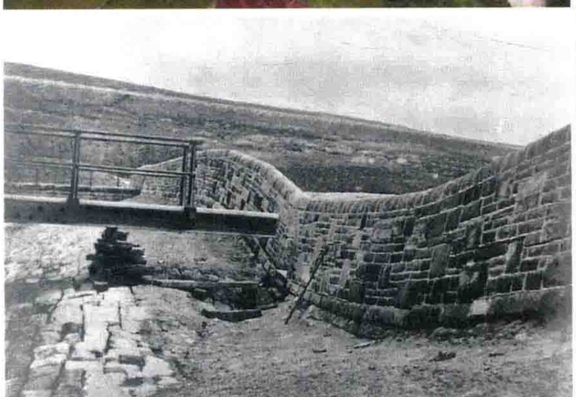
Lessons from incidents at dams and reservoirs - an engineering guide



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Lessons from incidents at dams and reservoirs – an engineering guide

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Summary

The focus of the guide is on failures and incidents at dams in Britain that have occurred between 1800 and 2012. The scope of the guide is limited to water-retaining structures. Some types of waste impoundments, such as tailings dams, may suffer similar types of malfunction, but these are not included.

Part 1 of the guide provides a historical overview of the subject, which shows how serious incidents have improved understanding of dam behaviour and the hazards posed by these structures. This part should not only be of interest to dam engineers but should also help those reservoir owners with limited technical knowledge to develop a basic grasp of the more significant aspects of the subject. It also shows the close links between historical incidents and failures and the development of reservoir safety legislation and guidance. The significance of draw-down rates and other provisions for dam incidents and emergencies are discussed.

Part 2 begins with a brief introduction to the various types of serious incident, and a classification and analysis of the modes of failure. This is followed by descriptions of over 100 British incidents and failures. There is some overlap with information presented in Part 1, but Part 2 constitutes a convenient reference section for readers interested in incidents of a particular type or at a particular dam.

Much can be and has been learnt from overseas incidents and failures and Part 3 provides information on some 20 overseas incidents. They include types of incident that have not occurred in Britain and also some incidents that have affected British dam practice and legislation. The incidents described in Part 3 are a very small fraction of the number of incidents recorded and published worldwide and publications that provide more comprehensive studies of overseas incidents are referenced.

Foreword

The history of dams and their misfortunes is essential reading for those responsible for the safety of reservoirs, including engineers appointed under current British legislation, personnel who visit reservoirs in the course of their duties, staff who operate and monitor reservoirs, and enforcement authority engineers. The number of casualties and property damage resulting from a breached dam can be greater than most other kinds of technological disaster. The structural stability and security of dams and reservoirs are of major importance for public safety in the UK where a substantial number of dams are located immediately upstream of densely populated industrialised areas. Although the probability of a dam failure is generally very low, the consequences of failure can be very great.

The information produced in this publication is based largely on published papers. Although every effort has been made to obtain accurate information, discrepancies exist between published sources on information such as date of completion, dam height, volume of reservoir and number of casualties. This is particularly the case with older structures.

Acknowledgements

This guide has made substantial use of the Science Report SC080046/R1 *Lessons from historical dam incidents* that was funded by the Environment Agency and was published on their website in August 2011. Following publication there was considerable support from dam engineers to have a hard copy version of the report. It was considered that provision of a permanent record of the contents of the report would keep this work available to engineers for decades to come when access to the soft copy through a website might become problematic. With support from the BRE Trust and Ian Hope (formerly of the Environment Agency, now with Severn Trent Water), the authors sought sponsorship from a number of water companies to enable this revised updated report to be published by CIRIA.

Authors

Dr J Andrew Charles

For most of his career Andrew Charles worked in the Geotechnics Division of BRE where his areas of research included the behaviour of embankment dams and his PhD involved the study of the behaviour during construction of a 73 m high rockfill dam. He has written more than one hundred and fifty journal and conference papers and three books including being a co-author of *An engineering guide to the safety of embankment dams in the United Kingdom*. In 1986 he obtained a DSc(Eng) degree from the University of London. He was Honorary Technical Secretary of the British Dam Society from 1986 to 1994 and received the Society's Bateman Award in 2002 and 2013. He was convenor of the European Working Group on Internal Erosion in Embankment Dams from 1993 to 2002 and since 1996 he has been a member of the Reservoirs Committee of the Institution of Civil Engineers. He was elected a Fellow of the Royal Academy of Engineering in 1999.

Dr Paul Tedd

Paul Tedd spent most of his career working in the Geotechnics Division of BRE, gaining a PhD in 1986 on tunnel lining performance. Reservoir safety studies have formed a major part of his work since 1985 and have involved research and field monitoring of many old puddle clay core dams with the emphasis on internal erosion and drawdown deformations. He is the joint author of four National Guides on dam safety published in the UK and more than 30 papers relating to dam safety. He was Honorary Technical Secretary of the British Dam Society from 1994 to 2003, and editor of four of the society's conference proceedings. He was the manager of the BRE National dams database since its inception in 1987 and developed it for risk analysis. He was involved in the development of the Environment Agency post-incident reporting dam database. In 2003, he was awarded a DSc(Eng) degree from the University of London and the British Dam Society Bateman award in 2013.

Alan Warren

Alan Warren is a chartered civil engineer with degrees in civil engineering and engineering hydrology. He is a Fellow of the Institution of Civil Engineers. He has spent most of his career with Halcrow Group Ltd working on dams and hydropower projects. He became Halcrow's chief engineer for dam engineering in 2008. He has project experience in more than 15 countries around the world and has published more than 25 technical papers and articles. In 2006 he was admitted to the 'all reservoirs' panel of engineers constituted under the Reservoirs Act 1975. In 2007 Alan led a project for the Environment Agency to develop a specification for post-incident reporting and investigations. He subsequently led the Environment Agency research contract SC080046/R1 *Lessons from historical dam incidents*. He has led investigations on a number of UK dam-related incidents, analysed the causes and disseminated the findings to the reservoir industry. Alan joined Mott MacDonald Ltd as a Technical Director in 2013.

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Although there has been substantial revision and updating of material in this CIRIA guide much of the text in the Environment Agency report remains. So it is appropriate to include the full acknowledgements, which are in the Environment Agency report.

In the preparation of the Environment Agency report by the Building Research Establishment (BRE) and the Halcrow Group Ltd substantial use has been made of work previously published on the subject:

- Binnie (1976) *The evolution of British dams*
- Skempton (1989) *Historical development of British embankment dams to 1960*
- Kennard (1995) *Four decades of development of British embankment dams.*

Work previously published by BRE has also been of assistance including Charles (1986) *The significance of problems and remedial works at British earth dams*, Charles (1990) *Deterioration of clay barriers*, and Tedd *et al* (1994) *Remedial works to clay cores of UK embankment dams.*

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Abbreviations and acronyms

AAR	Alkali aggregate reaction
ASCE	American Society of Civil Engineers
ASR	Alkali silica reaction
BNCOLD	British National Committee on Large Dams
BRE	Building Research Establishment (formerly Building Research Station)
BWB	British Waterways Board
CIRIA	Construction Industry Research and Information Association
CCOLD	Croatian Committee on Large Dams
DAC	Dense asphaltic concrete
Defra	Department of the Environment, Food and Rural Affairs
EA	Environment Agency
FEA	Finite element analysis
FERC	Federal Energy Regulatory Commission (USA)
HDPE	High density polyethylene
ICE	Institution of Civil Engineers
ICOLD	International Commission on Large Dams
IStructE	Institution of Structural Engineers
NERC	Natural Environment Research Council
NIEA	Northern Ireland Environment Agency
PFA	Pulverised fuel ash
PMF	Probable maximum flood
PVC	Polyvinyl chloride
RCC	Roller compacted concrete
SCPTu	Seismic piezocone (seismic cone penetration testing)
SEPA	Scottish Environment Protection Agency
SwedCOLD	Swedish National Committee on Large Dams
TWL	Top water level
USA	United States of America
USCOLD	United States Committee on Large Dams

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Part 1

Dam incidents and reservoir safety: learning from British experience over the last two hundred years

1.1 Introduction

'The history of dam building, since the dawn of civilisation, is a long series of failures. Man learns little from success but a lot from failure. Not to publish the facts about a failure, and we all know many reasons not to do so, is a severe breach of our duties as engineers.'

Londe, 1980

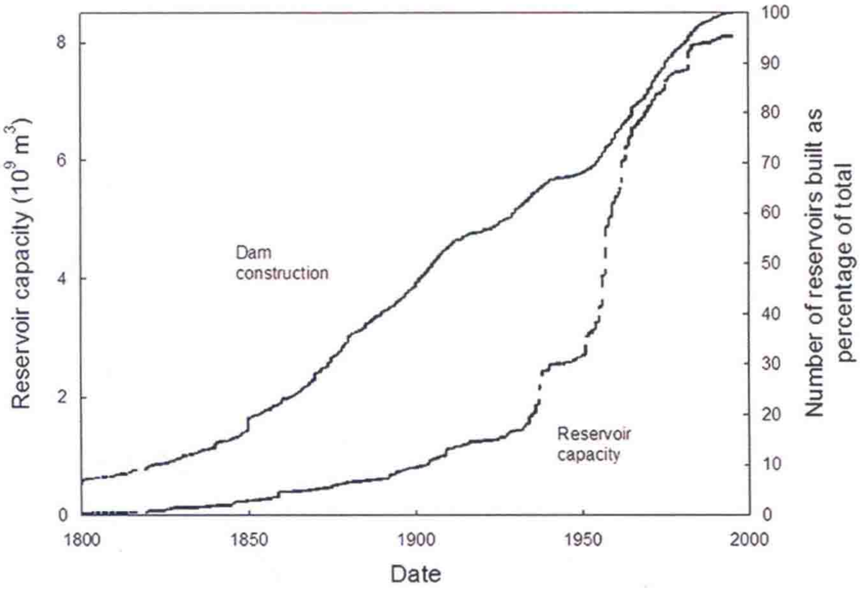
Taken out of context this observation by an eminent French dam engineer that the history of dam building is a long series of failures might cause undue alarm and despondency in those living below a large dam! Taken in its context it is a necessary reminder and exhortation to dam engineers to learn from past failures which is only feasible when such failures are thoroughly investigated and the results are published.

With most structural failures damage is limited to an area in the immediate vicinity of the building, but the structural failure of a dam and the consequent uncontrolled release of the stored reservoir water can cause destruction over a large area and the number of casualties can be greater than in many other kinds of technological disaster. Consequently the structural stability and security of dams and reservoirs are of major importance for public safety in a country such as Britain where a substantial number of dams are located immediately upstream of densely populated industrialised areas and, although the probability of a dam failure is generally very low, the consequences of failure can be very great.

While a dam failure could be broadly defined as some incident, occurrence or process whereby a dam does not perform that function for which it has been constructed, namely to safely store or impound a reservoir of water, dam failure generally means the uncontrolled release of a significant quantity of reservoir water. Nevertheless, the term is also used for the 'failure' of an embankment dam during construction, which is an event where inadequate shear strength in the fill and possibly also the foundation causes instability in one or both of the embankment slopes and may involve the foundations of the embankment. If such instability occurs before the embankment has begun to act as a water retaining structure, reservoir safety is not an issue. When a dam has been constructed and the reservoir basin filled with water, the dam is said to be 'in service'. Unlike failures during construction, failures in service are usually intimately connected with the particular function of the dam to impound a reservoir of water.

There is a long history of dam and reservoir construction in Britain. In the second half of the 18th century, many ornamental lakes were established in the landscaped grounds of country estates, many low mill dams were built for the textile industry and, by the end of the century, reservoirs were needed to supply the canals being built across the country. In 1788 there were 122 cotton spinning mills in Britain that were operated by water power, each with its own reservoir to regulate and store river flow and to serve a mill race channel or pressure conduit. During the first half of the 19th century, the demand for unpolluted water supplies to the rapidly expanding industrial towns led to a major increase in reservoir construction. This continued throughout the 19th and much of the 20th centuries but was followed by a decline in dam construction during the later part of the 20th century.

Figure 1.1 shows the growth in reservoir capacity and number of reservoirs since 1800 (Tedd *et al*, 2000). Less than 10 per cent of the current population of dams had been constructed by 1800 and few of those would have exceeded 6 m in height. Older dams were generally low structures with small reservoir capacities. The effect of constructing much larger reservoirs in the 1950s, in particular the construction of hydro-electric schemes in Scotland, is seen in the huge expansion of reservoir capacity. Timelines showing important incidents and developments in dam construction and legislation are presented for different periods.



Note
10^9 m^3 = a thousand million (or billion) cubic metres

Figure 1.1 ***Growth in British reservoir capacity and number of reservoirs***

Most British reservoirs are impounded by embankment dams, many of them built in the 19th century. Indeed, before 1900 nearly all British dams were of the embankment type with notable exceptions of Vyrnwy, Thirlmere, Burrator and Abbeystead. While a significant proportion of the dams built in the 20th century are of masonry or concrete construction, the majority of British dams are earth embankments and reservoir safety is thus intimately concerned with the behaviour and long-term performance of old embankment dams. Until the 1950s most embankment dams in Britain were built to a traditional design with a thin central core of soft puddle clay. The last major puddle clay core dam to be built in Britain was Jumbles completed in 1972 with a height of 26 m. More modern embankment dams have a wider core of rolled clay which is significantly stiffer and stronger than puddle clay.

When asked to cite failures of British dams, most engineers in the reservoir industry are able to quote Dale Dyke, Bilberry and Dolgarrog, together with recent serious incidents such as Ulley, but many may struggle to name more of the several hundred incidents that have occurred. The lack of knowledge of dam incidents can give rise to an unwarranted optimism with respect to the long-term performance of dams. A broad perspective on the range of incidents that have arisen in the past and which can arise again should counter this tendency and encourage a realistic outlook on the long-term deterioration of dams.

Fortunately, few catastrophic failures have occurred in Britain and since 1925 there has been no loss of life due to dam disasters. Table 1.1 lists the dam failures that caused loss of life. All of the dams listed are embankments except Eigiau which was a small concrete gravity dam that failed due to an inadequate foundation and led to the Dolgarrog catastrophe. That the vast majority of serious incidents have concerned embankment dams is not surprising since only about 10 per cent of British dams are built of concrete or masonry. It certainly should not be concluded that concrete or masonry dams are immune to problems.

During the last fifty years or so disastrous failures overseas have resulted in much loss of life and Table 1.2 shows that such catastrophic failures have occurred in all parts of the world and have involved different types of dam. Much can be learned from these failures, particularly those such as Baldwin Hills, Malpasset, Teton and Vaiont, which have been the subject of detailed investigation and substantial literature. A useful start to such study is given by Jansen (1980) *Dams and public safety*, which includes illuminating accounts of many of the dams listed in Table 1.2. ICOLD (1974) *Lessons from dam incidents* provides a study of dam failures from 1800 to 1965 and includes some 500 incidents, 200 of which could be described as failures. A number of these overseas incidents are summarised in Part 3 of this guide.

Table 1.1 ***British dam failures that caused loss of life (from Charles, 1993)***

Dam	Height (m)	Reservoir volume (10^3 m^3)	Date built	Failure		Deaths
				Date	*Type*	
Tunnel End	9		1798	1799	OF	1
Diggle Moss (Black Moss)			1810	1810	OF	6
Whinhill	12	262	1821	1835	IE	31
Brent (Welsh Harp)	7		1837	1841	OF	2
Glanderston				1842	OF	8
Bold Venture (Darwen)	10	20	1844	1848	OF	12
Bilberry	29	310	1845	1852	IE	81
Dale Dyke	29	3240	1863	1864	IE	244
Rishton				1870		3
Cwm Carne	12	90	1792	1875	OF	12
Castle Malgwyn				1875	OF	2
Clydach Vale				1910	OF	5
Skelmorlie	5	24	1861	1925	OF	5
Eigiau (Dolgarrog)	10	4500	1911	1925	FF	16
Coedty (Dolgarrog)	11	320	1924	1925	OF	16

Note:
Type of failure: IE = internal erosion, FF = foundation failure, OF = overtopping during flood.

Table 1.2 ***Some overseas dam disasters causing loss of life (1959–2009)***

Dam	Dam type	Country	Height (m)	Reservoir volume (10^6 m^3)	Date built	Failure		Deaths
						Date	*Type*	
Vega de Tera	CMB	Spain	34	7.8	1957	1959	SF	144
Malpasset	CA	France	66	22	1954	1959	FF	421
Vaiont	CA	Italy	265	150	1960	1963	L	2600
Baldwin Hills	Emb	USA	71	1.1	1951	1963	IE	5
Frias	Emb	Argentina	15	0.2	1940	1970	OF	>42
Banqiao	Emb	China	25	492	1953	1975	OF	**
Teton	Emb	USA	93	356	1975	1976	IE	14
Machhu II	Emb	India	26	100	1972	1979	OF	2000
Bagauda	Emb	Nigeria	20	0.7	1970	1988	OF	50
Belci	Emb	Romania	18	13	1962	1991	OF	25
Gouhou	Emb	China	71	3	1989	1993	IE	400
Zeizoun	Emb	Syria	42	71	1996	2002	OF	20
Camara	RCC	Brazil	50	27	2002	2004	–	5
Shakidor	Emb	Pakistan	–	–	2003	2005	OF	>135
Situ Gintung	Emb	Indonesia	16	2	1933	2009	IE	100

Note:

Dam type: CA = concrete arch, CMB = concrete and masonry buttress, Emb = embankment, RCC = roller compacted concrete.

Type of failure: IE = internal erosion, FF = foundation failure, OF = overtopping during flood, SF = structural failure on first filling, L = landslide of 260 million m^3 into the reservoir caused overtopping of the dam by a wave 125 m high, but remarkably the dam survived.

** It has been reported that tens of thousands died in this disaster that involved the failure of a number of dams of which Banqiao and Shimantan were the largest (Hjorth and Bengtsson, 2012).

Given the broad scope of this subject, this publication has been restricted in several ways. Although reservoir safety is essentially an international subject, and worldwide experience is of considerable importance, this publication is for the most part limited to dams and reservoirs in Britain. Waste impoundment structures such as tailings dams can present similar hazards to water retaining dams, however these structures have not been included since their inclusion would widen the subject into an area where the current safety legislation for water retaining dams does not apply.

Most reservoirs constitute a low probability-high consequence scenario and careful management of the risks is essential in order to maintain reservoir safety. Many factors affect the risk of failure since dams not only vary greatly in their design and construction, but their effectiveness in safely impounding a reservoir of water also depends critically on their foundation and all sites differ in their geology. Furthermore, human factors affect how a reservoir is operated and how a dam is maintained, monitored and kept under surveillance. With so many variables, recording and learning from the circumstances in which dam failures and serious incidents have occurred can be difficult. The following overview of the types of major incidents that have arisen over the last 200 years in Britain and the safety legislation that has followed from failures and incidents aims to provide an improved understanding of the subject.

1.2 19th century

At the beginning of the 19th century, most dams were small homogeneous embankments impounding small reservoirs. By the middle of the century, a fairly standard design of embankment dam had been adopted, with an upstream slope of one vertical in three horizontal (1V:3H) and a steeper downstream slope of 1V:2.5H or 1V:2H horizontal with a central puddle clay core. Although control of material and workmanship should ensure the integrity and watertightness of the central puddle clay core within the body of the dam, leakage could occur through the natural strata of the valley underneath or around the sides of the dam. Leakage could also occur within the basin of the reservoir. In the early puddle clay core dams, it was usual to extend the puddle clay into a cut-off trench below ground level thus connecting the core to a stratum of low permeability. The trench often continued into the valley sides. Sometimes very deep trenches were dug but the trench was usually quite thin, with vertical sides. The timeline in Table 1.3 shows key developments in British dam construction practice throughout this period.

Overtopping failures – inadequate overflows

Overtopping failures were a major hazard where overflow works were not adequate to cope with unprecedented rainfall. Such an event occurred when, following unusually heavy rainfall, the Whinhill dam breached at 23:00 on Saturday 11 November 1835 and the catastrophic release of the reservoir water resulted in the loss of more than 30 lives at Greenock in Scotland. The muted reaction to this type of dam failure at that time is well illustrated by the reporting of the catastrophe in *The Times* one week later. A paragraph headed 'inundations in Scotland', was largely devoted to the flooding and resultant damage caused by the Clyde overflowing its banks during the torrential rain in the area and just briefly mentioned the Whinhill dam failure. The only implied criticism of those responsible for the dam was the assertion: *"The original banks are said to have been raised without a sufficiently strong foundation"*.

When 13 years later, on 23 August 1848, a small dam failed by overtopping during a storm at Darwen (Bold Venture) in Lancashire with the loss of 12 lives (Aighton, 2003), the same attitude to a dam failure was exhibited in the verdict of the jury at the inquest.

> *'... all the deaths inquired into occurred by an accidental cause, that cause being the excessive rains of Tuesday night and Wednesday morning, by which the reservoir at Bold Venture Lodge overflowed and washed away the embankment...'*

A few years after the failure at Darwen, the perception of dam failures as unforeseeable accidents changed significantly when two dam failures in Yorkshire, Bilberry in 1852 and Dale Dyke in 1864, which were not obviously principally attributable to extreme rainfall events, caused major loss of life. However, both did occur during severe storms. In both cases there appeared to be a large element of human culpability and popular demand for reservoir safety legislation arose.