davies and McSaveney 2011). Landslide dam material has been earlier divided into soil, soil with some boulders, boulders with some soil and boulders, which was used for a preliminary risk evaluation of Wenchuan earthquake-induced landslide dams (Cui et al. 2009). Based on this, the classification might be simplified into three types based on PSDs: soil-dominated landslide dam ($s$-d) if $d_{30} \leq 2$ mm & $d_{60} \leq 30$ mm, gravel & boulder-dominated landslide dam ($g\&b$-d) if $d_{50} \geq 50$ mm and $d_{90} \geq 700$ mm, soil & gravel-dominated landslide dam ($s\&g$-d) if particle size is out of the above both. Two statistical functions of the Rosin-Rammler-Sperling-Bennett (RRSB) distribution and the power law distribution were used to fit the 83 PSDs and characterize the PSDs properties.

- Curve fitting with RRSB distribution

The RRSB function can be expressed as (Osbaeck and Johansen 1989):

$$R(d) = 100\exp\left(-\left(\frac{d}{d^*}\right)^n\right)$$

(1)

It can be written as a linear function ($\ln(\ln(100/R(d)))$ in Y-axis and $\ln d$ in X-axis) via natural logarithm transformation:

$$\ln(\ln(100/R(d))) = n\ln d - K_R$$

(2)

where $d$ is the particle diameter; $R(d)$ is the quantile of particles with diameter larger than $d$; $d^*$ is the size of particle with cumulative content smaller than 63.2%; $n$ is the slope of this straight line and presents the dispersion degree of particles; $K_R = n\ln d^*$ is the intercept absolute value of Y-axis. As the product of particle dispersion degree ($n$) and particle size ($d^* = d_{63.2}$), $K_R$ is deemed as a comprehensive reflection of landslide dam PSD property.

- Curve fitting with power law distribution

The power law function is expressed as (Tyler and Wheatcraft 1992)

$$\frac{M(r_i < r)}{M_T} = \left(\frac{r}{r_{\text{max}}}\right)^{3-D}$$

(3)

It also can be written as a linear function ($\ln (M(r))$ in Y-axis and $\ln r$ in X-axis) via natural logarithm transformation
\[ \ln (M(r)) = (3 - D) \ln r + K_F \]  

(4)

where \( r \) or \( r_i \) is the particle radius; \( r_{\text{max}} \) is the maximum radius for all over the particles; \( M(r_i < r) \) is the mass (or volume) of particles with radius smaller than \( r \); \( M_T \) is the total particles mass (or volume); \( M(r) \) is the quantile of particles with radius smaller than \( r \); \( (3-D) \) is the slope of this straight line, \( D \) is the statistical constant closely related to the material composition and inner structure of deposits; \( K_F = (\ln 100-(3-D)\ln r_{\text{max}}) \) is the intercept absolute value of Y-axis. As the function of particle size statistical constant \( (D) \) and maximum particle radius \( (r_{\text{max}}) \), \( K_F \) is deemed as a comprehensive reflection of the landslide dam PSD property.

2.2. Landslide dam inventory and geotechnical index creation

A total of 42 landslide dams were compiled, the data included dam geometry, hydrology characteristics, material composition, particle diameter \( d_{90} \), parameters \( K_R \) and \( K_F \), spillway form and dam longevity (Table 1). In the database, material composition was classified into 4 levels based on the suggestion by Cui et al. (2009), which would be used to make the classification guideline for landslide dam stability below. Material types, \( d_{90} \), \( K_R \) and \( K_F \) were estimated by the quantitative and qualitative descriptions of dam material in the literature. The accuracy of all these parameters is based on the raw data validity. It is noteworthy that the PSDs in the supplementary material and \( d_{90} \), \( K_R \), \( K_F \) in Table 1 are not all from the same landslide deposits, because the information for most of the cases is not all available.

After landslide dam formation, a lot of contributing factors determine its stability and evolution over time. Lake volume \( V_L \) and catchment area \( A_C \) are both important hydrologic parameters for dam stability, while \( A_C \) is a constant for a specific damming site no matter what the dam height is (Fan et al. 2012). Thus, here we chose \( V_L \) as the hydrologic parameter. Increase of dam height \( H_d \) and decease of dam width \( W_d \) would reduce the ability to resist erosion (Wassmer et al. 2004; O’Connor and Beebee 2009; Alexander 2010). Dam volumes are positively related to the stability. Larger particle sizes contribute to more stable dam texture and slower dam breach speed (Costa and Schuster 1988; Cui et al. 2009; Weidinger 2011). Although the representative particle size for landslide dam stability and breach processes has not been fully understood (Smart 1984; Casagli et al. 2003; Zhong et al. 2021), a dam performs relatively well in erosion resistance if its \( d_{90} \) is larger than 1000 mm (Delaney and Evans 2011; Wang et al. 2012). Therefore, here \( d_{90} \) was selected as the representative particle size in stability assessment. Besides, \( K_F \) and \( K_R \) were used to characterize the landslide dam PSD. Turning to the traditional morphological indices for guideline, geotechnical index expresses as

\[ MMI = K \log \frac{H_d^2 V_L}{V_D W_D d_{90}} \]

\[ = K \log (H_d^2 V) - K \log (V_D W_D d_{90}) \]  

(5)

where \( K \) is \( 1/K_R \) or \( K_F \).
| No. | Country | Landslide-dammed lake | Occurrence time | Dam volume $V_D$ (10^6 m$^3$) | Dam height $H_D$ (m) | Dam width $W_D$ (m) | Lake volume $V_L$ (10^6 m$^3$) | Charnement area (km$^2$) | Material composition | $d_{90}$ (10^{-3} m) | $K$ | Spillway form | Longevity | References |
|-----|---------|------------------------|-----------------|-------------------------------|-------------------|-----------------|-------------------|-----------------|-----------------|-----------------|-----|-------------|----------|------------|
| 1   | Bhutan  | Tsatichhu dam          | 2003            | 10                            | 110               | 900             | 7                 | —               | Soil            | 180             | 1.5 | 3.15       | Natural  | 300 days   | Dunning et al. 2006 |
| 2   | China   | Baige 1                | 2018.10.10      | 23.5                          | 43                | 1150            | 290               | 173500          | Soil            | 25              | 0.9 | 3.8       | Natural  | 2 days     | Jin, 2018         |
| 3   | China   | Baige 2                | 2018.11.03      | 6                             | 78                | 800             | 770               | 173500          | Soil            | 25              | 0.9 | 3.8       | Artificial | 9 days     | Jin, 2018         |
| 4   | Donghekou |                | 2008            | 12                            | 20                | 750             | 3                 | 1165            | Boulders with some soil | 500         | 2.2 | 2.6       | Artificial | 10 days    | He et al. 2010    |
| 5   | Ergangqiao |                | 2008            | 0.8                           | 45                | 235             | 0.7               | 160             | Boulders with some soil | 2500       | 5   | 1         | Artificial | ~1 year    | ED&RI, 2009a    |
| 6   | Gangou  |                       | 2008            | 0.35                          | 25                | 105             | 0.4               | 170             | Boulders         | 2500           | 5   | 1         | Artificial | ~1 year    | ED&RI, 2009a    |
| 7   | Guanmenshangou |            | 2008            | 2.7                           | 80                | 500             | 3.7               | 56.3            | Boulders         | 1000           | 4.5 | 1.3       | Artificial | ~1 year    | Jin, 2018          |
| 8   | Guantan |                       | 2008            | 1.2                           | 15                | 120             | 10                | 215             | Boulders with some soil | 500         | 2.2 | 2.6       | Artificial | 26 days    | He et al. 2010; Zhang et al. 2016 |
| 9   | Guanzipu |                       | 2008            | 2                             | 60                | 390             | 5.85              | —               | Boulders with some soil | 450         | 3   | 2.15      | Artificial | 22 days    | Zhang et al. 2016; Rao and Tang 2008 |
| 10  | Heidongya |                   | 2008            | 0.5                           | 30                | 250             | 0.2               | 192             | Boulders         | 1500           | 4   | 1.5       | Artificial | ~1 year    | ED&RI, 2009a; He et al. 2010 |
| 11  | Hongshihe |                   | 2008            | 8                             | 55                | 370             | 3                 | 63.5 km         | Boulders with some soil | 300         | 2.2 | 2.6       | Artificial | 10 days    | Zhang et al. 2016 |
| 12  | Hongshiyang |                | 2014            | 12                            | 83                | 753             | 260               | 13672           | Boulders         | 800             | 4   | 1.5       | Artificial | ~1 year    | KEC, 2015         |
| 13  | Hutiaoya |                       | 2008            | 4                             | 100               | 600             | 1.5               | 22.5            | Soil with some boulders | 180         | 1.3 | 3.5       | Artificial | 130 days   | MWCP, 2008        |
| 14  | Jiadanwan |                  | 2008            | 2.1                           | 60                | 400             | 6.1               | 164.5           | Boulders         | 1000           | 4   | 1.5       | Artificial | ~1 year    | ED&RI, 2009b    |
| 15  | Jia 1    |                       | 2018.10.17      | 50                            | 80                | 2400            | 605               | —               | Soil            | 20              | 0.8 | 3.9       | Natural  | 2 days     | Jin, 2019         |
| 16  | Jia 2    |                       | 2018.10.29      | 30                            | 77                | 3500            | 326               | —               | Soil            | 20              | 0.8 | 3.9       | Natural  | 2 days     | Jin, 2019         |
| 17  | Kuangban |                       | 2008            | 0.4                           | 25                | 150             | 0.6               | 175.5           | Boulders         | 2000           | 5   | 1.0       | Artificial | ~1 year    | ED&RI, 2009a    |
| 18  | Laoyingyan |                | 2008            | 4.7                           | 106               | 1000            | 10.1              | 28.5            | Boulders         | 1200           | 3.5 | 1.7       | Artificial | >1 year    | He, 2009; Pei et al. 2010 |
| 19  | Nanba    |                       | 2008            | 4                             | 30                | 350             | 6.86              | 156.2           | Boulders with some soil | 300         | 2.5 | 2.5       | Artificial | 53 days    | Dai et al. 2008   |
| 20  | Tangjiashan |             | 2008            | 20.37                         | 82                | 802             | 316               | 3550            | Boulders with some soil | 659         | 2.7 | 2.3       | Artificial | 29 days    | Liu et al. 2010; Hu et al. 2009 |
| 21  | Tangjiawan 1 |          | 2008            | 4                             | 40                | 532             | 15.2              | 60              | Boulders         | 1500           | 3.8 | 1.6       | Artificial | 24 days    | Rao and Tang 2008; Fan et al. 2019 |

(continued)
| No. | Country       | Landslide-dammed lake | Occurrence time | Dam volume $V_D$ $(10^6m^3)$ | Dam height $H_D$ (m) | Dam width $W_D$ (m) | Lake volume $V_L$ $(10^6m^3)$ | Chatham area (km²) | Material composition | $d_{50}$ $(10^{-3}m)$ | $K$ | Spillway form | Longevity | References                  |
|-----|---------------|-----------------------|-----------------|-------------------------------|---------------------|---------------------|------------------------------|---------------------|---------------------|----------------|---------|----------------|-----------|---------------------------|
| 22  | China         | Tangjawan 2           | 2016            | 0.65                          | 15                  | 270                 | 1.79                        | 60                  | Soil with some boulders | 163            | 1.8     | 2.9           | Artificial | 1 day          | Fan et al., 2019     |
| 23  | China         | Xiaogangjian          | 2008            | 2                             | 62                  | 300                 | 11                          | 330.1               | Boulders with some soil  | 1580           | 2.5     | 2.5           | Artificial | 30 days | ED&RI, 2009a; Ma and Zou 2008 |
| 24  | China         | Xiaojiqiao            | 2008            | 2.42                          | 64                  | 390                 | 20                          | 154.81              | Boulders with some soil  | 400            | 2.5     | 2.5           | Artificial | 24 days | He et al. 2010; Zhang et al. 2016 |
| 25  | China         | Xiaomuling            | 2008            | 0.3                           | 28                  | 300                 | 0.23                        | 181                 | Boulders with some soil  | 500            | 2.5     | 2.5           | Artificial | ~1 year | ED&RI, 2009a     |
| 26  | China         | Xujia 2               | 2008            | 7.5                           | 110                 | 750                 | 3                           | 107                 | Boulders               | 2000           | 5.5     | 0.8           | —            | Still alive | ED&RI, 2009a; field investigation |
| 27  | China         | Yangjiagou            | 2008            | 0.6                           | 50                  | 160                 | 0.85                        | 126.4               | Boulders               | 800            | 3.7     | 1.7           | Artificial | ~1 year | ED&RI, 2009a |
| 28  | China         | Yaqizgou              | 2008            | 1.8                           | 60                  | 250                 | 6.2                         | 135.3               | Boulders               | 850            | 4.8     | 1.1           | Artificial | ~1 year | ED&RI, 2009b |
| 29  | China         | Yibadao               | 2008            | 0.9                           | 30                  | 500                 | 0.55                        | 372.05              | Boulders with some soil | 800            | 3     | 2.15          | Artificial | ~1 year | ED&RI, 2009a |
| 30  | China         | Yinong                | 2000            | 115                           | 60                  | 2200                | 3000                        | 13533               | Soil                   | 170            | 0.9     | 3.8           | Artificial | 60 days | Shang et al. 2003; Liu et al. 2000 |
| 31  | China         | Yikaishu              | 2008            | 0.4                           | 30                  | 100                 | 0.3                         | 142                 | Boulders               | 1500           | 5.5     | 0.8           | Artificial | ~1 year | ED&RI, 2009a |
| 32  | China         | Zhonzu                | 2008            | 0.8                           | 30                  | 150                 | 0.1                         | 107                 | Boulders               | 1500           | 5.5     | 0.8           | Artificial | ~1 year | ED&RI, 2009a |
| 33  | China         | Hsiaolin village      | 2009            | 15.4                          | 44                  | 1500                | 9.9                         | 354                 | Soil                   | 17             | 0.8     | 4            | Natural    | ~1 hour | Hu et al. 2009 |
| 34  | China         | Taosu-Ling Lake       | 1941 ~ 1951     | 200                           | 200                 | 1600                | 157                         | —                   | Soil with some boulders | 170            | 1.9     | 2.7           | Natural    | 10 years | Dong et al. 2011a; Chigira et al. 2003; Chen et al. 2006 |
| 35  | Ecuador       | La Josefina           | 1993            | 20                            | 100                 | 1100                | 200                         | —                   | Soil with some boulders | 100            | 1.9     | 2.7           | Artificial | 33 days | Schuster and Evans 2011; Harden 2001 |
| 36  | Indonesia     | Ambon Island          | 2012            | 17                            | 137                 | 1660                | 24.8                        | —                   | Soil                   | 80             | 1.5     | 3.15          | Natural    | 1 year | Schuster and Evans 2011; Harden 2001; Schuster and Evans 2011; Crosta et al. 2007; Crosta et al. 2004; Crosta et al. 2011 |
| 37  | Italy         | Val Pola              | 1987            | 45                            | 60                  | 2500                | 22                          | —                   | Boulders with some soil | 1000           | 2.5     | 2.5           | Artificial | Still alive | Schuster and Evans 2011; Crosta et al. 2007; Crosta et al. 2004; Crosta et al. 2011 |
| 38  | New Zealand   | Mt Adams              | 1999            | 10                            | 100                 | 700                 | 7                           | —                   | Soil with some boulders | 100            | 1.8     | 2.9           | Natural    | 6 days | Hancox et al. 2005 |
| 39  | New Zealand   | Waikaremoana          | 2200yrs B.P.    | 2500                          | 400                 | 6000                | 5200                        | —                   | Boulders               | 20000          | 6      | 0.6           | —            | Still alive | (continued) |
| No. | Country   | Landslide-dammed lake | Occurrence time | Dam volume $V_D$ ($10^6 m^3$) | Dam height $H_D$ (m) | Dam width $W_D$ (m) | Lake volume $V_L$ ($10^6 m^3$) | Chathment area (km²) | Material composition | $d_{50}$ ($10^{-3} m$) | $K_R$ | $K_F$ | Spillway form | Longevity | References                                                                 |
|-----|-----------|------------------------|-----------------|-------------------------------|---------------------|-------------------|-------------------------------|---------------------|----------------------|-----------------|-------|-------|----------------|-----------|--------------------------------------------------------------------------|
| 40  | Pakistan  | Karli dam              | 2005            | 80                            | 130                 | 1587              | 90.28                        | 44.17               | Soil with some boulders | 150  | 1.9   | 2.7   | Natural       | 5 years     | Schuster and Alford 2004; Marshall 1927; Beetham et al. 2002             |
| 41  | Tajikistan| Sarez Lake             | 1911            | 2000                          | 600                 | 3900              | 17000                        | –                   | Boulders             | 5000 | 6     | 0.6   | —              | —          | Basharat et al. 2012; Dunning et al. 2007; Niazi et al. 2010            |
| 42  | Turkey    | A dam on Tortum River  | 1700s           | 180                           | 160                 | 3100              | 538                          | 1820                | Boulders             | 1000 | 3.5   | 1.7   | —              | —          | Still alive Schuster and Alford 2004; Ischuk 2006                      |

**Table 1. Continued.**
2.3. Classification guideline for landslide dam stability

For geotechnical index, landslide dams are considered to be stable when the outburst flood hazard is low (Miller et al. 2018). In fact, those landslide dams which gradually release lake water usually only cause small peak discharge and that may result in minor damage to downstream areas. The breach speed and discharge are closely related to dam material composition. The longevity of landslide dams is critical to hazard mitigation since it determines the available time to take temporary and permanent countermeasures (Yang et al. 2010; Shen et al. 2020). A disastrous landslide dam breach would possibly be avoided if the available time is more than 1 year. Thus, here we classified landslide dams that prevail longer than 1 year as the long-lived, 3 months-1 year as the mid-term-lived, and less than 3 months as the short-lived. Lately, a new method is proposed to calculate failure probability based on empirical data from Norway and around the world (Oppikofer et al. 2020), different failure probabilities correspond to different stability levels. And the lifetime of a dam that its failure is induced artificially is always shorter than if the dam erosion would take its natural course. Thus, we proposed a four-level scale of stability that was based on landslide dam material composition, longevity and spillway form (Table 2). Blue in the table was for apparent stability (level IV), yellow for moderately apparent stability (III), orange for moderate stability (II), and red for low stability (I). Earthquake (Fan et al. 2012; Romeo et al. 2017), changes in meteorological conditions (Hermanns et al. 2004b) and landslides into the impounded reservoir (Hermanns et al. 2004a) can play a part in landslide dam failures. However, they are not considered here for they represent special cases that are not frequent.

| Items for judge of landslide dam stability | Spillway form |
|------------------------------------------|--------------|
| | Artificial/Natural | Artificial | Natural | Artificial | Natural | Artificial | Natural |
| Longevity | | | | | | | |
| > 1 year | IV | IV | III | III | III | III | III |
| 3 months-1 year | IV | IV | III | III | III | III | III |
| 1-3 months | IV | III | III | III | III | III | III |
| < 1 month | IV | III | III | III | III | III | III |
| Material composition | Boulders | Boulders with some soil | Soil with some boulders | Soil |

Level IV (blue) represents the apparent stability, level III (yellow) represents the moderately apparent stability, level II (orange) represents the moderate stability, and level I (red) represents the low stability.

3. Results

3.1. Characteristic parameter K of landslide deposit PSDs

Landslide deposit PSDs were well described with RRSB and power law functions. According to PSDs curve fitting result by using RRSB function, the correlation coefficient $R^2$ was 0.84 ~ 1.00, and 93.98% of the values larger than 0.9. According to the PSDs curve fitting result by using power law function, the correlation coefficient $R^2$ was 0.75 ~ 1.00, and 90.40% of the values larger than 0.9. Fitted lines of three landslide dams were presented in Figure 1, which were the examples of $s$-$d$ landslide dams, $s$&$g$-$d$ landslide dams, and $g$&$b$-$d$ landslide dams, respectively. A significant linear relation between $\ln(\ln(100/R(d)))$ and $\ln d$ with RRSB function fitting, and $\ln$
and \( \ln r \) with power law function fitting was shown. For the fitted functions, \( y \) represented \( \ln(100/R(d)) \) or \( \ln(M(r)) \), \( x \) represented \( \ln d \) or \( \ln r \), and the absolute value of intercept was the \( K_R \) or \( K_F \) number.

Interesting relationships between statistical constants \( K_R \), \( K_F \) and all landslide deposit PSDs in our data set have been observed through careful investigation. Most \( K_R \) values were positively correlated with the particle size, while most \( K_F \) values were negatively correlated. The \( K_R \) was in \([0.50, 1.50]\) for 19 of 22 \( s\)-\( d \) deposit PSDs, \( K_F \) was in \([3.15, 4.35]\) for 19 of 22 \( s\)-\( d \) deposit PSDs; the \( K_R \) was in \([1.50, 3.00]\) for 40 of 49 \( s\&g\)-\( d \) deposit PSDs, \( K_F \) was in \([2.15, 3.15]\) for 45 of 49 \( s\&g\)-\( d \) deposit PSDs; the \( K_R \) was in \([3.50, 6.00]\) for 12 of 12 \( g\&b\)-\( d \) deposit PSDs, \( K_F \) was in \([0.6, 1.7]\) for 9 of 12 \( g\&b\)-\( d \) deposit PSDs, as shown in Figure 2. The few exceptional values that plotted outside the domains have been excluded from further analysis. In fact, some of these exceptional values were very close to the domain boundary. A summary of the correspondence between landslide dam type and \( K_R \), \( K_F \) was listed in Table 3. This will play a role in stability assessment below.

At present stage, we could not quantitatively characterize the relationship between each PSD and its \( K_R \) or \( K_F \) value. In every domain, not all \( K_R \) or \( K_F \) values increased with particle size. Figure 3 showed the PSD areas of the three value domains for \( K_R \) and \( K_F \). There were overlaps for the three areas, however the overlaps were relatively small when compared to the total areas. Although a rough conclusion is provided here, it might be a first attempt to offer a preliminary guidance for measurement of the dam material properties.

### 3.2. Dam stability assessment

The 42 landslide dams were divided into four levels based on guideline in Table 2. And then \( MMI_R \) (when \( K \) equals \( 1/K_R \)) and \( MMI_F \) (when \( K \) equals \( K_F \)) of these dams were calculated. Based on the results of stability classification and \( MMI \) calculation, we achieved the \( MMI \) limits of different stability levels for landslide dams

- \( MMI_R < 0.4 \), apparent stability (IV)
- \( 0.4 \leq MMI_R < 1.1 \), moderately apparent stability (III)
- \( 1.1 \leq MMI_R < 2.0 \), moderate stability (II)
- \( MMI_R \geq 2.0 \), low stability (I)
and

- $MMI_F < 3.0$, apparent stability (IV)
- $3.0 \leq MMI_F < 7.0$, moderately apparent stability (III)
- $7.0 \leq MMI_F < 10.0$, moderate stability (II)
- $MMI_F \geq 10.0$, low stability (I)

This geotechnical method based on $MMI$ index was also performed in Figure 4. It showed that the results of $MMIR$ and $MMIF$ were similar. Stability levels of four cases by using $MMIR$ (legends with excircle in Figure 4a) and six cases by using $MMIF$
(legends with excircle in Figure 4b) were not equal to the results based on classification guideline (Table 2). Thus, the assessment accuracies of $MMI_R$ and $MMI_F$ were 90.48% and 85.71%, respectively.

4. Discussion

4.1. Characteristic parameter $K$

Landslide dams with larger grain sizes usually have a relatively higher stability compared to those with finer grained composition, that rather favor drainage and erosion.
resistance (Dunning et al. 2006). Most PSDs in our database were obtained from a specific position in the landslide dam body. In fact, apart from grain size, spatial distribution of grain size also plays a key role in stability and the breach process. For example, material composition around the spillway is more important because it directly relates to dam-breach speed and breach form. Large boulders contribute to the spillway stabilization and prevent rapid downcutting into the dam (Plaza et al. 2011). Consequently, although the characteristic parameter $K$ based on PSDs presents grain size and grain size dispersion, and dam inner structure to some degree, it could not reflect the grain distribution in the whole dam body. Inner composition, structure, and geotechnical properties are usually unknown until the dam is artificially or naturally cut. Aiming for the prevention of damaging events, the goal should be to carry out that the landslide dam stability assessment and related hazard prediction prior to dam breach.

Combining field investigation of landslide (scarp) and dam material is one of the most frequently used method to understand inner structure and composition of landslide dams (Delgado et al. 2020). Seismic, geoelectric and electromagnetic methods or a combination of those are most common techniques (Fan et al. 2021). Dam heterogeneous interior consisting of various sub-facies depends on landslide structures and emplacement conditions, as well as the stratigraphic situation in the landslide source area which is typically preserved in rock avalanche and rock slide deposits (Abdrakhmatov and Strom 2006; Weidinger et al. 2014; Wang et al. 2016). Landslide composition and geological properties could be transferred to dam stability assessments (Fan et al. 2021). Thus, diverse engineering geophysical and geotechnical methods should not only be used to explore the internal structure of the dam and its material properties, but also to the potential damming landslide or its close slope. Then it will become possible to build a comprehensive parameter for characterizing

Figure 5. The dimensionless blockage index (DBI) for 31 dams of our inventory. Different DBI limits are also presented based on the inventories in this paper and the study of Oppikofer et al. (2020).
both dam composition and inner structure, and thus the geotechnical properties. Such characteristic parameters could be conducive to upgrade dam stability assessments and even breach discharge estimations.

### 4.2. Assessment differences between morphological and geotechnical methods

A morphological method that predicts the relative probability of dam breach has been developed based on empirical data from around the world, Norway and the Andes (Oppikofer et al. 2020). The likelihood of a dam failure $p_f$ could be estimated by using Eq. 6:

$$
p_f = \begin{cases} 
0 & \quad \text{if } DBI \leq DBI_{lower} \\
\frac{DBI - DBI_{lower}}{DBI_{upper} - DBI_{lower}} & \quad \text{if } DBI_{lower} < DBI < DBI_{upper} \\
1 & \quad \text{if } DBI > DBI_{upper}
\end{cases}
$$

Table 4. Dam stability and failure probability assessment based on different methods.

| No. | Landslide dams          | $MMI_{SP}$ | $MMI_{F}$ | Failure probability |
|-----|--------------------------|-------------|------------|---------------------|
| 1   | Baige 1                  | 3.221       | 13.22      | 1                   |
| 2   | Baige 2                  | 5.102       | 19.654     | 1                   |
| 3   | Donghekou                | -0.287      | -0.356     | 0.55                |
| 4   | Erganggiao               | 0.096       | 0.48       | 0.72                |
| 5   | Gangou                   | 0.087       | 0.435      | 0.75                |
| 6   | Guannenschangou          | 0.276       | 1.765      | 0.53                |
| 7   | Guantan                  | 0.748       | 5.438      | 0.59                |
| 8   | Heidongya                | 0.005       | 0.237      | 0.75                |
| 9   | Hongshihe                | 0.505       | 4.080      | 0.38                |
| 10  | Hongshiyin (still alive) | 0.599       | 3.855      | 0.99                |
| 11  | Hutaoya                  | 1.123       | 7.298      | 0.41                |
| 12  | Jiadanwan                | 0.355       | 2.391      | 0.65                |
| 13  | Kuangban                 | 0.099       | 0.495      | 0.75                |
| 14  | Laoyingyan               | 0.373       | 2.608      | 0.42                |
| 15  | Nanba                    | 0.467       | 3.528      | 0.61                |
| 16  | Tangjiaoshan             | 0.85        | 6.111      | 0.78                |
| 17  | Tangjiawan 1             | 0.232       | 1.738      | 0.42                |
| 18  | Tangjiawan 2             | 0.638       | 4.672      | 0.51                |
| 19  | Xiaoanggian              | 0.660       | 5.118      | 0.74                |
| 20  | Xiaojiaqiao              | 0.934       | 6.835      | 0.63                |
| 21  | Xiamulang                | 0.241       | 2.503      | 0.80                |
| 22  | Xujia (still alive)      | 0.093       | 0.330      | 0.52                |
| 23  | Yangjiagou               | 0.390       | 2.842      | 0.74                |
| 24  | Yaqizhou                 | 0.368       | 1.989      | 0.64                |
| 25  | Yibadao                  | 0.046       | 1.013      | 0.76                |
| 26  | Yigong                   | 3.420       | 13.903     | 0.70                |
| 27  | Yikeshu                  | 0.119       | 0.445      | 0.74                |
| 28  | Zhonzi                   | 0.109       | 0.404      | 0.87                |
| 29  | Hsiao village            | 2.111       | 9.164      | 0.48                |
| 30  | Karli dam                | 1.002       | 6.305      | 0.17                |
| 31  | A dam on Tortum River (still alive) | 0.398 | 2.759 | 0.53 |

Blue represents level IV and $p_f=0.25 \sim 0.75$, yellow represents level III and $p_f=0.25 \sim 0.50$, orange represents level II and $p_f=0.50 \sim 0.75$, red represents level I and $p_f=0.75 \sim 1$. 

Both dam composition and inner structure, and thus the geotechnical properties. Such characteristic parameters could be conducive to upgrade dam stability assessments and even breach discharge estimations.
of the upstream catchment area of some cases, the relationship between the ratio dam volume \( V_D \)/dam height \( H_D \) and the upstream catchment area \( A_C \) was plotted for only 31 of our 42 empirical dams following that approach (Figure 5). The \( DBI_{upper} \) was 4.976, the lowest \( DBI \) was 1.856 but it could not be not defined as the \( DBI_{lower} \), because there was not a lowest \( DBI \) for the stable dam in Figure 5. Here, we used the \( DBI_{upper} = 5.0 \) and \( DBI_{lower} = 1.2 \) suggested by Oppikofer et al. (2020) to assess the likelihood of a dam failure \( p_f \). Compared to our geotechnical index, this failure probability method had a relative more conservative assessment. As shown in Table 4, the ratio 4/31 by \( MMI_R \) or 3/31 by \( MMI_F \) had a I level and 9/31 by failure probability method had a \( p_f \geq 0.75 \); the ratio 5/31 by both \( MMI_R \) and \( MMI_F \) had a level \( \geq II \) and 25/31 by failure probability method had a \( p_f \geq 0.50 \); the ratio 14/31 by both \( MMI_R \) and \( MMI_F \) had a level \( \geq III \) and 30/31 by failure probability method had a \( p_f \geq 0.25 \); the ratio 31/31 by both \( MMI_R \) and \( MMI_F \) had a level \( \geq IV \) and 31/31 by failure probability method had a \( p_f \geq 0.0 \). Besides, one dam with a \( p_f \) of 0.48 had failed about one hour after its formation, and there was also a gradually eroded dam with a \( p_f \) of 0.38. Several dams with a \( p_f > 0.75 \) had been eroded gradually, and there was one stable dam with a \( p_f \) of 0.99.

Possible reasons for this difference between the two methods are obvious. For our geotechnical assessment method, we focus on morphological parameters, dam material, longevity and spillway form. However, the failure probability method based on \( DBI \) considers morphological parameters and dam evolution (breach or not) only. Dams with the same geometry and hydrology condition would also have different stability level and failure probability if grain size is different. Additionally, our compiled data set is empirical semi-representative for short lived dams (34 cases) but certainly not for long lived ones (8 cases). And our data counts only for about 30–70% of all landslide dams globally (Fan et al. 2020), while the method suggested by Oppikofer et al. (2020) includes all dams in the respective data sets thus also dams that prevailed for thousands to tens of thousands of years. Extending the inventory to more global dams might increase the overall proportion of stable dams as the remaining dams on the globe have a much longer longevity. This helps obtain \( DBI_{lower} \) and \( DBI_{upper} \) belong to the inventory itself. Here the \( DBI_{lower} \) and \( DBI_{upper} \) come from other landslide dam data.

### 4.3. The proposed geotechnical method

Although the geotechnical \( MMI \) index considers the grain size effect on dam stability, it is an attempt to develop a more effective assessment method considering dam geometry, hydrology and geology conditions. Factors of the \( MMI \) index are empirically chosen based on state of the art about landslide dams, as well as the availability of parameter data from our inventory. Besides, this index solely includes material parameters of dam PSDs and particle size \( d_{90} \) in the absence of detailed geotechnical information. Nevertheless, \( MMI \) index seems to be incapable of working well in the emergency stage due to the difficulty in obtaining inner PSDs shortly after dam formation (Fan et al. 2020). The efficiency of this method also depends on the method progress for investigating the internal conditions of landslide dams.
Stability classification is defined based on dam material composition, longevity and spillway form (Table 2). A dam with a longevity more than one year is assumed to have a relatively good stability. We base our definition of “relatively good stability” on the assessment that in most cases a catastrophic breach event could be prevented within one year or the population evacuated from the critical areas. This would be different to Norway where an outburst flood with a likelihood of a 1 in 200 years has to be assessed (Hermanns et al. 2013). Furthermore, geotechnical properties may tend stable if a dam survives beyond one year, which is conducive to dam stability (Fan et al. 2020, 2021). Our stability classification guideline presented here would be better if dam breach speed was included. Empirical data on dam breach process could be collected in our future dam breach experiments, such as the temporal relations between flood discharge and residual dam size. It is important to mention that our dam inventory is empirical semi-representative for short lived dams but not for long lived landslide dams. Thus, this geotechnical assessment method is for dams with a short or mid-term lifespan. More cases are needed to improve and test the limitation of MMI for different stability levels. An improved geotechnical method might even better help in landslide dam risk management with limited temporal resources. This is especially important in situations where multiple dams form simultaneously caused by a large triggering event.

5. Conclusions

So far, the role of impacting factors especially the material composition in landslide dam stability cannot be quantitative measured. On the basis of statistical analysis of landslide deposit PSDs, the parameters $K_R$ and $K_F$ were developed to characterize the material properties of soil-dominated, soil & gravel-dominated and gravel & boulder-dominated landslide dams in this contribution. As a next step, a geotechnical index MMI was suggested to predict landslide dam stability in the classes of short- and mid-term ones. This new index consisted of 6 parameters involving dam geometry ($V_D$, $H_D$, $W_D$), particle size distribution ($K$ and $d_{90}$) and river hydrology ($V_L$). Landslide dam stability was classified into four types based on dam material composition, longevity and spillway form. The geotechnical assessment method was proposed based on the MMI values and a landslide dam inventory with 42 cases. Due to the absence of more information on landslide dam composition, structure, and geotechnical properties, this work is not an ultimately conclusive suggestion but a first attempt to provide preliminary guidance.

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Data availability statement

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

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Table A1. Explanations for abbreviations and some terms in this paper.

| Abbreviations or terms | In full or definition | References |
|------------------------|-----------------------|------------|
| BI                     | Blockage Index        | Canuti et al. 1998; Casagli and Ermini 1999 |
| II                     | Impoundment Index     | (Casagli and Ermini 1999; Korup 2004) |
| DBI                    | Dimensionless Blockage Index | (Ermini and Casagli 2003) |
| IS                     | Backstow Index        | Korup 2004 |
| BI                     | Basin Index           | Korup 2004 |
| RI                     | Relief Index          | Korup 2004 |
| HDSI                   | Hydromorphic Dam Stability Index | Tacconi Stefanelli et al. 2016, 2018 |
| RRSB                   | Rosin-Rammler-Sperling-Bennett | Osbaeck and Johansen 1989 |
| MMI                    | Particle size distribution(s) | — |
| s-d                    | Soil-dominated landslide dam | This paper |
| s&g-d                  | Soil & gravel-dominated landslide dam | This paper |
| g&b-d                  | Gravel & boulder-dominated landslide dam | This paper |
| K                      | Characteristic parameter for quantitatively measuring landslide dam material properties based on landslide deposit PSDs | This paper |
| K_R                    | The K by using RRSB distribution | This paper |
| K_F                    | The K by using power law distribution | This paper |
| Short-lived dam        | Landslide dams that prevail longer than 1 year | This paper |
| Mid-term-lived dam     | Landslide dams that prevail 3 months-1 year | This paper |
| Long-lived dam         | Landslide dams that prevail less than 3 months | This paper |