Lessons from a dam incident

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SYNOPSIS. Panel Engineers learn much when they are called out to deal with dam incidents. This paper attempts to share the lessons from an incident at an anonymous dam. Fifteen lessons are identified, which if followed, will lead to a greater understanding of the properties of dams and their behaviour if failure threatens. It is recommended that this knowledge be used to compile 'emergency handbooks' to equip those handling emergencies to take previously planned measures to minimise the risks to lives and property downstream and to release water quickly from threatened dams.

LEARNING FROM EXPERIENCE

Panel Engineers learn much when they are called out to deal with dam incidents. Our dams will present less of a threat if all concerned in dam safety learn from and react to these lessons. Taking a cue from the ICOLD (1974) publication 'Lessons from Dam Incidents', this paper attempts to share the lessons from a dam incident. The lessons are mostly not new. Some are already statutory, many appear in the embankment (Johnston et al, 1999) and concrete (Kennard et al, 1996) dam guides, and others were mentioned in the guidance on preparation of section 10 reports (Dams & Reservoirs, 2001). However, putting them together in the context of a dam incident makes their relevance and usefulness all the more obvious, and will, I hope, encourage all owners to prepare 'emergency handbooks' on their reservoirs to assist those charged with handling any emergencies to deal with them promptly and effectively, without making an already difficult situation worse.

ANONYMOUS RESERVOIR

The dam in question will remain anonymous, the lessons are not site specific and naming the reservoir serves no purpose. I would ask readers to try to live through the experience as I did and add it to their own experience, perhaps equipping themselves to deal with future incidents all the more competently. Of course, I recognise that my approach was far from perfect and many of the lessons that I learnt will not be new to all readers!

Long-term benefits and performance of dams. Thomas Telford, London, 2004

ANONYMOUS ACKNOWLEDGEMENT

I would like to say that the owners of the anonymous reservoir responded magnificently to the demands of the incident, maintaining close liaison with the police and emergency services, and providing, without hesitation, all the extra people and equipment needed to deal with it.

THE SYMPTOMS AND WHAT CAUSED THEM

The first lesson related to establishing the cause of the problem. I was called out because a hole had appeared in the downstream slope of a typical British dam. It was about one metre deep and about 800 mm in diameter, and looked to me like the surface expression of piping. We probed down and seemed to reach a solid bottom and we jumped on the bed of the hole and it didn't collapse, but I thought that perhaps the movements that had led to the formation of the hole had also formed some kind of temporary arch across the erosion pipe. No other reason for the formation of the hole seemed obvious. This and the fact that a rush of water in the culvert at the toe of the dam had been reported at about the time the hole had been spotted, led me to think that internal erosion was probably the cause. Had something triggered it, or had there been slow erosion for years that had finally manifested itself as the hole? BGS at Edinburgh reported no seismic activity and water level in the reservoir had been constant for months, and long-term slow erosion looked like the culprit.

I felt it was important to identify the cause of the problem because the incident could then be handled accordingly. But after pondering, experimenting and investigating and finding no other symptoms to convincingly confirm this diagnosis, I realised that it was not going to be easy to identify the cause. Worse, not knowing the cause, I would have to recommend further action after making a judgement on whether the hole had resulted from a single event that would not re-occur, or whether it was the result of some event that would re-occur or continue, possibly at an accelerated rate, and lead to escalating damage. Not a satisfactory situation for a supposed expert to be in, but a useful first lesson - there will be many unanswerable questions during the course of an incident, the first being what has caused the symptom triggering the incident, but even without knowledge, you must recommend appropriate action, usually erring on the side of caution.

LESSON 1 – It is rarely possible to quickly identify the cause of the symptoms that lead to incidents, consequently initial actions cannot respond to the cause, they need to be generally cautious

GETTING TO KNOW THE DAM

In an effort to see where the leakage causing the erosion was, the water level was kept high, better monitoring arrangements were put in place, and I studied drawings and read a paper about repairs done at the dam many years before. Here was lesson two - write down your experiences in a reputable journal. I found being able to 'talk' to my predecessors invaluable and eliminated much of the conjecture that inevitably arises during incidents.

LESSON 2 – Record your experiences

IMPACTS OF IMPROVEMENT WORKS AT OLD DAMS

The paper revealed that there was much stony fill in the dam. The hole may have resulted from settlement of this fill, because it had been wetted, perhaps for the first time, by water released after a huge thunderstorm from perforated pipes recently laid along the toe to drain the mitre. Lesson three – think carefully about the impact of supposed improvement works at old dams. You probably know relatively little about them, especially the fill in their shoulders, and therefore you know little about the impacts your safety works might have. Don't enter into even simple improvement works lightly. Incidentally, the perforated toe drains were replaced by unperforated ones, which reduced flows reaching the culverts during rain, as Figure 1 shows.

LESSON 3 – Think carefully about the impact of works to improve old dams

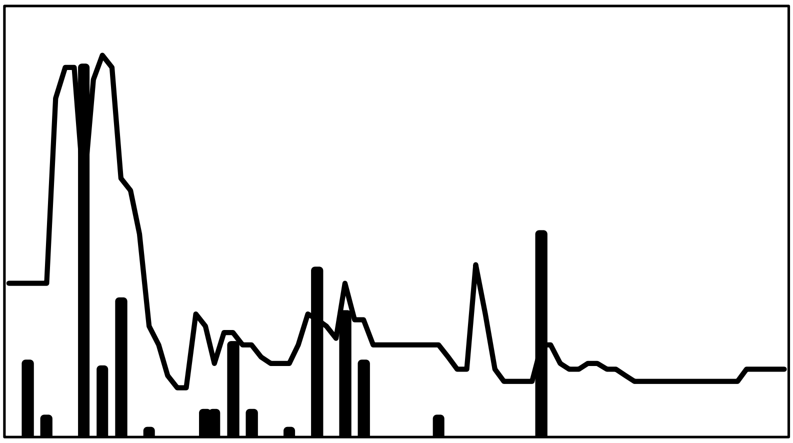

Figure 1 Rainfall and culvert flow over time

SAFETY FIRST

Then came lesson four. I realised that my forensic investigations had distracted me from the alarming fact that the real cause, whatever it was, might cause failure of the dam, releasing the water from the still full

reservoir on to the unsuspecting public downstream. I ordered the reservoir to be lowered forthwith.
LESSON 4 – Take precautions first, don't take chances.

RAPID DRAWDOWN
Lowering water level inevitably leads to the questions of how low and how quickly? On how quickly, I was very cautious because the paper had told the story of repairs to the upstream slope, and I didn't want to add to our woes by allowing water to escape from the reservoir through a slip of the upstream slope caused by too rapid a drawdown of the water level. The uncertainty could have been reduced if a rapid drawdown analysis had been done – lesson five. The guidance – 300 mm a day – is conservative in well-drained slopes (Reinius, 1948), but not conservative in clay slopes if the water level is drawn down a long way (Morgenstern, 1963). Modern numerical methods to analyse safe drawdown rates are also available (e.g. Dounias et al, 1996). All require knowledge of the fill in the upstream shoulder. In many British dams the shoulder fill is stony and well drained, consequently rapid drawdown rates will not cause failure. Some dams have clay upstream blankets as well as cores. Lowering the water level in these situations could leave a high water level between and the blanket may be ruptured.
LESSON 5 – Investigate fill in upstream shoulder and do rapid drawdown analyses

EMPTYING CAPACITY
The outlet pipework at the reservoir had an enormous capacity, though there was no rating curve. Lesson six – work out the opening v discharge relationship for the scour and other outlet valves. The maxima should be entered in the Prescribed Form of Record, Part 8, but a rating curve or table would be more helpful in an emergency situation.
LESSON 6 – Know how much water the emptying pipes can release

DOWNSTREAM RIVER CAPACITY
If I had not been constrained by drawdown failure worries, we could have lowered water level at a terrific rate, very re-assuring when there is a problem. However, the discharge might have gone out of bank and flooded properties downstream. Lesson seven – identify pinch points and low-lying properties near the river downstream, estimate likely in-bank flow capacity, send scouts out to pinch points when releasing water from the reservoir.
LESSON 7 – Know the capacity of the river downstream

CRITICAL RESERVOIR CAPACITY
The next question that arose was how far should we lower water level? Having postulated internal erosion, there was a possibility of a low-level

erosion pipe working back towards the reservoir, the symptomatic hole being a vertical tributary from it, and this could release the whole reservoir downstream. I thought that the consequences of this would decrease as the water level retained became lower; perhaps at some critical level there would be no significant damage downstream. The dambreak analyses (they had been done previously, otherwise another lesson would have been learnt) were dusted off and trials done with progressively smaller volumes of water escaping from the reservoir. The result? Even at 50% full, the number of properties at risk, while less than half of those when the reservoir was full, was still large, many up to 30 kilometres downstream. This confirms what we know (or it could be another lesson?), that the extent of dambreak impacts relates more to the river slope downstream of the dam, and therefore the flow velocity, than to the volume of water released. However, it would have been good to know about this before the emergency. At reservoirs with gentle downstream river slopes there might be a critical reservoir level at which no damage would occur downstream in a dambreak. Lesson eight – do dambreak studies with differing retained reservoir volumes to give guidance on how far to lower water levels in an emergency.
LESSON 8 – Know how much water needs to be released to reduce the threat to acceptable levels.

CONSTANT SURVEILLANCE
The emergency authorities had some direct questions. They needed to know when we would be able to tell them to evacuate people downstream. How would we know when the dam had started to fail? We expected that there would be accelerating movements, sounds of running water in the culvert, outbursts of dirty water into the culvert, subsidence of the crest and other manifestations of failure by internal erosion that we know about from the literature. The police noted that all these could occur at any moment. The order to evacuate depended on direct visual evidence. They instructed us to provide constant surveillance, with shelter and phones, at the dam. Lesson nine – faulty reservoirs should be under surveillance 24 hours a day, seven days a week. Provide experienced people, with a cabin and ready access to phones, they would be the ones who would trigger evacuation if failure seemed inevitable.
LESSON 9 – Faulty reservoirs should be under constant surveillance

DEFORMATIONS ON THE RUN UP TO FAILURE
The police questions about how would movements accelerate before failure occurred was a tough one. I have seen finite element analyses of movements prior to stability failures (e.g. Vaughan et al, 1989), but if internal erosion was occurring and the eroding water was somehow escaping without coming into view, what deformations could be expected and would there be any change in the rate at which they occurred. Also would they be

visible to the naked eye, or would they only be discernible by survey methods? Lesson ten – we should know more about deformations before failure, and what means would be required to monitor them.
LESSON 10 – How do dams deform on the run-up to failure?

SURVEY MOVEMENT MONITORING
We had set up monitoring pegs, read and co-ordinated in position and level daily by surveyors. As pre-failure deformation rates seemed (to me at least) something of an unknown, it was agreed that if the rate of deformation increased to be 25 mm or more between successive days, I would be called out to judge if failure was imminent. I relied on my innate knowledge of dams and earthworks to be able to make the judgement! I admit that by this time, when asked the question how likely did I think it was that failure would occur, I felt confident enough to say it was less that 50-50, mainly because there seemed no evidence of any serious signs of the causes of the damage, or of any changes in the dam's profiles.

The fact that we had simple pegs monitoring movement was re-assuring, and I recommend this is done in such situations, assuming that they don't develop rapidly, because it does provide evidence of malfunction or no malfunction, the latter being important in providing evidence to justify de-mobilising the emergency arrangements, when as often occurs, 'incidents' turn out to be non-incidents. Whether pegs should be permanently installed could be considered, though incident specific additions would probably be needed also. Lesson eleven – provide simple survey movement monitoring arrangements to monitor behaviour of dams during incidents.
LESSON 11 – Provide simple survey movement monitoring devices

FILL TYPES AND FAILURE MODES
While all these precautions were being dealt with, the matter of the cause of the incident, the 'hole', remained in question. If it was the top of an internal erosion pipe, the pipe below might be a sizeable cavern, and I felt that this precluded excavating into it. If a large hole was exposed, the excavator might fall into it. How would we stop an enormous hole forming, exposing the downstream side of the core, leading to its collapse and release of water, a terrible scenario? Could large quantities of filter be assembled and quickly shoved into the void if such a disaster struck? Such considerations had only one answer; don't dig into the hole until more is known about it. I have to confess that boreholes were to be done for other reasons at the dam, and this may have made such a decision easier.

However, if internal erosion were the cause, a knowledge of the fills, in the core and in the upstream and downstream shoulders, and the nature of the rocks in the foundation, would assist in assessing how vulnerable the dam would be to internal erosion. I knew something of the upstream fill because of the paper, and the core was puddle clay, but I knew nothing of the downstream fill, except that some, placed as part of the early repairs, was stony. The foundation, as seen in the culvert floor and in exposures near the dam, was open jointed sandstone.

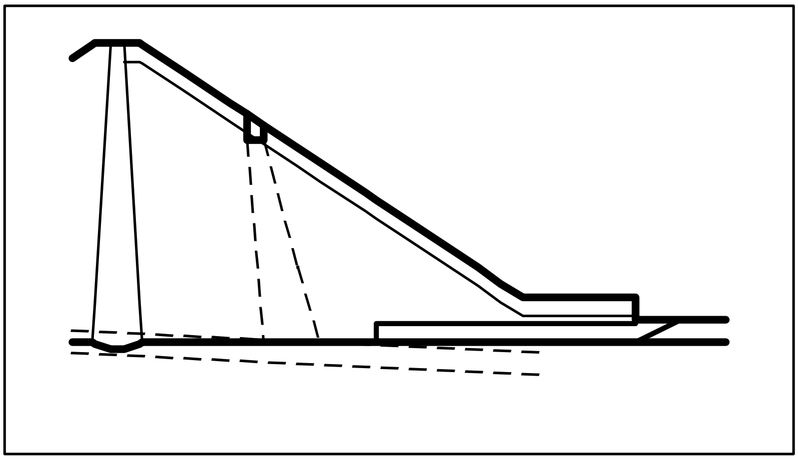

Figure 2 Erosion at interface between open-jointed foundation and fill; eroded materials carried downstream in joints in foundation rock, not visible in culvert. Subsidiary pipe leads to the hole on downstream slope.

As Figure 2 indicates, I postulated that water flowing in the open-jointed foundation rock might have slowly eroded through the base of the fill, including the core. Sediment in suspension was not visible in the culvert flows, but 'dirty' water containing eroded materials may have drained away below the foundation/fill interface and not been visible. An erosion pipe may have extended through the core, and the 'hole' may have been the top of a subsidiary pipe. This was worrying, but there were re-assuring signs, including no sign of local crest settlement (also being monitored by the surveyors) and no whirlpools in the reservoir (although they would not be formed if the upstream end of the erosion pipe broke out of the upstream shoulder at depth.).

Many of the anxieties about excavating into the dam and the potential for development of erosion pipes would have been dispelled if the properties of the fills were known. In our case the downstream fill was predominantly stone and gravel, not likely to be eroded, or to sustain open erosion pipes!

The property of the fills that can be most readily used is its in-situ permeability, easily measured in boreholes. Permeability values can be used as a qualitative indicator of the texture of the dam fills. However, the permeability values can be used quantitatively in drawdown stability analyses of the upstream slopes to establish the safe rate of drawdown. In the downstream slope the permeability values can be used in the 'perfect' filter equation (Vaughan & Bridle, 2004) to determine the filtering potential of adjoining fills, the shoulder fill against the core fill, for example, thereby indicating whether the dam is capable of self-filtering or is vulnerable to internal erosion.

LESSON 12 – Know the properties of the fills in the dam, core and shoulders, particularly their permeabilities.

WARNING THE PUBLIC AND ASSISTANCE WITH EVACUATION

When we considered what to do should the dam fail, we expected that police and owners' staff would enter vulnerable areas and advise residents to evacuate, assisting them as necessary. However, we learnt that modern 'duty of care' obligations would preclude sending staff, including police, into a situation where their lives may be at risk. The concern was that the flood wave velocity, and therefore the period during which police and owners' staff could safely assist evacuees, was very uncertain. This made it impossible to devise any system of tracking and warnings that would be sure to get people clear without failing to meet reasonable 'duty of care' obligations. There may have been time to help those living far from the dam; those nearer would have to be assisted by other means - a 'sky shout' helicopter! People would be told to evacuate by a voice from the sky. Many wouldn't be expecting trouble and might not believe their ears. How would they know which way to go to be safe? Rehearsals might have helped, but were not advised in the context of a possibly imminent failure, they may have caused panic. Leaflets were precluded for the same reason.

An unsatisfactory situation, but it leads to a most important lesson, lesson thirteen – there is not time to safely evacuate those living close to a suspect dam after the flood wave is released, i.e. before failure has definitely commenced. They may have to be evacuated before failure has commenced. Some dam failures have been telegraphed by clear signs, (e.g. Baldwin Hills, ICOLD 1974) giving more time for evacuation, but this is not always the case.

Some of the advice and recommendations that the police gave may have been coloured by my earlier less than 50-50 decision. I certainly felt confident enough not to insist on any pre-failure evacuation - but this is a decision that we will be called on to make in future incidents. It would be more effective if it were pre-planned and those living in the floodway were made aware of it

LESSON 13 – The time available to evacuate those in the floodway will be limited, plan to start evacuation before failure has definitely commenced.

PREPARING FOR DAM DISASTERS

Although dambreak analysis had been done at the dam, the incident showed that the contingency plan to deal with such a situation was generic and not site specific. This leads to lesson fourteen – that it is necessary to make full preparations to deal with evacuations to avoid dambreak floods. The provisions of the Water Act (2003) empower the Secretary of State to call for 'flood plans' to be prepared at reservoirs and it seems likely that they will be required for all high hazard reservoirs, where large numbers would be at risk should a dambreak occur. The statutory requirement for flood plans should lead to effective plans being put in place for high hazard reservoirs. Owners will still need to make plans, appropriate to the hazard posed, for all their reservoirs. Clear plans are needed and the emergency services and the public should know the plans, and what actions they will need to take if a dambreak occurs. They may need to be made aware of them by rehearsals, signposts, talks, and whatever other means seem appropriate, and there may be a need for routine refreshers.

LESSON 14 – Make clear contingency plans to deal with dambreak risks, alert the public to them and train them to evacuate effectively

BEING PREPARED AND 'EMERGENCY HANDBOOKS'

And that leads to the final lesson – owners, advised by dam professionals, can do a great deal to reduce the impacts of dambreaks. We have worked together under the Act and the good practice that has been developed around it, to make dams safe. We cannot eliminate all risk but we can prepare to deal effectively with the residual risk.

We tend to think that dealing with emergencies comes down to mobilising the contingency plan and evacuating people at risk. But a great deal can be done by analysis and at the reservoir, completely within the owners' control, to be prepared for emergencies. This improves the possibility of being able to control situations effectively, reducing the numbers of lives at risk by prompt evacuation and perhaps completely averting dam failure. An 'emergency handbook' about the reservoir would do much to equip Panel Engineers and owners' staff handling emergencies to deal effectively with a crisis. They would be much more in command of the situation; they would not be experimenting. They would know the consequences of opening up valves and other actions, and could balance the risks.

The fundamental objective is to save lives by prompt evacuation and by emptying, or lowering the water level in, the reservoir as quickly as possible without exacerbating an already difficult situation.

A most difficult decision is ordering evacuation, because to be effective at most reservoirs it needs to commence before it is certain that the dam will fail. Present knowledge does not equip us to be able to quickly detect how close to failure a faulty dam is. Our trained instincts and the performance of the suspect dam probably help us on this. A few years of focussed research would likely lead to better guidance. All the other technical information needed for emergency handbooks could be assessed from published information, some of it dating from many years ago.

If we knew, as we entered an emergency situation, who should be evacuated promptly, how many turns of the scour valve would lead to out of bank flow at critical points downstream; how many turns of the scour valve would precipitate rapid drawdown failure of the upstream slope and how much water should be released to reduce the risk to an acceptable level; we would be in control. We could give the emergency authorities more specific advice. If our observations of the performance of the stricken dam warranted it, we could go into the 'risk zone' and take a chance on local downstream flooding and upstream slope failure if it would bring the water level down more quickly and thereby reduce the number of lives at risk.

Also, if we knew more about the fill in our dams, particularly its vulnerabilities to drawdown failure and internal erosion, we could provide permanent or emergency stand-by measures to deal with them, thereby further reducing the probability of occurrence of emergencies or failure.
LESSON 15 – Be prepared, by finding out more about our dams and assembling emergency handbooks to equip us to deal with emergencies as effectively as knowledge allows.

INCIDENT OR DISASTER?
The incident had a happy ending, the dam did not fail, the reservoir was refilled and has performed satisfactorily since. As indicated on Figures 3 and 4 below, I concluded that the hole had formed following deformation brought on by a combination of circumstances associated with new drains and wet weather. The heavy rainfall discharged from the (temporarily) slotted toe drain and wetted the stony fill, which had been kept dry by the deep layer of clayey fill on the surface of the downstream slope. The wetting caused some movement of the fill as points were wetted and collapsed. The clayey surface fill had been cut through at top and bottom of the slope for new drains, and may have stretched a little. There was some evidence in a trial pit of soil movement into voids in the stony fill, local internal erosion.

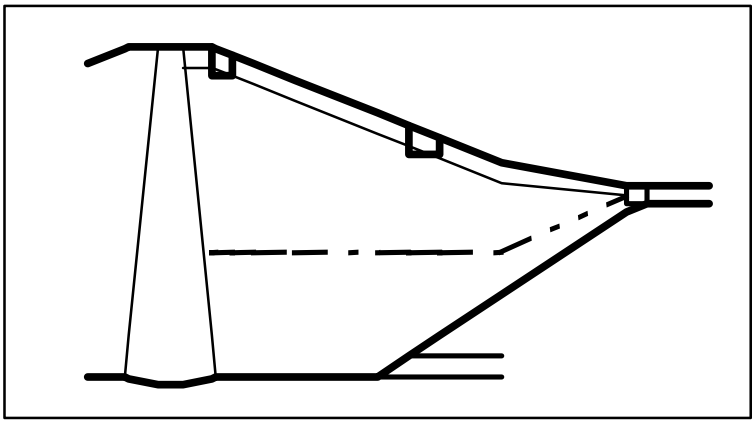

Figure 3 Cross section

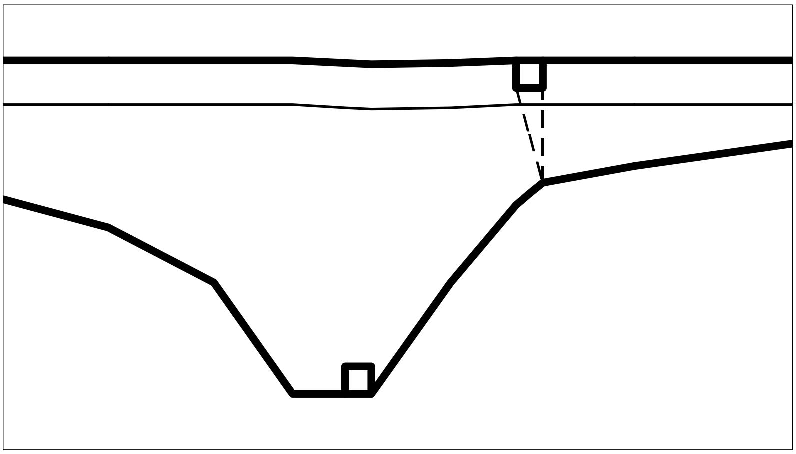

Figure 4 Longitudinal section

Figures 3 & 4 Conjectured mode of hole formation. Figure 3, cross-section, toe drain released water into stony fill, which may have settled slightly. Toe drain and crest drain cut through clayey surface fill, made slope less stable, allowed water in, surface fill moved. Figure 4, longitudinal section, foundation profile at hole position created differential settlement and adjustments in stony and clayey fill increased stress on clayey surface fill.

THE LIMITS OF OUR KNOWLEDGE AND USING WHAT WE KNOW

My final remarks relate to Panel Engineers and the expectations put on them. It would be easy to think that if you are appointed as a Panel Engineer, you must know enough about dams to respond expertly to any emergency. But as you have read, dealing with an emergency certainly revealed shortcomings in my knowledge, an admission shared, I imagine, by all but those entirely lacking in humility! While we will never know everything, it is disappointing that we do not routinely require safe drawdown rates and susceptibility to internal erosion to be checked using published techniques. Pre-knowledge on these issues would improve the safety of our dams and our effectiveness in dealing with emergencies. However, a proper sense of humility should not lessen our effectiveness in dealing with incidents. Those working with you will want clear and positive instructions as to what they are to do. I hope the lessons I've listed, when put into practice and assembled in emergency handbooks, will make that easier to achieve.

SUMMARY OF LESSONS

No	Lesson
1	It is rarely possible to quickly identify the cause of the symptoms that lead to incidents, consequently initial actions cannot respond to the cause, they need to be generally cautious
2	Record your experiences in a reputable journal, being able to 'talk' to predecessors is invaluable and eliminates much of the conjecture that inevitably arises during incidents
3	Think carefully about the impact of works to improve old dams
4	Take precautions first, don't take chances
5	Investigate fill in upstream shoulder and evaluate safe drawdown rate
6	Work out the opening v discharge relationship for the scour and other outlet valves
7	Identify pinch points and low-lying properties near the river downstream, estimate likely in-bank flow capacity, send scouts out to them when releasing water from the reservoir.
8	Do dambreak studies with differing retained reservoir volumes to give guidance on how much to lower water levels by in an emergency.
9	Faulty reservoirs should be under surveillance 24 hours a day, seven days a week. Provide experienced people, with a cabin or other shelter and ready access to phones.
10	We should know more about deformations before failure, and what means would be required to monitor them.
11	Provide simple survey movement monitoring arrangements to monitor deformations during incidents.
12	Know the properties of the fills in the dam, core and shoulders, particularly their permeabilities.
13	The time available to evacuate those in the floodway will be limited, plan to start evacuation before failure has definitely commenced.
14	Make clear contingency plans to deal with dambreak risks, alert the public to them and train them to evacuate effectively.
15	Be prepared, by finding out more about our dams and assembling emergency handbooks to equip us to deal with emergencies as effectively as knowledge allows.

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