RISK ASSESSMENT AND DAMS
IS IT SAFE?

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ABSTRACT

The use of risk analysis for dam safety is becoming more widespread. Dam owners are increasingly aware of the need for information on current and emerging practices from the world scene to determine how to proceed with the use of risk assessment. The paper summarises the findings of a Churchill Fellowship study into risk assessment for dam safety management. Dam owners, regulators and consultants from the United Kingdom, France, the Netherlands, Norway, Sweden, the United States and Canada were consulted for the study. Conclusions are drawn from the findings and recommendations made for future development.

INTRODUCTION

The development of risk assessment practices for dams has been going on for about twenty years. Over the past ten years, development and use has become more widespread and in Australia, some dam owners are applying risk assessment to dam safety.

Since the owners' duty of care will ultimately be measured against current Australian and overseas practise, in order to make judgements about using risk-based processes, it is useful to gain an understanding of world practice and developments.

This paper summarises the findings of a Churchill Fellowship study into the use of risk assessment for dam safety management. The aims of the study were to establish what processes were being used, to what purpose the information was being applied, determine the key issues being put for and against risk assessment and finally, to communicate the information to the Australian dams community.

Whilst some information is given about processes used for risk analysis, it is not dealt with in detail.

Countries visited during the study were the United Kingdom, France, the Netherlands, Norway, Sweden, the United States and Canada.
Discussions were held with dam owners, dam safety regulators, academics, public authorities, consultants and nuclear industry representatives.

In this paper, the term 'risk analysis' is used to describe methodologies aimed at determining the risk posed by a dam. The analysis can be either qualitative or quantitative.

The term 'risk assessment' is used to describe the processes of decision making using the outcomes from risk analysis.

The term 'Risk criteria' is used to describe criteria used in the risk assessment process to determine if the risks calculated through quantitative risk analysis are acceptable.

USE OF RISK ASSESSMENT AND RISK CRITERIA

The United Kingdom

<u>General</u>

Regulation in the United Kingdom (UK) is non-technical in that it does not specify standards of practice.

There is no current official support or use by dam owners of quantitative risk analysis or use of acceptable risk criteria. A reluctance to use quantitative risk assessment (QRA) is described as stemming from the difficulty in assigning credible probabilities of failure, the adverse ratio between the cost of QRA and the normal upgrade costs at UK dams and the

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success of the Reservoirs Act (1975) in limiting safety incidents.[1]

Scottish and Southern Energy

Scottish and Southern Energy is a major dam owner in the UK with 84 dams, 56 of which are included in the International Commission on Large Dams (ICOLD) world register. Since 1996, the company, with support from Babtie consultants, has developed a failure mode and effect criticality analysis (FMECA) process for its dams[1]. The company considers its stock of dams to be in very good condition relative to the UK standards. However, it also considers that surveillance, operations and maintenance practices should all be risk based, since these areas are not always adequately addressed by the standard approaches.

The initial work identified particular risks associated with flood gates and indicated that further detailed studies were required. These later studies resulted in a significant prioritised program of works to seven drum gates and to replace lifting gear for two radial gates.

Scottish and Southern Energy has also undertaken flood inundation mapping for extreme events and those associated with more frequent events including malfunction of flood gates. It is intended that the planning for these events will be shared with emergency planning agencies.

In summary,

> Scottish and Southern Energy based on experience to date consider risk assessment to be a vital part of the approach to dam safety and asset management. Risk assessment is complimentary to existing UK dam safety approaches and has been found to be cost effective and to make effective use of existing engineering resources and expertise. An open minded approach is essential to the success of risk assessment and we expect to continue developing our approach in the future and to continue our co-operation with dam owners in this field.[1]

Health and Safety Executive

In the UK it is worthwhile considering the activities of the Health and Safety Executive (HSE). The HSE advises and assists the Health and Safety Commission in the administration of the Health and Safety at Work Act 1974. Whilst it does not currently have a role in dam safety, their development of a tolerability of risk framework for hazardous industries is useful information.

Also, within the dams industry some practitioners consider that the HSE may take a future role in relation to dam safety.

In 1988, the HSE published the document 'The Tolerability of Risk from Nuclear Power Stations.' The document, reissued in 1992, set out a framework for public safety that has since become known as the Tolerability of Risk (TOR) framework. It describes HSE's philosophy of risk control for nuclear power stations. The HSE consider that the framework addressed the need to move from the division that things were either safe or not safe. The document was reissued in 1992 following public consultation, and the HSE believe that the underlying philosophy has since gained considerable acceptance by other regulators and industry as having wider applicability beyond nuclear power.[2]

The HSE also contend that balancing risks and benefits is critical in decisions relating to levels of risk that are tolerable.[2]

In relation to the risk of death, the HSE have guidelines, but note that the limits within the guidelines "rarely bite". They consider that this is because of societal concerns that arise about high consequence low probability events, that the limits reflect international agreements and that UK industries usually do better than the limits.

The HSE consider that risk analysis can provide essential information in risk management decisions. This view is clarified by advising cautious use, understanding the limitations and that the outcome should inform and not dictate decisions. It recognises that risk assessments will often be qualitative and not quantitative.[2]

Whilst the HSE have expressed the belief that the use of FN-curves (acceptable loss of life risk criteria) has drawbacks, but in the absence of other tools has proved useful. It is noted however, that the FN-curve criteria were developed for risks from particular installations and may not be applicable to different types of risk.[2]

As a general comment, the HSE appears to have developed a stronger position over time in relation to the "As Low as is Reasonably Practical" (ALARP) concept and achieving ALARP through 'good practice'. ALARP is a concept whereby the duty holder must demonstrate that measures introduced to control risks have been taken to the point where there would be a 'gross disproportion' between the effort to control risks further and the risk reduction that would be achieved. That ALARP may be achieved through 'good practice' is founded on the premise that a reasonable balance between costs and risks was achieved in developing the 'good practice'.[2]

It is understood that the stronger leaning to ALARP through 'best practice' is well recognised by the nuclear industry. Industry understands that meeting risk criteria is not sufficient in itself and that it must also be demonstrated that world 'best practice' has been used in design of any works or practices. It may be that this is not necessarily welcomed because of the additional costs that could be involved in meeting the requirement, if these are not balanced against the risk reduction benefit. It is not clear that the costs and benefits have always been measured in the development of 'best practice'.

CIRIA Report

At the time of writing the Construction Industry Research and Information Association (CIRIA), the UK based research association, had a research project in place in relation to dams and risk assessment – "CIRIA - 568 Risks & Reservoirs". The project is due to publish the final report in the Northern Autumn of 2000.

Whilst the report is in draft form at this time, it is understood to support FMECA for significant hazard dams rather than QRA. This is thought to be at least partly because of a perception that there is some difficulty in estimating probabilities of failure events and the expense of such analyses.

FMECA can be undertaken on a semi quantitative basis, but does not result in specific probabilities of failure. It is therefore most useful for ranking dams for further investigations or works. Such a system is not compatible with considering individual or societal risk from dam failure, so the consideration of such matters is not appropriate in relation to this methodology. The underlying foundation of this approach is then that current practice in the UK dams industry is 'good practice' as defined by the HSE.

France

In France, the term "risk assessment" is commonly used to describe the process of checking whether a dam satisfies the standards defined by the regulations. This is not the process of risk assessment as defined in this paper.

The philosophy of dam safety in France is one of "not accepting risk on dams" through ensuring that dams with the potential to endanger lives meet standards and that emergency procedures are in place. There is a recognition that the process does not result in zero risk, but that the residual risk, whilst not quantified, is considered to be low enough as to be considered negligible.

Dam owners in France are not currently using QRA, but some owners are using FMECA type analyses to manage component safety and direct capital and maintenance programs.

The Netherlands

Flood Protection

Regulation in relation to dams in the Netherlands applies mainly to publicly owned flood protection infrastructure. The Netherlands has been amongst those Countries at the forefront in the use of risk assessment for many years.

Without flood protection, about two thirds of the Netherlands is flood prone, from the sea or rivers. A quarter of the Country is below mean sea level.

Following severe floods in 1953 in which over 1800 people died, the 'Delta Commission' was established and in 1958 set down the basis for safety standards to protect against high water. The Commission proposed what could be referred to as a risk based approach to consider the costs of dyke construction versus economic damages should the dyke fail for each dyke ring. However, because of technical difficulties, including the assignment of probabilities to dyke failure, a simplified approach based on prescribed water level, with a margin for waves conditions was adopted, or "overtopping probability".

The standards vary from 1/10,000 to 1/1,250 annual exceedence probability (AEP), depending on the economic activities, the size of population in the protected area, and the nature of the threat (river or sea). The standards were adopted into legislation in 1996 with the Flood Protection Act. The policy is aimed at meeting standards by 2001.[3]

At the same time, there is a move toward a new safety philosophy based on risk assessment, where safety is related to the risk of flooding in terms of the probability of flooding and consequences. The aim is to look at all contributing factors, including the integrity of the dykes in order to determine risk reduction strategies.

A research program, Marsroute of the Technical Advisory Committee for Water Retaining Structures (TAW), is working toward the development of reliable techniques to estimate failure probabilities for dyke systems. This work is well advanced at this time, with several sample calculations for dyke systems having been undertaken.

The indications are that substantially higher probabilities of failure than the "overtopping probability" are being calculated. The aim is to reach a position where flood risk can be compared to other societal risks and risk standards and thereby establish an acceptable level of safety.

Risk Criteria - General

In the Netherlands, safety concerns about LPG fuel sales and estimates of potential consequences resulted in 1978, in the introduction of planning controls within 150 m of filling stations. Subsequent regulation of industrial hazards has been shaped by the LPG regulations and follows a risk based approach.[4]

Dr. Ben Ale of the Institute of Public Health and Environment (RIVM), is recognised as a leader in the field of risk analysis. He was part of a team that prepared the basis of government policy for environmental risks. Dr. Ale has received the "Outstanding Achievement Award" from the Society for Risk Analysis and is a member of the Board of Directors of the International Association for Probabilistic Safety Analysis and Management (IAPSAM).

In relation to risk criteria in the Netherlands, Dr. Ale has explained that,

> For individual risk an upper acceptability in new situations or new developments of 10^{-6}/year holds for establishments and for the transport of dangerous materials. In existing situations a sanitation limit of 10^{-5}/year is upheld. For Schiphol airport these limits are 10^{-5}/year and $5*10^{-5}$/year respectively. These last limits are under debate and thus subject to change.[5]

Dr. Ale also notes that a new general ordinance is in preparation, in which these risk limits are given full legal status. Further,

> For societal risk an advisory limit is given for establishments and transport as is depicted in Figure (1). It should be noted that in spatial planning the limit for transport will only be observed within 200 m from the route. For air transport and other sources of risk no limit has been set.[5]

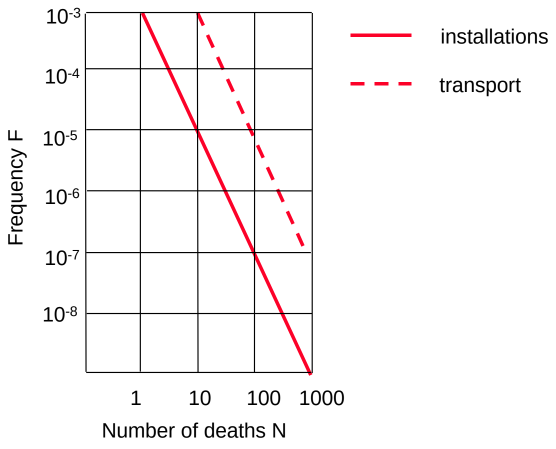

Figure 1 – Advisory Societal Risk Limits in the Netherlands

"On a national scale, comparison of risks can focus attention as to which risks are more threatening than others and which risks involve most people (fig 2).[6]

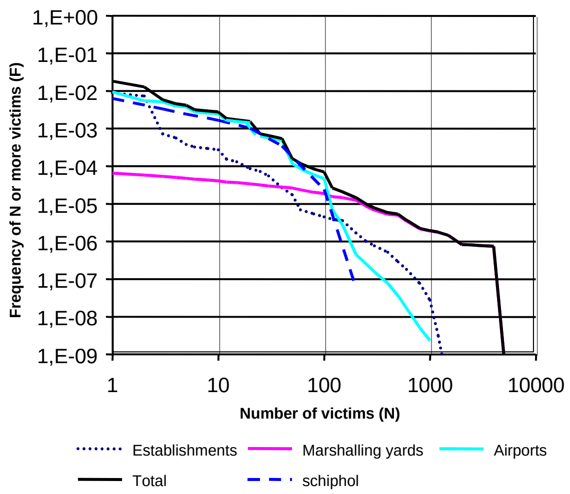

Figure 2 – Societal Risk in the Netherlands (Yearly Environmental Report RIVM, 1999)

Dr. Ale notes that expert judgement is embedded in all activities pertaining to risk analysis and assessment and that if a result is obtained by judgement rather than rigorous scientific analysis it should be reported.

He also comments that in relation to uncertainty, risk assessments and judgements are based on best estimates.

In another paper on standards for risk[7], Dr. Ale discusses the use of directional criteria, that is criteria that do not give explicit values but give a direction or intent. For example ALARA (as low as reasonably achievable) or ALARP (as low as reasonably practicable). Dr Ale notes that, "in an increasingly competitive environment …….. any cost is damaging the competitive edge."[8]

Owners may then say that any additional costs to exceed a standard are excessive and when this is combined with uncertainty about what is "safe" makes it cost effective to argue for not going beyond standards.

The ALARA and ALARP criteria also are under increased pressure to try to express all costs and benefits in monetary terms. "There are great advantages in this approach in the context of a market economy because it takes safety from a vague ethical concept into a good with a price worth paying."[8] The problem is that it is very difficult to place a value on life or injuries or environmental damage. Costs also can be difficult to value because of benefits that can also flow from those costs.

"In summary, it can be concluded that currently there is not yet a clear understanding of how to use cost benefit analysis in an organised way in risk management".[9]

These comments would appear to indicate some doubt about the practicality of the approach by the HSE in the UK, whereby cost benefit analysis is put forward as one method of measuring progress toward an ALARP condition.

It is clear that there is a solid foundation of use of QRA and acceptable risk criteria for public safety in the Netherlands.

<u>Risk Criteria - Flood</u>

In relation to flood defences, this approach is being extended into a research program to enable a switch to safety based on the risks of flooding per dyke ring area. This is a further development on the approach taken since the 1953 flood event of basing safety on flood return periods. Work to date has been focussed on calculating the probability of failure of dyke systems, but in the future calculations of damages will be added to the equation to determine risk (probability of the event and consequences) in each case. A process to evaluate acceptable risk will be required. It is expected that this process will mature over the next five to ten years. The Technical Advisory Committee says,

> The aimed for switch in safety policy with respect to flood defences will need to be intensively discussed at both a social and political level. The basic principle for the legislator in this process will be that the new safety approach will result in at least an equal level of safety.[10]

Risk Perception

In relation to the perception and decision processes based on risk assessment, Dr. Ale provided some insights into the issue in his paper regarding “Trustnet”.[11] The paper is based on a series of seminars held on the subject of risk communication and social trust. The paper points out the extreme complexity of decisions about the acceptability of hazardous activities, related to what are the benefits and if so to whom and where, uncertainty about the risks for catastrophic hazards, benefits and disbenefits not being applied to the same group, arguments between experts and others about hazards and risks.

Dr. Ale points to a reduction in trust of experts who have tried to “educate” people about the difference in expert opinion and the views of the public. The need for openness by experts and a need to ensure that experts remain working in the realm of risk analysis (the calculations) and leave the risk assessment (what is acceptable) to policy makers is strongly made.[11]

It may be that the public reaction to risk based information will not be adverse because people realise that there are risks in society and appreciate the information being in the open. The public reaction may not be as forgiving if the risks are covered up or lied about.

Risk Policy

There is some difficulty in the process of directing technical risk analysis approaches to risk assessment in the policy forum. An approach used in the Netherlands is to accept that the analysis outcomes, whilst representing the best possible information at the time, will probably be subject to change over time as the science improves. Therefore, the advice to politicians, who must drive the criteria setting through the political process, is that the policy should include provisions for review in five years to check how well the policy has worked and to review further developments in the scientific and social context.

Policy developers consider it is essential to involve all people with an interest and ensure that those who must pay if works are required agree with the risk-based methods on which the policy would be based.

Policy developers also recognise that whilst there can be large confidence limits on assessments, it is difficult for the political process to deal with that type of information and therefore, the most probable estimates are used in developing policy.

Norway

In Norway, the regulations are managed by the Norwegian Water Resources and Energy Directorate (NVE), through their Safety Department. The NVE issued Guidelines for Risk Analysis for Dams in 1997. The Guidelines refer to the use of risk assessment for prioritisation of remedial works, selection of the remedial option and as a tool for emergency planning measures. The guidelines when issued, included only probability assessments.

Several analyses for dams have been undertaken. Most have focussed on the dam failure probabilities and although a model has been developed for estimating consequences, it appears that the profession are concentrating on refining the assessment of failure probabilities prior to moving to detailed consequence assessments and developing risk criteria.

At least two case studies of the analysis of failure probabilities for Norwegian dams are to be presented at the ICOLD 2000 Beijing conference.

Dr. K. Hoeg (past President of ICOLD) in a 1998 paper[12] put forward some considerations relating to the use of risk analysis. He pointed out that the new performance regulations being developed in Norway "state that alternative solutions are acceptable as long as analyses show that the resulting risk level is no higher than that implied by the regulations."[13]

Dr. Hoeg also considered that "The main purpose of carrying out a risk analysis is to provide decision support"[14] and "Risk analysis provides a framework for systematic application of engineering judgement and available statistics in decision making"[15]. He believes that factors of safety do not provide a transparent level of safety and that probabilistic risk analyses can assist in exposing uncertainties. Even though a failure mode may be missed in analysis, this can also occur with deterministic solutions. The key is to "improve our understanding of dam/foundation behaviour and failure mechanisms, resist complacency, and improve quality assurance and control."[16]

Dr Hoeg also states that the use of the concept of acceptable risk (risk criteria) is controversial.

Several papers have been published about risk analysis (effectively probability of failure assessments) of Norwegian dams. In a paper by T Aamdal,[17] there are included comments on the process by independent consulting firm Veritas, who have experience in the offshore oil industry. Interestingly, the comments tend to suggest the use of more rigour in the methodology, amongst other things pointing to "statistics, analysis and computations" and "sensitivity analysis".

Sweden

The Swedish Government has considered the establishment of regulations for dam safety on several occasions, including recently, at which time it was indicated that regulation may be required.

In response, dam owners set up their own guidelines – the RIDAS guidelines of 1997. The RIDAS guidelines are due to be reviewed in 2001. More recently, the Government has stated that dam owners are wholly responsible for the safety of dams and for the consequences of dam failure. This has placed even greater emphasis on owners to understand fully the risks within their portfolios.

Risk analysis is being considered as a methodology to prioritise the remediation of dam safety deficiencies. In this regard, Vattenfall, the power company and major dam owner in Sweden, with consultant SwedPower, have been working with both quantitative and FMECA type analyses to evaluate what methodologies would be suitable for their purposes.

An interesting dam safety issue in Sweden relates to the stability of embankment dams. Particularly those constructed with glacial till (moraine) core material. There are 27 embankment dams higher than 15 metres in Sweden that have developed sinkholes. This is equivalent to 20% of Sweden's large earth and rockfill dams.[18]

In some cases remedial works have been undertaken whilst in others enhanced surveillance is in place to monitor developments. In this regard, Vattenfall/SwedPower are investing in joint research into improved seepage monitoring techniques in addition to that also being done within the European Union.

United States

General

Attitudes to the use of risk assessment vary widely from no formal use whatsoever to adoption as a normal dam safety process. However, risk assessment is certainly on the agenda, and the subject of debate throughout the country.

At the moment, the Bureau of Reclamation, Washington and Montana States are the only users of risk analysis techniques as an integral part of a dam safety program that was identified during the study. Some States use a basic level of risk analysis as a tool for prioritising regulatory efforts, but normally fall back to standards based approaches for long-term remediation, apart from isolated cases where the consequences of failure at the dam are low.

Bureau of Reclamation

The Bureau of Reclamation (Reclamation) is responsible for a portfolio of over 350 dams, forming a significant part of the water resources infrastructure of the western United States. As such, Reclamation is amongst the worlds largest dam management agencies and the activities and views of the organisation in relation to risk analysis and assessment must be carefully considered, particularly as Reclamation is actively using these methodologies.

A degree of understanding of Reclamation's position in relation to risk analysis and risk assessment can be gained from their methodology document.[19] The fundamental basis appears to be that risk analysis and assessment are considered a means to the improved management of the risks that are an inherent part of dam management, recognising the limited availability of resources to remediate those risks. Reclamation state that,

> Tightening budget constraints suggest it is appropriate to use risk determinations as a tool to direct funding to those issues presenting the greatest risks.[20]

The Federal authorising legislation for the dam safety program states:

> *In order to preserve the structural safety of Bureau of Reclamation dams and related facilities, the Secretary of the Interior is authorised to perform such modifications as he determines to be reasonably required.*[21]

Responding to the congressional mandate, Reclamation has refined the goal as follows:

> *The objective of the Safety of Dams Program is to ensure that Reclamation structures do not present unacceptable risks to public safety, property, and welfare. This requires identifying structures which pose unacceptable risks and taking corrective actions to reduce or eliminate these risks in an efficient and cost effective manner. Reclamation policy is to provide safe structures, but this does not imply a risk free environment. A safe dam is one which performs its intended functions without imposing unacceptable risks to the public by its presence.*[22]

The mention of "unacceptable risks" suggests that there are guidelines used to determine if risks are unacceptable. This is the case and Reclamation uses a two-tier system to measure calculated risks against.

Although the two-tier system is used as a guide, it would be incorrect to postulate that this is the only criterion used to determine dam safety actions. Risk assessment is used to assist in the evaluation of public safety, economic, resource and social concerns within the overall dam safety decision making process. Other factors that may be considered are operational, economic, public involvement, water use, and legal requirements.

Risk analysis benefits are described as including the ability to compare risks resulting from varying loading conditions at and between dams, an improved understanding of dam behaviour, as a guide for further investigations, as being able to assess the effectiveness of risk mitigation measures and as a way to effectively allocate resources. The aim is to ensure that dams representing the greatest risk receive priority for funding and/or evaluation.[23]

Reclamation categorises risk analysis into two types known as baseline and risk reduction. A baseline risk analysis can be a portfolio level analysis, a basic analysis performed by a senior engineer as part of a six yearly comprehensive facility review or a project team risk analysis.

The project team type of risk analysis is the most detailed and requires the preparation of event trees with associated probabilities and consequence estimates. Areas of uncertainty can be identified for decision-makers and information gaps, which if filled would significantly improve estimates, are also identified.

The risk reduction analysis is in two parts. The first part consists of identifying the highest component contributors to risk and then devising alternatives to reduce risk, either structural or non-structural. The second part is evaluating the alternatives for effectiveness of risk reduction.

Reclamation uses a two-tier system for their public protection guidelines. The first deals with loss of life considerations, whilst the second deals with public trust.[24]

The Tier 1 Guidelines require the plotting of estimated annualised loss of life estimates against estimated loss of life for dam failure separately for each load category. Guidance is then given to the actions that should be considered if the annualised loss of life is greater than 0.01, between 0.01 and 0.001 or less than 0.001. The plots are assessed taking into account confidence limits on the estimates and whether there are any single high consequence events.

The Tier 2 guideline relates to public trust whereby Reclamation recommend that each individual dam has a maximum combined annual probability of failure of 1 in 10,000. This is to ensure a reasonably low probability of failure of a dam within the Reclamation portfolio within the next 50 years.

The guidelines include examples for cost effectiveness calculations and sample plots.

The paper, "Achieving Public Protection with Dam Safety Risk Assessment Procedures"[25], includes a statement in relation to how "risk assessment approaches are intended to be an additional tool that leads to improved decisions by helping to accomplish the following objectives:

- Recognises that all dams have some risk of failure
- Considers all factors contributing to risk
- Identifies the most significant factors influencing risk and uncertainty, which facilitates efficient targeting of additional data and analyses
- Identifies a full range of alternatives to manage risk, including monitoring and other non-structural methods
- Focuses funding and resources toward risk-reduction actions that achieve balanced risk between dams and between failure modes on individual dams
- Establishes stakeholder credibility and due diligence for risk-reduction actions"

There is no doubt that Reclamation uses risk analysis processes as a fundamental part of their dam safety decision-making (risk assessment). Following discussions with key personnel, it was concluded that Reclamation uses risk processes for more than the prioritisation of their works program. If the outcome of risk assessments result in risks that Reclamation determine to be low enough as to not warrant action (in the absence of other influences), even if a standards approach would determine otherwise, then works are not undertaken and dam safety funding is invested elsewhere.

This does not mean that work will not be taken at some time in the future (never say never), but it appears that there will be no action unless the risk situation or guidelines change.

The Public Protection Guidelines document does not include background on how the Tier 1 guideline was constructed, nor any indication as to whether the public had input to the guidelines. However, it is understood that whilst there was no public input into the guidelines, Reclamation do have public input once it is determined that risk reduction works are warranted. The likelihood of loading, the dam response and consequences are all provided to the public to highlight critical conditions that require remedial works, but not in comparison to any risk threshold.

<u>Washington State</u>

The state regulator for dams, Washington State Dam Safety Office (DSO) uses risk concepts as part of their dam safety program. The methodology was developed to meet the competing needs of providing consistent dam safety across the State whilst working with limited resources. Risk processes were seen as being useful, but a QRA for every project was not feasible. An approach was developed that uses risk concepts and procedures in a standards-based framework.[26]

A concern of the DSO was that applying strict standard design events would result in an unbalanced level of public protection across the State. The primary driver here is that the probability for probable maximum precipitation (PMP) and maximum credible earthquake (MCE) estimates vary considerably

with geographic location. For example the AEP of the PMP can vary from 10^{-6} to 10^{-9}. There was also recognition that the use of PMP and MCE as design loading standards does not result in zero risk, nor does it recognise differences in consequences between sites.
A process known as the Design Step Format is used to take account of the desire to achieve balanced protection across the State and incorporate the extent of consequences into design.

To include public protection into the design step process, benchmarking was undertaken against levels of safety provided by other engineering disciplines, Government regulations and risks that the public is exposed to in ordinary life. Use was also made of "back calculations" of codes used by the Department of Energy in setting performance goals for its facilities. This resulted in life loss numbers being set to design steps through each design step probability. If plotted on a societal risk curve the results are conservative in comparison to similar guidelines prepared by other organisations.

In order to select the design step level, a consequence rating system was developed to take into account consequence categories.

Utility curves and rating tables are used to implement the system. For example, a utility curve is used to determine consequence-rating points from the population at risk. The points system has been calibrated to ensure that the life loss guideline is met in relation to annual exceedence probability (AEP) for loss of life.

Design loading levels are derived from magnitude frequency relationships. In relation to flood loading, a conservative approach is taken for new dams, whilst loading parameters closer to the mean are used for existing dams.

Seismic loading is more problematic for the DSO, since recent work has identified the potential for Mw 9 earthquakes with relatively short return periods. This could double the acceleration levels used for dams design on the West Coast. However, the probabilistic method is still used, albeit at mean values of acceleration. The DSO considers that further advances in the science will result in lower variance to estimates. When available, previous studies will be revisited.

For static loads such as seepage, redundant design procedures are used for new dams and qualitative assessment is used to estimate the probability of failure for existing dams.

The DSO considers that since the design step format approach was implemented in 1990, it has been successful in providing an adequate level of protection against failure between projects across the State and to prioritise compliance efforts. 40 of the 46 dams identified under the National Dam Inspection Program prior to 1990 have been repaired and 78 of an additional 101 dams identified as unsafe since 1985 have been repaired.

The methodology used by Washington State DSO is based on a simplified risk based system. It implicitly includes societal risk guidelines and attempts to provide a consistent level of safety for similar dams in terms of the consequences of failure across the State. The methodology is also used to prioritise the efforts of the DSO.

The State does not provide any funding to owners for upgrades, but does undertake most of the investigative studies. They have found that this has been a useful tool in dealing with owners as the owners can use the data in supporting cases for upgrading works.

The DSO arranges for briefing sessions with the affected populations where there are severe deficiencies at an upstream dam. Emergency action plans are required for all dams at which there is potential for loss of life. The owner is responsible for preparing the plan and to get a sign off by the County authorities for the plan.

The guidelines for the design step format are not directly referred to in the legislation, but the legislation provides for the establishment of guidelines for dam safety. The acceptance or otherwise of guidelines is at the State Government Department level.

<u>Montana</u>

The State of Montana also has elements of a risk-based approach to dam safety. At least flood capacity is determined by loss of life estimates at each site. The methodology was developed in conjunction with public meetings and a stakeholder reference group.

Both Washington and Montana States have their dam safety decision making criteria available on the Internet.

Utah

A risk-based process is used to prioritise the efforts of the Utah State dam regulator, the Dam Safety Section, but not to determine the extent of remedial works.

The prioritisation process is a point scoring system based on Utah dam failure statistics. Dam elements are rated from 1 to 5, then multiplied by a factor to give a score for that element. Scores are added, then multiplied by the "humans at risk" score to give the "Total Risk Score"

The elements are spillway, guard gate, piping, slope and seismic.

Utah State University and RAC Engineers and Economists

Dr. David Bowles, Professor of Civil and Environmental Engineering at Utah University together with RAC Engineers and Economists have played and continue to play a significant role in the development of risk based approaches to dam safety.

They have undertaken considerable work within the United States and Australia over many years, in particular in applying the Portfolio Risk Assessment process and are currently working with the Corps of Engineers in demonstration projects using risk assessment.

In their 1999 paper,[27] Bowles et al point out the benefit of risk management in enhancing dams management. "When properly implemented, it can result in a more rapid and more cost effective achievement of risk reduction at aging dams. This approach (risk enhanced approach) seeks to a) develop a thorough understanding of the dam safety risks, and b) explore the options and provide a basis for managing these risks in the context of the owner's business."[28]

The paper points out the benefits of risk identification, exploring options, justifying and prioritisation of actions.

World Bank

From 1991 to 1999, the World Bank provided assistance for a Dam Safety Assurance and Rehabilitation Project in India. The objectives of the Project were to improve the safety of selected dams in the project states through remedial works, installation of basic safety facilities and strengthening the institutions of the Borrower and the project states responsible for assuring dam safety. This was the first World Bank project directed entirely at dam safety. ICOLD standards were followed for the project.

The scope of the project covered four states (Madhya Pradesh, Orissa, Rajasthan and Tamil Nadu) and remedial works on 33 dams.

Whilst initial works were not prioritised on a risk basis, draft risk guidelines were prepared under the project and are being finalised through the National Committee on Dam Safety. Perhaps not surprisingly, given the varying worldwide views on risk assessment, there are some varying views within the Indian dams community regarding the use of risk assessment, even in a prioritisation role.

Corps of Engineers

The Corps have responsibility for a total of 569 dams in the United States. Of these dams, 407 are embankment dams and 162 concrete. Of the embankment dams, 356 are high hazard, 36 significant and 15 low hazard.

A fundamental role of the Corps in relation to dams is to provide flood control works to save lives. The nature of flood control dams results in a peculiar dam safety situation, that is that a high proportion of the Corps embankment dams have not experienced "first filling" to spillway flows. From a total of 243 high hazard ungated dams, only 41 have spilled and record high pool levels have only been over relatively short durations.[29]

The Corps are engaged in a five-year research program into the use of risk analysis for dam safety. Current views are that the use of risk analysis seems promising for prioritisation of works and that it may be used to support conventional decision making. At least one demonstration analysis has been completed and it is understood that another is underway.

Risk analysis is used for decision making for navigation structures where loss of life is not an issue. The program is primarily focussed on mechanical and structural components and is used to provide economic justification of projects and apportion costs between stakeholders.

A paper on risk analysis for hydrologic risk prepared for the Corps[30], contains some detailed commentary in relation to the use of risk assessment. The report recognises the challenge of providing levels of safety for large dams that take into account the trade-off between costs and benefits. Also, that "Every dam safety decision is an implicit decision about the allocation of resources in society"[31] and "Neither the deterministic method nor the probabilistic method really attempts to efficiently allocate resources in the dam retrofit situation."[32]

In the paper, recognition is given to the "rational and responsible position"[33] of using quantitative risk assessment to balance risk reduction costs with consequence reduction. However, there is not a recommendation to replace traditional methods with risk assessment, but to use risk assessment as an aide in the decision making process. It appears that the authors recognise the benefits of risk assessment and believe that there should a "move from the use of implicit risk associated with such a deterministic or selected worst-case design standard to a policy determined by a reasonable and explicit risk target"[34], but consider that further development is required.

California

Dam safety regulation in California is standards based. Following the failure of St Francis dam in 1928, legislation was strengthened, providing for supervision over non-federal dams in the State. Following failure of the Baldwin Hills dam in 1963, the legislation was amended to include offstream storages. The legislation provides for new dam or existing dam modification approvals, supervision of works and operation and maintenance.

Dams covered by the regulations are those 7.6 metres or more in height and having a capacity of $62*10^3$ m^3 or more.

An interesting application of risk assessment was applied to the Eastside Reservoir Project. The project consisted of the construction of three dams to form a pumped storage for urban supplies with a capacity of $990*10^6$ m^3 for the Metropolitan Water District of Southern California. The dams of the project represent the largest earth and rock fill reservoir project in the United States, with a total embankment volume of over $84*10^6$ m^3.

The methodology was undertaken by Woodward-Clyde consultants and published in 1996[35]. The methodology was based on a logic tree approach where "the occurrence of the event is decomposed into component events whose probability have a better chance of being estimated using analysis, available data, or judgement of a panel of recognised experts."[36] The method was seen as providing an improved understanding of system performance of the dams as well as an estimate of probability of failure of the dams.

The analysis resulted in an Estimated Range of Mean Annual Probability of Failure for the two main embankments of 10^{-7} to 10^{-9}. It was considered that the results were consistent with the conservative design adopted, the controlled filling period, detailed testing and monitoring and the small ration of drainage area to surface area. Whilst the degree of influence of expert judgement on the result was recognised, it was felt that since the results were one to three orders of magnitude lower than threshold levels of "acceptable risk", they provide assurance that the risks would be sufficiently low even if the subjective probabilities were to increase.

CANADA

BC Hydro

BC Hydro is a major Canadian Dam owner. They are the third largest electric utility in Canada and are responsible for 61 dams.

There has been significant development in dam risk management processes at BC Hydro since 1997. The development includes a changed approach to risk assessment, resulting in the "Proposed BC Hydro Tolerable Risk to Life Criteria", which were never adopted by the organisation, becoming obsolete. Those criteria should therefore no longer be quoted.

The new dam safety decision-making framework includes consideration of:

- Conformance to authoritative good practice.
- Regulatory requirements.
- Corporate values.
- Social expectations.
- Quantified risk.

BC Hydro believe that risk regulation for dams is not as developed as risk regulation in other hazardous industrial activities and that the framework takes account of this, whilst also ensuring that the process is consistent with established principles of industrial safety management.

In relation to quantified risk analysis, there is a consideration that in most cases, quantification of the probability of failure will include subjective estimates. Therefore, they conclude that it becomes necessary to ensure the meaning of the estimated values is clearly understood and that this understanding directs how the results of the analysis can be appropriately used.

Regarding risk assessment, there is an increased emphasis toward individual risk. Whilst still considering societal risk, the 'risk to individuals' receives much greater emphasis than previously. Measurement against risk criteria - either individual, societal or economic - follows an approach of the risks being "unacceptable" above specified limits and to be reduced to an ALARP condition below those limits, rather than being "tolerable".

For measurement of an ALARP condition, the concept of 'gross disproportion' is employed. In the UK, the Health and Safety Executive (HSE) says that this is achieved where there is a 'gross disproportion' between the effort to control risks further and the risk reduction that would be achieved.

BC Hydro's re-formulated approach to catastrophic risks posed by dams, although independently developed, aligns with the principles set down by the HSE in its discussion document 'Reducing Risks, 'Protecting People'.

In this way efforts are directed at "striking a balance between the need to protect against the risks and the needs of society for the benefits generated by the dams"[37]. With recognition that an owner cannot meet this balance without consultation with the relevant stakeholders.

B.C. Hydro have a risk based scheme for prioritising "investigations of actual or potential deficiencies identified through routine surveillance and/or periodic dam safety reviews" called 'PREP'.[38]

The interface between the prioritisation process and the periodic Dam Safety Reviews is the FMEA/FMECA studies that the organisation has introduced into the Dam Safety Review process. These studies provide information in relation to identification of potential deficiencies and assistance to the dam safety engineer in judging the rating of those deficiencies.

In addition, "Application of these principles is entirely consistent with traditional dam safety practice – Careful application of the process results in entirely defensible risk based dam safety decisions – all dam safety investigations are some form of risk analysis – all dam safety decisions are some form of risk assessment."[39]

It was concluded that BC Hydro intend to use a three level approach to risk analysis. The first is FMEA/FMECA to prioritise dam safety remedial works or to identify the need for further information, the second is in prioritising dam safety investigations ("PREP"), and the third is to undertake detailed probabilistic analysis if further detailed understanding of a particular issue is required.

CONCLUSIONS

Risk Analysis

Typically, those practitioners favouring the use of risk assessment as an aide to normal dam safety practice point to the benefits of improved understanding of dam behaviour and its assistance in providing a basis for the prioritisation of dam safety efforts at or between dams.

Over the past decade, activity in the development and use of risk analysis techniques for the dams industry has accelerated and become more widespread.

Risk Criteria

To assist in decision making, the risk determined from risk analyses can be measured against criteria indicating what may be considered to be reasonably acceptable levels of risk. For loss of life considerations, societal and individual risk criteria are used.

Within the world dams industry, the development and use of societal and individual risk criteria is not widespread and is somewhat controversial.

Of organisations from the Countries visited, only the USBR explicitly use risk criteria to establish acceptable levels of dam safety. Washington State's regulations implicitly include acceptable risk concepts and Montana State have included the concept in their new regulations for spillway size.

The main arguments raised against the use of loss of life criteria for dam safety can be summarised to three issues.

Firstly, the wide confidence limits on probability and consequence estimates result in too much uncertainty to allow sensible measurement against criteria. Secondly, because "judged" probabilities are required for some elements of the analysis, it is not acceptable to compare the resulting calculated risk to acceptable risk criteria. Thirdly, the conflicting philosophy of whom should decide what is an "acceptable" risk.

A further argument from some relates to the degree of sophistication of the risk analysis processes used within the dams industry at the moment and whether it compares well to the practices used in other high consequence, low probability industries that compare analysis results to risk criteria.

However, the degree to which the same arguments apply to the past and current use of loss of life criteria in other industries is open to question.

Proponents of the use of acceptable risk criteria point to society's limited resources to deal with risk reduction and the need to apply those resources in a logical and equitable way. It does not appear to be reasonable, for example, to accept a certain level of risk from a chemical or nuclear facility on the basis that the benefit is worth the risk and then to apply standards which may provide a much greater level of safety for a nearby dam. The question becomes one of how much is society prepared to pay for dam safety?

Others say that the argument relating to "who decides what's acceptable" could be applied equally to current standards. That is, if standards are to be used, shouldn't those who are exposed to the residual risk, and it is generally agreed that there is some residual risk, decide if that is acceptable?

Since there remains residual risk after the implementation of standards based on hazard category, the process could be described as the application of a form of risk assessment. Whether the process used to determine the hazard categories is a "reasonable" way to distribute risk and is acceptable to the public exposed to the risk is not usually questioned.

It does not seem reasonable to contend that using risk criteria is not acceptable on the grounds of due process, and yet not question the standards that are being followed. Either in terms of the magnitude of the inherent risk, the concept of "acceptable risk" that is implicitly included, or whether the standard has been established using reasonable process.

An issue not often raised is the differing levels of public safety that can occur across a jurisdiction through the application of standards. This is based on the geographic variance in the probabilities of probable maximum precipitation and seismic hazard. The application of standards based on these events can result in varying levels of risk across a geographic area. Furthermore, whereas the incremental consequences from an earthquake-induced failure are commonly in excess of those from a flood-induced failure, the probabilities of the flood events used in design are typically one to two orders of magnitude less than the earthquake probabilities.

Summing Up

Over the past few decades, major dam failures, at least in the developed countries have been rare. This has had an influence in dams occupying an apparently low, or no risk compartment in the minds of the public and politicians. Whereas the development of risk processes for other industries over the past few decades has been driven by either catastrophic accidents or public dread of a process, dam safety has not been exposed to the same combination of pressures. Certainly failures have occurred, but the political outcomes have been directed toward regulation and the use of standards, without questioning of the level of residual risk that remains once standards are applied. There appears to be poor public understanding of the potential consequences of a dam failure, as there is in general of the potential energy in elevated stored water.

Where the costs of dam safety are not obvious to the public and owners can generate funding for upgrading works without substantially affecting the price of the product created from the stored water, there is a tendency for regulators to insist on a standards approach and not contemplate risk processes, since there is no particular driver to take any other approach. However, the situation is more problematic for owners of water supply dams, particularly rural water supplies, where dam upgrade costs can have a dramatic affect on the price of water supplied from the dam. The political influences, usually dormant within the industry until the costs are known and the argument of who should pay is raised, are quite rightly, suddenly active and asking, “Is this a reasonable investment compared to the other competing priorities in society”?

The current efforts in research and development in the use of risk analysis and assessment appears to be undertaken, with a couple of exceptions, by a relatively small number of dedicated, but underfunded, experts and interested owners. Whilst there is a growing recognition of the cost of dam safety, without a complimentary recognition of the risk posed by large dams in comparison to other high consequence, low probability industries, it is unlikely that the funding situation will improve.

As new dam construction has slowed in developed countries, efforts to review the safety status of existing dams have grown. This is resulting in a large body of dam safety information becoming available over a relatively short period of time. As the accumulated cost estimate to undertake standards based remedial works continues to grow, there will be increasing pressure from contributing customers and Government to justify the expenditure. It is unlikely that continued reference to standards alone will be acceptable, unless the basis for those standards can be justified.

Finally, in the absence of any other methodology, risk analysis, whether through qualitative or quantitative methods, provides a valuable tool for understanding dam behaviour, assisting in the definition of strategic surveillance, identifying interim risk reduction measures and for the prioritisation of investigations and works to reduce risk.

The current arguments against the use of risk criteria in determining what is appropriate for the ultimate safety level for a dam are recognised. However, efforts to improve these procedures are needed so that policy makers can be provided with the technical information necessary to reach objective decisions about the investment of society’s limited resources toward dam safety.

Ultimately, the issue of what is safe enough for society at a particular dam, will be determined by society and their representatives, taking into account many factors of which the risk posed by a dam is one element. Therefore the rigorous application of a pass or no pass criterion is not an issue. What is at issue is a means by which an understanding of risk from dams can be communicated in a meaningful way and compared to other risks that society is exposed to.

SUGGESTED FUTURE DEVELOPMENT

1. Risk analysis processes continue to be developed and used as a tool to improve the understanding of dam behaviour, identifying surveillance requirements and to prioritise investigations and risk reduction works.

2. Quantitative risk analysis processes currently developed for dams be benchmarked against those processes used in industries where the outcomes of such analyses are compared to risk criteria as part of the risk assessment process.

3. The outcomes of quantitative risk analysis benchmarking be used to determine what further research and development is required for quantitative risk analysis for dams to be used with risk criteria to establish acceptable safety levels for dams.

4. Regulators, in conjunction with owners, work with Government to advance the concept of risk criteria, encourage investment in development and engage the stakeholders in the process of risk assessment.

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