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The 2016 Geoffrey Binnie Lecture: Dam Engineering – the last 50 years, the next 50 years

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This paper is an expanded version of the Geoffrey Binnie Lecture given by Dr Peter Mason at the 19th Biennial BDS Conference 2016 held in Lancaster. Dr Mason stepped onto his first construction site as a first-year student in the summer of 1966. His lecture considers some of the major developments in dam engineering seen by the writer over the past 50 years and speculates about what the next 50 years might bring.

1. Introduction

Ladies and gentlemen, it is a great honour to be invited to deliver the Geoffrey Binnie Lecture for 2016. Of course, one of the first challenges was deciding what to talk about, but then I remembered that as a Sandwich Course Student, I stepped onto my first construction site in the summer of 1966, exactly 50 years ago. I spent 6 months learning about tunnelling and the England football team won the World Cup. I cannot claim a correlation between the two, but I do like to think that my subsequent career has progressed somewhat more consistently than that of the English football team.

Of course, 50 years ago things were different for engineers. Design generally involved hand calculations with slide rules, design charts and seven-figure log tables. Drawings were done by hand and there were no scientific pocket calculators. They came in 1972 with the first HP-35. Computers were the size of rooms and had to be fed by punched cards. We still worked in imperial units.

In 50 years, there have been many changes to the way we work and many advances in the various fields which go to make up dam engineering. It is the changes and advances in some of these areas that I would like to explore with you today and then build on those to speculate about what we might see in the coming 50 years.

We will start with weather forecasting or as we engineers prefer to call it, ‘Hydrology’!

2. Hydrology

In the middle of the twentieth century, there was a consensus among hydrologists to focus on deriving extreme floods by focusing on the statistical analysis of rainfall data coupled with rainfall-runoff modelling. The change was made possible by the availability of new, electronic computing power and assumed that rainfall was essentially random. This meant that predictions for the future could be based on probability theory and that with enough data one could calculate, for example, the 1 in 1000 or even the 1 in 10 000 risks of extreme events occurring.

However, estimating such extreme probabilities needs a lot of data and even in the UK, far more than existed. Prior to 1960, there were just 600 stations with typical record lengths of 50 years and so ~30 000 station years of data. 1961 saw the addition of a further 6000 stations. This meant that the analyses for the 1975 Flood Study Report (NERC, 1975), which took place in the early 1970s, was able to claim that it was based on 96 000 station years of data. However it, of course, must be remembered that two-thirds of that, that is about 60 000 station years, covered a period of only 10 years.

More data have been assembled since. The 1999 Flood Estimation Handbook studies (IH, 1999) were based on 151 245 station years and the more recent long period rainfall studies on 171 904 station years. However, the records used are still heavily weighted over the period from 1960 to 2000. In other words, it is more of a spatial record than an extensive time history. It is unfortunate that we still talk about 1 in 1000 year events when what we really mean is a 1 in 1000th annualised probability of an event occurring based on a few years of relatively recent records. Of course, that does not matter if rainfall is essentially random and there are no long-term trends over time. But is that the case?

In the 1990s, I was working in Uganda on the Owen Falls Hydropower Project and discovered that the level of Lake Victoria, and hence the flows into the entire White Nile system follow a regular periodicity closely tied to variations in solar output. The relationship is so clear that it is really beyond dispute and I and now others have published on it extensively (Mason, 2006, 2010; Stager *et al.*, 2007). It can also be seen in the level records for Lake Naivasha and Lake Tanganyika and indeed in other long-term proxy records.

Further south, long-term periodicities on the Zambezi have affected floods and yield at the Cahora Bassa dam in Mozambique and at the Kariba dam further upstream. The effect on Kariba was especially notable and caused the coffer-dams to overtop during construction and the main flood relief works to be upgraded from 6000 to 9000 m^3/s while the dam was being built.

More recently, I became involved in feasibility studies for a possible dam on the Kafue river in the Zambezi catchment. We discovered a 200-year tree ring record which had been calibrated in the USA to give a 200-year average annual rainfall record. Recent values calibrated well against the river gauging records and we could show clear historic periodicities of more than 200 years and with a correlation coefficient close to 90% (Figure 1).

Recorded swings in cumulative river gauging data have been demonstrated throughout Africa from 1945 to 2000, while in South America the average annual flows in the massive Rio Parana have been shown to correspond to solar variation during the whole of the twentieth century. In the UK, May and Hitch of the Meteorological Office identified periodicities in certain aspects of UK rainfall data (May and Hitch, 1989).

Unfortunately, there seems to be surprisingly little interest in all this by 'conventional' hydrologists. One would have thought that being able to predict the likely times of flood and/or famine would be of interest to many such as Aid Agencies and Economic Planners, but it would be wrong to underestimate the degree of inertia in such things and the power of 'conventional wisdom'.

One of UK's greatest climate scientists was Professor Hubert Lamb who founded the Climate Research Centre at the University of East Anglia. It was later renamed the Hadley Centre. When I wrote to him about this many years ago his reply commented on, 'the sways of fashion in science' and that similar work had now been largely, 'dropped in favour of the more lucratively funded pursuit of CO_2 and global warming'. I think one could also add that many like the concept of probabilities as they can be used to generate statistics for use in other areas such as risk analyses and financial analyses. In doing so, they automatically generate answers which can then be used to justify decisions in lieu of having to take responsibility for personal judgement.

So, what of the future? With the increased data on weather events that the next 50 years will bring and with the increased connectivity that the Internet has brought I believe that such clear relationships and periodicities in weather and rainfall patterns will eventually become undeniable. In the UK, I see rainfall data being subdivided into a number of main weather systems for separate analysis. Even now the effects of El Nino on the UK weather are becoming more apparent, as are the influences of the jet stream and 'atmospheric rivers'. With time, such studies should also make it easier to separate and better differentiate between the changes due to the natural cycles and those caused by man-made global warming. In short, I would hope that in 50 years it will be possible to predict not just the likely magnitudes of extreme rainfalls but also give some idea of when and where they are likely to happen.

3. Hydraulics

Of course, having decided on the size of flood we have to dissipate its energy before releasing it into the river downstream. In

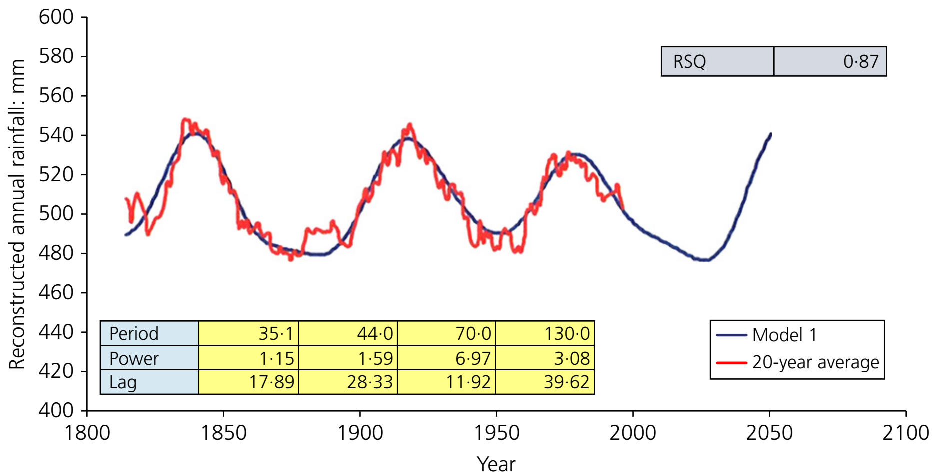

Figure 1. Fast Fourier transform based curve fitting to Zambia – Zimbabwe Reconstructed Rainfall data since 1810

the 1960s, designing a stilling basin for dissipating the energy of flood releases was straightforward. There were many standard arrangements developed by the US Waterways Experimental Station and made widely available through publications such as the Design of Small Dams (USBR, 1987).

But then things started to go wrong. Cavitation partly demolished the teeth in the stilling basins on some of the Pit River dams. At the Tarbela dam in Pakistan slabs weighing more than 800 t were lifted out of position by pressure differentials (Figure 2). The same happened at the Netzalcotl dam in New Mexico. Ball-mill action by the circulating debris has ground down the surfaces of the stilling basins at a number of dams in the USA such as the Libby, Dvorsak and Kinzua. Forty years of sluicing silt-laden flows led to the erosion and virtual loss of the 40 mm thick stainless steel liners to the deep sluices at the Rosieres dam in the Sudan. The unplanned erosion of the plunge pools downstream of the two Tarbela spillway chutes in Pakistan led to repair costs of ~US$200 million.

In most cases, the problem was the effects of scale. Arrangements that worked well in small models were extrapolated up to design heads, velocities and forces beyond those which the construction materials or systems could resist. In 1982, I studied the prototype histories of more than 300 hydraulic energy dissipaters from a number of countries. My resulting paper in the ICE Proceedings (Mason, 1982) led to a design chart on the preferred usage of the different types which has appeared in several textbooks although in many others I'm afraid the standardised solutions developed in the 1950s are still all too often repeated without qualification.

At the same time, cavitation damage was proving to be a problem on a number of high head chutes. Again, the problem was one of scale. High-velocity flows were vapourising at irregularities and the subsequent, high-intensity bubble collapses were literally excavating the concrete. The solution came in the form of air troughs which have now been embraced by many designers almost to the point of overuse.

However, the challenges and the need for innovation continue. Old solutions to minimising flood rise using labyrinth weirs have resurfaced in the form of piano key or PK weirs, including useful recent applications in the UK (Figure 3). Failures of the Ulley and Boltby stepped masonry spillway chutes led to Environment Agency funded research which has given us a far better understanding of their hydraulic performance and especially the vulnerability of poorly sealed wall joints (EA, 2010).

Massive downstream flow deflectors have been used to focus gated outflows into narrow downstream gorges such as at the 185 m high Tekezi dam in Ethiopia. At the Dasu dam in Pakistan, I designed a multi-jet arrangement which achieved a similar outcome. In other cases, dam crest vibration has been induced by the instability of crest overflows. This in turn has been traced to a sympathetic acoustic resonance between the overflowing sheet and the trapped air pocket beneath it. It is still an issue solved more by trial and error than by design prediction.

When the massive Yacetera dam discharged one of its first major floods in 1994, several thousand fish were killed by the supersaturation of the flow with dissolved gases in the deep stilling basins. When the air came out of solution, the fish in

Figure 2. Removal and destruction of stilling basin slabs in excess of 850 t by hydraulic action, at Tarbela dam, Pakistan in 1976

Figure 3. Renewed interest in Labyrinth spillways as shown by this example of retrofitting to a glory hole spillway to raise water levels at the Black Esk reservoir in the UK

the shallows downstream got severe bends and died. In recent years, I have been working with BC Hydro of Canada advising on ways to avoid this at the Site C dam in Canada. Here, low flows will be directed to only the upper surface of the water in the downstream stilling basin. The aim is to avoid diving jets and hence the problems at Yacetera. The interesting thing about Site C modifications is that they also produce a better hydraulic performance at probable maximum flows and so represent a modification that should perhaps be considered on all simple stilling basins.

Vortex drop shafts, hydraulic brakes and orifices to control large tunnel flows are all innovations that have emerged in recent years and which are expanding the ranges of options available to hydraulic engineers. Perhaps one more worth mentioning is the Roberts Crest Splitter. If the arrangement had been developed in the USA, I think it would almost certainly now be a universally adopted and standard solution for dissipating energy from high head overflows. But it was developed by Col Roberts in South Africa. Even so awareness and usage is spreading and will hopefully continue. I have been involved in the successful use of the arrangement on major dams in South Africa, Sri Lanka and at the Wadi Dayqah dam in Oman.

Again, what of the future? Here I think the solution hinges on one thing: the increased use of computational fluid dynamic (CFD) modelling. The models are in many cases still best used in conjunction with physical models but the ability to quickly model changes and model fluid dynamics at full scale, including air entrainment, will make the use of CFD modelling a fundamental part of any major design. Indeed, this is already happening. I would expect this to develop still further with CFD becoming the definitive way of producing the most economic arrangements in a way that also ensures safe and secure operation.

4. Structural concrete design

I spent many years at the start of my career running design teams and preparing reinforced concrete designs for hydraulic structures. We constructed bending moment and shear force diagrams and allowed for torsion and enhanced shear capacity near supports. We used books with structural design charts but in 50 years I believe all that will be historical memory. As students launch into their careers, along with CFD, Mathcad and AutoCAD packages on their laptops they will all have finite-element packages. Why not? Any shape, even a simple beam, will simply be modelled, loaded and analysed and with reinforcement added according to principal stress magnitudes, locations and directions. Indeed, packages may even do that for them now to some extent, along with producing the bar schedules. Again, why not? We can do that already for straightforward arrangements. It will simply need adapting to more complex shapes. Of course, the design codes will need to be rewritten in terms of principal stresses rather than shear, torsion and bending moments but that should also not be too difficult.

The only other prediction I will make in this area about the next 50 years will be on the likelihood that many hydraulic structures built in the 1970s and 1980s may need to be replaced or strengthened. Limit state codes were introduced in the early 1970s and with durability controlled by a focus on a ‘designed crack width’. The result was a closely spaced rebar operating at much higher stresses and with mild steel universally replaced with high tensile steel. It also resulted more crucially in concrete covers being reduced.

At around the same time, research by the UK Cement & Concrete Association (Beeby, 1978) demonstrated that, after about 6 months, there is little correlation between surface crack width and reinforcement corrosion. The reason is quite simple. Corrosion occurs as an electrolytic process within the concrete matrix and with the transfer of ions between different parts of the embedded rebar. Best long-term durability is ensured by maximising the concrete cover to the reinforcement and by using a high paste and low water/cement ratio mix to reduce the permeability of the cement matrix. Unfortunately, the changes to limit state design had taken all these aspects in the opposite direction.

In this case, I think durability requirements are now better understood, but over the next 50 years I believe that a number of our structures may need replacement or repairs with epoxy systems or with bonded plates. In fact, I wonder in future if we might see this leading back to further increases in cover, an increased use of corrosion-resistant rebar and/or waterproofing systems applied to concrete when new.

5. Concrete and masonry dams

One of the biggest events regarding concrete at dams in the past 50 years has been the effects of alkali aggregate reaction (AAR). Generally, the issue is not serious and involves a slow and gentle swelling of the concrete. Problems emerge when the swelling or expansion is significant, when the geometry of the dam leads to structural cracking and/or when the tolerances on mechanical parts such as gates, are lost leading to jamming and seizure. Some major dams such as Kariba and Cahora Bassa are affected and many in the UK (Figure 4). One UK dam, the Maentwrog dam in North Wales, has been replaced due to AAR and it is possible that over the next 50 years some others in the world will also come to the end of their useful life. However, in most cases the next 50 years will see the serviceability of such dams being maintained through careful monitoring and management.

Figure 4. Leakage past gate seals due to AAR-induced expansion of the dam concrete at the 175 m high Cahora Bassa dam in Mozambique

Figure 5. Final stages in the construction of the Can-Asujan, FSHD in the Philippines in 2005

Perhaps, the biggest revolution in concrete dams in the last 50 years has been in terms of concrete placement. The economics of concrete dams was drastically improved using roller compaction to the extent that for any new, mass concrete dam, roller-compacted concrete (RCC) is now the default option. To date more than 700 dams have been completed worldwide. There are still some differences in approach between high paste and dry lean mixes but even these are becoming less. Specific techniques have been developed to the extent that many, such as the Chinese, will vibrate reinforcement into the RCC effectively producing reinforced concrete around internal rooms and on surfaces where rebar is required.

More recently, still roller compaction techniques have been used to develop faced symmetrical hardfill dams (FSHD). This form of construction comprises cement stabilised as-dug material into a trapezoidal shape which is then faced upstream for waterproofing. It is a simple and robust technique with good seismic characteristics and capable of safely overtopping. It is also suitable for stiff soil foundations and not just rock. I had the satisfaction of designing one of the first of these, the Can-Asujan dam in the Philippines (Figure 5). Both the Japanese and Chinese have now standardised the technique in their own ways and an ICOLD Bulletin on them is under preparation. Most examples are sealed upstream using a slip-formed, reinforced concrete slab; but more recently the Filiatrinos FSH dam in Greece was completed and sealed upstream using just a geomembrane.

But perhaps, the very latest innovation is again the Chinese use of grouted rockfill to form mass concrete dams. The Chinese refer to these as rock-filled concrete or, RFC, dams. Something similar was attempting in the UK in the 1950s and called ‘Colcrete’, but the results were variable. The Chinese approach comprises placing 300 mm and above rockfill in shutters and effectively grouting it up using a small diameter aggregate, superplasticised concrete. At present, about 80 dams have either been completed or are under construction using this technique. It features particularly good thermal characteristics with net temperature rises on hydration in the order of only 5–8°C as the hydration heat of the cement paste is absorbed into the rockfill. Interlock and shear transfer between layers is of course excellent.

In parts of Africa multiple arch masonry dams suit the availability of cheap labour and when combined with modern finite-element analyses are proving to be a very cost-effective option.

The way forward in future may be governed more by simplicity as a way of driving down costs and not by overspecification. For example, a 50 m high concrete gravity dam will develop foundation stresses in the order of 1·0 MPa. A similar FSHD will produce only 0·5 MPa. Implied concrete cube strengths of either are only in the order of 5 MPa and certainly in the case of the FSHD this does not change much under earthquake. Clearly, such low stresses do not require conventional concrete or even hard rock foundation. Perverse as it may seem the future may see us going back to much weaker and simpler mixes as being all that is needed and with minimal associated Q_a/Q_c requirements.

6. Embankment dams

A number of things have come together over the years which have favoured the construction of embankment dams.

They have included the continued development and understanding of soil mechanics as a science, the widespread availability of computers, appropriate software for complex analysis and the development of large, heavy earthmoving machinery. These have led to the construction of ever higher and more sophisticated embankments. One especially notable achievement was the 147 m high Mangla dam in Pakistan. This was completed in 1967 and so ties in well with our 50-year horizon. The design was led by Geoffrey Binnie, in whose name this series of lectures is commemorated. The dam was one of the first in the UK to be analysed using slip circle analysis, something which is now routine. It was also the first to have its design dominated by considerations of internally sheared clays. From 1997 to 2007, I was fortunate enough to be involved in raising the dam by another 10 m.

Of course, Mangla and its neighbour Tarbela were both classic earthfill dams built of, and on, some materials that were potentially highly erodible. The design of the filters between the cores and shells of such dams had long been built on empirical relationships. Unlike the safety factors which could be calculated for slip circle failures and for mechanical performance in general of such dams it frustrated many that while internal erosion was one of the main causes of earth dam failure no similar safety factors could be identified. In recent years, this has been addressed by applying event trees and statistical risk assessments to the individual events themselves. We now have the internal erosion toolbox developed by the US Bureau of Reclamation (USBR, 1987), US Army Corps of Engineers (USACE, 2009) and the University of New South Wales and the new ICOLD (2016) guidelines. These have indeed represented a big step forward but even now individual probabilities have to be assessed largely based on guesswork, albeit hopefully experienced guesswork using carefully crafted guidance documents. While the results may be represented to two decimal places, as one of the main authors of the USBR (1987) toolbox advised me once, 'all you are really going to know at the end of the assessment process is whether the dam is generally safe, unsafe or somewhere in-between'. Risk assessments are now being increasingly applied to many aspects of dam engineering although similar cautions apply. Points which appear on as low as reasonably possible diagrams should perhaps be more realistically represented as vaguely shaded zones.

But perhaps the biggest embankment dam development in the past 50 years has been that of the concrete faced rockfill dam (CFRD). Early rockfill dams suffered from severe settlement. This became especially apparent when one slumped by more than 2 m during construction due to heavy rain. Sluicing rockfill into position became the norm until it was replaced by controlled compaction in layers using heavy plant. Such dams were sealed with upstream membranes and eventually the use of a thin reinforced concrete slab became the norm. Confidence grew when the 110 m high Cethana dam was completed in Tasmania in 1971 and which doubled the height of previous CFRDs. I was fortunate enough to be retained to inspect a number of Tasmanian dams in 1990, including Cethana, and found it to be in excellent condition.

Nowadays, especially when rockfill is plentiful and core material is not, the CFRD is the favoured choice for dams and many examples now extend to around 200 m in height. However, with increased confidence also came overconfidence. Leakage along the plinth joint became a common problem and then several high dams such as Mohale, Tianshengqioa, Barra Grande and Campos Novos, all constructed with basalt aggregate, featured serious face slab failures (Figure 6). The problem was traced to a combination of dam height, valley shape, the type of rock and a reduction in the number of movement joints in the slabs. Lessons were learned and, in particular, more movement joints have now been reintroduced in such slabs and with internal and external seals. Interestingly, rockfill dams with central concrete core walls have a statistically much better safety record than CFRDs, or indeed any other type of dam, although these have largely fallen out of fashion.

Advances in the earth sciences generally have also continued in the last 50 years. One aspect of this has been the tremendous advances in the understanding of rock mechanics brought about by the work of Evert Hoek and others (Hoek and Bray, 1974; Hoek and Brown, 1980) and the use of techniques such as finite-boundary methods, non-linear analyses and programmes such as FLAC and RockLab. There have been similar advances in foundation treatment such as the advent of

Figure 6. Upstream face joint spalling at the Mohale concrete-faced rockfill dam in Lesotho in 2007

grout intensity number grouting techniques, colloidal mixers and new options for improved grout mixes. However, all these require almost their own dedicated presentations and so here we will simply acknowledge them.

So, what of the future? In the case of earth embankments soil properties are accessed based on a whole range of empirical indices and tests which have been developed over the years. May it be possible at some point to redefine and derive the properties of any soil material from the soil chemistry and just a few basic geometric parameters? When it comes to construction, compaction of soils on site can now be monitored by feedback systems into the cabs telling the drivers when the required degree of compaction has been achieved. There is no longer a need to define an arbitrary number of passes. Indeed, the driver no longer needs to be in the cab. Remote control of driverless construction machinery is now established and used in Japan. We are moving towards a time when the complete construction of an embankment could arguably be preprogrammed and automated much in the way that assembly factories work, and with operators required principally to monitor and maintain the plant. Nowadays, monitoring and control do not even have to be done in the same country. This approach would tend to favour simplified designs but even the construction of adjacent filters can be simplified by simultaneous placement. All this is possible now and while not the norm, remember we are looking 50 years ahead.

7. Dam safety

Ladies and gentlemen, at this point I realised that my talk was getting overly long and I was about to prepare sections on monitoring and interpretation, risk assessments and legislation. Then I realised that they are all aspects of the same thing: dam safety.

Ensuring that a dam is safe is about appropriate maintenance and it is also about understanding the dam and its behaviour. This requires monitoring.

I am always amazed to find dam owners monitoring and filing data but otherwise doing nothing with it. I tell them that all they are doing is assembling evidence which can be used against them at the public enquiry should anything go wrong. The whole point about taking instrumentation readings is because those readings should be telling the engineer something about the way the dam is behaving and the engineer needs to be finding out what that is.

In the case of the Victoria dam in Sri Lanka, seepage rates increased once the reservoir reached a certain elevation on first impounding. This is not unusual in a double-curvature arch dam where the flexure of the dam can cause a localised foundation crack at the upstream heel. It is why the grout curtain in arch dams is often located centrally rather than upstream. It was that experience which helped me guide South-West Water on the technical requirements of the contract they needed to place when they called for engineering advice on sealing the left flank of the foundations to Wimbleball buttress dam.

In the case of Victoria, the seepages decreased as sedimentation started to seal the foundations. In the case of Wimbleball, seepages initially seemed to be broadly proportional to the reservoir level; however, when I plotted them with the seepage points joined as a timeline more was revealed. A hysteresis effect could be seen with seepages increasing every time the reservoir levels increased and decreased (Figure 7). It indicated that material was being lost and that the foundation materials were unstable.

A similar hysteresis effect can be seen with the crest length of the Dinas concrete arch dam in Wales. The dam is affected by the AAR in the concrete and so is expanding, although when the annual length-change cycles are compared, it can be seen that the overall expansion rates are now much lower than in the early years after construction.

When assessing the risk of dam failure one of the key parameters is frequency of monitoring. The potential failure risk can be considerably reduced if monitoring is frequent and measures are in place to respond immediately should an emergency occur. There are a number of major dams in the world with continuous real-time monitoring of key failure indicators with links to alarms and phones to 24 h monitors.

In 50 years I see this as becoming routine in high-consequence dams where significant human life or economic loss is threatened. Could yet another step be to make the results available in real time on the Internet so that interested members of the public could take part and be reassured much in the way one can dial in now to many public web cams? And before objections are raised I would ask the question why not?

Embedded temperature, pressure and strain cells for continuous monitoring could be coupled to the use of unmanned drones and surveillance cameras to enable routine regular inspection in even the remotest of locations.

In recent years, risk analyses have played an ever more important role in assessing dam safety and while I suspect we will see many more changes in future to what is accepted as current best practice, all sequential events in a failure event tree will end with one assessing the likelihood of detecting potential failure followed by another assessing the likelihood of being able to intervene to prevent it. I would argue that the

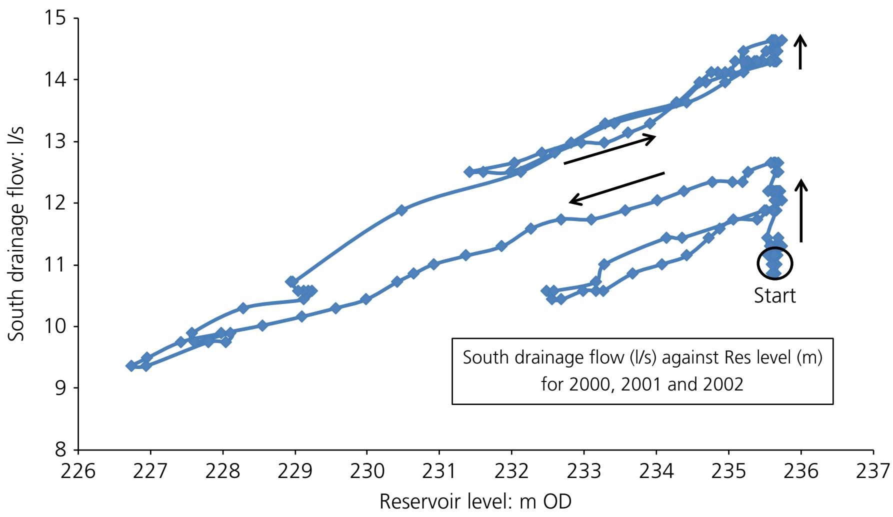

Figure 7. Plot of seepage flows versus reservoir level for Wimbleball dam showing instability of the foundation material between 2000 and 2002

more we can guarantee the certainty of the outcomes from these last two events, the more the rest of the event tree becomes redundant and the risk of failure vanishingly small. I suspect that this is where attention to risk is actually and correctly, taking us.

Of course, monitoring has to be focused on having identified the key failure mechanisms and so also assumes that the dam safety engineer will have sufficient time to review the results of monitoring and assess what it indicates. In an ideal world, one would also hope that any dam safety legislation is compatible with that notion or even that it encourages it.

In that sense, I am not sure that the recent changes to UK dam legislation have been useful. Storage capacities which will define whether a reservoir will be subject to legislation will drop to 10 000 m^3 in Wales while remaining at 25 000 m^3 in England. The loss of any human life is paramount to reservoir category designation in all areas, but heritage is now also a dominant factor in Scotland whereas it is not referred to in England. Traditional panel reports and certificates have been retained in England while Scotland has moved towards just certified lists of requirements, something which is likely to make the next ten yearly inspections very expensive. Most legislators seem to have followed England's example of changing the English language such that the word risk has been redefined to mean hazard, although Scotland are trying to adhere to more conventional usage and Northern Ireland look like they will retain categorisation based on the word hazard. In all cases, the level of bureaucracy has increased. This can be a good thing, as can checklists, provided they still allow time for experienced engineers to stand back and think about issues and above all to use judgement.

I like to think that one attribute that UK engineers are lucky enough to have, almost as part of a national psyche, is common sense. I have found that at all levels when it comes to those engaged in reservoir management, from panel engineers to supervising and operations staff. Let me also share with you three questions that I always ask myself when inspecting a reservoir over and above of course applying all the usual requirements of the act and considering appropriate UK and international guidance.

The first question I ask myself is, 'if my mother was living downstream of this dam would I be happy?' If a dilemma emerges which calls for difficult judgement I also ask myself, 'what would Derek do?' I should explain that Derek Knight was an early mentor of mine who was also an AR panel engineer and who was obsessed about always doing 'the right thing'.

Lastly when completing my report, I ask myself, 'If a serious incident occurs in future at the reservoir and I am standing in court 5 years hence giving evidence, could I defend the report I have produced and the decisions and recommendations I have made?'

In short, I believe there is always a case for standardising many aspects of reservoir engineering but coupled with sufficient freedom and flexibility to use the experience and judgement that panel engineers bring and which they have built up during their careers and which is especially appropriate when assessing dams where each one will have its own uniqueness and idiosyncrasies. In doing this, there is particular value in overseas experience where one can still become involved in the design and construction of new dams. This used to be easier when the UK aid was tied to trade and also to basic infrastructure, something I still think that any UK government should move back to. Not only does it provide a better guarantee of useful product delivery it builds international relationships which can last a lifetime.

So, what of the future? I think increasing standardisation is inevitable but that we in the UK need to address the apparent disintegration of consensus which is taking place at present with regard to reservoir safety legislation. In 50 years, I see an increasing international, and perhaps even a European consensus, on what reservoir safety control should comprise. I believe we have a part to play in that debate while at the same time there is also good legislation elsewhere and guides from places as far apart as Australia and Canada from which we could usefully learn. I see further changes ahead and I would like to think increasingly shared knowledge and understanding of these issues. It is an area where organisations such as ICOLD and some well-known UK trade journals already play a valuable role.

8. Sedimentation

Sedimentation is the elephant in the room which is why I have left it till last. At present billions are spent annually on new dams and reservoirs, but storage is being lost faster than it is being replaced. It is happening at the rate of about 0·8%/year. An estimate at the ICOLD Conference in Brasilia suggested that a third of the world's reservoir storage had disappeared by 2010 and two-thirds will be lost by 2050 (ICOLD, 2009). This is well within our 50-year horizon. All areas of the world are affected.

We must also remember that only fine sediment normally reaches the dam wall. Coarser sediments will settle in the upstream areas and can affect flood storage and flood routing capacity. The lack of sediment transport can also lead to downstream river degradation and loss of nutriment. In some areas of the world such as the River Nile in Egypt this has led to the loss of coastline at river deltas.

Population growth and poor catchment management are exacerbating the problem and leading to reduced water storage becoming an increasing problem in some parts of the world. There is a need for a better appreciation of the issue, a need for better management of reservoir operation in conjunction with adequate flushing facilities. There is a need to work with others towards a holistic approach to river basin management.

The future will see an increased understanding of the issues as storages are lost and the results are felt by civilian populations. There will be a need to retrofit flushing facilities in many reservoirs. Modified reservoir operations will ensure that large floods are passed at low reservoir level through low level outlets. For small reservoirs, there will be an increased use of dredging and developments are already underway on continuous dredging with downstream discharges perhaps by way of Archimedes screw turbines, an arrangement which has a positive net energy output.

9. Some final wishes for the future

So far, I have summarised where I feel some directions are taking us. I see hydrology daring to become more predictive and computer software increasingly guiding bespoke hydraulic and structural designs and analyses. Improved software and intelligent interrogation methods will allow ever more sophisticated monitoring and interpretations of dam behaviour in real time. That in turn should significantly reduce the risk of failure.

One of the great beauties of dam design is the ability to select in each case from an almost infinite number of alternative solutions in which the best compromise is achieved between hydraulics, structures, geotechnics, hydrology and geomorphology, cost and risk. However, there is still a tendency by some to preselect which type of dam they want and to try and 'make it fit', or to use 'standardised' arrangements in situations where something much better is possible. There can still be a tendency by companies to use generalised structural and geotechnical departments for those aspects of dam design and without the holistic understanding and experience needed to get the best overall solutions. There is still a tendency for dam designers to separate between embankment dams and concrete dam specialists and without an integrated approach which explores all options including hybrids and variants.

I wish for a future where dam design remains a speciality in its own right such that the designers retain the ability to work across the spectrum of disciplines. Specialists will still need to be there and will of course remain valuable but the overall concepts must remain guided by the wider view. This will involve a full appreciation and understanding of alternatives and also the most appropriate type for a given situation. In future, this may start to require a better understanding of life cycles and even the eventual need for removable dams. It will likely involve an increasing use of new materials and techniques.

Lastly, I believe we should remember the words of the economist John Kenneth Galbraith (1971) who said that it is the duty of each generation to leave behind civic monuments for the next. Dams are such monuments and I believe need to be treated as such rather than simply as utilitarian, industrial structures. When I started at Gibb many years ago, all dam projects had an architect allocated to them to ensure that form was also considered. It is a practice which seems to have disappeared.

Figure 8. The Wadi Dayqah dam in Oman featuring the writer's layout. Crest splitters were added to increase safe unit spillway discharge and the dam curved to enhance structural redundancy, better suit spillway hydraulic requirements and to enhance aesthetic appearance

When I designed the Can-Asujan dam in the Philippines, I curved it at negligible cost. Similarly, at the Wadi Dayqah dam in Oman, I was queried when I changed the earlier straight alignment to a curved one (Figure 8). I explained the benefits in terms of structural redundancy, hydraulic performance and aesthetic improvement and the question was never asked again. Again, the change was cost-neutral and I understand that the dam has become something of a tourist attraction.

There are many examples where thought has been given to form and legacy, from the Khadjoo bridge dam in Iran dating back to 1650 to the more recent Lake Lanexa dam in the USA. Dams can be used to accommodate sculpture as at the Arriaran dam in Spain. Spillways can be used as a canvas as at the Cuevas dam. At the Eibenstock dam in Saxony artistic grit blasting has been used to render a commemoration to salmon on the downstream face of the concrete dam.

Ladies and gentlemen, I hope I have shown that the recent history of dams has been one of innovation and change. It has been a great pleasure to share my personal experiences of some of those changes with you and to speculate about possible future change. Many of you will have your own visions about what some of those might be. What I would say is be imaginative and seize those opportunities for future innovation. Make them your own. Be prepared as well to look overseas as you will likely find others wrestling with the same problems as you. They may have even developed solutions.

Ladies and gentlemen, as dam engineers you are members of one of the noblest professions, providing reliable supplies of freshwater and power for the benefit of society and future generations. Thank you so much for giving me the opportunity to share my thoughts with you on that. Thank you so much for listening.

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