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Review

Review of Historical Dam-Break Events and Laboratory Tests on Real Topography for the Validation of Numerical Models

Francesca Aureli [1,*], Andrea Maranzoni [1] and Gabriella Petaccia [2]

1 Department of Engineering and Architecture, University of Parma, Parco Area delle Scienze 181/A, 43124 Parma, Italy; andrea.maranzoni@unipr.it
2 Department of Civil Engineering and Architecture, University of Pavia, via Ferrata 3, 27100 Pavia, Italy; petaccia@unipv.it
* Correspondence: francesca.aureli@unipr.it

Abstract: Dam break inundation mapping is essential for risk management and mitigation, emergency action planning, and potential consequences assessment. To quantify flood hazard associated with dam failures, flooding variables must be predicted by efficient and robust numerical models capable to effectively cope with the computational difficulties posed by complex flows on real topographies. Validation against real-field data of historical dam-breaks is extremely useful to verify models' capabilities and accuracy. However, such catastrophic events are rather infrequent, and available data on the breaching mechanism and downstream flooding are usually inaccurate and incomplete. Nevertheless, in some cases, real-field data collected after the event (mainly breach size, maximum water depths and flood wave arrival times at selected locations, water marks, and extent of flooded areas) are adequate to set up valuable and significant test cases, provided that all other data required to perform numerical simulations are available (mainly topographic data of the floodable area and input parameters defining the dam-break scenario). This paper provides a review of the historical dam-break events for which real-field datasets useful for validation purposes can be retrieved in the literature. The resulting real-field test cases are divided into well-documented test cases, for which extensive and complete data are already available, and cases with partial or inaccurate datasets. Type and quality of the available data are specified for each case. Finally, validation data provided by dam-break studies on physical models reproducing real topographies are presented and discussed. This review aims at helping dam-break modelers: (a) to select the most suitable real-field test cases for validating their numerical models, (b) to facilitate data access by indicating relevant bibliographic references, and (c) to identify test cases of potential interest worthy of further research.

Keywords: dam-break modelling; real-field test cases; validation of numerical models; historical dam-break events; laboratory tests; real topography; review

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1. Introduction

Artificial dams are hydraulic works of fundamental importance for human development since ancient times due to the great benefits provided by the storage of large water volumes, such as a water supply for drinking and irrigation purposes. The first dams known date back to 3000 BC in Mesopotamia. In recent times, as early as 1800, technological progress has allowed construction of large dams. The most impressive ones have been built within the last century, when, moreover, the number of dams has significantly increased according to water demand. In addition to supplying water and controlling floods, modern dams are often designed for power production.

However, despite its great benefits, the storage of large volumes of water poses serious risks for the downstream areas. Unfortunately, over the centuries, the history of retaining dams has been studded with disasters of various types, sometimes of great magnitude, with loss of human lives and destruction of downstream properties, agricultural lands, historical sites, industrial and productive settlements, and urban areas. Even though a time-related analysis shows that the frequency of failure of large dams has been reduced by a factor of four or more over the last forty years worldwide [1], dam incidents still occur at present with a non-negligible frequency [2–4]. In the current year, the failure of the Rishiganga dam (India), induced by a glacier avalanche, caused a catastrophic flood in the downstream valley with many casualties and huge damages to four hydropower plants. Moreover, the state of emergency was declared over toxic wastewater leaks in Florida due to the dreaded breach of the Piney Point reservoir. In this case a potential disaster was ultimately fortunately averted.

Wider dissemination of awareness on risk factors affecting dam safety is constantly necessary due to the presence of old and new hazardous conditions that can have an adverse effect on stability and efficiency of retention barrages. Some examples of such adverse factors are dam aging [5] and insufficient spillway capacity due to long-term alteration of weather patterns and exacerbated climatic extremes (e.g., [6,7]).

All these elements can increase dam-break flood risk in downstream areas, which is further amplified by growing exposure of human settlements and potential high vulnerability to flooding [8]. For this reason, research related to the assessment of the hydraulic risk resulting from the failure of retaining structures is constantly ongoing and involves scientists from all over the world. Moreover, the lessons learnt by dam accidents and catastrophes in the past are still very relevant [9,10]. Although there are countless works on the general subject of dam safety (e.g., [11–17]), only the ones that significantly helped in drafting the review are mentioned in this paper.

Among the possible aspects linked to the topic of dam safety [18,19], the assessment of flood hazard associated with a potential total or partial dam collapse is of key relevance and is strictly required by national technical guidelines worldwide [20–23]. To this end, relevant flooding variables must be predicted by numerical models, which have seen a growing and unstoppable development for decades, especially thanks to the constant advances in computational techniques (e.g., [24–26]). For use in practical applications, dam-break numerical models must be efficient and robust, and capable to accurately track wetting and drying fronts and handle all the complexities that characterize unsteady free surface flows on real topographies. The verification and validation of these models are then necessary before the application to real case studies. Model verification can be performed by comparing numerical results with available analytical solutions of dam-break problems (which usually hold under the shallow water approximation [27]). However, such analytical solutions, which in some countries have even influenced the drafting of legislation on dams, deal with schematic geometries and cannot adequately represent the complex phenomena occurring on real topographies. On the other hand, numerical models can be validated against field or experimental data. Accordingly, in recent decades, great attention has been devoted to set up suitable databases from laboratory dam-break investigations [28–30].

Field data can be derived from the analysis of historical dam-break events. However, such catastrophic events are fortunately rather rare, and available data on flood dynamics are typically inaccurate and incomplete. Indeed, there is no targeted preparation or general attitude for collecting of a rich amount of information at the dam site and in the downstream areas during a calamitous event of this kind. Nevertheless, in some cases, data collected after or occasionally during the event (mainly maximum water depths and flood wave arrival times at selected locations, and extent of the flooded areas) are sufficient to set up interesting validation test cases, provided that all other essential data required to perform numerical simulations are available (i.e., the digital elevation model of the floodable area and, possibly, of the reservoir, and the input parameters defining the dam-break scenario).

This paper reviews and provides an exhaustive list of the historical dam-break events for which datasets are available for validation purposes. The cases identified are organized in two groups: the former includes well-documented cases with extensive and complete data; the latter refers to cases with incomplete or inaccurate data, which could actually be completed without excessive effort with further research [31–39]. Laboratory investigations on dam-break flow in physical models reproducing real topographies are also considered.

The main aim of this review is to provide modelers with a set of real-field test cases for validation purposes, facilitating the retrieval of the corresponding data. An additional aim is to contribute to the studies related to dam safety, according to the philosophy of the 2019 ICOLD World declaration on Dam Safety: *The profession of dam engineering has a profound ethical responsibility to carry out its professional duties so that dams and reservoirs are designed, constructed and operated in the most effective and sustainable way, while also ensuring that both new and existing dams are safe during their entire lifespan, from construction to decommissioning* [40].

The paper is organized as follows. Well-documented dam-break real events are presented and analyzed in Section 2. Historical dam-break events open to further study to complete the validation datasets are presented in Section 3. In Section 4, dam-break investigations on physical models reproducing real topographies are discussed. Type and quality of the available data for each test case are highlighted in specific tables for the three categories. Finally, some conclusions are drawn in Section 5.

2. Well-Documented Dam-Break Test Cases

Table 1 reports twenty well-documented historical dam-breaks found in the literature for which the writers have deemed the available data adequate to validate numerical models. These events are indeed documented with exhaustive information and real-field data concerning breach formation and the water volume stored in the upstream reservoir before breaching. Data on the propagation of the dam-break flood wave downstream are also available in most of these cases. Some events listed in Table 1 have already been inserted in other databases, especially concerning the peak outflow resulting from an earthen dam failure [41–46]. The same applies to some dam-break cases presented in the next section.

Table 1 is organized in 23 columns. Columns from 2 to 4 report dam name, location and type, respectively. The table is divided into six different sections according to the dam type. Columns 5 and 6 specify the cause and year of the disaster. Among the twenty dam-break events considered, 60% refers to earthfill dams, 25% to concrete dams, 10% to rockfill dams, and 5% to tailing dams. The most frequent causes of failure for this set of historical events are piping (PI, 35%) and overtopping (OT, 30%), followed by quality problems and design errors (QP, 15%), erosion (ER, 15%), and poor management (PM, 5%). Most of the disasters included in this set occurred between 1950 and 2000 (55%), while only 5% occurred before 1900, 15% between 1900 and 1950, and 25% after 2000 (15% between 2000 and 2010, and 10% between 2010 and 2020). The fact that 25% of the well-documented disasters examined here occurred in the last two decades might seem surprising, but it has to be considered that in recent years input and validation data, such as a digital terrain model (DTM), rainfall data, and aerial photographs before and after the flooding, are available more frequently than in the past. Therefore, in the writers' opinion, the presence in Table 1 of a high number of dam-break cases occurred in the last twenty years is probably due to greater availability of information rather than to a real increase in the incidence of this calamitous event.

Table 1. Well-documented dam-break test cases.

(1) N.	(2) Dam Name	(3) Country	(4) Type [1]	(5) Cause [2]	(6) Year	(7) References	Available Information [3] (8) Dam Char.	(9) Reserv. Char.	(10) Reserv. Level	(11) Phot. Docum.	(12) Breach Char.	(13) Dam Mater.	(14) Breach Devel.	(15) DTM	(16) Storm	(17) Peak Flow	(18) Breach Outfl.	(19) Water Marks	(20) Hydrogr.	(21) Flood Timing	(22) Flooded Areas	(23) Sim. Flood [4]
1	Baldwin Hills	Calif. (USA)	EF	PI	1963	[47–52]	•	•	•	•	•	•	•	•		•	○		•	•	•	2D-FV
2	Xe Pian – Xe Namnoy	Laos	EF	ER	2018	[53]	○	•	•	•		•		•	•			•		○	•	1D-FD; 2D-FV
3	Gangneung	South Korea	EF	OT	2002	[54,55]	•	•	•	•				•	•			•	•	○	•	2D-FV
4	Kelly Barnes	Geo. (USA)	EF	PI	1977	[56–59]	•	•	•	•	•	•		○	•	•		•			•	
5	Lake Ha! Ha!	Canada	EF (DK)	OT	1996	[60–68]	•	•	•	•	•	•		•	•	•	•				• *	1D-FD; 2D-FV
6	Lawn Lake & Cascade Lake	Col. (USA)	EF	PI	1982	[69–72]	•	•	•	•	•	•	•	○		•		•		•	○	1D-FV
7	Quail Creek	Utah (USA)	EF	PI	1989	[73–75]	•	•	•		•		•	○		•		•		•		1D-FD
8	Teton	Idaho (USA)	EF	PI	1976	[76–81]	•	•	•	•	•	•	•	○		•		•	•		•	1D-FD
9	Um Al-Khair	S. Arabia	EF	PI	2011	[82]	•	•	•	•	•	•		•	•	•		•				1D-FD
10	Zeyzoun	Syria	EF	PM	2002	[83,84]	•	•						•		•		•	•	•		1D-FD
11	Gleno	Italy	CO	QP	1923	[85]	•	•	•	•	•		•	•				○		○	•	1D-FV
12	Malpasset	France	CO	QP	1959	[86–88]	•	•	•	•	•		•	•				•		•	○	2D-FD, FV; 3D
13	Palagnedra	Switzerland	CO	OT	1978	[89]	•	•	•	•				•	•	•		•	•	•		2D-FD
14	Sella Zerbino	Italy	CO	OT	1935	[90]	•	•	•	•				•	•	•		•		•		2D-FV
15	St. Francis	Calif. (USA)	CO	PI	1928	[91–93]	•	•	•					•				•		•	•	2D-FV; 3D
16	Taum Sauk Up.	Miss. (USA)	RF	QP	2005	[94–98]	•	•	•	•				•		•		•			•	1D-FD
17	Tous	Spain	RF	OT	1982	[99–101]	•	•	•	•				•	•	•		•		•	•	2D-FV
18	South Fork	Penns. (USA)	CF	OT	1889	[73,102–105]	•	•		•	•			•	•	•		•		•	•	
19	La Josephina	Ecuador	LD	ER	1993	[106,107]	•	•	•	•		•	•	○		•	○	•				1D-FD
20	Stava	Italy	TA m	PM-QP	1985	[108–111]	•			•		•		○				•		•		1D-FV; 2D-FV

[1] Type: CF = composite fill; CO = concrete; EF = earthfill; DK = dike; LD = landslide; RF = rockfill; TA = tailing. [2] Cause: ER = erosion; OT = overtopping; PI = piping; PM = poor management; QP = quality problems and design errors. [3] • = complete; ○ = uncertain, incomplete or not readily available; * = geomorphic effects; m = mudflow. [4] Numerical model: approach-method; FD = finite difference; FV = finite volume.

Column 7 of Table 1 provides relevant references in which the selected dam-break events are described. The remaining columns detail the type of available information for validation purposes for each entry. The quality or completeness of this information is indicated through different symbols. The full dot indicates that the available information is rather detailed, exhaustive, and accurate. The empty dot denotes incomplete or vague information (i.e., not accurate or not immediately available in quantitative terms). The availability of dam and reservoir characteristics, as well as of data concerning the water level in the reservoir before the failure, is indicated in Columns 8–10. Column 11 informs if photographic documents on the dam remnants (from which important data on the final breach shape and dimensions can be derived) and on the consequences of the dam-break flood in the downstream area are available. Data availability on breach formation, breach geometry, and dam materials is specified in Columns 12 to 14, while the availability of topographic data and rainfall data of the storm event (which sometimes is related to the dam-break) is indicated in Columns 15 and 16. Finally, the availability of other real-field data useful to validate numerical models is highlighted in Columns 17 to 22 (peak outflow and breach outflow hydrograph, water marks, water elevation or discharge or velocity data at selected locations, flood timing, extent of the flooded areas, respectively).

The peak flow at the dam was recorded or estimated from observations in 70% of cases considered in Table 1. Historical photographic documentation is available in 85% of cases. Rainfall data were recorded only in 45% of cases. A terrain model or topographic cross-sections are available for all the cases. Focusing on data concerning the dam-break flooding, the most available information is related to water marks (90% of cases), while time series of flooding variables are provided only in 25% of cases. Flood timing and maps of flooded areas are available in 70% and 65% of cases, respectively.

As regards the ten dam-break events involving earthfill (EF) dams, breach outflow is rarely known (only in 20% of cases), while breach characteristics and breach development data are available in 70% and 40% of cases, respectively.

Among the five concrete (CO) dam failures listed in Table 1, the Malpasset and St. Francis ones (entry no. 12 and 15, respectively) are probably the most famous. However, water marks and flood timing are available for all these five dam-break cases. Flooded areas are present in 60% of cases, while hydrographs of relevant flooding variables are available only in 20% of cases. An estimate of peak outflow was provided in 40% of cases.

Only two historical disasters involving rockfill (RF) dams were considered as well-documented. Water marks and flooded areas are known for both cases. The Tous dam failure is probably the most famous disaster involving a rockfill dam.

Column 23 indicates whether numerical simulations of the dam-break events were already carried out and which types of models were used. The literature review has shown that 90% of the well-documented cases listed in Table 1 have already been numerically simulated and that only two events have not yet been modelled (i.e., Kelly Barnes and South Fork, entry no. 4 and no. 18 in Table 1, respectively), although enough data for numerical modelling seem to be available in both cases.

Finally, it is worth noting that the Lake Ha! Ha! breakout flood (entry no. 5) was characterized by significant geomorphic effects along the flooded valley, while a highly destructive mudflow was generated by the collapse of two tailing dams in the Stava disaster (entry no. 20). The La Josefina dam-break (entry no. 19) was caused by the erosion of a natural dam produced by a landslide, which obstructed a river confluence forming two ephemeral lakes.

3. Dam-Break Test Cases Open to Further Study

Numerical modelers are usually very interested in lesser known historical dam-break events. Indeed, the simulation of new challenging cases supports a robust assessment of models' potentialities and effectiveness. In addition, real events always pose new challenges to numerical models, which encourage the development of more sophisticated and performant computational codes. Finally, the ability of the numerical models to adequately reproduce different real phenomena is one of the fundamental prerequisites for their use for hydraulic risk assessment.

Table 2 lists thirty seven historical dam-breaks for which the data retrieved in the literature are inaccurate or incomplete. This is confirmed by the fact that only a few of these cases were simulated and used for validation purposes. Often these events are documented with relevant, albeit scarce, data concerning breach formation and geometry, water level in the upstream reservoir before breaching, and propagation of the dam-break wave downstream. However, in the writers' opinion, an in-depth research is possible to gather further information and complete the validation datasets for most of these scarcely documented real cases.

Table 2 is organized with the same structure as Table 1. Almost 60% of the dam-break events included in this table refer to homogeneous (EF) or composite earthfill (CF) dams, 11% to rockfill (RF) dams, 11% to tailing (TA) dams, 6% to concrete (CO) dams; coal waste (CW), gravity (GR), masonry (MA), tephra (TE) or natural (NA) dam categories amount to approximately 3% each. In the cases involving tailing dams, the dam failure resulted in a destructive mudflow. Some events concerning earthfill dams were already considered in the literature, especially in the framework of breach formation and evolution modeling [4,6,28,29,33]. Nevertheless, for these cases, further data are often available, allowing the setting up of interesting benchmark tests for hydrodynamic dam-break models, too. Considering the list of Table 2, the most frequent cause of failure is overtopping (OT, 24%), followed by erosion (ER, 16%), quality problems and design error (QP, 14%), piping (PI, 11%), poor management and liquefaction (PM and LI, 8% each). Only occasionally dam failure is due to sliding (SL), undercut erosion (UE), lahars (LA), earthquakes (EQ), or a combination of different processes. As regards the year of failure, most of the disasters included in this set occurred between 1950 and 2000 (51%), while only 8% occurred before 1900, 14% between 1900 and 1950, and 27% after 2000. Also for this category of dam-break cases, it can be stressed that the presence of a high number of cases occurred in the last twenty years is probably due to greater availability of information rather than to a real increase in the incidence of such calamitous events.

The geometric characteristics of the dam and reservoir are known in 95% and 73% of cases, respectively. The characterization of the dam material is available in 27% of cases. The water level in the reservoir at the time of the collapse was reported only in 62% of selected events. The peak discharge at the dam was estimated in 41% of cases. Historical photographic documentation is available in 73% of cases. Data of the rainfall event, which potentially triggered the dam collapse, were recorded only in 35% of cases. A terrain model or topographical cross-sections are available only for 49% of cases.

Time series of breach outflow are very rare (available only in 5% of cases), while breach characteristics and breach development data are available for 68% and 24% of cases, respectively. Focusing on data concerning dam-break flooding, water marks are documented in 57% of cases. As for the previous set of well-documented cases, hydrographs of flooding variables are rather sporadic (only 24%), as well as data on flood timing (30%). The boundaries of flooded areas are available in 46% of cases.

Column 23 of Table 2 shows that only seven cases (19%) were already simulated by 1D or 2D numerical models. No numerical simulations of the other cases were found in the literature, even though a fair amount of information is present for some of these cases, both in terms of dam and reservoir characteristics and of the hydro-meteorological event that triggered the disaster.

It is worth noting that topographic data concerning the reservoir and downstream floodable area are currently available only for a limited number of events listed in Table 2. In some cases, especially for the more recent events, this gap could be filled considering terrain models freely downloadable from the web and other available resources. Freely downloadable world DTMs (from satellite images) are increasingly popular and are experiencing a constant and rapid development in terms of spatial resolution and accuracy (e.g., [112,113]). It can be predicted that DTMs with a spatial resolution in the order of 10 m will be probably freely available (or available at a low cost) soon. As an example, consider the Ivex dam (entry no. 8 in Table 2), located on the Chagrin River immediately upstream of the village of Chagrin Falls, northeast OH, USA. Thanks to the historical images from Google Earth, it is possible to geolocalize the two cascade reservoirs and reconstruct with satisfactory accuracy the main characteristics of the territory and the built-up areas at the time of the event. The availability of the ALOS Global Digital Surface Model "ALOS World 3D–30m" (AW3D30), freely downloadable from the JAXA website [114], could provide the topographic information (with acceptable spatial resolution) required to perform numerical simulations. Also, the MERIT Hydro dataset and other global digital elevation models (GDEMs) could be considered to set up the test case [115,116]. The roughness parameter involved in shallow water models can be set on the basis of the local land cover, which can be obtained from suitable databases (e.g., [117]). Moreover, in the absence of first-hand data concerning the breaching and flooding processes, useful validation data can be obtained through the analysis of remotely sensed images, which can occasionally be available. As an example, some authors used multi-spectral images from the Sentinel-2A satellite, commonly exploited for forest and land cover change monitoring, to integrate the observations collected in post-event survey campaigns [118].

Approximately half of the earthfill (EF) dam failures present a significant amount of test and validation data (at least 50% of the fifteen data categories considered under the heading of "Available Information" in Table 2). Among these, entry no. 4, referring to the Edenville and Sanford dams (failed on 19 May 2020), shows data in eleven of the fifteen categories considered. For this event, a large number of extraordinarily interesting videos and aerial photos is available online concerning dam breaching and the propagation of the flood wave downstream (e.g., [119,120]). As for the group of earthfill (EF) dams, in only one case the available information covers less than 25% of the data categories considered. Information in more than 50% data categories exists for four of the six composite fill (CF)-type dams and for all the rock fill (RF)-type dams. Only one of the four tailing (TA) dam-break cases is rather well documented. It is worth noting that a considerable amount of data, albeit rather inaccurate, is available for the flood induced on 26 February 1972 by the failure of a coal slurry impoundment at the Buffalo Creek coal mine, in West Virginia, USA (entry no. 33 in Table 2).

Other dam-break events, not included in Table 2 due to the current substantial lack of publicly available data, could be however very interesting. For example, an exceptionally rich photographic documentation is available for the Frenchman dam-break event [121], which occurred on 15 April 1952. This catastrophic dam failure was already mentioned in well-known literature studies on breach formation and evolution modeling [122].

Table 2. Dam-break test cases open to further study.

(1) N.	(2) Dam Name	(3) Country	(4) Type [1]	(5) Cause [2]	(6) Year	(7) References	Available Information [3]															(23) Sim. Flood [4]
							(8) Dam Char.	(9) Reserv. Char.	(10) Reserv. Level	(11) Phot. Docum.	(12) Breach Char.	(13) Dam Mater.	(14) Breach Devel.	(15) DTM	(16) Storm	(17) Peak Flow	(18) Breach Outfl.	(19) Water Marks	(20) Hydrogr.	(21) Flood Timing	(22) Flooded Areas	
1	Apishapa	Col. (USA)	EF	PI	1923	[13,123–127]	●	●	●		●	●				●						
2	Black Hills	S.Dak. (USA)	EF	OT	1972	[128–131]	○			○					●	○		●	●	○	●	
3	Centennial Narrows	Ariz. (USA)	EF	PI	1997	[132–135]	○			○	○				●	●			●			
4	Edenville + Sanford	Mich. (USA)	EF	ER-OT	2020	[136–143]	○	○	○	●	○		●	○	○			○	○		●	2D
5	Fujinuma	Japan	EF	SL-OT	2011	[144,145]	●		●	●	○	○		○							○	
6	Hatchtown	Utah (USA)	EF	QP	1914	[146,147]	○			●	○			○				○		○		
7	Ivanovo	Bulgaria	EF	PM	2012	[148,149]		○		●				●				○			●	
8	Ivex	Ohio (USA)	EF	PI	1994	[150]	●	●	●	●	●		●		●	●						
9	Lake Lee	Mass. (USA)	EF	ER	1968	[151,152]	●	●	●	●				○				●		●	●	
10	Little Deer Creek	Utah (USA)	EF	QP	1963	[153,154]	●	●	●	○	●		●			●		○			○	
11	Nahal Oz	Israel	EF	QP	2001	[155]	●	●	●	●	●			○		●					● *	
12	Niedow	Poland	EF	OT	2010	[156,157]	●	●	●	●	●		●	●		●		●				1D-FD
13	Opuha	New Zealand	EF	PM	1997	[158]	●	●	●	●	●			○		○				●		
14	Otto Run	Penn. (USA)	EF	OT	1977	[48,73,102,159]	●	●			●				●	●						
15	Panshet	India	EF	OT	1961	[160]	●	●							●							1D-FD
16	Zhugou	China	EF	OT	1975	[161]	●	●	●						●	●						
17	Banquiao	China	CF	OT	1975	[161–165]	●	○	○	○	○		●		●	●			○			
18	Belci	Romania	CF	OT	1991	[33,166–168]	●	○	●	○	○				○		○	●	○		○	
19	Big Bay Lake	Mississippi	CF	PI	2004	[73,169,170]	●		○	○	○	○	○					●		○	●	1D-FD
20	Bila Desna	Czech. Rep.	CF	ER	1916	[171]	○	○		○	○			○				○			○	
21	Dale Dike	England	CF	ER	1864	[172–176]	○			○		○						○			○	
22	Lake Delhi	Iowa (USA)	CF	OT-ER	2010	[177–181]	●		○	●	●		●	○	●				○			
23	Overholser	Okla.(USA)	CO	OT	1923	[182]	●	●			●			●								1D-FD
24	Vega de Tera	Spain	CO	QP	1959	[183]	●			●				●				●				1D-FD
25	Aznalcollar	Spain	RF	LI	1998	[184–187]	●	●		●	●	●		○				○		○	○	
26	Castlewood	Col. (USA)	RF	OT	1933	[122,188–191]	●	●	●	●	●	●			○	●				○	○	
27	Gouhou Dam	China	RF	ER	1993	[163,192–195]	●	●	●	○	●	●				●			○			
28	Hell Hole	Cal. (USA)	RF	PM	1964	[196]	●	●	●	●	○			○	●	●	●	○ *	●			
29	Brumadinho	Brazil	TA [m]	LI	2019	[197–202]	○	○		○	○	○	○	●						○	●	2D-FV
30	El Cobre Old	Chile	TA [m]	EQ	1965	[203–205]	●	●										●				
31	Fundão	Brazil	TA [m]	LI	2015	[206,207]	○		○	●				○				○			●	
32	Merriespruit	S. Africa	TA [m]	SL-OT	1994	[208–211]	●	●	●		●			○							●	
33	Buffalo Creek	W.Virg. (USA)	CW	ER	1972	[212–216]	○	○	○	○		○			○			○	○	○		
34	Pantano de Puentes	Spain	GR	QP	1802	[217,218]	●	●										●				
35	Austin	Tex. (USA)	MA	UE	1900	[36,219,220]	●		○	○	○		○					○		○		
36	Tangiwai	New Zealand	TE	LA	1953	[221–223]		●	●							●		●		●		
37	Huohua Lake Natural Dam	China	NA	EQ	2017	[118]	●	○	●	●	●	●		●				○ *			○	2D-FD

[1] Type: CF = composite fill embankment; CO = concrete; CW = coal waste; EF = earthfill; GR = gravity; MA = masonry; NA = natural dam; RF = rockfill; TA = tailing; TE = tephra. [2] Cause: EQ = earthquake; ER = erosion; LA = lahar; LI = liquefaction; OT = overtopping; PI = piping; PM = poor management; QP = quality problems and design errors; SL = sliding; UE = undercut erosion. [3] ● = complete; ○ = uncertain or incomplete or not readily available; * = geomorphic effects; [m] = mudflow. [4] Numerical model: approach-method; FD = finite difference; FV = finite volume.

4. Dam-Break Test Cases Based on Physical Modelling

Physical model investigations of dam-break floods over real topographies are rather rare in the literature. Table 3 shows 4 cases found by the authors with extensive experimental datasets. Experimental dam-break test cases concerning schematic idealized geometries are much more numerous and are based on dam-break experiments aimed at analyzing specific issues or hydrodynamic effects of selected topographic singularities on both fixed [224–228] or movable bed (e.g., [229]). However, the complexities occurring, all together, in physical models where a real topography is reproduced cannot be found in these idealized cases.

Among the test cases listed in Table 3, the Toce River test (entry no. 3) concerns a flash flood not induced by a dam-break but produced by an inflow hydrograph supplied through a pump. In this test, the rapidity of the flood propagation is comparable to that typical of dam-break floods. Therefore, the Toce river test case is usually included among the physical model tests for dam-break numerical models, although it is not a dam-break case in the strict sense. In all other cases listed in Table 3, the dam-break flood is generated by the sudden removal of a gate, miming an almost instantaneous collapse of a dam. Physical model test cases concerning flooding (on real topography) caused by levee breaches (e.g., [230]) are not considered in this review.

Probably, the best known dam-break dataset obtained from a physical model concerns the Malpasset dam-break event (entry no. 2 in Table 3). In 1964, an undistorted 1:400-scale physical model was built in the EDF laboratories to reproduce the historical catastrophic flooding induced by the total collapse of the dam, which occurred in 1959. Original data on the model topography and details about the construction technique are not available. However, Goutal [87] provides a dataset of 13,541 points (obtained from digitalization of historical topographic maps) describing the topography of the valley and the floodplain downstream of the dam. Hervouet and Petitjean [86] support the hypothesis that model bottom roughness was adjusted to reproduce correctly the field observations regarding the real event, and suggest that a roughness Manning coefficient ranging from 0.025 to 0.033 $m^{-1/3}s$ is used in the numerical computations based on shallow water equations. During the laboratory investigation, maximum water levels and dam-break wave arrival times were measured at nine points located along the valley downstream of the dam. These data are usually merged with the field data of the real event (water marks and arrival times at some locations) to form a complete dataset for validation purposes. This test case was used by many modelers (e.g., [88,231–233]) and was also considered within the frame of the CADAM European project [28].

A lesser known dam-break test case based on physical modeling concerns the collapse of the Cancano I dam (entry no. 1 in Table 3). The consequences of this hypothetical event were studied by De Marchi [234] on a 1:500-scale physical model reproducing a stretch (approximately 16 km long) of the very irregular alpine valley downstream of the dam. Unfortunately, elevation data of the model bottom (built by connecting several cross-sections of the valley through a concrete-lined surface) are not available. To fill this gap, Pilotti et al. [235] provide a 60-m DTM extracted from a current DTM of the valley. Moreover, they suggest a range of values for the Manning roughness coefficient at the real scale (0.04–0.055 $m^{-1/3}s$), based on dimensional analysis considerations. Moreover, the bathymetry of the Cancano I reservoir was not exactly reproduced in the physical model, and detailed information about this point was not reported in the original work by De Marchi [234]. Despite these shortcomings, this test case is exceptional in the availability of measured discharge hydrographs at three control cross-sections (namely the dam section and two significant cross-sections downstream) for two different scenarios of total and partial dam-break. In addition, the measured boundaries of the flooded areas along a stretch of the downstream valley are available for both the collapse scenarios. Pilotti et al. [236] and Pilotti et al. [235] simulated this test case at the real scale using 1D and 2D models, discussing the issue of potential scale effects that can affect the comparison between numerical results and experimental data.

Table 3. Physical models of dam-break on real topography.

(1) N.	(2) Dam Name	(3) Country	(4) Type [1]	(5) Scale	(6) Year [2]	(7) References	Available Information [3]														(22) Sim. Flood [4]
							(8) Dam Char.	(9) Reserv. Char.	(10) Reserv. Level	(11) Phot. Docum.	(12) Breach Char.	(13) Breach Develop.	(14) Peak Flow	(15) DTM	(16) Rough.	(17) Waterm./ Gauge	(18) Arrival Times	(19) Hydrogr.	(20) Flooded Areas	(21) Breach Outfl.	
1	Cancano I	Italy	CO	1:500	1943	[233–235]	•	○	•	•	•	•	•	○	•		•	•	•	•	1D-FV; 2D-FD, FV
2	Malpasset	France	CO	1:400	1964	[86–88,231–233]	•	•	•		•	•		•	•	•	•				2D-FD, FE, FV, LB; 3D
3	Toce River *	Italy	-	1:100	1999	[237–242]				•			•	•	•	•	•	•			2D-FV
4	Ürkmez	Turkey	EF	1:150 h–1:30 v	2013	[243,244]	•	•	•	•	•	•	•	○	○	•	•	•	○	•	2D-FD

[1] Type: CO = concrete; EF = earthfill. [2] Year: year of construction of the physical model. * = Flash flood (No dam-break). [3] • = complete; ○ = uncertain or incomplete or not readily available. [4] Numerical model: approach-method; FD = finite difference; FE = finite elements; FV = finite volume; LB = lattice Boltzmann.

Another interesting test case proposed in the framework of the European IMPACT research program [29,30] refers to a hypothetical flash flood in a 1:100-scale physical model reproducing a 5-km long stretch of the Toce valley (entry no. 3 in Table 3), in which an idealized urban district is placed [237]. Data concerning the model topography (9928 bottom elevation points) and the locations of the buildings (organized according to two different patterns) are provided (at the model scale) in supplemental files. Moreover, the authors suggest the optimal value of 0.0162 $m^{-1/3}s$ for the roughness coefficient of the concrete bottom of the physical model. Three inflow hydrographs with different peak discharges were considered as upstream boundary conditions. Water depth time series were measured at ten selected points, eight of them located within or near the urban area. This case was used by a large number of modelers to validate numerical models of urban flooding (e.g., [238–242]).

The last test case reported in Table 3 (entry no. 4) refers to the experimental investigation carried out by Guney et al. [243] on a distorted (1:150 horizontal scale and 1:30 vertical scale) physical model reproducing the reservoir of the Ürkmez dam and the downstream region (including an urban area) potentially floodable as a result of the hypothetical collapse of the dam. Only a topographic map of the floodable area is available and no indications are provided on reasonable roughness values for the concrete bottom of the model. A partial dam-break with trapezoidal breach was assumed. Flood depth time series were measured at eight selected positions in the floodable area, along with time series of vertically-averaged velocities and vertical profiles of flow velocity at selected times at other four points. Finally, some information about the timing of the dam-break wave propagation was obtained from videos of the experimental runs. Haltas et al. [244] simulated this test case at the real scale using a combined 1D-2D numerical model and compared predicted flow depth hydrographs with the (scaled) experimental ones. A 1-m DTM was used to create the computational grid and maps of land use were utilized to estimate a spatial distribution of Manning's roughness coefficient.

The physical model test cases considered in this review were chosen on the basis of the presence of experimental data on the propagation of the dam-break wave in downstream areas. However, it is worth noting that several laboratory experiments on breach formation and growth in earthfill dams are reported in the literature (e.g., [245,246]). Valuable and interesting results of experimental field investigations at the prototype scale are also available (e.g., [247]). All related experimental data can be useful for validating numerical models of breach development.

5. Conclusions

This paper outlines historical dam-break events currently and potentially available for the validation of dam-break models. This kind of data is indeed very useful to assess the predictive capabilities of numerical models on real topographies. Data available for each test case have been listed in two different tables concerning well-documented and scarcely documented cases, respectively.

These tables can be useful for modelers to select the most suitable real-field test cases for validation purposes, thereby supporting the development of robust and accurate computational models of dam-break flow. The extensive literature review helps the modelers to identify relevant references where available information on the selected dam-break events can be retrieved.

It is worth noting that two of the well-documented dam-break cases have not been simulated yet, despite the available dataset appears extensive and complete. The list of scarcely documented historical dam-break events (for which the dataset is rather incomplete or inaccurate) indicates potential test cases open to further research, which in addition are of potential scientific and historical interest. For this set, approximately half of the cases are characterized by a significant amount of data, covering at least half of the model and validation data categories considered. Gaps in the availability of topographic data and roughness information can be filled using freely downloadable world DEMs and land cover databases.

Dam-break test cases based on physical models reproducing real topographies have been listed in a separate table, in which the experimental data available for validation purposes are specified. Further physical model investigations concerning dam-break flows on real topographies would be welcome to widen available experimental datasets. Actually, extensive and accurate datasets of relevant hydraulic variables can easily be obtained from laboratory investigations on physical models under controlled conditions. However, in this case, particular care must be paid to the model scale to avoid scale effects.

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