Past incidents help to shape future dam safety strategies

The fact that major dam failures are extremely rare is testament to the fact that continuous efforts are made by the dam engineering profession to refine knowledge in the field of safety. A recent ICOLD initiative to re-examine past dam incidents and accidents and to see what lessons can be learnt, will have made an important contribution to enhancing dam safety.

The importance of communication, learning from past experience, comprehensive training for dam operating personnel, and providing adequate levels of redundancy for critical control equipment were among a number of key issues identified as vital, during a two-day workshop in Stockholm in November 2013. Experts from more than 20 countries met to discuss 'Accidents and incidents – What can we learn?' at the workshop, which was jointly organized by SWEDCOLD and ICOLD's European Club.

Twelve case studies relating to failures, or incidents which could have led to failures, were discussed in depth, with frank and constructive analysis of the various contributory factors. Some cases related to design or construction aspects, others to human error, but more often a combination of factors had led to hazardous conditions. Recurrent themes echoed by a number of speakers over the two days were: the need for knowledge sharing; the importance of not only focusing on extreme events, when a number of seemingly minor incidents could also lead to catastrophic failures; and, the need to base future safety policies and procedures on lessons learnt from the past.

ICOLD Vice-President Jose Polimón welcomed participants on behalf of the European Club. In his opening address he underlined the importance of training and capacity building, of encouraging more young people into the dam engineering profession, and of increasing public awareness activities, including by the use of social networking. With respect to dam safety, he felt that greater use of risk analysis should be encouraged. A future challenge for the profession, Polimón said, would be increasing knowledge about climate change.

Polimón added that in his new role as Vice President of ICOLD, he would do his best to improve communication between the various ICOLD Committees, and also strongly support the regional clubs. He congratulated SWEDCOLD on the initiative to hold the workshop.

Chairman of the organizing committee, Anders Isander of E.ON, set the scene for the technical sessions by calling for a greater safety culture to be created in the industry. "Local governments and authorities can play a role", he said, "but only the industry can take responsibility". He added that ICOLD had a vital role to play in this respect.

The need for documenting and sharing information was particularly critical in preparing young engineers to be responsible for existing water infrastructure, he stressed, especially as some of the world's dams were more than 100 years old. Problems could arise when not all documents were available from the time of a dam's construction, and young engineers may not understand old terminology, or even old types of materials used for construction, he added.

Dr J. Polimón, Vice President of ICOLD, welcomed delegates to the Workshop on behalf of ICOLD's European Club. In this opening address, he stressed the importance of capacity building and training. Later in the Workshop he gave a presentation on the failure of the Aznalcóllar tailings dam in Spain.

Isander acknowledged that over the past 10 years, huge developments had been made in methods of studying old dams. "We have a lot of data", he said, "but the problem may be to know which data are critical and not to make wrong assumptions".

He pointed out that the aviation and nuclear industries were very proficient in sharing information, and it was surprising that a mature profession like dam engineering had much to learn from these "younger industries".

Commenting on the fundamental reason why accidents occurred, Isander said that they were a sign of deficiencies and weaknesses, often based on uncertain factors, and sometimes on human behaviour.

In general, dam engineers were good at traditional forms of accident analysis (the technical approach), but human and organizational factors also needed to be

Chairman of the Workshop's Organizing Committee, A. Isander of SWEDCOLD. He called for "a greater safety culture in the dam engineering industry." ICOLD was playing a great role in this respect, he felt.

M. Poupart, Chairman of ICOLD's Dam Safety Committee, told delegates about ICOLD's e-database of dam incidents.

addressed, Isander said. To underline this point, he quoted from Einstein: "Without changing our patterns of thought, we will not be able to solve problems created with our current patterns of thought".

Michel Poupart of France, Chairman of ICOLD's Committee on Dam Safety, discussed ICOLD's 'e-database' of incidents. He began by reviewing ICOLD's previous publications dealing with safety (Bulletins 59, 99, 130 and 154). The publication 'Lessons from incidents', published in 1974, had reviewed 266 cases, and in 1983 an important work entitled 'Deterioration of dams and reservoirs' had documented 1105 cases. Bulletin 99 had been an analysis of failures, with details of 179 cases. In 2005, Poupart said, a decision had been taken to update ICOLD's database, and a questionnaire had been sent to national committees. Only 15 had responded, which underlined the fundamental difficulty of obtaining data. In some cases, Poupart said, there was a reluctance to share data, and in other cases legal aspects could be an impediment. Useful information had been received, however, from the USA, UK and Sweden.

As well as a lack of international input, there was also an imbalance in the kinds of problems for which information was available. Examples of well documented phenomena were internal erosion, overtopping, and face slab cracking of CFRDs. It would be interesting, he felt, to collect more information on recent cases of problems relating to newly built dams.

Valuable data were generally available from countries where it was mandatory to report incidents to the relative authorities. Poupart added that it was important not only to collect data, but also to validate it. Plenty of information on failures could be found on the Internet, but this could not be considered significant without a process of validation.

He felt it would be constructive in the future for the Committee on Dam Safety to inter-act with the Committees on Surveillance, and on the Register of Dams.

During the discussion, Mike Cambridge, from Cantab Consulting, UK, stressed the need to ensure that all countries reported to the same standard; past attempts by ICOLD had demonstrated that some countries would report relatively minor incidents (sometimes more than once), and other countries without regulations in place would not report quite serious incidents at all. This could lead to unrealistic assumptions being made about trends and statistics, which could be detrimental to the reputation of some countries.

Overtopping and flood risk

The first technical session was chaired by Prof Ignacio Escuder of Spain, and it focused on risks and incidents of overtopping. Prof Escuder noted in his introduction that overtopping could cause a wide range of situations, from minor incidents to major failures.

Human issues were often involved, for example, the way in which gates were operated, and in some instances, different levels of management being involved with safety.

One relative advantage of overtopping compared with other hazardous phenomena, he felt, was that it took time to develop, and therefore generally provided the opportunity for warning systems to be activated, and for evacuation procedures to be implemented. Therefore, even in the case of a major overtopping incident, loss of life could often be avoided.

The first case study was presented by Jonathan Hinks of HR Wallingford, UK. He discussed the 16 m-high Ulley dam, near Sheffield, constructed in 1873, for water supply (it had been sold to a national park in 1986, when the water supply had no longer been needed). While he pointed out that the incident had not constituted a major failure, it had inconvenienced a lot of people, he said.

The embankment dam, with a puddle clay core, had originally been equipped with a masonry stepped spillway. A new spillway had been added, at the left abutment, during upgrading work in 1943. Further upgrading work had been done, to raise the spillway crest level by 1.8 m.

In June 2007, during heavy rainfall (92.4 mm of rain had fallen over the night of 24/25 June) the sidewall of the old spillway had failed, as a result of high hydrodynamic forces. 1000 people had been evacuated, and one of the UK's major motorways (the M1) had had to be closed. The case had led to some interesting studies on spillway hydraulics.

The rainfall had represented a 200-year event, Hinks said; 6.1 m^3/s had been discharged from the old masonry spillway, and a further 4 m^3/s from the 1943 spillway. Erosion of the downstream shoulder of the dam had resulted, followed by the collapse of the walls

Dr J. Hinks, of H.R. Wallingford, UK, discussed an incident at the Ulley embankment dam in the UK. This underlined the importance of communication between government departments and dam safety engineers, to ensure that the hazard classification of a dam could be appropriately selected.

Prof I. Escuder of Spain chaired the session on overtopping and flood risk. A relative advantage of overtopping, compared with other hazards, he said, was that the problem normally took some time to develop, generally allowing time for warning systems to be activated.

of the old spillway. Skimming flow of more than 8 m/s had occurred in the stepped spillway channel.

Stones had been dislodged from the sidewalls, and it had not been clear whether this had been caused by high pressures behind the stones, or low pressures in front of them.

Regarding the condition of the side walls at the time of the incident, Hinks said that most inspecting engineers probably would have considered them to be sound.

A key point, Hinks observed, was that eight coal seams had been worked in the past, in the vicinity of the dam. The dam owners had purchased the pillar below the dam, so mining had not continued there, and it had probably been considered that the mines (at depths of 300-677 m) would not have caused a problem for the stability of the dam and associated works. As coal mining in the UK had virtually stopped in recent years, Hinks suggested that people had tended to disregard the significance of old mines. In this case, subsidence caused by the old mine shafts could have led to the creation of a difference in levels between the two spillway sills. (It was agreed during the subsequent discussion that disused mines anywhere near a dam should be regarded as a serious hazard.) Hinks pointed out that Ulley dam had been classified as a Category C structure, which meant no risk to life in the case of failure. However, he pointed out that there was a high-pressure gas main just downstream, and also the busy M1 motorway nearby. He explained during the discussion that this surprisingly low classification of the dam in the light of the gas main nearby had probably come about because those responsible for the dam had not been aware of this. It was not uncommon, he said, for information to be withheld about the location of strategically important infrastructure, for reasons of national security. Hence, a risk to a dam could be caused by a panel engineer responsible for its safety not being informed about some infrastructure believed by politicians to represent a security risk.

After the 2007 incident, Hinks said, the reservoir category had been increased to A. The spillway capacity had also been increased to pass the PMF, and a new bottom outlet had been constructed, to increase discharge capacity further.

Among the main lessons from the Ulley incident, according to Hinks, were that:

- the hydrodynamics of masonry spillways should be carefully checked;
- checks should be made for 'hidden infrastructure';
- a high standard of maintenance was obviously required;
- emergency plans (in the UK) should dovetail with the Civil Contingencies Act, 2004;
- geology and mining issues should have been addressed in this case; and,
- at Ulley the drawdown capacity (of the bottom outlet) was too low, at only 150 mm/day.

The next case, discussed by Carl Rizzo of Paul Rizzo & Associates, USA, concerned the upper reservoir of the 450 MW Taum Sauk pumped-storage scheme in the USA, which had failed abruptly on 14 December 2005. The scheme had been in operation since 1963, he said. The original upper dam had been a rockfill structure, with uncompacted rockfill having been placed in 3 m lifts. There had been a 3 m-high parapet wall all around the crest of the dam (something which would no longer be accepted in engineering practice, Rizzo remarked). Very little freeboard had been provided.

A critical aspect, he said, related to the quality and placement of the rockfill material. The sluicing method had been used, whereby rocks had been dumped and pushed into place with jets of water. He surmised that a shortage of water may have meant that the process had not been done to a sufficient standard. He also suggested that a lot of fines had been left within the rockfill material.

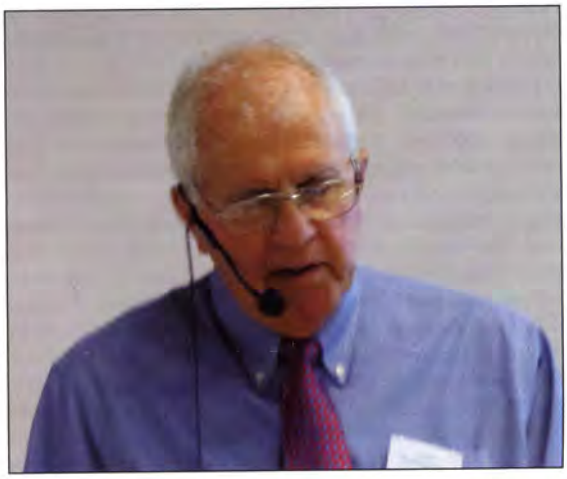
The failure had been dramatic, with a 213 m breach being formed in the dam, and all vegetation being washed away. 1.5×10^9 gals (6.8×10^9 litres) of water had overtopped the dam.

Studies had been commissioned by the Federal Energy Regulatory Commission, and also by the owner, Ameren Missouri, the latter having commissioned Rizzo & Associates to conduct a forensic examination, to find the root cause of failure.

A number of shortcomings to the original design had been revealed during the forensic study.

Rizzo pointed out that the 3 m parapet wall, embedded in the crest and slopes, had been used before the failure to retain water (when it had certainly not been designed to do so). Erosion had been found below the parapet wall, and it was agreed that this was likely to have pre-existed the failure, as waves would have splashed over the wall during heavy wind.

Foundation conditions had been another issue. In the interface between the rockfill and the foundation, rusty



Carl Rizzo of Rizzo Associates, USA, who reflected on factors which had contributed to the failure of the upper reservoir at the Taum Sauk pumped-storage plant, in 2005.

The new RCC dam forming the upper reservoir at Taum Sauk. Major emphasis was placed on preparation of the foundations for the new dam, which involved a complete redesign.

weathered rock had been found, and it was clear that there had been insufficient excavations down to good quality rock before construction. Leakage of around 60 ft/s (18.3 m/s) had occurred during operation of the dam. A liner had been installed to deal with the leakage problem, but when this had been removed, voids had been found beneath the concrete face.

Level detection sensors had been provided in the dam, Rizzo continued, but the mechanism to secure them had not been well maintained and had come loose, so the sensors had shifted. It was clear that visual maintenance should also have taken place.

Another post-failure analysis, by FERC, had pointed out that no overflow spillway had existed, and also supervising personnel were found to be inadequate.

The remedial project at Taum Sauk had consisted of a completely new design for the dam, which was an RCC structure with a conventional concrete facing. Major emphasis had been placed on foundation preparation. Also an overflow release structure had been added.

During the subsequent discussion, it was agreed that if an adequate and regular regime of monitoring had taken place at Taum Sauk, the failure could have been avoided. Rizzo commented that as the ring dam had operated satisfactorily for some 40 years, the approach to surveillance had become somewhat relaxed. A fundamental lesson to be learnt from cases such as this, was that a long period of successful operation should not be assumed to indicate that all was well for continued safe operation.

Karl Rytters, of Sekond, Sweden, described events leading to the failure of the 20 m-high Noppikoski rockfill dam, during a major storm in 1985, and the post-failure analysis. He mentioned that there were twin 20 MW powerplants in the area, one at Noppikoski, and another upstream at Vässinkoski which was also important to protect.

The Noppikoski dam had been unmanned, and controlled remotely from about 50 km away. When the storm occurred, the operator from Vässinkoski had gone to look at the Noppikoski dam. He initially considered that the situation was not critical and left the site; subsequently it had not been possible to get back.

As the situation deteriorated, a mobile crane had been ordered, but it had had to come from 50 km away by helicopter, and on that Friday evening, it was not possible to locate anyone who would be ready to fly it. The helicopter could not arrive at the dam before the following morning.

It had then been decided to open the emergency spillway at Vässinkoski, but this was equipped with cylindrical gates, and it had not been possible to open them in view of the water level. Welding work had been required to increase the height of the cylinder. The whole process to open these emergency gates had taken 21 hours, Rytters said.

Reflecting on the cause of the failure which followed, Rytters said that there were a number of factors to consider. First, hydrological data records for the catchment area were inadequate. This could be described as a relatively 'low budget' powerplant, and there had been inadequate emergency planning. The actual failure had probably been based on a number of factors, the principal ones being overload combined with reduced resistance. He stressed that in this respect, a dam should be regarded as a system, and non-linear developments should be taken into account, including a combination of loadings. In this case, he concluded, there had been possible errors in design, construction, operation and control. Human issues, uncertainties about, for example, the foundations and material, external disturbances, changes in state, and issues associated with the maintenance regime had all combined to cause the failure.

Concluding on the causes of the failure, Rytters said these could be summarized as eight main points:

- the inflows and rate of their increase had been underestimated;
- the type of spillway gate had not been appropriate;
- the spillway gate hoist had also not been suitable;
- the means of accessing the site and communications had not been appropriate for remote operation;
- the 'emergency spillway' had not been intended for rapid activation in flood situations;
- the saddle point adjacent to the dam had been too low;
- the back-up power supply had been unreliable; and,
- there had been a shortage of qualified personnel.

Maria Bartsch, a dam safety engineer of Svenska Kraftnät, asked what lessons could be learnt from this case. Rytters replied that something had been gained in terms of experience, but still there was not enough emphasis on non-linear aspects.

Isander commented that more attention should be paid to less-than-extreme events, with multiple aspects, so the results could be handled better. He added that access roads were critical in cases of such an emergency, and also the competence of maintenance staff.

Rytters added that no single system would be good enough to cope with an emergency; therefore back-up was always essential.

Internal erosion

The session on internal erosion was chaired by Tony Deakin of the Environment Agency, UK, who began by outlining the role played by his organization, including research activities in the field of safety, part of which involved spotting trends and learning from them. Work by the agency was done on behalf of the industry, he said, and research results were freely accessible on the Internet. Case histories on incidents and failures could be found, for example.

N. Snorteland, Director of the Risk Management Centre at the US Army Corps of Engineers (who had formerly worked at the Bureau of Reclamation), gave an example of a case where lessons could have been learnt, but had not been, from an incident at Fontenelle dam in Wyoming in the 1960s, which he felt could

have prevented the Teton dam failure in 1976. He commented on different approaches between the Bureau of Reclamation (owner of Teton) and the Army Corps of Engineers, during the 1960s and 1970s. The Bureau, he said, was building a large number of irrigation dams. In some cases, he commented, engineers had never actually visited the dams they had designed.

At the site of the Fontenelle irrigation dam, the geological conditions had not been favourable, and during first impounding, a considerable amount of seepage had occurred. A slide had occurred in 1965, with material being washed away from the dam body. The structure had been inspected, and a decision had been taken simply to put the material back. Later that year, in September, a much larger slide had followed. On this occasion, a team from USACE had inspected the site, and it had then been decided to add a foundation filter.

Meanwhile, Snorteland said, Teton dam had been under design. There the foundations were also not favourable, featuring highly fractured rock, and this situation should have been treated very conservatively, he pointed out.

In 1969, a test grouting programme had been carried out, and the grout take had been very substantial. Snorteland said that it had therefore been decided not to continue with grouting, but to dig a larger key trench, as it was considered a more cost-effective way to reduce seepage.

He referred to the much more conservative approach which had been adopted, by the Corps of Engineers, at the Ririe embankment dam, some 30 km away. This dam had incorporated 17 types of materials, with progressive filter zones downstream of the core. There had also been shotcreting of breccia and clay interbeds which had been observed at the abutments, and state-of-the-art foundation treatment. In effect, multiple lines of defence had been provided, Snorteland said, and seepage had remained at a very low level. This dam had a similar height to Teton, he added, but only half the reservoir capacity.

At Teton, he continued, impounding had been relatively fast (around 150 ft or 46 m, within two months), and water had begun to seep into the foundations.

Turbid water had been observed in the water leaking downstream on the day before the failure.

Snorteland concluded that a number of fundamental points could have been learned from Fontenelle, which could have prevented the failure at Teton. These had, on the other hand, been applied at Ririe, and the dam had performed well.

He felt that one important aspect had been that decisions regarding Teton had been taken at a low level, and that there had been a lack of clear organizational responsibility.

Summarizing lessons for the future, Snorteland stressed that more than one line of defence should be used against seepage. Also, flows could occur in man-made structures, and defence measures should be adopted assuming that flaws would occur. Finally, he felt that an external review of designs and decisions was a key step in evaluating the safety of a structure.

Asked whether the Teton failure had led to improvements in the approach to safety, Snorteland said that the accident had indeed led to new and more stringent legislation, and also some changes in the organizational structure of the Bureau of Reclamation.

Escuder asked whether improvements in dealing with erosion had resulted, and Snorteland replied that the profession was today much more experienced in this respect. He added that it could not be calculated numerically to the same degree as other phenomena, but it was possible to identify weak points, and failure modes. Accurate numerical modelling was still 15 to 20 years away, he felt, adding: "You have to imagine how things might happen, rather than calculate how they will happen".

The breach of Teton dam, USA, in 1976. N. Snorteland of USACE, USA, pointed out lessons which could have been learned from a previous incident at Fontenelle dam. He stressed that there should be "more than one line of defence" to cope with seepage.

C.O. Brandesten and P. Viklander of Vattenfall, Sweden, gave a joint presentation about an incident of leakage and the formation of a sinkhole at the Suorva dam, the second largest storage dam in the country. The hazard classification of this dam, Brandesten said, was that it "would cause an unacceptable strain on the economy if it failed".

The incident described had occurred in October 1983, when the reservoir had been just a few centimetres below full supply level. At 10.00 hrs on 4 October, Brandesten said, leakage with turbid water had been discovered (by a retired Vattenfall engineer); however, this had only been reported to the local manager at 16.00 hrs. Inspections had taken place by local managers at 17.00 hrs and 19.00 hrs; by 21.00 hrs local and national media had been calling the regional director, and by 23.50, the Generation Management office in Stockholm had been informed. By the evening, the leakage had reached 100-130 l/s in two places, and turbid water could be observed 200 m downstream at Kärtjejaure.

The following day a sinkhole had been discovered, Brandesten said, when a Vattenfall dam expert had visited the site. Local police had been informed about the situation, and maximum generation and spilling had begun, to drawn down the reservoir level. The reservoir had eventually been lowered by 1 m.

On 6 October, work had begun to fill in the sinkhole, and experts had advised that there was no cause for further concern. It was observed that a self-healing process was occurring. Nevertheless, between 7 and 9 October, a further expert inspection had been made, and tracer investigations began, which continued for some 10 days. On 19 October, a governmental accident investigation had begun.

Various measures taken after the tracer tests had included geotechnical investigations of the core, drilling into the bedrock, laboratory tests, and a programme of grouting with cement bentonite. Extra fill material had been added as a support downstream, as well as riprap. As a result of the incident, Viklander said that regular visual inspections now took place at the dam, as well as measurements of leakage, pore pressures, movement, and so on.

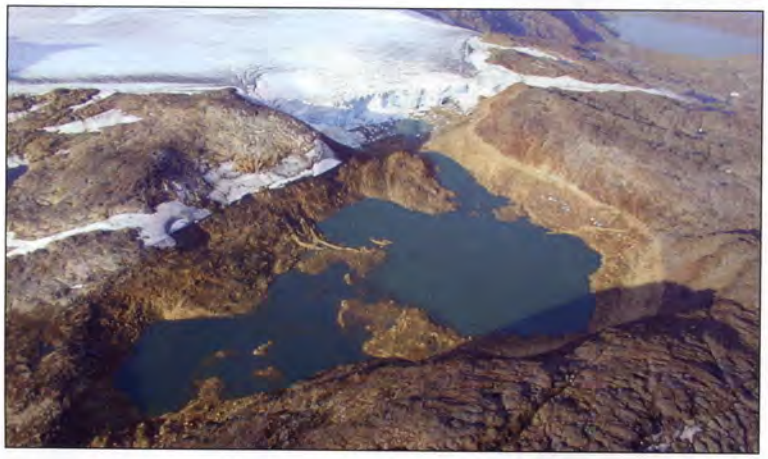
Tony Deakin of the UK Environment Agency, who chaired the session on incidents of internal erosion.

An interesting point made in this case was that the regular four-yearly inspection of this dam had taken place just six days before the incident, and everything had appeared normal.

Viklander concluded that the root causes of the incident at Suorva could be summarized as:

- Degradation of the original grout curtain (there had been some chemical impact on the grout curtain caused by graphite slate).
- Grouting technique: grouting had been done vertically.
- Bad quality rock, with local weak spots (fissures, faults, cracks and crush zones).
- Problems with the rock-soil surface contact.
- Impact of load on the rock: it was found that cracks close to the surface could open by 1 mm.
- Core investigations had revealed wet and loose areas.
- Filter quality was inadequate: the material was partly separated and in the higher elevations, too coarse.
- The support fill material (blasted rock) had high leakage values.
- Internal erosion and hydraulic fracturing had therefore occurred.

In conclusion, Viklander reported that as a result of this incident, Vattenfall had reviewed its methods for surveillance and monitoring, and an internal dam safety group had been established. Dam safety legislation had also been reviewed.



The Blåmannsisen glacier, where a glacial outburst flood caused 46 × $10^6 m^3$ of water to flow into the Sisovatn reservoir. Describing the incident, V. Pedersen of NVE stressed that attention should be given to all possible exceptional loads on a dam, and it was important "to know the secrets of the catchment area".

In drawing overall conclusions for this session, Tony Deakin commented that some key points were: the importance of good communications, including internal ones in large organizations; the need for designers to visit dam sites and be willing to change some aspects of design, if unanticipated conditions were encountered; and, the importance of good emergency systems, which should be regularly tested, well known to the relevant personnel, and accompanied by a clearly defined allocation of responsibility.

At the end of the session, J. Laasonen of Fortum, Finland, and Chairman of FINCOLD, presented some information about ICOLD's Working Group on Dam Incidents, which had been created following the European Club meeting in Venice in April 2013. Its aim was to analyse incidents, study the measures taken, with a view to improving communications. He noted that in his country, five incidents of internal erosion, and two incidents at tailings dams, had contributed to the studies. Information was currently being collected from authorities in various countries, and a Workshop was planned to take place in 2014 in Finland.

Miscellaneous case studies

The next session, chaired by L. Hammar of Vattenfall, Sweden, grouped five further European case studies relating to incidents or failures.

V. Pedersen of NVE, Norway, described two unusual incidents in Norway, which, he said, demonstrated how exceptional loads could threaten dams.

In his introduction, he mentioned that around 93 dam breaches had occurred in his country between the 18th century and 2010, but these had mainly involved very small dams (<10 m high). No major incidents had occurred, as a result of the country's generally favourable conditions for dam construction, such as excellent bedrock and good quality materials. There had also been a very early focus on dam safety, he noted, with a dam safety department being established by the Government in 1909. Norway had been a member of ICOLD since 1930, he added.

The small failures which had occurred, he continued, had generally been the result of inadequate freeboard or spillway capacity, or human error. While the past record had been relatively good, Pedersen felt that climate change could present new challenges.

The first case he described related to a 'Jøkulhlaup' (glacial outburst flood), which had occurred on 5 September 2001, close to two 20 m-high rockfill dams used for hydropower (the Siso dams). Over two days, the water level in the Siso reservoir had risen by around 3 m, and about 46 × $10^6 m^3$ of water had been 'dumped' into the reservoir from the glacial lake, Pedersen said. The level of the glacial lake had gone down by about 51 m during these days.

Because the instrumentation system monitoring level measurements had not been functioning properly, no one had noticed the problem, until a backpacker had woken up floating in his tent, and contacted the dam owner, Pedersen said.

In fact the Siso dams had been uprated in 1998: the moraine cores had been heightened, rockfill embankments had been replaced, and new riprap installed, so they were considered to be very safe structures. Pedersen said it was clear that without the upgrading work carried out after the 1998 inspections, the original dams could not have withstood this incident. In the

event, despite the huge volume of floodwaters entering the Siso reservoir, the water level had remained around 3 m below the maximum water level.

Reflecting on what could have happened, Pedersen said that if the glacial outburst had occurred with the Siso reservoir full, and with average inflow from the catchment and no production at the hydro plant, then the water level would have reached 0.7 m above the moraine core, but would still have been 1.1 m below the dam crest. Because of the filter and transition zones above the moraine, flow through the dam would have been within the limits of its drainage capacity and the stability of the riprap.

Pedersen commented that there had been at least six glacial outbursts over the previous ten years, and although glaciologists had had knowledge of these, the information had not been conveyed to the dam owner or NVE.

An important lesson learnt from this case was that more efforts and resources should be devoted to mapping all relevant and potential loads on dams, especially any possible exceptional loads. Pedersen stressed that attention should be given to all surroundings of a dam, and it was important to know "the secrets of the catchment area".

A second case Pedersen referred to was that of the Bleikvatn concrete gravity dam, constructed in 1961, and impounding a 170×10^6 m^3 reservoir. Cracking had occurred in 1997 as a result of a collapse of some mining tunnels and caves, 140 m below the dam. (Mining work had begun in the area in 1957, Pedersen explained).

The dam had not failed, but serious cracking and leakage had occurred, and at one end settlement had reached between 1 and 4 m. The gate house had been totally uplifted. Pedersen commented that a total failure of the dam would have had catastrophic consequences.

As a result of the incident, a new rockfill structure had been constructed 800 m upstream of the old one, Pedersen said, and a new labyrinth spillway had been provided. Dykes had also been built along the mining areas. This once again underlined the point that attention should be given to all areas surrounding a dam, Pedersen said, especially if it was in an area of past industrial activity. Again there had been a communication problem, with little contact having been established between the mining company and the hydropower company. He added that the dam owner could therefore not have known that the rock base in the Bleikvasslia area had, over the years "become like perforated cheese".

A joint presentation followed, by Prof J. Riha and J. Jandora or Brno University of Technology in the Czech Republic, about incidents at the Mostiste and Moravka embankment dams as a result of internal erosion.

Prof Riha described the 33 m-high Mostiste embankment dam, which had been constructed on the Oslava river between 1955 and 1960 to supply water to about 70 000 consumers. The reservoir volume was around 12×10^6 m^3.

Riha said that unusual behaviour had begun after 35 years of operation, in 1995:

- wet areas had been observed below the dam;
- successive vertical displacements of the dam crest had been recorded;
- a void had been discovered in the dam core (1.5 m^3 of soil had been flushed out); and,
- there had been seepage at the entrance to the grouting gallery.

Prof J. Riha of the Czech Republic discussed an incident of hydraulic fracturing at the Mostiste embankment dam in his country.

Riha commented that no toe drain had originally been provided, to measure seepage.

As a result of the deterioration in the dam behaviour, local drainage had been installed.

Geological surveying had revealed hydraulic fracturing in at least two places within the core, which was thought to have been caused by the use of poor core material. There had also been missing filters in the upper part of the dam, and poor compaction in the upper vertical section of the core.

A contributing factor for the sudden deterioration after so many years of operation, Riha said, was that during refurbishment of the single bottom outlet in 1995/96, water had had to flow over the spillway continuously for eight months, when previously the spillway had only operated occasionally.

Riha then described emergency management of the situation from January 2005, which had included lowering of the reservoir level by 13.3 m, and updating the dam breach analysis and early warning system. A 7 m-wide section of the side spillway had been removed, so that water would not pass through the sensitive area and the outflow capacity could be increased, and provisional repairs were done to the core (low-pressure grouting).

General view of the Workshop participants. About 90 people took part in the discussions, from 20 countries.

L. Hattingh, a Consultant from South Africa, gave details of incidents at gated spillways in Namibia and South Africa.

A vertical slurry wall had been provided along the crest; the slurry wall had been inclined, which had been critical to protect the area where the erosion had occurred. After this, numerical analyses had been done to check the stability of the dam, and improvements had been made to the monitoring system. In conclusion, Riha reported that the dam had operated without any further problems for almost eight years.

His colleague Dr Jan Jandora then presented the case of the Moravka dam, where the bituminous sealing had collapsed in 1996.

This 39 m-high structure had also been built for water supply, and impounded a $12 \times 10^6 m^3$ reservoir. It was the first dam in the Czech Republic to have a bituminous concrete upstream face, Jandora said.

During first filling in 1965, the first leakage had occurred (400 l/s). The reservoir had been drawn down, the lining had been repaired, and the reservoir refilled. Extensive leakage had occurred again, and the drawdown and repair process had been repeated. Then, Jandora said, in 1996 the bituminous sealing had completely collapsed, and a 4×6 m hole had appeared in the upstream face. The dam had not actually failed, but leakage had reached 600 l/s.

Repairs had been carried out in three stages, between 1997 and 2000, Jandora said. The first stage had involved draining the left abutment and installing a new drainage gallery. Then in 1998, the grout curtain had been refurbished, a new bottom outlet tunnel had been installed in the right abutment, Howell Bunger valves had been placed in the existing bottom outlets, and the monitoring system had been upgraded. Finally, between mid-1999 and 2000, the upstream facing had been repaired, and a Carpi geomembrane had been installed on the old bituminous layer. Jandora reported that the dam has now been operated satisfactorily for nearly 14 years.

Conclusions about the cause of the accident were that:

- there had been an unsuitable regime of subsurface water at the left abutment; and,
- internal erosion and suffusion of the dam body material had occurred, leading to erosion of the base of the bituminous layer.

Louis Hattingh, of Hattingh Anderson Consultants, South Africa, described several incidents at gated spillways in his country, presenting both success stories and less favourable cases.

Hattingh began by pointing out that in Namibia and South Africa, most dams were built to store large volumes of water, and few major floods had occurred since 1940.

However, a major flood event had occurred in

The Hardup dam in Nambia, where well trained staff took swift action to avert a disaster during a major flood in 2006.

Namibia in 2006, which could have caused a problem for the Hardup asphalt-faced rockfill dam. This dam impounds a reservoir with a capacity of $300 \times 10^6 m^3$. Hardup's spillway is equipped with four radial gates, and Hattingh pointed out that redundancy had been provided in the methods of operating the gates: the options were to operate them by electricity from the national grid, and there was also a standby generator which was regularly tested, as well as a small additional mobile generator.

During the 2006 incident, the first flood peak (in January) had reached 4000 m^3/s; half of the city of Marienthal had been under water. A second peak had then occurred, and the gates at Hardup had been opened to release 500 m^3/s. Further flood peaks had occurred until the fifth one, on 26 February, which had caused a power failure, and also failure of the mobile phone network. The team at the dam site had reacted swiftly to open the gates using the small generator. Hattingh used this example to demonstrate the importance of properly trained personnel, and also of providing redundancy in gate control systems.

The case at the Bospoort dam, which Hattingh described next, was not such a good example, and he pointed out that it was a question of luck that a failure had not occurred. This dam, originally with a 23 m-high concrete gravity section flanked by embankments, and later heightened and modified to a concrete gravity structure equipped with 12 radial gates, had been built to supply water for the platinum mining area of South Africa. The gates had been operated by grid electricity, with a small mobile generator as a backup. The dam had been inspected at the beginning of the rainy season in late 2004, and a number of deficiencies had been identified. Water had been spilling over the radial gates, as the dam was being operated at a higher level than it should have been. Some cables had been stolen which should have been able to bring power from the grid, and it had been revealed that the operator, stationed 30 km away, only visited the site once a week. Furthermore, five of the 12 cables in the gate operating system were found to have corroded badly, and Hattingh suspected that mild steel rather than stainless steel had been used for the cabling, to save money.

A rehabilitaton project had therefore taken place; the gated spillway had been replaced by two uncontrolled labyrinth spillways, and overall the risk at the dam had been brought to an acceptable level, avoiding what

Prof P. Obernhuber of Verbund Hydro, Austria. He described several challenges associated with building high arch dams in wide valleys, and stressed the importance of stable abutments, in ensuring the stability of a high arch dam.

Hattingh described as a "failure waiting to happen".

The third case Hattingh referred to was the 33.7 m-high Lake Arthur concrete gravity dam, in the Eastern Cape area of South Africa. This dam had been heightened with the addition of roller gates in 1939. Since construction, much of its reservoir capacity had been lost to siltation, Hattingh said, adding that the water depth today was only around 4 m, compared with a 20 m level of silt! In 1950, when the dam had been operating at full supply level, a major flood had occurred. There had been no early warning system. The operator at the dam had attempted to open the gates, but could only manage to open 20 of the 66 gates. Overtopping of the non-overspill crest had then occurred, so the operator had been forced to leave, as it would have taken all day to open all the gates. Hattingh quoted this case to demonstrate the importance of taking into account the time required to operate mechanical equipment. In this case, the opening speed of the gates had represented a fatal flaw in the design, he said, adding that the lack of a backup control system, and inadequate maintenance had exacerbated the problem.

During the following discussion Prof Escuder reiterated the importance of considering a combination of factors in assessing risk: for example, a moderate flood combined with gates not opening could be enough to cause a failure. There was an unfortunate tendency only to concentrate on extreme events, he felt.

Prof R. Pohl of the University of Dresden, Germany, mentioned that he had conducted a survey on failures of gates and valves, and this had indicated that 1 per cent of gates of all types would fail during an emergency; however, he said it had been voluntary for owners to respond to the survey, so it was not possible to know whether the statistics were accurate. Prof Escuder said that 1 per cent could be a little optimistic in his opinion; he thought 85 per cent reliability was a more accurate assessment.

Prof P. Obernhuber of Verbund Hydro, Austria, gave a talk on difficulties associated with high arch dams constructed in wide valleys. He referred to several cases of Austrian dams where remedial measures had been necessary to deal with issues such as cracking.

The 200 m-high Kölnbrein arch dam, built between 1971 and 1979, for example, had experienced a high level of seepage into the galleries during first filling of the 200 $\times$ $10^6 m^3$ reservoir, when the water level had been within 12 m of the high water level. High pressure around the grout curtain had occurred, and cracking both upstream and downstream could be observed. He described the crack propagation process, and remedial work which had been carried out subsequently, involving the construction of a 70 m-high supporting dam. This solution had worked well, he reported, although further grouting had been necessary in 2011/12.

At the 186 m-high, 506 m-long, Zillergründl dam, built between 1980 and 1985, foundations conditions had been good; a concrete block had been built on a fault zone, and the dam had been equipped with an upstream apron from the beginning, Obernhuber said, so that the grout curtain could be away from the zone of tensile stresses. Calculations for the dam had been carried out using the trial load method.

At this dam, cracking had also occurred during first filling. Remedial measures had involved changing the drainage system and grouting the cracks with resin. It had been concluded that vertical displacements at the dam base had been caused by water load; uplift pressures had not been an issue.

The dam, he said, was well instrumented, with more than 1000 devices installed, and had performed satisfactorily since the remedial work.

In his conclusions, Obernhuber said that for the base area in the central part of thin arch dams in wide valleys, membrane shear forces reduced the normal forces. Opening of the base joints would lead to the ingress of water. Uplift pressure would lead to a further reduction in the effective normal forces. He pointed out that membrane shear forces generally were not picked up by the traditional trial load method of calculation.

His first conclusion was that the overall stability of a dam could be ensured, as long as the abutments were stable.

For high arch dams in wide valleys, particular issues to consider were low vertical forces and high shear forces, as well as tensile stresses in inclined planes. Water pressure into an initial crack would lead to crack propagation. His second conclusion was that complete relief of the upstream heel from water pressure could provoke cracks, but crack propagation caused by water pressure would stop at a drain.

L. Deroo of ISL, France, described the failure of the 50 m-high Camera RCC dam in Brazil, on 17 June 2004 during first filling (with the water level 5.5 m below the maximum). The dam had had a classical design, he said, but construction had gone ahead before the design had been refined, and the contractor had been alone on site. Deroo pointed out at the beginning of his talk that various reports had been prepared

The Zillergründl arch dam in Austria. Cracking during first filling had led to grouting work and a change in the drainage system, as reported by Prof P. Obernhuber of Verbund Hydro.

L. Deroo of ISL, France, described lessons learned from the failure of the Camara RCC dam in Brazil. He felt an independent review of the design of this dam could have been helpful in preventing the accident.

by Brazilian experts about the incident, but as-built drawings had not been available.

Several months before the failure, in February 2004, there had been a large inflow into the drainage gallery, bringing with it eroded material. A damp spot had been observed at the foot of the downstream face, and some drains had become clogged, as a result of which a new outlet had been provided, in May, to drain the gallery.

On 7 June 2004, 10 days before the failure, the engineer recommended drawing down the reservoir, but this had not been done; in retrospect it is clear that this would have saved the dam, Deroo said. He added that the post-failure reports do not contain any data from monitoring systems, and it seems therefore that instruments had not been in place, or in working order.

At 19.15 hrs on 17 June, local residents had heard a loud bang. The initial failure had been along the drainage gallery, Deroo continued, without damage to the spillway section. But a few days later, the top of the RCC had also failed.

The incident had caused five fatalities as well as major economic losses, he reported.

While causes and responsibilities were still in dispute, Deroo said, the main physical cause was thought to be a geological accident in the foundation, which had not been adequately assessed or addressed.

While acknowledging that there could be differences of opinion about the precise cause and sequence of failure, Deroo suggested that infiltration of water into the weathered shear zone (the 'slip surface') had occurred. This infiltration would have brought solid materials into the drains and gallery, causing the drains to clog and lose their efficiency. Two possible sequences could have followed:

- Equilibrium of the whole base of the dam would have been lost, but the top of the dam could have rested on the spillway and left bank because of the arching effect. The base would have failed following the preformed geological slip surface and weakness in the dam (cracking).
- Alternatively, the foundation at the left bank, comprising individual blocks, had not resisted the uplift pressure downstream of the dam. The blocks had been dislodged and washed away. Then the left section of the dam had lost its foundation, but the top would have again rested on the spillway because of the arching effect, and the base would have failed, in the same way as mentioned above.

Lessons from the Camara failure, Deroo said, could be summarized as follows:

- Traditional stability computations could not have helped. Gravity dam stability assessment remains a matter of expertise.
- An independent review of the design might have led to a decision to excavate blocks on the left bank.
- A greater number of monitoring devices (piezometers, pressure cells, pendulums and fissurometers) could have helped to reach a decision to empty the reservoir before the failure.

Deroo then compared the failure of Camara with the historical failure of the 15 m-high Bouzey dam in France in 1895, for which a lot of data and reports existed. In this case the failure had occurred ten years after construction, suddenly, and with no warning, and there had been 88 fatalities. The main cause had been tensile stresses in the dam body, combined with the low quality of the masonry. The cracking had occurred during extremely cold conditions. In this case, progressively increasing leakage had occurred since the start of impounding in 1884. Maximum displacements at the crest had been 34 cm, but the reservoir had not immediately been drawn down. Eventually, in 1889, some reinforcement work had been done, and the dam had continued to operate for five years. On 27 June 1895, an initial breach had occurred near the crest, followed by sudden total failure.

Possible theories about the cause had included the effect of pore pressures in the dam body, but Deroo pointed out that this would not explain everything that had happened. Additional contributing factors could have been ice loading on the cracked dam, and thermal tensile stresses acting vertically on the dam.

Lessons from the Bouzey failure, Derou said, were that:

- The upstream facing plays a vital part in masonry dam stability. Cracking of the upstream face of a masonry dam is much more dangerous than for a concrete dam.
- Masonry tensile strength within the facing might be necessary to ensure stability, even when not indicated by simple (horizontal) calculations.

Deroo concluded by stressing that a combination of factors would generally be the cause of a failure.

Tailings dams

In a session chaired by A. Isander of E.ON, Sweden, two presentations were made relating to tailings structures.

ICOLD Vice-President J. Polimón, of Spain, spoke of the failure of the 27 m-high Aznalcóllar tailings dam in his country. He said that there had not been extensive site investigations after the failure, and the site had been infilled with earth, so it had been difficult to analyse this case.

The starter dam for the tailings scheme had been constructed between 1978 and 1980. The scheme comprised two reservoirs, with a dividing dyke. The storage in the reservoirs at the time of failure had been $30.8 \times 10^6 m^3$, Polimón said.

Problems had begun with high seepage at the toe, from November 1994. Grouting in the junction zone had been done in 1995, and wells had been drilled in

the toe to reduce the seepage. In February 1998, seepage water had been pumped out at a rate of 1000 m^3/h. The failure had then occurred in April 1998, during the night, so there had been no eye witnesses. There had also been no consensus of opinion about the sequence of failure, with several hypotheses being put forward. There had been confusion about the pore pressures in the foundation, and discussion on the operative shear strength parameters, Polimón continued. It had been agreed that monitoring had been poor, and doubts had also been raised about the construction history, seepage incidents, the suppression of filters, and so on.

Polimón suggested that factors which deserved more attention included:

- deficient construction;
- the change in discharge points which had occurred, and the excessive amount of impounded water;
- foundation seepage being forced through drainage wells at the toe;
- the lack of warning displacements;
- the scour by the river at the failed dam;
- the probable existence of old slides in the foundation;
- the possibility of acid attack of the marly ground;
- the two flood waves which had occurred; and,
- general mismanagement of the dam.

In conclusion, Polimón emphasized the great importance of an immediate and objective analysis after a dam failure, which should be carried out by a multidisciplinary team of experts. It was important, he continued, to avoid prejudgement of failure modes, and to identify both the main and secondary causes. Also, he stressed that the operational team at the dam should be experienced and well trained.

In the case of Aznalcóllar, the failure had been unexpected and difficult to explain. The hypotheses elaborated had been incomplete, and Polimón felt that a number of factors had been overlooked. No satisfactory back-analysis had been carried out, and reports published had been highly deterministic, he added.

The final presentation was by M.R. Cambridge of Cantab Consulting, UK, who took the example of the Cavendish Mill Tailings Dam 1 (TD1) failure in the UK to illustrate the point that historic tailings dams incidents should be used in the development of emergency plans. He began by showing a comparison of recent failures with historic incidents, linking pairs of incidents (recent and historic) with each of seven different failure modes. He pointed out that this was a timely reminder that "engineers ignore history at their peril".

Cambridge said that in the UK, according to the Extractive Waste Directive of 2006, emergency planning was required for mine waste facilities as part of the operating permit, if the predicted consequence of failure as a result of the loss of structural integrity, or incorrect operation, could lead to "non-negligible potential for loss of life, serious danger to human health, or serious danger to the environment".

Development of an emergency plan, Cambridge said, involved an assessment of the resulting downstream impacts. He continued that the establishment of the worst credible failure of a mine waste facility, which could lead to the development of a breach and subsequent downstream flood, could be derived from historic failure events, as well as the design and construction history of the facility. Using this approach, he felt, the critical parameters for both emergency planning and any other environmental risk assessments could be defined.

Failure of the Aznalcóllar tailings dam in Spain, described by ICOLD Vice-President Dr José Polimón. He stressed the importance of an immediate and objective analysis after a dam failure, which had not happened in this case, making agreement on the failure mode difficult.

Turning to the case of Cavendish Mill TD1, he explained that Cavendish Mill had been a fluorspar mine in Derbyshire, UK, with both open-cast and underground extraction having been undertaken for 50 years, up to 2010. The TD1 facility had been a non-impounding paddock dam, confined by 12 to 15 m-high earth and rockfill embankment dams, which had been constructed between 1961 and 1962.

Tailings disposal had been done by hydro-cycloning, resulting in alternating deposits of coarse (sandy) and fine (silty) tailings. The facility had closed in 1968, with the surface being partially restored for grazing, but it had been re-classified in 1994, to enable extraction of the tailings for reprocessing.

A geotechnical assessment had been done in 1998, Cambridge continued, resulting in liquefaction potential being recognized. A protective bund had been installed, and working practices had been modified.

The failure had occurred on the morning of 22 January 2007, following a month of very wet and cold weather. Sharp frost had been recorded the night before, with superficial thawing on the morning of 22 January.

The surface of TD1 had become saturated, perimeter surface water drains had blocked, and sinkholes had appeared. The excavation face had remained generally stable, apart from some inevitable tension cracks.

Around 7.00 hrs on 22 January, an initial small-scale slope failure had developed above the excavation face, possibly induced by freeze-thaw action in the water-filled tension cracks. At 08.15 hrs, liquefaction had been triggered in the retained tailings, which had then flowed into the adjacent pond. The protective rockfill bund had subsequently overtopped, causing water to be displaced by the tailings inflow. Various major roads and houses had been flooded. Progressive slope failures and liquefaction had continued, and then the embankment had overflowed, causing tailings and water to be discharged.

By 11.00 hrs, the tailings overflow from TD1 had been stemmed, and only a minor flow of dirty water had continued off-site. Liquefaction events had continued within a confined area until late evening, but with no further discharges beyond the site.

M.R. Cambridge, a Consultant from the UK, described the failure of the Cavendish Mill TD1 tailings dam. He said that lessons from historic incidents should be the basis of emergency planning for the future.

The conclusions from the UK Health and Safety Executive report were that the initiation of failure in an otherwise stable excavation face was most likely to have resulted from a change in local drainage conditions, induced by the heavy rainfall of the preceding weeks, and to have been exacerbated by the freezing action of the preceding night's temperatures.

The development of a flow slide from this small initiating event had resulted from the location of a zone of 'sensitive' tailings, adjacent to the initial failure surface, and to drainage conditions in the area. The liquefied tailings, which had included water from the surface depository, had flowed towards the confining bund, away from the available void space, which would otherwise have provided sufficient buffer storage within the excavation area.

The volume of water, tailings and other debris discharged off-site had constituted less than 5 per cent of the total material and water discharged from TD1.

It had also been concluded that the prompt action of the operating company in infilling the breach had prevented significant additional volumes of tailings from being released.

A relatively small increase in height of the rockfill bund had been recommended, to provide robust storage for all remaining tailings in the upper 3-4 m of the depository. Further control measures had also been specified.

Cambridge noted that the simple single-phase failure of the old tailings dam at Cavendish Mill had developed into a two-phase incident, because of the configuration of the site, and as a result there had been some impacts on downstream communities.

Cambridge observed that in the UK, regulators tended to be familiar with dam break analyses for water supply dams, but not for mine waste facilities. He felt that national models for water supply reservoirs, where available, needed to be adapted for high hazard mine waste facilities, to accommodate the differences in failure modes and breach development.

Lessons learned from Cavendish Mill, Cambridge concluded, could be summarized as follows:

- it was necessary to expect the unexpected;
- tailings flow may not follow logical paths;
- the presence of the water bodies' downslope increases the extent of downstream inundation, but may alleviate the solid content;
- emergency planning must absorb lessons from historic failures; and,
- downstream impacts may be of short duration only, particularly where the catchment has been affected by local geology/mineralogy over a long (>1000 year) period.

Conclusions

In drawing the Workshop to a close, Chairman of the Organizing Committee, Anders Isander, concluded that the event had been a very good experience for all. The limited number of participants had been effective in devoting ample time to each topic, and to stimulating active and open discussion.

A significant point which had emerged, Isander said, was that information and communication were vital parts of dam engineering operations. He stressed the importance of finding and using historical documentation.

"It is becoming more common to have a so-called 'PTO' perspective when studying not only accidents and incidents, but also when planning and executing projects and operations", he continued, explaining that PTO stood for People, Technology and Organization, and was a method to evaluate the interaction between these components. Today, information in its own right should be added, he felt, so a more appropriate term could be PTOI.

Organizational aspects had featured in a number of the case studies presented, Isander continued, and it had been stressed that staff should have the right instructions on how to do things, as well as the authority to go ahead and do them. This kind of clear mandate was essential, for example, in emergency preparedness.

He also noted the importance of proper training of staff and co-workers, to heighten their awareness and to increase competence.

Another key point, Isander mentioned, was the necessity to see dams as components of a bigger system; the use of 'systems engineering' was becoming more and more common in practice, he said. He added that it was necessary to consider the interaction between these parts, and to include not only technical components, but also human and organizational aspects.

Documenting and keeping good records of how things had been done was another important issue, Isander felt. A number of speakers had stressed the importance of not only studying extreme events, but also the combination of less extreme ones. The difficulty, however, was knowing which parameters to study, and in which combinations. Isander felt that this was a task to be pursued in future research.

Finally, he referred to ICOLD's effort to build a database for dam incidents, and he agreed that there would be a great interest in it; it was important to discuss how to encourage the feeding of the database, and how best to use the data.

His concluding thought was: "If nothing else, the cases we have heard about are reminders of our imperfection, and should prevent us from becoming complacent. As one speaker remarked: 'Engineers ignore history at their peril". ◊