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Investigation of dam incidents and failures

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History tells us that dams can bring many benefits to society but there is also a long history of 'near-miss' incidents and failures that, in some cases, have led to great loss of life. The investigation of incidents and failures around the world has led to improvements in the design and construction of dams with the aim of reducing the risk of failure. By illustration of a number of examples and case studies, the objective of this paper is to explain the role of the investigating dam engineer in understanding the factors that contribute to dam safety incidents. The paper concludes that there is a role for more effective sharing of information both nationally and internationally to improve dam design and construction and reduce the risk of failure. The paper outlines how this might be achieved.

1. Introduction

The idea of forming a barrier across a valley to store river water dates from pre-history. In the twenty-first century, there is growing concern for global water scarcity and the need to maintain and create reservoirs for water storage will become more important (Warren, 2010). Dam construction can provide one or more of many benefits, including improvements to water supply reliability, irrigation, hydropower, navigation and flood control.

A dam incident can be taken to mean any sequence of events that gives rise to concern for the short-term safety of a dam and results in non-routine actions to preserve its safety. Where such actions fail to prevent a large uncontrolled release of water from a reservoir, the incident is considered to be a dam failure. For as long as man has built dams and other types of structures, there have been dam incidents and failures. To quote Gordon (1978):

> All structures will be broken or destroyed in the end, just as all people die in the end. It is the purpose of medicine and engineering to postpone these occurrences for a decent interval.

Of the many types of dam construction around the world, embankments made of earthfill and/or rockfill represent the most common type. Dam embankments commonly fail through the action of the water that they hold back. Reservoir water pressure is unrelenting in seeking out any crack or fissure through the embankment or under the embankment to generate leakage, and possibly erosion, in gaining a natural equilibrium. By creating a reservoir, the potential of water to be released in a sudden uncontrolled manner is also created, posing a small but finite risk to those living in the path of a dambreak flood wave. Thousands of people might be at risk from any one failure and the cost of infrastructure damage might exceed £1 billion where large reservoirs are sited in areas of dense population (e.g. west London). It follows that even if the estimated probability of such a failure is less than one in a million in any one year, stringent regulatory controls are appropriate to ensure that the safety of such dams is managed appropriately through monitoring, surveillance and regular independent review. Table 1 (reproduced from Charles *et al.*, 2010) lists some notable dam disasters from recent history around the world.

In the UK, one of the most devastating historical dam failures was the Dale Dyke disaster (Figure 1), which left 244 people dead in the vicinity of Sheffield. The Dale Dyke dam failed during the first filling of the reservoir on the night of 11 March 1864. The Home Secretary, Sir George Grey, appointed two civil engineers, Robert Rawlinson and Nathaniel Beardmore, to assist in the inquiry into the cause of the catastrophe. A leader in *The Times* on 17 March 1864 argued that those threatened by reservoirs could not be expected to defend themselves and needed protection. The verdict of the jury at the inquest on 24 March 1864 included the statement:

> in our opinion, there has not been that engineering skill and that attention to the construction of the works, which their magnitude and importance demanded; that, in our opinion, the Legislature ought to take such action as will result in a governmental inspection of all works of this character; and, that such inspections should be frequent, sufficient, and regular.

In their report to the Home Secretary, Rawlinson and Beardmore were critical of both the design and construction

Dam	Dam type*	Country	Height: m	Reservoir volume: 10^6 m^3	Date built	Failure† Date	Failure† Type	No. of deaths
Vega de Tera	CMB	Spain	34	7·8	1957	1959	SF	144
Malpasset	CA	France	66	22	1954	1959	FF	421
Babii Yar	Emb	Ukraine	—	—	—	1961	OF	145
Vaiont	CA	Italy	265	150	1960	1963	LA	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	118	492	1953	1975	OF	‡
Teton	Emb	USA	93	308	1975	1976	IE	11
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	—	2009	IE	100

*CMB, concrete and masonry buttress; CA, concrete arch; Emb, embankment; RCC, roller compacted concrete
†SF, structural failure on first filling; FF, foundation failure; OF, overtopping during flood; LA, 270×10^6 m^3 landslide into the reservoir caused overtopping of the dam by a wave 125 m high, but remarkably the dam survived; IE, internal erosion
‡It has been reported that tens of thousands died in this disaster, which involved the failure of a number of dams, of which Banqiao was the largest

Table 1. Selected international dam disasters causing loss of life

of the dam, but they did not endorse the recommendation from the jury for government inspection, stating:

> We cannot, however, recommend it for adoption. Any approval of plans or casual inspection of waterworks embankments cannot ensure ultimate safety in such works. The responsibility must remain, as at present, with the engineer and persons immediately connected with the works. Magistrates have jurisdiction under clauses inserted in recent Waterworks Acts.

Figure 1. Postcard photograph of the Dale Dyke dam breach (courtesy of ICE)

It would take two further dam failures in 1925, and further loss of life, at Dolgarrog and Skelmorlie to instigate the introduction of reservoir safety legislation. The Reservoirs (Safety Provisions) Act 1930 (TSO, 1930) introduced regular reservoir inspections by specialist engineers. This act was further developed in the Reservoirs Act 1975 (TSO, 1975) (recently amended under the provisions of the Flood and Water Management Act 2010 (TSO, 2010)). Although there has been no loss of life in Britain since the first introduction of reservoir safety legislation in 1930, many dam incidents continue to occur every year, some requiring urgent action to prevent dam failure. Internationally, the Kolontàr dam disaster in Hungary in October 2010 is a reminder that the standards of design and construction applied to tailings dams should be very similar to those for water reservoirs. Up to 700 000 m^3 of red toxic sludge escaped from this reservoir, causing many deaths and injuries and polluting a large area that included a tributary of the River Danube. Unfortunately, this is not the first disaster of its kind: for example, the Stava tailings dam disaster in Italy failed in 1985, killing 269 people. In the UK such reservoirs are covered by the Mines and Quarries (Tips) Act 1969 (TSO, 1969) and strict regulatory controls are applied to the design, construction and operation of such dams (Cambridge, 2008).

This paper aims to provide some insight into how the investigation of dam incidents and failures can contribute to our understanding of the many ways in which dams can and do fail. Two recent case studies are described to illustrate the diversity of problems that can arise and the role of the investigating engineer is discussed. The paper is written in the context of UK dam incidents although much of the paper is relevant to dam investigations worldwide.

2. Learning from dam incidents and failures

Structural failures can commonly be assigned to one of the generic causes outlined in Table 2. Most dam failures can be assigned to one or more of the categories listed in Table 2 but, as a type of civil engineering structure, dams are particularly diverse in their application, design and construction. Every dam is designed and constructed to reflect a unique set of requirements and limitations relating to:

(*a*) reservoir use and size
(*b*) reservoir water level fluctuations in use
(*c*) site geology, seismicity, topography and hydrology
(*d*) availability of appropriate local materials
(*e*) nature of the materials used in the construction
(*f*) economics
(*g*) client requirements
(*h*) state/regional/national design guidance and regulatory controls.

This makes it difficult to assign incidents and failures to simple sets and sub-sets. As with other major civil engineering structures, it is essential to appreciate the background against which the incident or failure occurred.

Catastrophic failures in dams are quite rare but serious incidents continue to occur frequently around the world. In these cases, dam failure is usually averted through recognition of a major problem and appropriate intervention. A typical intervention is to reduce the pressure on the dam by lowering the reservoir water level. Notably, investigations of 'near-miss' incidents can often provide greater learning opportunities than failures. This follows from the facts that:

(*a*) there are far more near-miss incidents than dam failures from which useful information can be gleaned
(*b*) near-miss incidents can provide useful information on the effectiveness of the steps taken and the circumstances under which catastrophic failure was averted
(*c*) free of the legal consequences associated with the loss of a

Generic cause	Examples
Project planning	• Lack of clear scope • Conflicting client expectations
Site investigation	• Inadequate scope or extent of ground investigations • Mis-interpretation of information
Design errors	• Conceptual design errors • Lack of redundancy • Failure to identify all loads and load combinations • Calculation errors • Detailing deficiencies • Specification deficiencies • Failure to consider surveillance, monitoring and maintenance
Construction errors	• Inappropriate temporary works • Improper sequencing • Improper methods or timing of construction • Excessive construction loads
Material deficiencies	• Material inconsistency • Premature deterioration • Fabrication defects
Operational errors	• Structural alterations • Operation beyond the scope of the design • Change in structure use • Inadequate surveillance, monitoring or maintenance

Table 2. Generic causes of structural failure

dam and its consequences, respondents and witnesses are more likely to cooperate fully with investigators

(*d*) dam failures can destroy some or all of the evidence from which learning could have been achieved.

In many cases, forensic investigations are carried out where there has been a significant financial loss or loss of life, and the findings inform litigation. If we are to learn from problems arising with dams, it is clearly essential that all major incidents are investigated and the findings widely disseminated. Only then can we hope to improve the reliability and performance of dam structures.

3. Investigation and reporting

In planning an investigation, an important first step is the selection of the investigator. The desirable attributes of an investigator are as follows.

(*a*) Objectivity – no report will be better than the integrity of the report writer. Any criticism of people, designers, contractors, materials or functions must be constructive. A partisan approach or attitude will devalue the report. It is essential to clearly separate opinion from fact.
(*b*) Independence – if a report is to be treated as credible, the independence of the investigator must be beyond all reasonable doubt. Any possible conflict of interests should be declared.

Through the investigation of the causes of incidents or failures, the role of the investigating engineer can serve one or more of the following purposes:

(*a*) to assess sources of claims and litigation
(*b*) to assist in the resolution of disputes affecting property of life
(*c*) to prepare engineering reports for the dam owner/operator to rectify problems
(*d*) to inform statistics and knowledge of the circumstances through which an incident occurred, thereby informing the adequacy of current guidance and standards relating to design, construction and operation.

The usual goal of an investigation is to establish the root cause of the incident or failure. The steps taken to establish the root cause will vary in every case, but typically it will be necessary to establish the mode and sequence of events, the loadings acting on the structure at the time of the incident and the capacity of the structure to deal with the conditions prevailing at the time of the incident.

In assessing incidents at dams, there are often human aspects that need to be dealt with in a firm but sensitive manner. It will be important to determine the steps taken, and when, at the time the incident was first declared. Typically there will have been attempts to deal with the incident before professional advice was acquired. The scope and frequency of dam monitoring (for example, seepage flow monitoring) and surveillance (adequacy and regularity of owner/staff visits to the dam) will need to be determined. Lack of routine maintenance might be relevant. In the case of statutory reservoirs (subject to periodic professional dam inspections), compliance with the recommendations of previous inspection reports should be assessed. A typical dam incident investigation should normally include:

(*a*) appreciation of the purpose and scope of the investigation
(*b*) a review of previous reports and data (inspection reports, drawings, monitoring data)
(*c*) a search for past technical papers relating to the dam (the British Dam Society bibliography (BDS, 2010) can be useful in this) that might highlight recognised frailties with the dam or unusual site characteristics
(*d*) a preliminary visit to the dam site
(*e*) interviews with the dam owner and any other affected parties
(*f*) review of the conditions prevailing at the time of the incident (e.g. rainfall records, reservoir water level, seepage monitoring records, piezometer readings, photographs) to deduce the most likely mode of failure
(*g*) detailed visit to the dam site to gather further information to support or counter the likely mode of failure; in some cases, ground investigations are required
(*h*) engineering calculations/analysis based on the evidence (physical and/or anecdotal) and review of the capability of the dam structure to cater for the apparent loading conditions prevailing prior to the incident being declared
(*i*) issue of a report.

In assessing the effectiveness of any formal emergency planning provisions, it is valuable to review and comment on the effectiveness of any such plan put in place by the dam owner and/or by the local authorities. The investigator must be given adequate time and resources to do the commission justice. If the report is to have any value, its conclusions must be founded on adequate information.

4. Case studies

Dams generally have a very low annual probability of failure but with so many dams in operation around the world, incidents and failures occur every year. Although only a fraction of these are widely publicised, most catastrophic dam failures are fully investigated and the findings made known. A significant number of incidents have been due to insufficient investigations of dam site geological conditions or misinterpretation of the prevailing hydrological conditions.

Incident investigations can lead to advances in knowledge of how dam construction materials behave under certain conditions. For example, defects in the core of Balderhead dam in 1967 were found to have been derived from hydraulic fracturing despite the fact that a filter layer had been provided downstream of the core to counter any migration of fine material. Investigations led to important developments in filter design (Vaughan and Soares, 1982). The case study discussed in Section 4.1 is of a similar nature in that the investigation identified a new vulnerability that has since been addressed through targeted research.

4.1 Ulley reservoir, UK

Ulley reservoir was created in 1873 by the construction of a 16 m high embankment dam. The reservoir is owned by Rotherham Borough Council and is used for amenity purposes as part of a country park. During flood events, overtopping of the embankment was prevented by allowing water to flow down a spillway channel. However, in passing the significant floodwater that resulted from severe rainfall in June 2007, the wall of the spillway channel failed. As the channel was located adjacent to the earthfill forming the downstream side of the embankment, the failure of the wall led to rapid erosion of the dam earthfill material behind the wall. This erosion threatened the overall stability of the dam embankment. In response to the incident, the M1 motorway was closed and residents thought to be at risk downstream of the reservoir were evacuated. Emergency action was taken to:

(*a*) divert flow from the damaged spillway
(*b*) lower the reservoir using temporary pumps
(*c*) import rockfill to fill the eroded section of embankment.

Fortunately, these emergency actions averted dam failure. In the months following the incident, an investigation was led by two leading dam engineers to:

(*a*) review the history and prior condition of the dam
(*b*) discuss the incident management and response with the coordinating engineer and dam owner
(*c*) assess whether there might be lessons for reservoir safety.

The findings of the investigation are covered by Hinks *et al.* (2008). The main benefits of the investigation were twofold. First, the incident highlighted the benefit of comprehensive emergency planning documentation. Although good generic arrangements for working with the emergency services were in place, an on-site emergency plan did not exist. The incident highlighted the need for an emergency plan that would detail key drawings, valve operation procedures, the capacity of the scour pipe, emergency contacts and standby procedures for emergency works (contractors, staff and suppliers). A reservoir inundation map, showing the likely extent of the floodwater in the event that the dam breached, would have been useful in planning the evacuation of downstream residents. The Flood and Water Management Act 2010 provides for improvements in emergency planning.

Figure 2. Ulley reservoir 25 June 2007: the masonry stepped spillway structure on the dam mitre fails to prevent major erosion of the adjacent dam embankment, threatening the stability of the dam ©Jim Claydon, courtesy of Rotherham Borough District Council

Second, the exact physical mechanism by which the spillway wall collapsed under high-flow conditions could not be determined with certainty. Research was later carried out on the pressures that can be exerted on masonry blocks from within wall joints on a stepped spillway configuration. It was postulated that the spillway wall collapsed due to pressure

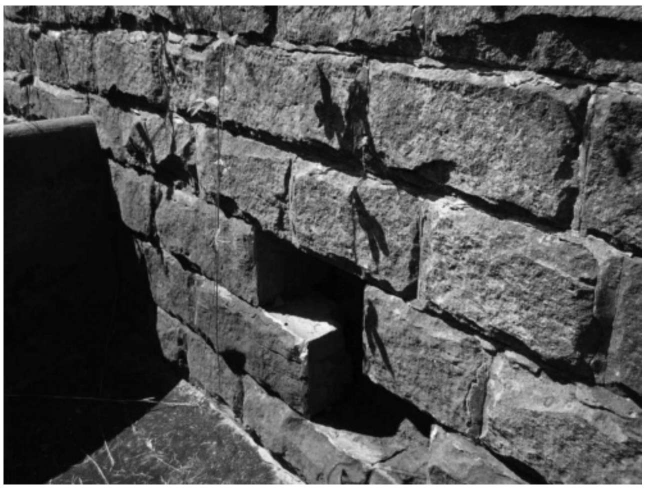

Figure 3. Ulley reservoir 2007–2009: investigations and research found that masonry stepped spillway walls might have been prone to block displacement and collapse under high-flow conditions ©Halcrow

differentials sufficient to pluck out masonry blocks, thus causing the wall to collapse. Recent research has confirmed this mode of failure to be feasible and new guidance on the inspection and maintenance of stepped masonry spillway channels has been published to aid dam owners and engineers (Winter *et al.*, 2010) (Figures 2–4).

4.2 Taum Sauk dam, USA

The Taum Sauk pump storage plant, located in Missouri, USA, had been operational since 1963. The failure of the upper dam highlights the fact that some failures arise as a result of complex combination of factors that are often unrelated.

The reservoir was impounded on all sides by a concrete-faced dumped rockfill dam with a maximum height of approximately 26 m. The reservoir was filled by pumping; it received no natural inflow (other than rain falling directly on its surface) and had no spillway facility. Water level monitoring and high-water alarm systems were installed to guard against the risk of overfilling the reservoir. Despite these provisions, the reservoir water level overtopped the dam crest in December 2005, leading to a loss of stability and eventual catastrophic breach. The breach led to the release of over 5 million cubic metres of water down the west slope of Proffit Mountain and into the East Fork of the Black River in a 25 min period. Surprisingly, there were no fatalities. The maximum level recorded by the water level transmitter was El. 485·76 m but the actual peak reservoir level (based on post-incident physical observations) was approximately El. 486·95 m.

Post-incident forensic investigations were conducted by both Paul C Rizzo Associates and the Federal Energy Regulatory Commission (FERC). Rizzo's investigation concluded that the

Figure 4. Ulley reservoir 2010: the dam received major repairs including a new spillway structure located near the centre of the dam. New legislation to improve provisions for emergency planning was passed ©Peter Smith Photography, courtesy of Arup consultants

Figure 5. Taum Sauk reservoir 14 December 2005: catastrophic failure of the embankment led to the release of over 5 million cubic metres of water in less than about 25 minutes (photograph courtesy of Ameren)

failure mechanism was a stability failure caused in turn by saturation of the embankment through overtopping of the reservoir rim (Paul C Rizzo Associates, 2006). A number of contributing factors relating to the geotechnical characteristics of the dam material were also reported. Human error led to misplacement of the high-water alarm sensors such that overfilling of the reservoir was not communicated to the control centre. This led to overtopping of the perimeter parapet wall and instability of the embankment.

The forensic investigation performed by FERC documented similar findings to the Rizzo report on the factors leading up to

Figure 6. Failure of Taum Sauk reservoir (photograph courtesy of Ameren)

the overtopping of the parapet wall (FERC, 2006). However, the FERC investigation differed on the failure scenario, suggesting that erosion below the parapet wall was the cause of the instability rather than internal water pressure within the embankment alone.

Investigations were also conducted by other agencies including the Missouri Public Service Commission, Missouri Highway Patrol and the Missouri Attorney General's Office. The investigations resulted in no criminal charges against the reservoir owner and operator (Ameren) but did require a payment of fines to the FERC. Ameren entered into a consent judgement with the State of Missouri to settle all environmental and natural resource damage claims. The original dam has recently been replaced with a dam of roller compacted concrete construction, the largest of its type in North America (see Figures 5–7).

It is notable that full details of the investigation (FERC, 2006) have been made freely available on the internet so that the global dam community can learn from this incident and the owner has adopted a highly responsible approach in dealing with the aftermath of the incident. The full details of the incident demonstrate that dam failures can occur through a complex combination of numerous natural and human events and factors, any one of which might have averted the disaster under different circumstances.

5. An open approach

In recent years there has been a perceptible shift towards an open approach to learning from dam incidents and failures. In addition, efforts are being made to gather information on dam incidents from countries around the world to develop a database to serve research. Many countries recognise the value of cooperation. In the aftermath of the Sichuan earthquake disaster of May 2008, the Chinese government invited representatives from an international committee for dam seismic safety to visit the province and to learn from the damaging effects of the earthquake on over 300 dams, including the Zipingpu concrete-faced rockfill dam which was about 2 years old at the time (Hinks, 2009). This approach allows information to be effectively disseminated and for the information to be considered when producing new design and construction guidance for the international engineering community.

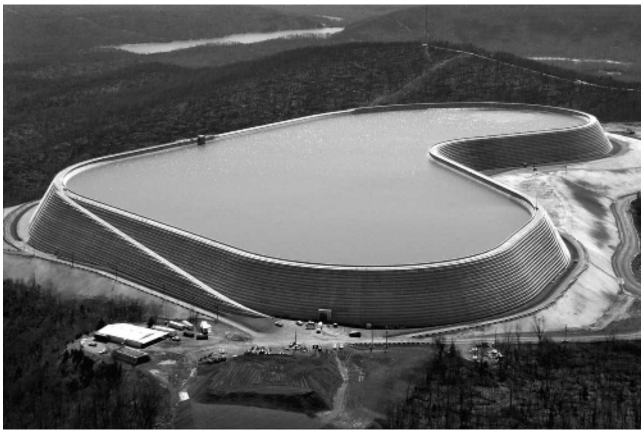

Figure 7. Taum Sauk reservoir 2010: the dam embankment has been rebuilt using roller compacted concrete (photograph courtesy of Ameren)

Since 2007, a new system for reporting and investigating dam incidents has been administered by the Environment Agency (EA) in the UK (Warren and Hope, 2006). This is referred to as the post-incident reporting (PIR) system and it provides for voluntary reporting of incidents and collation of information on a national database. The PIR system also allows for investigations where the consent of the owner is first gained. Reports are published annually on the EA website and describe the incidents that have occurred and the possible lessons that can be learned (EA, 2009). Reporting under the current system is voluntary and confidential. Dam owner details and reservoir names are not disclosed except where agreed with the owner or where the incident is already in the public domain. The UK government places considerable importance on providing effective means of learning from incidents. The Confidential Reporting on Structural Safety (Cross) is a programme of the Standing Committee on Structural Safety (Scoss) for collecting, analysing and publishing concerns about the safety of systems (Scoss, 2010). The PIR system has much in common with Cross.

Experience in administrating the system has indicated that the reporting of incidents is less than complete under a voluntary reporting system. This was particularly apparent following the 2007 flood events in England. The reasons for non-reporting are believed to be concerns for:

(*a*) the effect on corporate image
(*b*) the amount of time/effort in dealing with the reporting or investigation
(*c*) fear of prosecution
(*d*) reputation.

In 2010, provisions for a new mandatory system of reporting were included in the Flood and Water Management Act 2010. Once these measures have been implemented, the effectiveness of the PIR system should be enhanced.

There are precedents from other industries for mandatory reporting of incidents. For example, the Railways (Accident Investigation and Reporting) Regulations 2005 apply when railway accidents or incidents occur. Notifiable incidents, which are listed in schedules, must be notified within three working days. Similarly the Air Accidents Investigation Branch has an incident reporting system under the Civil Aviation (Investigation of Air Accidents and Incidents) Regulations 1996. Under this statutory instrument, 'incident' means an occurrence, other than an accident, associated with the operation of an aircraft that affects or would affect the safety of operation; a 'serious incident' is an incident involving circumstances indicating that an accident nearly occurred. Incident investigators have wide-ranging powers. The consequences of dam failure can greatly exceed the consequences of a rail or air disaster and it can be argued that a mandatory incident reporting system for dams is long overdue.

In the aftermath of any serious dam failure that leads to loss of life or significant damage to property or the environment, experience shows that a dam owner might engage in a 'blame game' to protect the company image or value and to try to mitigate exposure to compensation claims. However, the approach taken by Ameren in the aftermath of the Taum Sauk incident demonstrates that corporate image need not suffer greatly by being honest, open and cooperative. Perhaps of greater concern are the 'near-miss' incidents where there is no public knowledge of the incident and the owner may choose not to provide details and share points of learning with the wider technical community. Mandatory reporting in the UK will clearly go some way to addressing this. However, the benefits of reporting must also be clearly communicated to dam owners. Governments have a responsibility and role in promoting a close sense of technical community so that all can fully understand the issues and risks involved in designing and operating high-risk assets.

6. Learning and dissemination

There are many examples of how the investigation of dam incidents has led to improvements in design, construction, operation and monitoring of dams. Historically, dams were designed largely on the basis of past experience. Embankment slopes, for example, would largely reflect previous successes with little or no account taken for the variability of fill materials, foundations or operational conditions. Developments in soil mechanics and modern construction equipment have changed the way in which dams are now designed and constructed.

Despite these advances, incidents have continued to occur even in modern dams. In 1984, the Carsington dam embankment failed during its construction, delaying its completion by 7 years. The rotational slip extended over a length of nearly 500 m, with the embankment crest dropping 11 m and the upstream toe moving 13 m horizontally. Faced with one of the largest geotechnical failures of a structure in Britain, the owners sought independent advice and appointed consulting engineers Babtie Shaw & Morton and Professor Alec Skempton of Imperial College London to report on technical matters relating to the slip (Rocke, 1993). The high profile of the failure led to the Department of the Environment appointing an independent expert, Roy Coxon, to report on the actions being taken to investigate the failure. The Coxon report (Coxon, 1986) recommended that review panels, which are now widely used internationally, should be used in the UK to oversee the design and construction of large dams.

Experience has found that dam embankments are particularly difficult to categorise due to the diversity of arrangements, geometry and materials; this is compounded by site foundation conditions, which are always unique. Most embankments are formed by the most variable of engineering materials (i.e. soil). Clearly, no two dams are the same and the conditions and threats that influence their security are also unique. Nevertheless, attempts have been made to develop databases of dam characteristics and to record incidents. In the aftermath of the Carsington incident, the Buildings Research Establishment developed a database of dams that included information on incidents. This database was further developed in 2006 as part of the new PIR system described in Section 5.

Recent research in dam safety has tended to consider the following components in an incident:

(*a*) a threat, or initiating event (e.g. a flood), that potentially could lead to
(*b*) a hazard to dam safety (e.g. the capacity of the spillway being exceeded), potentially giving rise to
(*c*) a mode of failure (e.g. embankment overtopping and erosion leading to dam breach).

The new national database aims to identify the threats and the likely eventual failure mode (even where the dam did not actually fail). The database can also record the actions taken to avert failure, the investigations carried out following the incident, the nature and frequency of dam performance monitoring and surveillance prior to and following the incident, and the nature of any physical works undertaken to repair and/or improve the structures. Any associated research and technical papers associated with the incident are also recorded.

In addition to the annual PIR reports (EA, 2009), it is important to review the database periodically to scope the requirement for any new or revised engineering guidance to address the findings of post-incident investigations. Reservoir research priorities should be informed by the UK database and by international incidents and databases as and when they are developed.

As well as keeping track of new incidents, it is very important for practitioners to not lose sight of the lessons from historical dam failures that are already in the public domain. The EA has recently commissioned a report (Charles *et al.*, 2010) to highlight the lessons that can be learned from 100 selected incidents and failures that have occurred in Britain since the end of the eighteenth century.

Learning about dams is promoted by the British Dam Society. Their website provides general information on dams and has information for both students and professionals (BDS, 2010).

7. Conclusions

As in any field of forensic engineering, the main aim of the investigator is to find the truth. Such investigations can be conducted for a wide range of purposes. Engineers have a professional duty to disseminate their knowledge so that all can benefit from lessons from incidents. In a field such as dam engineering, where the consequences of structural failure can have dramatic and wide-ranging implications, governments have a role to support and encourage the sharing of information at both national and international level.

The annual probability of a well-designed and properly constructed dam failing, or even coming close to failure, is generally very small. Society demands this of civil engineering structures, especially where failure could cause loss of life. Given the many thousands of dams in Britain alone, it is inevitable that some structures will give cause for serious concern every year and a small number have failed. When major dam incidents or failures occur, the investigating engineer can play an important role in contributing knowledge to the construction industry on the conditions under which the incident occurred. Only by learning from mistakes can engineers hope to reduce the number of incidents.

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