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A new look at the statistics of tailings dam failures

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ABSTRACT

Tailings dams are commonly built incrementally to increase the storage capacity of the Tailings Storage Facility (TSF), usually without interrupting the mining activities. Dam management practices, lack of knowledge on tailings behaviour and the poor performance of monitoring and management processes have resulted in disastrous tailings dam failures with human and economic losses, as well as huge environmental consequences to ecosystems and local communities. In the literature, correlation analyses have been carried out considering different variables: stored volume, released volume, runout distance, dam height, peak discharge. Several databases of tailings dam failure are available online, each with different levels of detail. This paper computes the statistics of tailings dam failures using an up-to-date database on failures and a catalogue of existing TSF. The existing correlations between stored and released volumes have been verified using a larger database. The new proposed regression analysis considers the functional relationship between released volume and characteristics of the dam such as height and stored volume (i.e., dam factor). The effect of construction type, fill material and failure mode on the released volume has also been evaluated as well as the frequency of tailings dam failure as function of the construction method. Tailing dams built using the upstream construction method turn out to be more prone to failure, and more susceptible to static and dynamic liquefaction. The new correlation provides more reliable estimates of the expected released volume as a function of dam height and stored volume and should prove useful for runout analyses and risk assessment of tailings dam failure. Finally, the analyses carried out show that there is no correlation between the water pond extension and the released volume.

1. Introduction

Tailings are the waste result of mining processes. They are a mixture of sand and silt with high content of unrecoverable metals, chemical reagents and process water employed during raw materials extraction. Tailings are usually discharged as a slurry to a storage area commonly known as Tailings Storage Facility (TSF). Usually dams or embankments are used to retain the stored tailings. Tailings dams are built and raised to increase the stored capacity, often without interrupting the mining activities. This construction approach differs from the one used for water-retaining dams, which are completely built before becoming operational. Most of the tailings dams were built several decades ago and about 45% have been constructed with the upstream method, which is considered the least stable among the tailings dam construction methods (Wei et al., 2013).

The advances in mining technology over the past 100 years have made it economically feasible to mine lower grades of ore and to increase the excavated volumes (Bowker and Chambers, 2016). On the other hand, until recently, there has been little change in practices related to management of the increased tailings volumes. The uncertainties on physical and chemical characteristics of tailings, together with dam management practices, are of growing concern (https://www.tailings.info/basics/tailings.htm). The lack of knowledge on tailings behaviour and the poor performance of monitoring and management processes can be considered as the main predisposing factors of dam failures.

Tailings dam failures have resulted in disastrous environmental and human tragedies. The different tailings dam databases considered in this study (ICOLD, WISE, World Mine Tailings Failures, n.d, CSP[2]) indicate that since 1915, a total of 257 failures have been recorded with circa 2′650 fatalities and 250 million m^3 of contaminated residues released to the environment. Almost 50% (115 million m^3) of the released volumes have been recorded after 2000, with circa 640 fatalities. These data highlight that the challenge of safely storing mine waste is growing in scale and complexity (GRIDA, 2016). The threat is further complicated by the increased severity and frequency of extreme weather events due

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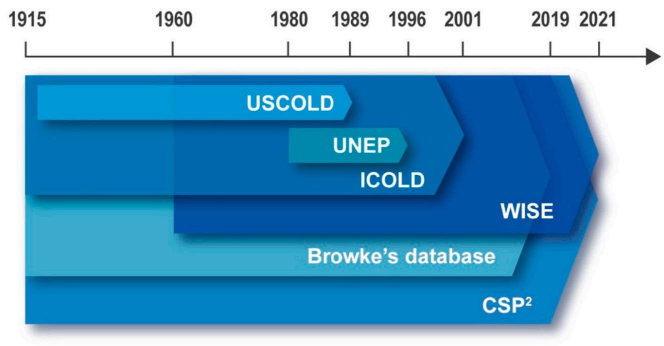

Fig. 1. Timeline with existing databases on tailings dam failures and accidents.

to climate change (IPCC, 2021; Franks et al., 2011). Heavy rainfall has been identified as the trigger in 25% of global and 35% of European tailings dam failures (Rico et al., 2008; Hu et al., 2021).

Materials released due to tailings dam failures can travel hundreds of kilometres (Glotov et al., 2018; Yu et al., 2020; Lumbroso et al., 2021), reaching rivers and lakes and inundating land with toxic slurry polluting and killing flora and fauna. An example of how catastrophic such events can be, is the Brumadinho dam failure in 2019 in Mina Córrego do Feijão, Minas Gerais, Brazil. The failure released around 10 million cubic metres of mine waste (Rotta et al., 2020) towards the valley (Lumbroso et al., 2021). The slurry travelled downstream killing 270 people and causing enormous damage to the environment, local ecosystems and communities. Clarkson and Williams (2020) estimated that the economic impact (social and environmental) of a major tailings dam failure can be between $750 million and $56 billion.

However, after the recent catastrophic tailing dam failures in Mariana in 2015 (Fundão dam) and in Brumadinho in 2019 (Dam 1 at the Córrego do Feijão) Brazil, the situation is rapidly changing. A wide range of guidelines, standards and regulatory documents are now available that can assist an operator in establishing a tailings risk assessment and management system, e.g., RIDM, 2015 (ISO 2394:2015); MAC, 2019; GISTM, 2020. All the major mining companies are reassessing and upgrading their tailings management practices. Qualitative and/or quantitative risk assessment for the evaluation of tailings dam safety is receiving increased attention and risk-informed decision-making (RIDM) is recommended as the norm in tailings management practice. RIDM, 2015 (ISO 2394:2015) quantifies the uncertainties and risks to enable making a decision on whether the risk is acceptable or not. The objective is always to minimize the risk of life loss, economical losses and other losses. One of the most common methods used for quantitative risk assessment of both tailings and water-retaining dams is the Event Tree Analysis (Lacasse and Höeg, 2019), where one considers all the plausible scenarios that could lead to dam failure and the consequences of failure if the scenarios do occur. The scenarios are built up as chains of events along the branches of the event tree. An occurrence probability must be assigned to each event. These probabilities could be based on detailed probabilistic analysis of the failure mechanism, statistics of historical events for similar dams, expert judgement or all three.

The statistical analyses presented in this paper aim at achieving a better understanding of potential tailings volume released in a failure and providing useful statistical information to help performing runout analyses and risk assessment for tailings dam failures.

Table 1
Information available in the CSP² tailings dam incident database.

MINE/PROJECT & LOCATION	
ORE TYPE	
DAM TYPE	
DAM FILL	
DAM HEIGHT (meters)	
STORED VOLUME (cu. meters)	
ICOLD INCIDENT CLASSIFICATIONS	Type Number
	Type key
	Type cause
	ICOLD incident number
INCIDENT	Year
	Date
RELEASE (cu. meters)	
RUNOUT (km)	
DEATHS	
SOURCES	
NOTES	

2. Tailings storage facility databases

2.1. Databases on tailings dam failures

All the databases available online and described in this paper are summarized in a timeline in Fig. 1. It should be noted that each database is not necessarily complete for the time period it covers. Tailings dam failures have been documented since 1915 (ICOLD, 2001). The International Committee on Large Dams (ICOLD, 2001) provides a catalogue of 221 tailings dam accidents, and includes the information provided in the databases of the US Committee on Large Dams (USCOLD, 1994) and the United Nations Environment Programme (UNEP, 1996). Specifically, USCOLD gathered information on 185 cases that occurred in the USA during the period 1917–1989 and the UNEP survey collected information on global tailings dam incidents for the years 1980–1996. The information on tailings dam accidents and failures in the USCOLD 1994 and UNEP 1996 databases were collated with information about the TSF failures that occurred in the period 1996–2001 in the ICOLD database. The ICOLD database provides the following information for each entry: location, date, ore, dam type, fill material, dam height, stored volume, incident type, volume released, and runout distance travelled by the volume. ICOLD (2001) classified the causes of tailings dam failures in nine categories: static failure (SI), seepage and internal erosion (SE), structural and foundation conditions (FN), overtopping (OT), structural inadequacies (ST), seismic instability (EQ), mine subsidence (MS), external erosion (ER), unknown (U). This classification will be used for the analysis of causes of failures.

Other databases on tailings dam accidents and failures are available on internet. The database of World Information Service on Energy (WISE)-uranium project WISE Uranium Project, 2019 (https://www.wise-uranium.org/mdaf.html) is mostly focused on the health and environmental impacts of uranium mining and nuclear fuel production. The database provides information on major tailings dam failures since 1960 and the collected information is continuously updated. The following data are collected for each entry: date and type of incident, location, ore, volume released, and impacts.

One more source of information on tailings dam failures is the website https://worldminetailingsfailures.org/. The information in this database is based on the analyses of Bowker and Chambers, 2015. This catalogue includes the information provided by ICOLD (2001) and provides information about TSF failures not presented in the WISE or ICOLD inventories. The number of failures and accidents are updated up to March 2019 and are available as an Excel file freely downloadable (https://www.resolutionmineeis.us/sites/default/files/references/bowker-2019.pdf).

Another important catalogue on tailings dam failures is provided by the Centre for Science in Public Participation (CSP²). The centre provides training and technical advice to grassroots groups on water pollution and natural resource issues, especially those related to mining (http://www.csp2.org/). CSP² also maintains a spreadsheet of tailings dam failures and accidents, which is continuously updated and available at http://www.csp2.org/tsf-failures-from-1915. The catalogue comprised 351 entries (as of March 2022) divided among TSF dam wall failure, TSF impoundment component, TSF external component/operation, other failures and significant events with tailings disposal stored.

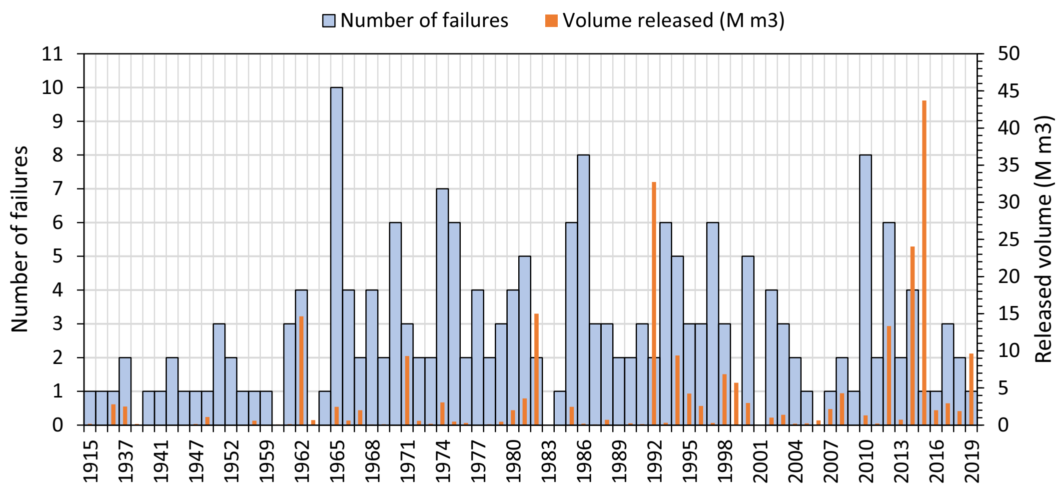

Fig. 2. Number of failures (left axis, blue columns) and volumes released (right axis, red columns) per year since 1915. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2.2. Tailings facility failure data used for new statistical analyses

The CSP^2 database was used to perform the analyses described in this paper because it was the most detailed and updated database on tailings dam failures available online. However, it is important to underline that this database is likely to be incomplete and cannot be considered exhaustive of all the tailings dam incidents worldwide. Many smaller incidents and some failures are never reported and remain not known. The information gathered in the CSP^2 database comprise: mine/project and location, ore type, dam type, dam fill material, dam height, stored volume, ICOLD incident cause classifications, incident year, incident date, volume released, runout, deaths, sources of information (Table 1).

Among the different entries, the 'ICOLD incident cause classifications: Type Number' specifies the incident type, classified according to the following classes: 1a. Active Dam Failure, 1b. Inactive Dam Failure, 2a. Active Tailings Accident, 2b. Inactive Tailings Accident, 3. Groundwater. When an impoundment has been completely filled, or when tailings production has ceased, the tailings dam and its retained impoundment is described as inactive (ICOLD, 2001), otherwise it is considered active.

The analyses carried out in this paper only consider the types "1a" and "1b", counting actual failures and not accidents. Type "1" always designates a failure in the dam itself involving an unplanned release of tailings (Bowker and Chambers, 2015). This selection reduced the 351 tailings dam entries (accidents and failures) to 257 failures. This dataset was used for statistical and correlation analyses, excluding the entries where no information on significant variables was available.

2.3. Tailings facilities catalogue considered for new statistical analyses

In January 2020, the Investor Mining and Tailings Safety Initiative, a group of 112 institutional investors that represent US\$14 trillion in assets under management, with support from UNEP, launched a census of tailings dams around the world (https://tailing.grida.no/#header). The group requested specific disclosure on tailings facilities to publicly listed extraction companies. The requested information covered 20 aspects of each tailings facility, including coordinates, raise type, current maximum height, current tailings stored and hazard categorization. The disclosure questions were developed in consultation with independent technical advisors, industry experts, and four mining companies. A table providing the full list of questions and the database are available in Franks et al., 2021. Currently, there are 1′743 tailings facilities in the database, whereof 725 are active TSFs. However, this number represents an underestimation since the dataset is concerned mainly with presently active tailings facilities and assets, omitting some closed facilities and the large number of abandoned facilities for which a responsible can no longer be found (Franks et al., 2021). Based on the results of this survey, a searchable online database of the disclosures was published by GRID-Arendal in January 2020 (http://tailing.grida.no). From the total number of entries, a selection was carried out to consider dam structures only, excluding in pit-landform and other types of tailings storage, for the analyses carried out in this paper.

3. Rationale behind the analysis and statistical approach

Earlier correlation analyses have been carried out considering different variables: stored volume, released volume, runout distance, dam height, peak discharge. The runout distance depends on many site-specific variables such as the type of tailings, water content, slope and topography downstream of the dam, and the presence of paved roads or rivers, among others. An empirical correlation between runout distance and released volume that ignores site-specific factors can lead to erroneous interpretations and such correlation analysis has therefore not been performed in this study. Instead, a correlation analysis between the released volume and a weighted product of dam height and stored volume (called the dam factor) was developed. Rico et al., 2008 correlated the dam factor with runout distance and peak discharge, considering it as a crude index of the energy expenditure at the dam when it fails (Hagen, 1982; Costa, 1988). The dam factor was also used in Costa, 1988 to indirectly measure the potential energy (i.e., peak discharge in m^3 per second) due to water-retaining dam failures. However, reliable data on the peak discharge due to tailings dam failures is not available.

In this paper, the new proposed statistical analyses verify the existing correlations between stored and released volumes obtained by Rico et al., 2008 and Larrauri and Lall., 2018, using a larger database. Moreover, a regression analysis has been conducted using a database of 71 tailings dam failures. The analyses examine the functional relationship between released volume and characteristics of the dam such as height and stored volume (i.e., dam factor). Furthermore, to inspect the probability of failure, the failure dataset was compared with the catalogue of existing dams published by GRID-Arendal (see Section 2.3).

Moreover, Rourke and Luppnow, 2015 proposed an alternative preliminary relation between released volume and water pond surface area, with the aim of providing a better correlation for the released volume. The correlation was then analysed considering 5 failures. In this paper, the Rourke and Luppnow correlation was tested considering 9 failure cases.

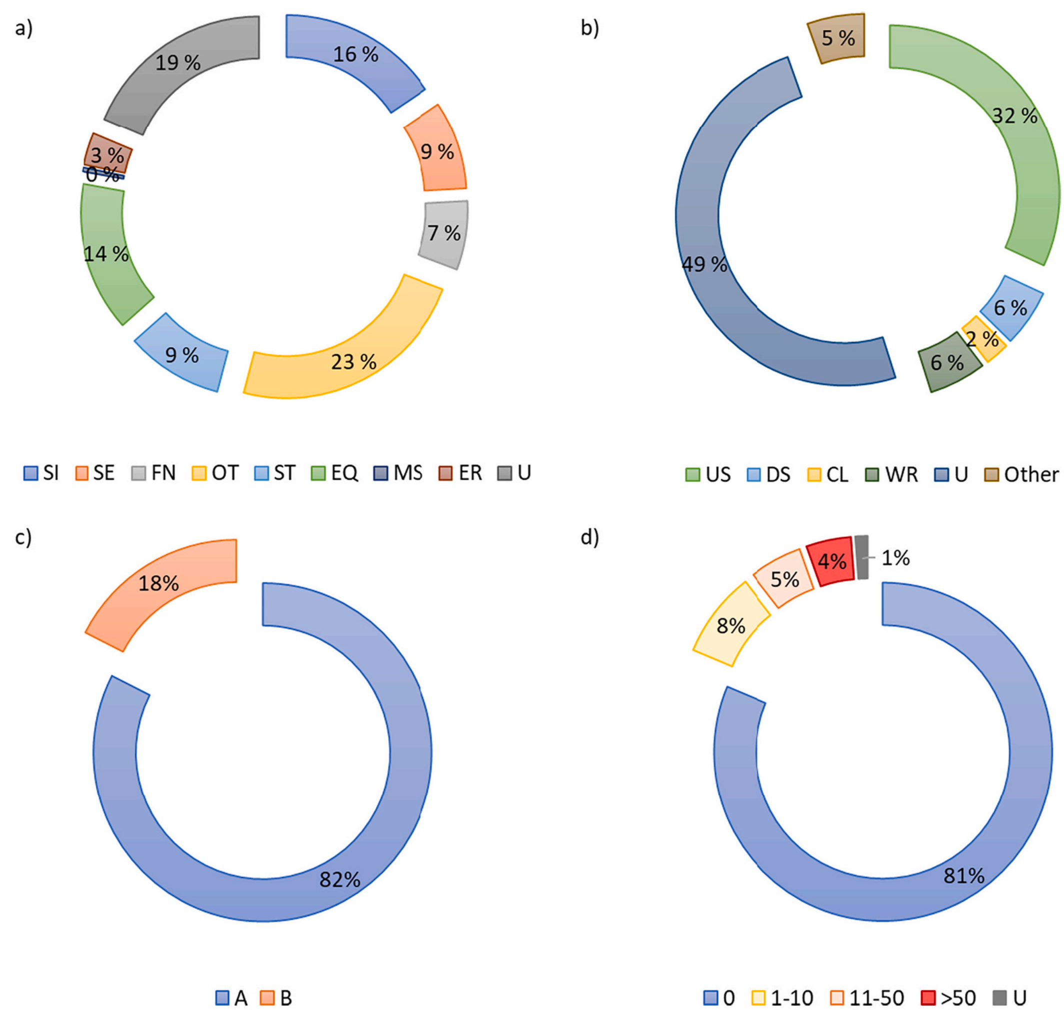

Fig. 3. a) Reported causes of tailings dam failures: static failure (SI), seepage and internal erosion (SE), structural and foundation conditions (FN), overtopping (OT), structural inadequacies (ST), seismic instability (EQ), mine subsidence (MS), external erosion (ER), unknown (U); b) Reported number of failures by dam construction method: upstream (US), downstream (DS), centreline (CL), water retention (WR), unknown (U), other type of construction; c) Number of reported failures for active (A) and nonactive(B) tailings dams; d) Consequences in terms of categories of number of human losses.

4. Results of statistical analysis on the failure database

4.1. Historical trends and causes of failures

The analyses carried out using the publicly available database CSP[2], highlights that the historical trend regarding the number of failures has an average of 2.5 failures per year (Fig. 2) and an average released volume to total stored volume ratio of about 0.27. Overtopping, static liquefaction and dynamic liquefaction are the most frequent causes of tailings dam failure (Fig. 3a). This finding agrees with previous findings in ICOLD, 2001 and GRIDA, 2016. The failure mode for 52 failures of the 257 cases (19%) is not known. Thus, even a larger percentage of failures might be attributable to the three main failure modes (Fig. 3a). The data also highlights that the upstream method is the dam construction type with the highest percentage of failure (32%). However, for half the failures (49%) collected in the database, the construction type of the tailings dam is unknown (Fig. 3b). Of the recorded failures, 82% involved active tailings dams (Fig. 3c). For 17% of the cases, the failures had consequences in terms of human losses, with 4% with more than 50 victims (Fig. 3d).

4.2. Released and stored tailings volumes

From the tailings dam failure database (see Section 2.1), only the entries containing information on both the released and the stored volumes (71 entries) were selected for this analysis. A correlation between released (R) and stored volumes (V) was done using linear regression analysis and the result was compared with the one published in Rico et al., 2008, and Larrauri and Lall, 2018. In Rico et al., 2008, the authors correlated the volume released with the stored volume for 22 cases that had complete information on volumes. Subsequently, Larrauri and Lall, 2018, added six more cases to the database. A comparison between the dataset used in this paper and the one published in in Rico et al., 2008, and Larrauri and Lall, 2018, is presented in Table 2. The correlation between released and stored volumes is plotted in Fig. 4.

The equations from Rico et al., 2008, and Larrauri and Lall, 2018, are very similar, and so are the coefficients of determination (r^2, close to 0.9). The r^2 value is a statistical measure that represents the proportion of the variance for a dependent variable.

The result obtained in this study, with a larger failure dataset (70 entries, ID170 excluded because has a very small released volume), highlights that the coefficient of determination r^2 for the correlation between stored and released volumes reduces to 0.59 (Table 3), thus indicating a weaker correlation with a larger number of failures. This difference in the uncertainty of the correlation is important if one is to use such correlations to assign probabilities in an event tree analysis and other risk assessment methods or to evaluate the expected released volume for runout analyses.

Table 2
Dataset used in this paper. The dataset of 28 failures used by Larrauri and Lall (2018) are highlighted in grey.

No	ID	Location	Year of failure	Stored volume (Mm^3)	Released volume (Mm^3)	Height (m)
1	9	Brumadinho, Mina Córrego do Feijão, Minas Gerais, Brazil (Vale)	2019	12.000	9.570	87
2	15	Hector Mine Pit Pond, MN, USA	2018	0.185	0.123	17
3	29	Louyang Xiangjiang Wanji Aluminum, China	2016	2.000	2.000	45
4	31	Fundao-Santarem (Germano), Minas Gerais, Brazil (Samarco = Vale & BHP)	2015	56.400	43.700	110
5	36	Imperial Metals, Mt. Polley, British Columbia, Canada	2014	74.000	23.600	40
6	38	Dan River Steam Station, North Carolina (Duke Energy)	2014	155.000	0.334	12
7	44	Sotkamo, Kainuu Province, Finland (Talvivaara)	2012	5.400	0.240	25
8	45	Padcal No 3, Benquet Philippines (Philex)	2012	102.000	13.000	NA
9	52	Ajka Alumina Plant, Kolontár, Hungary (MAL Magyar Aluminum)	2010	30.000	1.000	22
10	57	Las Palmas, Pencahue, VII Region, Maule, Chile (COMINOR)	2010	0.220	0.170	15
11	58	Veta del Agua Tranque No. 5, Nogales, V Region, Valparaíso, Chile	2010	0.080	0.030	16
12	65	Taoshi, Linfen City, Xiangfen county, Shanxi province, China (Tahsan Mining Co.)	2008	0.290	0.190	50.7
13	69	Mineracao Rio Pomba Cataguases, Mirai, Minas Gerais, Brazil, Mineração (Industrias Quimicas Cataguases)	2007	3.800	2.000	35
14	74	Tailings Dam, USA	2005	0.500	0.170	43
15	79	Partizansk, Primorski Krai, Russia (Dalenergo)	2004	20.000	0.160	NA
16	82	Sasa Mine, Macedonia	2003	2.000	0.100	NA
17	86	San Marcelino Zambales, Philippines, Bayarong dam (Benguet Corp-Dizon Copper-Silver Mines Inc)	2002	47.000	1.000	NA
18	94	Aitik mine, near Gällivare, Sweden (Boliden Ltd)	2000	15.000	1.800	15
19	96	Baia Mare, Romania	2000	0.800	0.100	7
20	102	Los Frailes, near Seville, Spain (Boliden Ltd.)	1998	15.000	6.800	27
21	113	Sgurigrad, Bulgaria	1996	1.520	0.220	45
22	119	Omai Mine, Tailings dam No 1, 2, Guyana (Cambior)	1995	5.250	4.200	44
23	120	Middle Arm, Launceston, Tasmania	1995	0.025	0.005	4
24	126	Merriespruit, near Virginia, South Africa (Harmony) - No 4A Tailings Complex	1994	7.040	0.600	31
25	142	Maritsa Istok 1, Bulgaria	1992	52.000	0.500	15
26	143	Tubu, Benguet, No.2 Tailings Pond, Luzon, Philippines - Padcal (Philex)	1992	102.000	32.243	NA
27	144	Ajka Alumina Plant, Kolontár, Hungary	1991	4.500	0.043	25
28	150	Stancil, Maryland, USA	1989	0.074	0.038	9
29	156	Unidentified, Hernando, County, Florida, USA #2	1988	3.300	0.005	12
30	170	Story's Creek, Tasmania	1986	0.030	0.0001	17
31	176	Niujiaolong tailings pond, China	1985	1.100	0.730	40
32	177	Bonsal, North Carolina, USA	1985	0.038	0.011	6
33	178	Prestavel Mine - Stava, North Italy, 2, 3 (Prealpi Mineraria)	1985	0.400	0.180	29.5
34	180	Cerro Negro No. (4 of 5)	1985	2.000	0.500	40
35	181	Veta de Agua No. 1, Chile	1985	0.700	0.280	24
36	182	Niujiaolong, Hunan (Shizhuyuan Non-ferrous Metals Co.)	1985	1.100	0.731	40
37	183	Olinghouse, Nevada, USA	1985	0.120	0.025	5
38	195	Sipalay, Phillippines, No.3 Tailings Pond (Maricalum Mining Corp)	1982	22.000	15.000	NA
39	199	Balka Chuficheva, Russia	1981	27.000	3.500	25
40	203	Tyrone, New Mexico (Phelps Dodge)	1980	2.500	2.000	66
41	210	Churchrock, New Mexico, United Nuclear	1979	0.370	0.370	11
42	215	Arcturus, Zimbabwe	1978	0.680	0.039	25
43	216	Mochikoshi No. 2, Japan (2 of 2)	1978	0.480	0.003	19
44	217	Mochikoshi No. 1, Japan (1 of 2)	1978	0.480	0.080	28
45	227	Zlevoto No. 4, Yugoslavia	1976	1.000	0.300	25
46	232	Madjarevo, Bulgaria	1975	3.000	0.250	40
47	234	Mike Horse, Montana, USA (Asarco)	1975	0.750	0.150	18

(continued on next page)

Table 2 (*continued*)

No	ID	Location	Year of failure	Stored volume (Mm^3)	Released volume (Mm^3)	Height (m)
48	240	Bafokeng, South Africa	1974	13.000	3.000	20
49	242	Deneen Mica Yancey County, North Carolina, USA	1974	0.300	0.038	18
50	243	Silver King, Idaho, USA	1974	0.037	0.014	9
51	250	(unidentified), Southwestern USA	1973	0.500	0.170	43
52	253	Brunita Mine, Caragena, Spain (SMM Penaroya)	1972	1.080	0.070	25
53	254	Buffalo Creek, West Virginia, USA (Pittson Coal Co.)	1972	0.500	0.500	16
54	256	Cities Service, Fort Meade, Florida, phosphate	1971	12.340	9.000	15
55	264	Mufulira, Zambia (Roan Consolidated Mines)	1970	1.000	0.068	50
56	276	Hokkaido, Japan	1968	0.300	0.090	12
57	287	Mir mine, Sgurigrad, Bulgaria	1966	1.520	0.450	45
58	289	Gypsum Tailings Dam (Texas, USA)	1966	6.360	0.130	16
59	293	El Cobre Old Dam	1965	4.250	1.900	35
60	294	El Cobre New Dam	1965	0.350	0.350	19
61	297	Los Maquis No. 3	1965	0.043	0.021	15
62	298	Bellavista, Chile	1965	0.450	0.070	20
63	308	Cerro Negro No. (3 of 5)	1965	0.500	0.085	20
64	315	Castano Viejo Mine, San Juan, Argentina	1964	0.027	0.017	9
65	317	Louisville, USA	1963	0.910	0.667	31
66	318	Huogudu, Yunnan Tin Group Co., Yunnan	1962	5.420	3.300	19
67	324	Jupille, Belgium	1961	0.550	0.136	46
68	325	La Luciana, Reocín (Santander), Cantabria, Spain	1960	1.250	0.100	24
69	328	Mailuu-Suu #7 tailings dam (Kyrgyzstan)	1958	1.200	0.600	NA
70	347	Los Cedros, Tlalpujahua, Michoacán, México	1937	11.480	2.500	35
71	349	Barahona, Chile	1928	20.000	2.800	61

4.3. *Predicting released volume from dam height and stored volume*

The finding that a larger dataset on tailings dam failures leads to a weaker correlation between stored and released volumes implies that the stored volume (V) cannot be considered as the only parameter describing the released volume (R). The dam height (H) also plays an important role. A multi-linear regression was done on the log-transformed values expressing released (R) and stored (V) volumes in cubic meter (m^3) and height (H) in meter (m), with a model of the following type:

$$log(\mathrm{R}) = \beta_0 + \beta_1\, log(\mathrm{V}) + \beta_2 log(\mathrm{H}) + \varepsilon \tag{1}$$

where ε is assumed to be a normally distributed random variable with mean zero. Taking exponentials of both sides, assuming base-10 logarithms, the equivalent model was obtained:

$$R = 10^{\beta0+\varepsilon}\ \mathrm{V}^{\beta1}\ \mathrm{H}^{\beta2} \tag{2}$$

The dataset used for this regression was the subset of the incidents obtained by filtering the CSP^2 database on missing values, either in released volume, dam height or stored volume. The resulting dataset consisted of 64 entries (see Table 2). One failure (ID170) was considered as an outlier and removed, because it had a very small released volume (100 m^3) compared to other dam failures. More details, and a discussion is contained in the supplementary material. The fitted parameters along with standard error, t-statistic and the associated *p*-values, are shown in Table 4.

The t-value is the rate between estimate and the standard error. The p-value is the probability of obtaining an estimate deviating more than the observed estimate under the zero hypothesis. The r^2 value for the regression quantifies the proportion of the variance explained by the model and was calculated to be 0.64. The standard deviation of the residuals is 0.55. Hence, according to the model, about 93% of the predicted released volume lies within a factor of 10 (see supplementary material) of the actual released volume. A comparison between observed and predicted released volume is shown in Fig. 5.

Generally, a p-value smaller than 0.05 is taken to mean that the estimate is statistically significant. Both p-values for **β1** and **β2** are lower than 1 per thousand, indicating that it is natural to include both height and volume in the model. The insignificant p-value for the constant just means that the constant for the model is not significantly different from zero. This may occur when the area of interest is far from the origin. As already discussed, one may join the height and volume into a single variable by taking their product, labeled here as the dam factor. The result of the multivariate regression displayed in Table 4 indicates that simply taking the product is suboptimal with respect to the prediction of released volume, since the difference between **β1** and **β2** is considerable (see section 1.7 of the supplementary material "predicting release volume"). Instead of taking the product, the above weights could be used to define an adjusted dam factor (ADF):

$$log(\mathrm{ADF}) = \beta_1\, log(\mathrm{V}) + \beta_2\, log(\mathrm{H}) \tag{3}$$

Eq. (1) will be:

$$log(\mathrm{R}) = \beta_0 + log(\mathrm{ADF}) + \varepsilon \tag{4}$$

To visualize the rationale behind the adjusted dam factor, a scatter plot of the incidents in the log-stored-volume and log-height plane was prepared in Fig. 6, with the size of the marker indicating the released volume. The contour lines of the adjusted dam factor are also included. The angle of the contour lines is determined by the relation between β_1 and β_2 (note the scaling of the axis). From the figure one may observe how the adjusted dam factor is fitted so as to capture the increasing released volume as a function of both dam height and stored volume.

In Fig. 7, the log of the released volume is plotted versus the log of the adjusted dam factor. Note that by definition, the slope of the fitted linear model is unity. While Fig. 6 reveals how incidents are scattered with respect to height and stored volume, it is easier to spot the extent to which the incidents deviates from the best linear fit from Fig. 7. In particular, two incidents labeled 216 and 156 have low released volume compared with adjusted-dam-factor (ADF). These are the incidents in Mochikoshi (Japan) of 1978 and Hernando (Florida, USA) of 1988 respectively. Both incidents may be considered as outliers, but they do not have a considerable leverage on the fitted model. However, removing these two and the one labeled 38, which has a considerable leverage (i.e., a large impact on the fitted values) the r^2 increases to 0.75 (see supplementary material for the coefficients $\beta_{0,}$ $\beta_{1,}$ β_2).

In Fig. 8, the different variable distributions and the correlation among them are shown. The figure highlights that the highest correlation is obtained for the combination released volume (R) and adjusted dam factor (ADF).

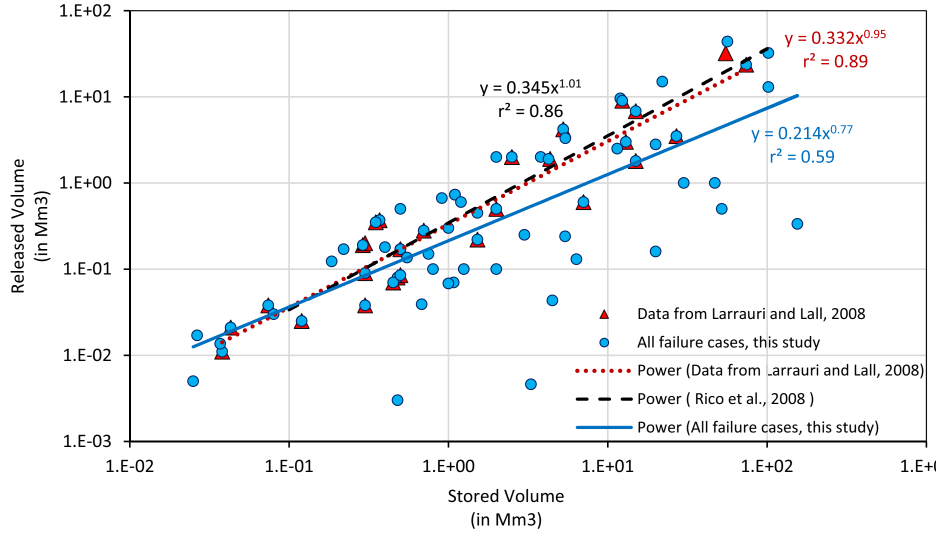

Fig. 4. Correlation between released and stored volumes of TSFs: Comparison between Rico et al. (2008), 22 cases, Larrauri and Lall (2018), 28 cases and the equations derived in this paper, 71 cases.

Table 3
Comparison of r^2 and new correlation with Rico et al. (2008) and Larrauri and Lall (2018).

Dataset	No of failures	Correlation	r^2
Rico et al. (2008)	22	$R = 0.354 \times V^{1.01}$	0.86
Larrauri and Lall (2018)	28	$R = 0.332 \times V^{0.95}$	0.89
Updated dataset	70	$R = 0.214 \times V^{0.35}$	0.59

Table 4
Result of multiple linear regression between Released volume, Stored volume and dam Height.

	Estimate	Std. Error	t-value	p-value
β_0	0.330	0.502	0.656	0.514
β_1	0.611	0.089	6.845	4.59e-09
β_2	0.994	0.273	3.637	0.000575

5. Influence of failure mode, construction and fill on volume released

5.1. Effect of construction method and failure mode on released volume

Having established a relationship between released volume and adjusted dam factor, it would be possible to use this relation to correct for the effect of dam height and stored volume by subtracting predicted released volume from the observed released volume. This quantity is known as the residual (ε). It is important to note that for 15 of the 70 failures, dam construction method is missing. This is not surprising given the fact that many dams are in fact of a mixed construction type.

In Figs. 9 and 10, the residuals (ε) associated with the regression of released volume with adjusted-dam-factor are displayed in box plots with respect to dam construction method and failure mode respectively. Failures of dams constructed with the centreline (CL) method (Fig. 9) appear to have a higher release volume after adjusting for volume and height, whereas all other construction methods have approximately same released volume. The water-retention dams (WR), constructed with the same technical characteristics of water dam, show significantly lower variance. To address the significance of the increased released volume associated with centreline dams (CL) one may add dam-type as a

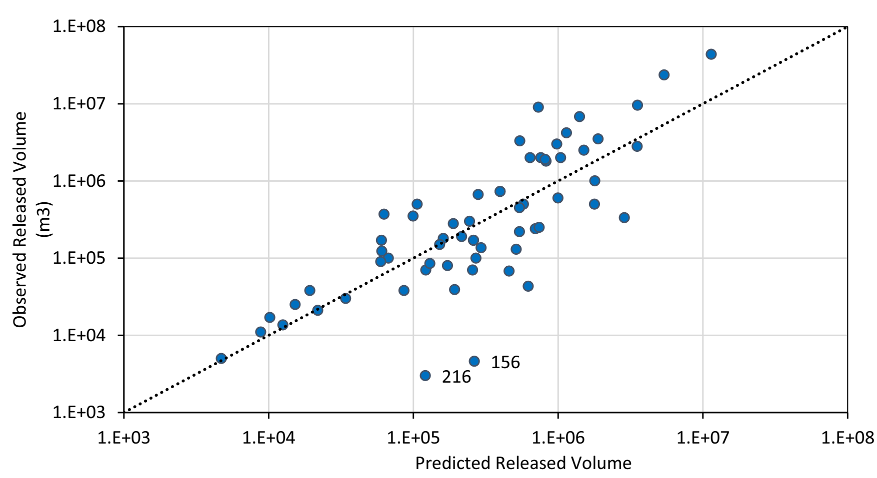

Fig. 5. Observed and predicted released volumes (m^3).

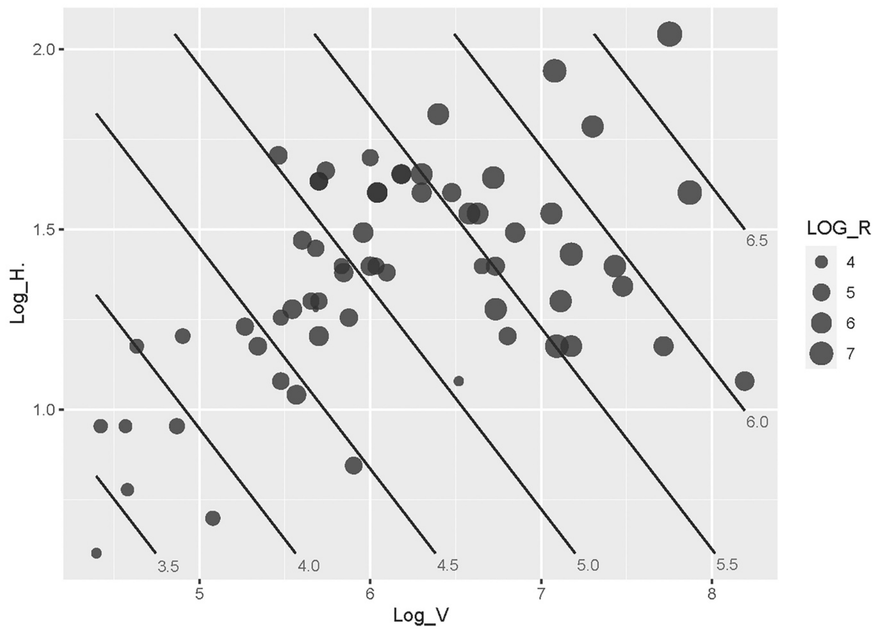

Fig. 6. Tailings dam failures categorised after stored volume and dam height. The size of the marker indicates the released volume. The black lines are contours of the adjusted dam factor.

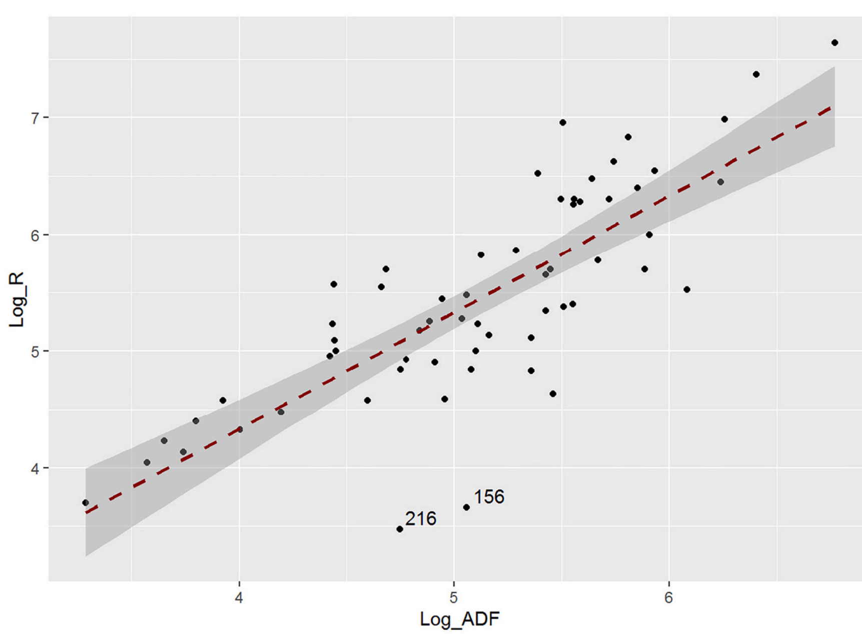

Fig. 7. Correlation between released volume and adjusted dam factor. The red dotted line displays the best linear fit and the shaded region displays the 95% confidence interval of the regression line. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

categorical variable to the regression. This yields a *p*-value of 0.02 indicating that the effect of this variable is statistically significant (supplementary material). However, there are only three cases with the CL construction method. Such finding should therefore be treated with caution.

Failures associated with the foundation (FN) shows higher released volume (Fig. 10). Testing the inclusion of failure mode as a categorical variable yields a p-value of 0.03 also indicating that the failures of type FN are indeed associated with a higher released volume after adjusting for volume and height. However, again, there are only three cases. Similar observations apply to the failures classified as unknown failure mode (U). A similar analysis of the effect of dam fill on the released volume indicated that failures of dams using mine waste (MW) as fill material was associated with slightly higher released volume. Figures are presented in the supplementary material.

5.2. Dependency of failure mode on dam construction method

This section looks at the dependency between failure mode and the dam construction method. The analysis was carried out by making a contingency table that has as columns the failure modes and as rows the dam types (Table 5). The failures with unknown mode (U) are also largely not classified in terms of dam construction method.

For the analysis, all failures with unknown failure mode and

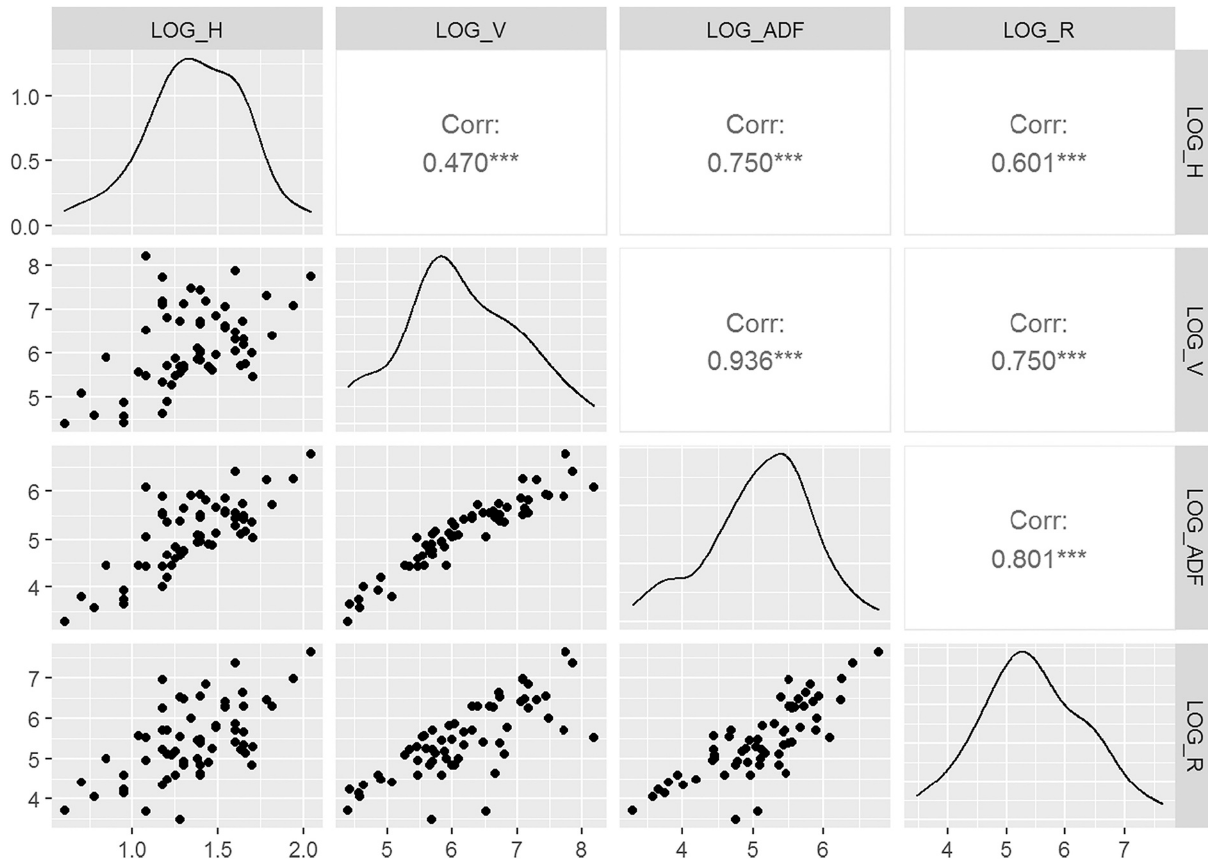

Fig. 8. Correlation, distributions and scatter plot of the variables. The adjusted dam factor (ADF) includes the effect of both stored volume and dam height (H = dam height; V = stored volume; R = released volume).

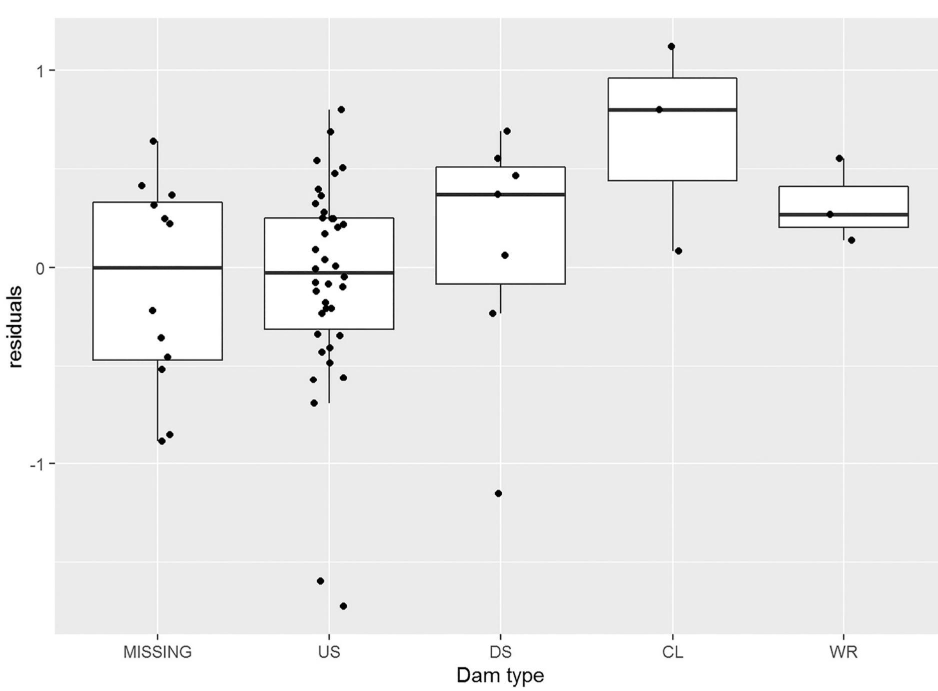

Fig. 9. Residuals of the regression of released volume vs adjusted dam factor as a function of dam construction method: upstream (US), downstream (DS), centreline (CL), water retention (WR), unknown (U).

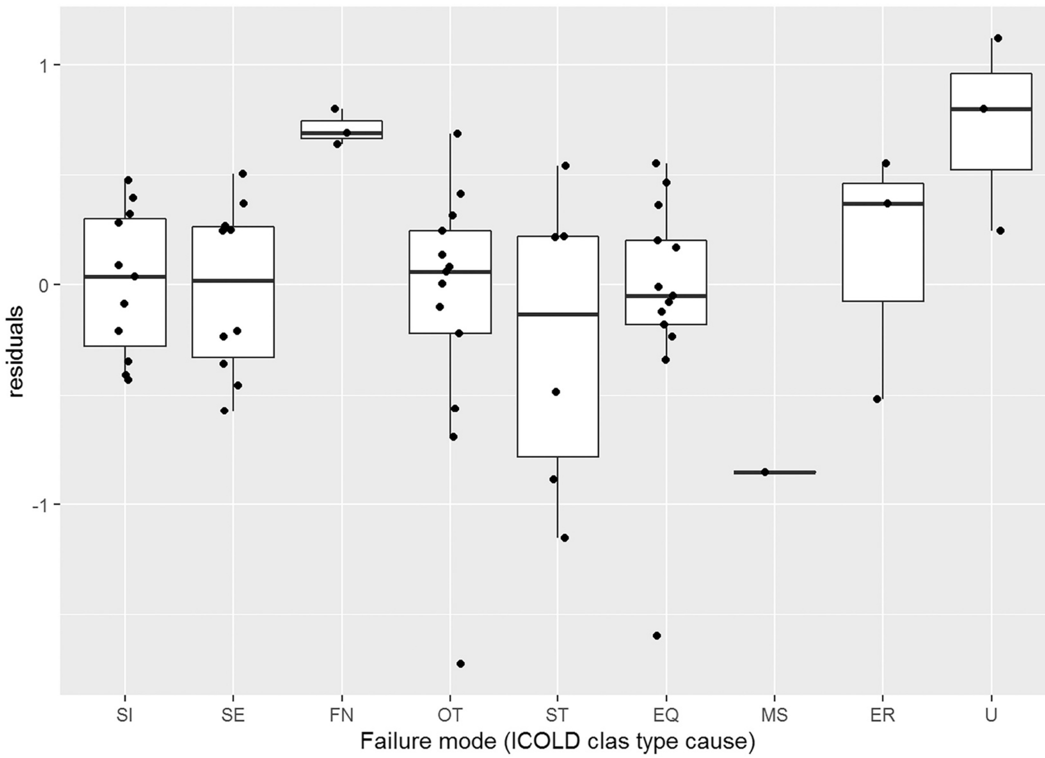

Fig. 10. Residuals of the regression of released volume on adjusted-dam-factor as a function of failure mode: static failure (SI), seepage and internal erosion (SE), structural and foundation conditions (FN), overtopping (OT), structural inadequacies (ST), seismic instability (EQ), mine subsidence (MS), external erosion (ER), unknown (U).

Table 5
Contingency table of number of failures by failure mode and dam construction method.

	SI	SE	FN	OT	ST	EQ	MS	ER	U	Sum
not known	11	12	7	39	19	12	3	6	56	165
US	32	7	5	17	5	34	1	1	4	106
DS	6	4	4	3	3	7	0	1	2	30
CL	1	2	5	3	1	0	0	0	2	14
WR	5	4	4	4	1	1	0	4	3	26
Sum	55	29	25	66	29	54	4	12	67	341

Table 6
Matrix of standardized Pearson residuals from the Fisher test on the dependency of dam construction method and failure mode.

Construction method	Failure mode					
	SI	SE	FN	OT	ST	EQ
US	1.53	−2.00	−3.32	−0.03	−0.90	2.77
DS	−0.72	0.74	0.61	−0.91	1.12	−0.08
CL	−1.57	0.69	3.43	0.76	0.30	−2.17
WR	−0.15	1.54	1.41	0.49	−0.20	−2.24

unknown dam construction method were excluded. The MS and ER failure modes were also excluded because the number of cases is much lower than for the other failure modes.

For carrying out the analysis we introduce the hypothesis (H_0) stating that failure mode and dam construction method are independent variables. The hypothesis is tested using a Fisher Exact Test. This results in a p-value of less than 0.001, which is strong evidence of an association between the two variables, i.e., that the hypothesis H_0 may be rejected. To extract information on which values in Table 5 that may be considered abnormal under the hypothesis of independence, the standardized Pearson residuals are shown in Table 6. A residual that exceeds 2 in absolute value indicates a clear lack of fit (abnormality) between the hypothesis of independence and the corresponding observed value in Table 5 (shaded cells in Table 6). Residuals lower than +1.5 are outlined in grey. From Table 5 we observe that failures of upstream dams (US) are more frequently of the type SI and EQ, while they are very rarely associated with FN. From Table 6 we can state that US construction method is more susceptible to SI and EQ failures, i.e., the 32 failures of type SI and 34 failures of type EQ are higher than what to expect, while 5 failures of type FN are much fewer than what to expect considering the hypothesis that failure mode and dam construction method are independent variables (H_0). Similarly, the centreline dams (CL) seems to be more susceptible to FN failure mode, i.e., 5 failures associated with FN are much higher than expected. The downstream (DS) construction method, is not particularly prone to a specific failure mode. The water retention construction method (WR) is prone to fail for seepage and internal erosion (SE). Failures due to overtopping (OT) seems to be largely independent of construction type, so it can occur for all tailings dam construction methods. Recall that the table does not say anything about which type of dams are more likely to fail. However, a certain construction method being more prone or susceptible to certain types of failure modes will induce a dependency of the variables. In Section 6 we will address the question on the association of failure and dam type, which indeed sheds some light on the frequency issue.

5.3. The influence of static and seismic liquefaction on the volume released for upstream dams

The correlation between the released volume and the adjusted dam factor was established considering the dataset on tailings dam failures including all the failure modes. In this analysis, it is proposed to consider only the upstream dam failures for static (SI) and seismic liquefaction (EQ), excluding the other modes, since this construction method has been proven to be more susceptible to these failure modes (Section 5.2).

Table 7
Result of multiple linear regression between Released volume, Stored volume and dam Height for the subset SI-EQ considering the construction method upstream (US).

	Estimate	Std. Error	t-value	p-value
β_0	−0.157	0.497	−0.315	0.756
β_1	0.762	0.349	6.704	2.7e-06
β_2	0.705	0.113	2.018	0.058

Performing a regression of log-released volume and log-adjusted dam factor on the subset of SI and EQ failure modes reveals a better fit and the fitted values are provided in Table 7. Originally, the SI-EQ subset contained 21 entries. It yielded an r^2 value of 0.82. Random subsampling of datasets of the same size reveals that the observed r^2 value of 0.87 is among the top 6%. The standard deviation of the residuals is 0.27. In Fig. 11, the log-released volume is plotted against the log of adjusted-dam-factor for the failure modes SI and EQ considering the construction method upstream (US).

6. Cases of failure and non-failure

The catalogue of existing tailings facilities and the database on failures were used for comparative analyses. The two databases have overlapping variables, such as dam height, stored volume, and construction method. It should be kept in mind that a failure is an incident in time, while the catalogue of existing tailings dams is a record of the situation at the time of the census. The number of both failures and existing tailings facilities can be underestimated. Probably the catalogue of existing dams has a higher underestimation of number of dams than the catalogue of failures. The number of existing tailings dams today is estimated to be about 8000 (Franks et al., 2021), so four times the current number in the database; combined with missing data on the age of the failed dams, an estimate on the failure rate is a difficult task. Still, it is by comparing the overlapping features of the two databases that a mean of associating features with failures can be obtained.

Fig. 12 shows the comparison between dam height and stored volume of the two databases. It appears that the distribution of the dam height is similar for the two databases. On the other hand, in terms of volume stored, there is a slight tendency towards smaller stored volumes in the failure dataset. Applying the mean as a test statistic, the hypothesis that the smaller volume is simply a random artefact is rejected (see supplementary material). It could be deducted that dams with smaller storage volumes are more likely to fail because dams storing large volumes have higher standards and monitoring technologies. However, this assumption is not justified by the dam height distributions. Another explanation can be that the stored volume is systematically underestimated or underreported in the failure database. However, it is important to underline that tailings dams grow with age and that a failure is an incident in time. The discrepancy here may be a result of how time affects the two databases and can be also influenced by the percentage of active and closed tailings dams in the two databases. The failure database is a static record of tailings dam characteristics at the time of the failure, while the catalogue of tailings dams is a picture of the situation at the time of the census.

Joining the databases on failures and existing dams, the fraction of failures as a function of the dam construction method has been computed (Fig. 13). From Fig. 13 we observe that for a relatively high fraction of the incidents in the failure database the construction method was not known (see Section 4.1). For the tailings dam failures with a documented construction method, a higher frequency (relative to total number of dams in the catalogue of tailings dams) is observed for the upstream method (0.13), followed by the centreline construction method (0.11) and the downstream construction method (0.07). This result partially confirms what is stated in ICOLD 2001 and Rico et al., 2008b, and shown in terms of percentage in Section 4.1. An analysis with the failure database only (Fig. 3b) suggests that the downstream method is second in term of number of failures. (ICOLD, 2001; Rico et al., 2008). The analysis presented in Fig. 13, using failure and non-failure databases, shows that the frequency of failures is lower for the downstream method compared to the centreline. This result agrees with

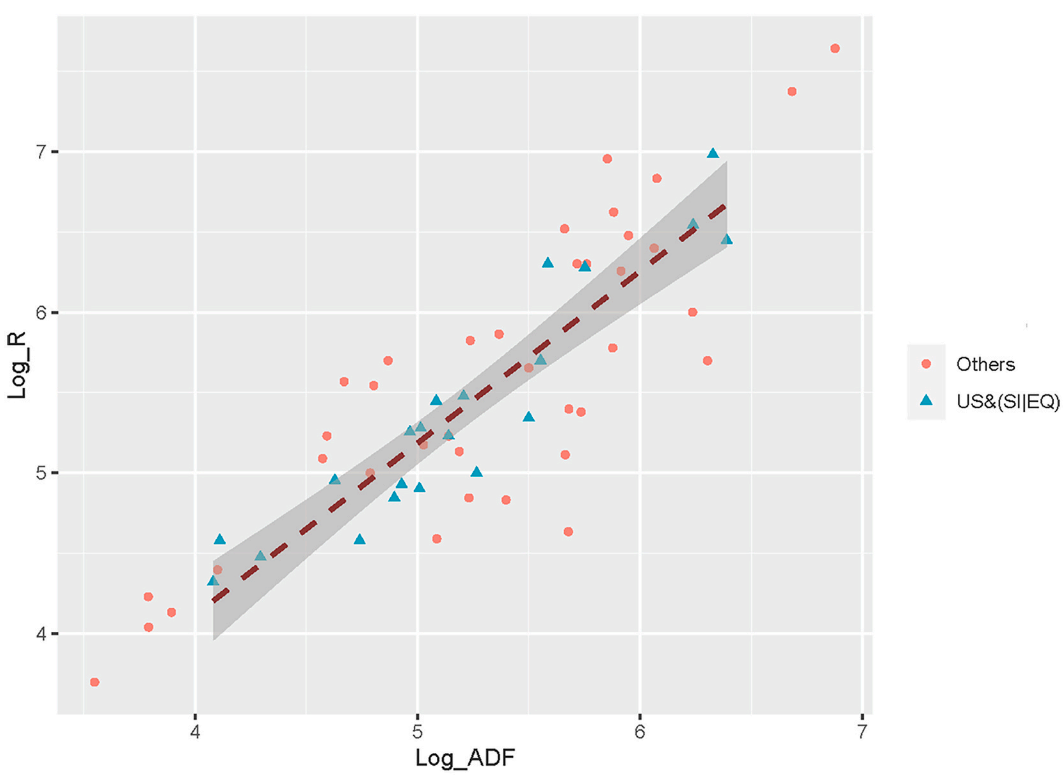

Fig. 11. Relation between released volume and adjusted dam factor for the failure modes SI and EQ subset, considering the construction method upstream (US).

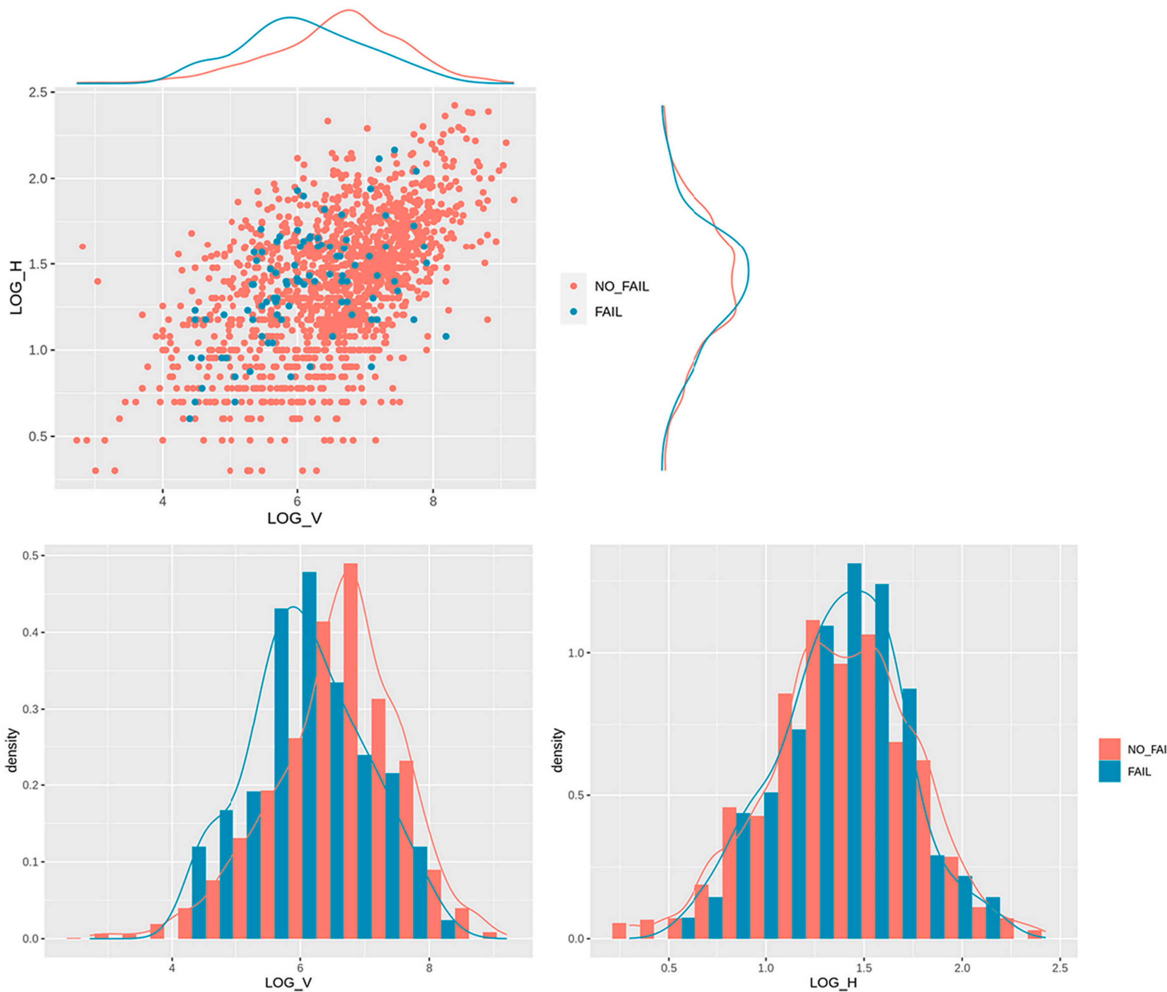

Fig. 12. Comparison between dam height (H) and stored volume (V) in the failure database (in green) and the catalogue of existing tailings dams (NO_FAIL in red). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

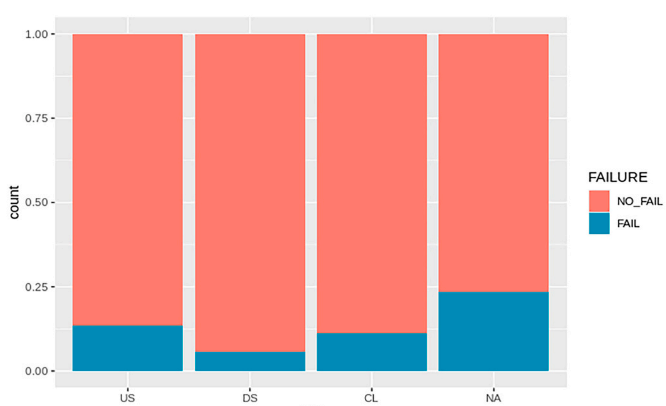

Fig. 13. Fraction of dams in the failure dataset to the total number of dams in both datasets as a function of the dam construction method. US = upstream; DS = downstream, CL = centreline; NA = not known.

the survey carried out by Franks et al., 2021, who highlighted that active upstream facilities show a higher incidence of stability issues than other construction methods.

To further investigate the relation between failure and dam type we summarized the data in the frequency Table 8, classifying the tailings dams from the two databases according to construction method, considering the ones classified as upstream (US), downstream (DS) and centreline (CL) (Table 8). To verify that the two variables may not be considered as independent, a χ^2-test was carried out. The resulting p-value associated with the hypothesis of independence is less than 0.0001, indicating that the hypothesis may be rejected. In Table 9, the associated standardized Pearson residuals are shown. The residuals measure the deviation of the value in each cell of Table 8 with respect to the expected values under the hypothesis of independence. A residual that exceeds 2 indicates an abnormal value with respect to the hypothesis of independence. From Table 9 we may conclude that the 106

Table 8
Number of tailings dams classified as upstream (US), downstream (DS) and centreline (CL) in the failure database (FAIL) and the catalogue of existing tailings dams (NO_FAIL).

	US	DS	CL	Total
NO_FAIL	685	488	110	1283
FAIL	106	30	14	150

Table 9
Standardized Pearson residuals for Table 8.

	US	DS	CL
NO_FAIL	−4.03	4.35	−0.31
FAIL	4.03	−4.35	0.31

Table 10
Released volume, released/stored volume ratio and the pond ratios for eight TSFs.

TSF	Released volume (m^3)	Released/stored volume ratio	Pond ratio
Brumadinho	9,570,000	0.79	0.012
Fundao	43,700,000	0.77	0.3
Mt Polley	23,600,000	0.31	0.72
Kolontár	1,000,000	0.03	0.75
Las Palmas	170,000	0.77	0
Merriespruit	600,000	0.08	0.14
Bafokeng	3,000,000	0.23	0.3
Stava	180,000	0.45	1

failures for dams of construction type US are far more than expected, while the 30 failures associated with dams constructed with the downstream method are far less than expected. Combining these results with the analysis on failure mode and dam type in Section 5.3 indicates that upstream dams are indeed more vulnerable to failures of type SI and EQ compared with the other construction types.

7. Pond ratio, release volume and stored volumes

Rourke and Luppnow, 2015 proposed an alternative estimation of the expected volume released after a tailings dam failure. They considered the area of the pond together with the ratio of stored and released volumes at failures. However, information on pre-failure water pond extents are scarce and Rourke and Luppnow, 2015 collected information for 5 cases only. They defined a linear equation between the volume ratio (released volume on the stored volume) and the pond ratio (ratio between the pond surface and the TSF surface). Even though the general assumption (i.e., important role played by the pore water pressure) is somewhat true, the applicability and the trustworthiness of the method are not supported by the evidence. To examine the correlation, this present analysis added three new cases (in shaded rows) and recomputed the volume and the pond ratios for the five cases reported in Rourke and Luppnow, 2015 (Table 10). As illustrated by the blue circles from this study in Fig. 14, there is no clear trend between the volume ratio and the pond ratio. The presence or absence of a large pond alone does not correlate with the occurrence of failure, nor the volume released. An important role is played by saturation conditions, contractive vs dilative soil, undrained vs drained conditions, state and characteristics of the tailings dam. These aspects can all be considered as predisposing factors of a failure. On the other hand, the presence of a pond may increase the potential for overtopping. Perhaps, by considering the overtopping failures only could lead to an improved correlation. Unfortunately, not enough data are available to perform such a test.

8. Discussion and conclusions

Several databases of tailings dam failure are available, each with different levels of detail. All of them are originated from the ICOLD database published in 2001. The most complete and continuously updated one is the CSP[2] - Tailings Dam Failures database. Together with this failure database, a catalogue of existing tailings dams was used to perform statistical analyses on failures modes and dam construction methods. The catalogue of tailings dams was created by the Investor Mining and Tailings Safety Initiative and, based on the results of the survey, a searchable online database of the disclosures was published by GRID-Arendal in January 2020 (http://tailing.grida.no).

From the CSP[2]-Tailings Dam Failures database, correlations were established considering the following variables: stored volume, released volume, dam height. The new statistics showed that when using a larger number of tailings dam failures than before, the correlation between stored and released volumes had lower coefficient of determination r^2 (0.59) than the findings of previous authors. However, the released volume is not a function of the stored volume only, but also of the height of the dam and other parameters such as mechanical properties of the tailings stored. A higher correlation ($r^2 = 0.64$ and 0.75 excluding the outliers 38, 156, 216) was found correlating the adjusted dam factor (see eq. 3) with the released volume (R).

The dependency between failure mode and dam construction method was also investigated. The results show that upstream dams are more susceptible to static liquefaction/slope instability (SI) and dynamic liquefaction (EQ). Upstream constructed structures may lead to the build-up of excess pore water pressure which for specific soil conditions or under cyclic loading may lead to static and/or seismic liquefaction. On the other hand, centreline dam, are more susceptible to the failure mode due to structural and foundation conditions (FN),i.e., centreline dams are overrepresented on failures of type FN (see Tables 5 and 6). This finding is difficult to explain, and it may be an anomaly due to too few data points. The main reason for foundation problems is lack of proper site investigation before dam construction and a weak layer in the foundation subsoil that is not identified. The upstream and downstream construction methods will also lead to foundation issues if there is a weak layer below the dam. The centreline constructed dams are more robust than US dams for several other modes of failure and generally have steeper slopes. These factors may also partly explain the

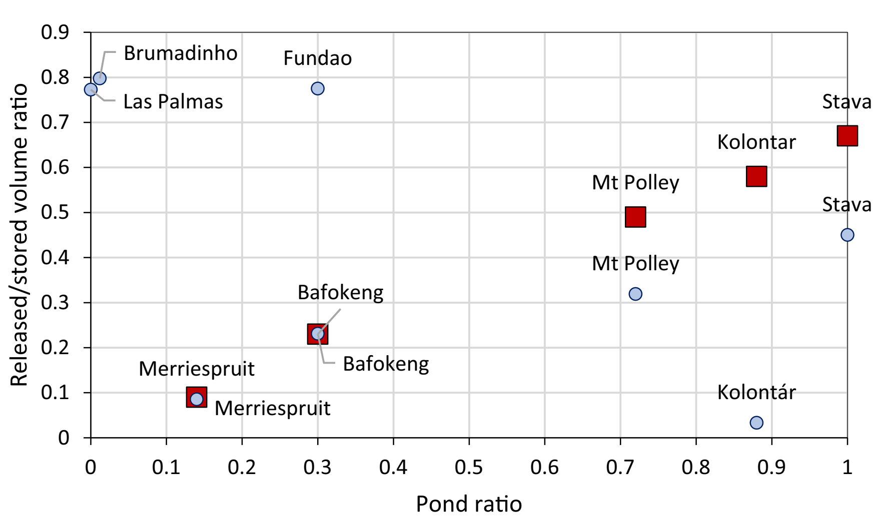

Fig. 14. Released/stored volume ratio as a function of pond ratio. In squares the values from Rourke and Luppnow (2015), in circles the data from this paper.

relatively high percentage of dam failure due to foundation failure for centreline constructed dams.

The use of both failure database and catalogue of existing tailings dams allowed the evaluation of the frequency of failures as a function of the dam construction method. The ranking of the dams, according to their frequencies from higher to lower, are: upstream, centreline, downstream. Then, comparing the distribution of stored volume and dam height from the two databases, it is possible to notice a discrepancy between the distributions of the stored volume for failure and non-failure cases. More data are needed for investigating the reasons behind this observation. There is a systematic lower bound for the volume stored of the breached tailings dams. It could be that the volumes stored reported are a systematic underestimation of the actual volumes stored by the dam. Perhaps this could also lead to an underestimation of the released volumes. It was not possible to find out from the databases when the tailings dams were constructed. Thus, the most likely failure rate of tailings dams cannot be evaluated with the current database. Knowing the age of the breached dams could be a useful information to define the fail rate and to compare these variables with the ones obtained from the catalogue on existing dams. Finally, the new statistical analyses showed that there was no correlation between the water pond and the released volume. The water, and specifically the condition of saturation, certainly play a role in the failure mechanisms; but the extent of the pond itself does not correlate directly with the released volumes.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.enggeo.2022.106657.

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