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LONG-TERM BENEFITS AND PERFORMANCE OF DAMS

Chapter 3. Risk assessment and reservoir management

Sri Lanka Dam Safety and Reservoir Conservation Programme

LAURENCE ATTEWILL, Jacobs GIBB, Reading
LJILJANA SPASIC GRIL, Jacobs GIBB, Reading
JAMES PENMAN, Jacobs GIBB, Reading

SYNOPSIS. The history of dam engineering in Sri Lanka dates back some 4,000 years to when ancient Ceylon developed control of the water streams to satisfy the needs of an advanced civilisation. These great works of irrigation are even more impressive, and attract even more interest, than many remains of ancient monuments, palaces and temples. Dam engineering practice in Sri Lanka has been continued to date to include large reservoirs such as Victoria, Kotmale, Randenigala, Samanalawewa.

Under the Dam Safety and Reservoir Conservation Programme (DS&RCP) 32 major dams were inspected and studied by Jacobs GIBB. The scope of the investigations included inspection and technical studies covering seismicity, instrumentation, stability, spillway adequacy and reliability. In addition water quality, sedimentation and catchment land use were assessed. Institutional issues included a review of dam safety legislation, establishment of a data management centre, identification of local research resources and training and skill enhancement for the local engineers.

PROJECT BACKGROUND

DS&RCP of Mahaweli Reconstruction & Rehabilitation Project (MRRP), funded by the IDA and managed by the Joint Committee (JC) has an objective to implement a qualitative management system for all major dams in Sri Lanka in order to improve their safety. The JC comprises the staff from the three dam owners, namely the Mahaweli Authority of Sri Lanka (MASL), the Irrigation Department (ID) and the Ceylon Electricity Board (CEB).

In year 2000, under the MRRP a Risk Assessment study of the 32 major dams in the Mahaweli river basin and adjoining basins was conducted. The study showed that while the modern dams have generally been built to current standards of the world's best-used practices, the same cannot be said

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

for the other dams. Many dams are showing signs of ageing while others have significant deficiencies in monitoring, maintenance, reservoir conservation and other issues. A vast majority of dams including numerous dams managed by ID have not had an overall safety review and risk assessment.

The main objective of the DS&RCP is to assess safety of the selected 32 major dams and to recommend remedial works as well as to assist Sri Lanka in establishing a long term dam safety programme.

PROFILE OF DAMS

The DS&RCP covered 32 dams out of a total dam population in the island of over 300. The 32 dams, whose location is shown in Figure 1, can be categorized as follows:

Mahaweli multipurpose dams

4 of the 32 dams are large modern dams on the Mahaweli river serving both hydropower and irrigation purposes: Kotmale and Randeningala (rockfill), Victoria (arch) and Rantembe (concrete gravity). In addition, Polgolla diversion barrage supplies the Sudu Ganga and associated power stations and irrigation schemes. The five dams are owned and operated by the MASL.

Hydropower dams

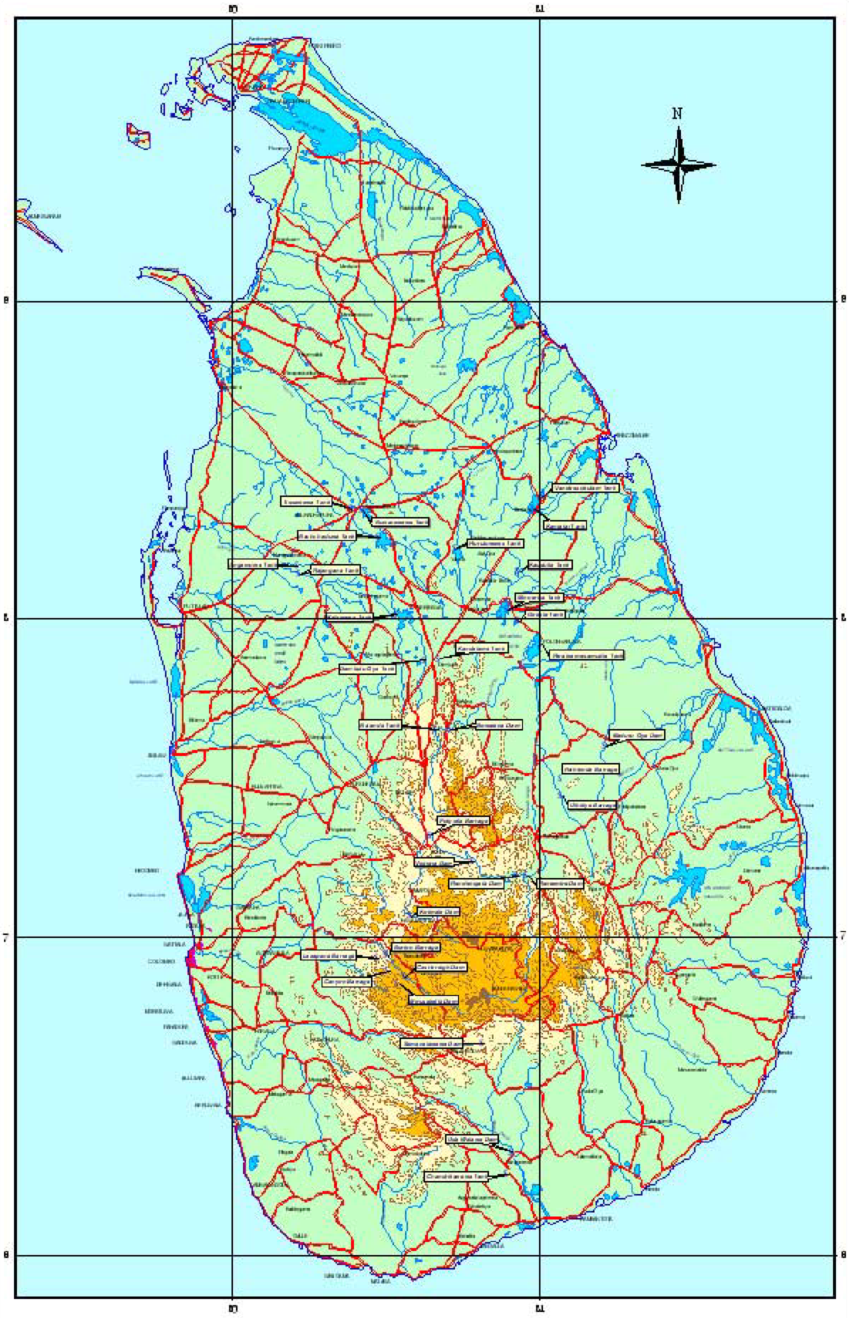
6 of the 32 dams are single purpose hydropower dams owned and operated by the CEB. 5 of these dams are concrete gravity dams on the Laxapana river system constructed in the 1950’s. The sixth, Samanalawewa is a rockfill dam constructed in the 1980’s.

Irrigation dams

The majority of the dams are single purpose irrigation dams and are owned and operated either by the ID of the Ministry of Agriculture or the MASL. 13 of the irrigation dams owned and operated by the ID were originally constructed over 1500 years ago and are still in use after successive rehabilitation and reconstruction campaigns.

Inspections

All 32 dams were inspected early in the programme following a procedure typical for a periodic inspection under the UK Reservoirs Act 1975. Of the 32 dams, all the 14 dams owned and operated by MASL had previously been inspected, by staff of the Sri Lankan consultancy CECB, and reports were available. Irrigation dams are generally inspected monthly or quarterly by ID staff who complete a proforma report. There is no evidence of CEB dams having been previously inspected.



Mahaweli Restructuring & Rehabilitation Project
Dam Safety and Reservoir Conservation Programme

Dam Location Map
FIGURE 1

Figure 1 Location map of dams

CONDITION OF DAMS

Summary of condition

Our conclusion on the overall safety of the 32 dams from the work carried out under this activity is that there are very few unsafe dams, but that there is a range of issues that need to be addressed in order to preserve and in some instances to improve the status quo. Adequate dam safety depends on three separate factors: design, construction, and operation / maintenance.

Although the design of the dams ranges from the simple homogenous embankments of the ancient dams to the sophisticated double curvature arch of Victoria, there is no instance where the safety of a dam is jeopardised by poor design.

There are several dams where the standard of construction has been below an acceptable level, and at several dams poor construction may jeopardise dam safety.

Generally maintenance is barely adequate, and if this situation is not improved the safety of the dams will slowly deteriorate.

Recommendations

Recommendations were made in the report of:

- Remedial works, categorised by priority
- particular maintenance items
- instrumentation and monitoring
- investigations and studies
- the nature, frequency and scope of future inspections

Spillways

Spillway capacity

Assessment of adequacy of spillway capacity comprised, for all 32 dams, the collection, review and detailed analysis of all hydrological data relevant to the dams.

Two methods were used for estimation of the design inflow floods: the statistical approach which is based on historic records of the annual maximum flows recorded at all gauging stations in Sri Lanka and the unit hydrograph method.

The statistical approach is based on the maximum annual flows for each year of record for the 80 gauging stations in Sri Lanka, providing some 2,000 station years of record. The results of the study are presented as a graph of the standardised flood peak versus the probability or return period of the flood (Figure 2). Three curves are presented, as follows:

- Curve no. 1 grouping all Sri Lankan gauging stations together
- Curve no. 2 for areas where the mean annual rainfall is < 2000 mm
- Curve no. 3 for areas of average rainfall
- Curve no. 4 for areas where the mean rainfall is > 3,400 mm

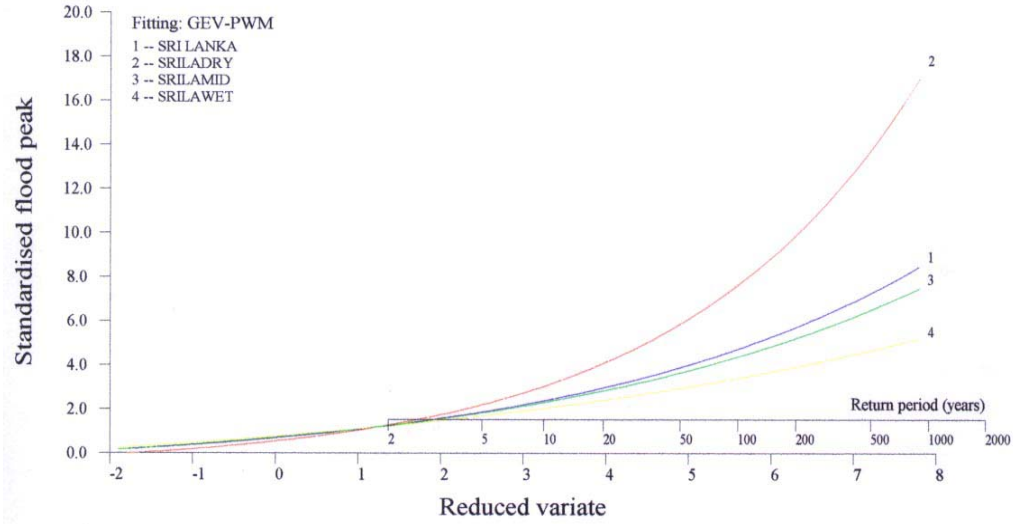


Figure 2: Regional Flood Frequency Curves

Because of the high density of population downstream of the dams, spillway capacity was also checked for the PMF. The PMF inflow hydrographs were obtained by a simplified version of unit hydrograph method and the estimation of the probable maximum precipitation (PMP) over the catchment. The PMP was estimated from the maximum recorded rainfall at each meteorological station over the period of record, which for many stations exceeds 100 years.

The check of the adequacy of the spillways and other outlets of the 32 dams showed that all but three of the spillways had adequate capacity: for these dams extra capacity can be economically and safely provided by heightening the dams concerned.

Spillway reliability

Of the 32 dams, 22 are either wholly or partly dependent on gated spillways for their safety. Of these spillways, 19 are electrically actuated, although most are capable – in theory – of manual operation. Nine of the 22 gated spillway were rated high reliability with no significant remedial works required.

Stability

Embankment dams
Among the 22 embankment dams, only the 4 modern rockfill dams and one zoned embankment had geotechnical information available from the original design stage which proved that the dams were stable. The geotechnical information for the remaining 17 earth embankments (13 of which are ancient) was either very poor or non - existent. Therefore stability of these 17 dams was carried out using an assumed range of lower bound strength parameters.

Based on the stability results 17 dams were grouped into the following three groups:

- Group 1 - FOS<1.3 - Investigation required (4 dams)
- Group 2 - 1.3<FOS<1.5 - Investigation required if high ground water levels or specific defects were identified in the inspections (7 dams)
- Group 3 - FOS>1.5- No investigations required (6 dams)

It was recommended that for four dams from the first group site investigations be carried out and the stability reassessed using the parameters from the investigation. In addition, three other dams from the second group also required investigations because of defects identified during the dam inspections.

Concrete dams
Out of 10 concrete dams, 9 are gravity dams with heights varying from 18.3m to 42m, and Victoria dam, a 120m high concrete arch dam on the Mahaweli Ganga.

Safety of the dams to sliding and overturning as well as the stress at the key points was checked for the normal, unusual and the extreme loading conditions.

Seven dams were found to be stable with an adequate safety margin under all loading conditions. However, three dams, Castlereigh, Nalanda and Norton dam were found not to have sufficient safety margin and appropriate remedial works – improved foundation drainage - were recommended.

Instrumentation

It was found during our inspection that the dams constructed recently were equipped with electronic instrumentation to measure seepage, pore pressure, deformations, deflections, movements, temperature and various other parameters. This equipment, whilst operating well for a number of years, has rarely been serviced or calibrated. Where equipment has failed there has been little funding available for its maintenance or repair which has resulted in the equipment being abandoned. In some cases, a lack of understanding of a system has led to equipment being abandoned or deemed inappropriate.

The dams that were constructed in mid 20th century have fewer instruments, and the ancient dams usually have no instrumentation at all.

Currently, dam monitoring is undertaken by dam owners and on many of the sites the monitoring is carried out on a regular basis. However, data recording and handling procedures often vary from site to site. The instrument monitoring staff has a basic understanding of the instrument operation but the data handling procedures are not standardised.

Following the inspection, we have recommended and specified additional instruments: these comprise for most dams the collection and measurement of seepage and the provision of survey monuments to enable settlement surveys to be carried out. Standardisation of data recording and presentation was proposed. It was also proposed that the records will be in a centralised data record library within the Data Management Centre in Colombo and will be available via the GIS system.

OPERATION AND MAINTENANCE (O&M)

The perceived shortcomings in present O&M procedures are as much the product of inadequate budgets and the failure of management to recruit, train and financially reward staff of the calibre necessary to operate and maintain large dams, as they are deficiencies in management procedures and practices. This in turn may be seen as being a failure by Government to recognise the importance of the security of the nation's stock of large dams to the national economy, and the threat that unsafe dams pose to the public at large. For this reason, it has been necessary to take full recognition of the initiatives that have been discussed to restructure the main water management agencies, to introduce a new Water Act and to set up a regulatory framework for dam safety. The form that the regulatory framework will take will impose obligations on dam owners that will significantly affect the procedures to be adopted for O&M and safety surveillance.

LONG-TERM BENEFITS AND PERFORMANCE OF DAMS

Prior to the preparation of Guidelines for Improvement of O&M and Emergency Procedures we examined the current practices which are applied within each of the agencies. They are summarised below.

O&M

Procedures for O&M of the large MASL dams are now well established. All of the new dams have O&M manuals prepared by the designers which set out routine procedures for O&M as well as emergency procedures, particularly in the event of a major flood.

Procedures for operation of CEB dams are determined in Colombo to meet energy requirements within the distribution system. The procedure adopted is that gate operating staff are assigned to provide 24-hour cover at each of these dams whenever the water level approaches FSL and continues until the water level has again fallen below FSL.

Operation of the ID dams is regulated by a departmental circular which covers the whole irrigation scheme as well as the headworks.

Emergency Preparedness

Some effort has been made at the big dams to prepare for emergencies, in that key staff have been listed with their home contact details, contact details have been compiled for the emergency services and other key authorities, and lists of emergency service providers have been made. But generally, there has been no attempt to identify risks, to set levels of alarm in response to different emergency situations, or to determine the actions and persons responsible in any set of circumstances. Also, there is no programme of formal training for operating staff in dealing with emergency situations.

Prepared Guidelines for Improved O&M and Emergency Action Plans (EAP)

We proposed that improved management practice for Sri Lanka's stock of large dams requires that the three principal agencies adopt a structured, simple and standardised approach to O&M and Emergency Preparedness. The guidelines were drawn up for preparation of Standard Operating Procedures (SOPs) and EAPs for all dams in Sri Lanka. Prototype documents were also produced that are intended for universal application by the three agencies.

RESERVOIR CONSERVATION

Extent of sedimentation and pollution

In world terms, Sri Lankan reservoirs are not severely affected by either sedimentation or pollution. However the pressures exerted by a rapidly expanding population have resulted in environmental degradation of one third of the total land area. Soil erosion is most severe in the high catchments on steep slopes at mid levels, which are used for market gardening and tobacco production: it is estimated that erosion rates for these land uses are 150t/ha/year, compared with 0-10 t/ha/year for paddy, forest and well managed tea. The actual sediment yield of the catchments varies between 0.5 t/ha/year to 4 t/ha/yr for lowland and upland reservoirs respectively. Of the 32 reservoirs studied only two, Polgolla and Rantembe are seriously affected by sedimentation.

Similarly water quality is becoming a more serious problem because of increasing levels of nutrients, pesticides and effluents entering the watercourses.

Conservation policy

A national conservation policy is required to reverse the adverse trends in sedimentation and water quality in order to protect the countries water resources. Sediment yields will be reduced and the water quality improved by:

- propagation of appropriate land use, including grassing or reforesting steep and high level areas currently used for agriculture, the prevention of overgrazing and the adoption of soil conservation measures
- the adoption of appropriate land use and fiscal policies to improve land tenure systems and discourage the fragmentation of land
- improvement of urban waste water treatment and the disposal of solid waste
- better management of fertilizers and pesticides
- enforcement of the 100m buffer zone of grassland and trees around the reservoir perimeter.

Considerable efforts are already being made in the conservation of the Mahweli catchments, including research, public awareness and farmer training. This work needs to be intensified and extended to all catchments.

TRAINING

Background

Inadequate skill levels were identified as a drawback to overall dam safety. Many of the skilled and experienced operators, technicians and site engineers have left the MASL, ID and CEB for better prospects. The younger operators, engineering and other relevant professional staff, are with limited experience and little exposure to appropriate best practices. It was recognised that there is a lack of a well-structured training and competency assessment programme, and that as a result staff training was an important component of the DS&RCP.

Training Framework

A training framework was produced based on assessments of the workforce capacity of 32 dams and their gaps in skills. The assessments were carried out based on the questionnaires, workshop and interviews with the staff and the senior management of MASL, CEB and ID.

The staff required training was grouped into the following groups:

Group A	Engineers in Charge/Chief Engineer: professionally qualified engineers generally with more than 10 years experience who are potential senior managers
Group B	Civil engineers and technicians engaged in dam monitoring who aspire to become Engineers in Charge or Chief Engineers
Group C	Electrical/Mechanical engineers and technicians who are responsible for the operation of spillway and sluices

A training programme was developed that comprised 9 training modules and technical presentations in 5 technical areas which were delivered by the Consultant. Around 150 staff received the training under this programme, namely 43 staff from Group A, 46 staff from Group B and 95 staff from Group C.

Nineteen local trainers were also identified from all three organisations. The trainers received technical training along with the trainees and in addition they also attended a course in communication and presentation skills. The trainers delivered one training course under our supervision when we had a chance to comment on their performance.

DAM SAFETY MANAGEMENT CENTRE

It is the intention that the three dam owning organisations combine to set up a Dam Safety Management Centre (DSMC), which would be a quasi autonomous body to coordinate the following activities for all dams in Sri Lanka:

- Data management and appraisal
- Emergency technical co-ordination
- Dam survey unit
- Implementation of dam safety programme for 32 dams

- Extension of dam safety programme to other dams
- Monitoring compliance with dam safety code of practice
- Steering group for dam safety legislation
- Training of dam owners staff
- Liaison with IESL and other stakeholders

DAM SAFETY LEGISLATION / CODE OF PRACTICE

As was required by the terms of reference, we prepared a paper outlining the main provisions of future dam safety legislation in Sri Lanka, based on a review of legislation in UK, USA, Sweden and India. The main provisions of the proposed legislation were:

- The dam owner is responsible for the safety of the dam
- A register of dams would be compiled and maintained by the enforcement authority
- Dams would be subject to mandatory inspections by independent engineers
- Recommended remedial works would be mandatory

After much internal discussion the Client decided that Sri Lanka is not ready for legislation and that the proposed provisions should be contained in a Code of Practice. The DSMC will be responsible for monitoring compliance with this Code.

PORTFOLIO RISK ASSESSMENT

Objective

Portfolio Risk Assessment (PRA) provides a rational method of improving the safety of a group or portfolio of dams in the care of a single owner or organization. PRA enables owners to determine

- How much dam safety expenditure is justifiable
- The priority of dam safety measures
- The rate of expenditure
- The risk profile of their portfolio

PRA involves the following steps:

- Engineering assessment of dams
- Assessment of risk posed by dams in their existing state and after dam safety measures
- Definition of dam safety programme

Risk assessment

The risk for all 32 dams was assessed both by the semi-quantitative “Failure Modes, Effects and Criticality Analysis” (FMECA) method and a quantitative analysis in which the probability of a dam failure and the cost of the consequences are expressed numerically.

In the semi quantitative estimate both the probability and the consequences of failure are expressed by a scoring system developed which is based on that and described in the CIRIA publication C542 Report, Risk Management for UK Reservoirs. In this the probability of failure of a dam can be expressed as the product of at least two factors:

- The probability of an event (slope instability, flood overtopping etc)
- The probability of the event resulting in failure of the dam

Both probabilities are expressed in terms of a score in the range of 1 (very unlikely) to 5 (likely).

In the quantitative assessment, event tree analysis is used to estimate the probability of failure and the consequence of failure is based on an estimate of the loss of life and economic loss from inundation mapping. The results of the risk analysis are shown on the F-N plot in Figure 3.

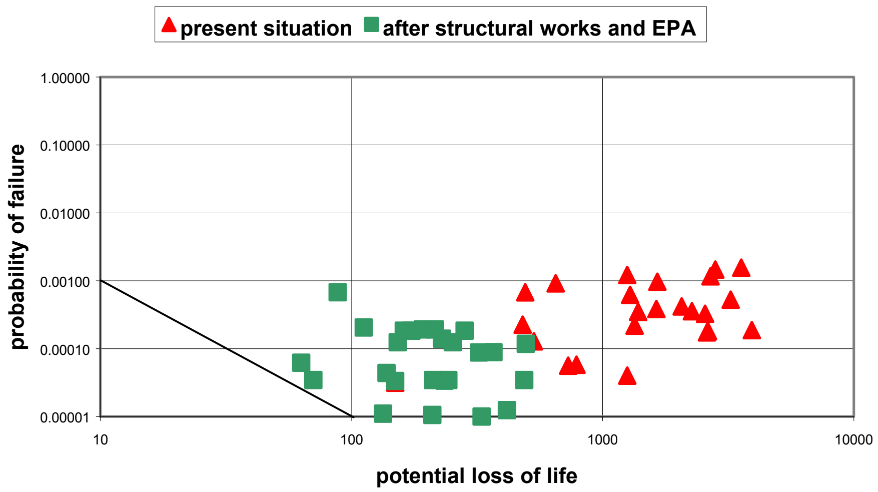


Figure 3 F-N plot

<u>Dam Safety programme</u>

The dam safety programme comprises both structural and nonstructural measures, as follows:

Structural measures

Improvements to spillways and outlets	Rs 434 million
Repairs to upstream slope protection	Rs 265 million
Dam and foundation drainage	Rs 338 million

Non structural measures

Monitoring systems	Rs 43 million
Early warning systems	Rs 67 million

The total capital cost of the entire programme is Rs 1150 million or US$ 11.5 million.

Evaluation

The evaluation of the economic viability of structural measures uses the concept of risk cost, which is expressed as product of the probability of failure and economic loss, to express the benefits.

Because the b/c ratio for the entire programme is low (0.2), consideration has been given to the early implementation of the most urgent and beneficial components. A plot (Figure 4) showing the decrease in risk cost with increasing levels of expenditure on structural measures will assist in deciding the extent of this initial phase.

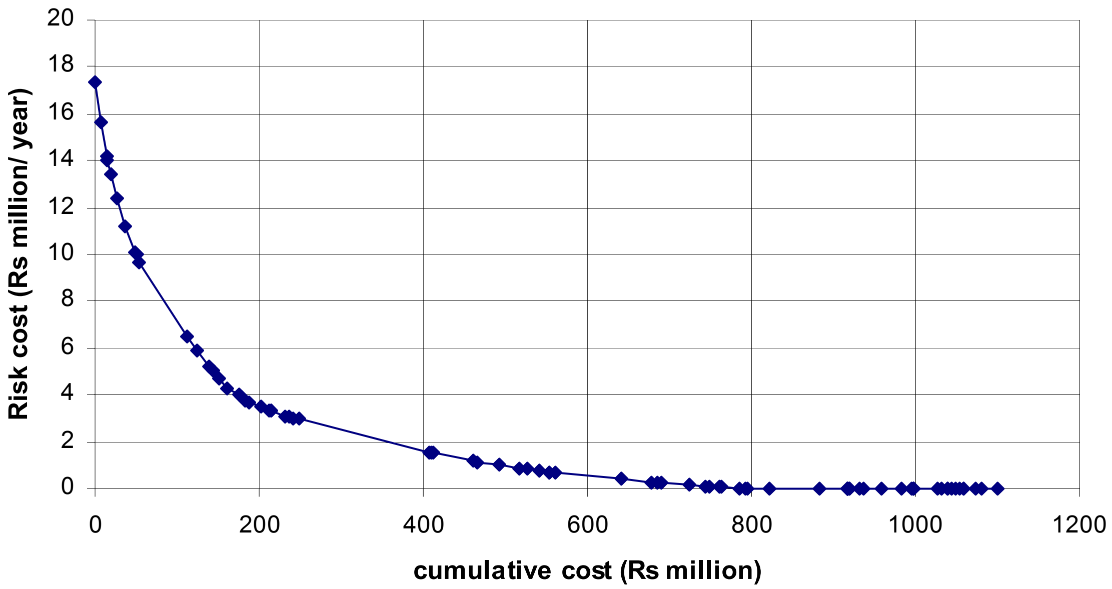


Figure 4: Risk cost vs cumulative cost of structural measures

CONCLUSION

While the full dam safety programme of Rs1,100 million is desirable, 85% of the dam safety improvements can be achieved with the expenditure of just half this sum. This reduced programme approaches economic viability and is recommended.

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Condition assessment of Government-owned dams in Finland

P. VUOLA, Finnish Environment Institute, Helsinki, Finland
R. KUUSINIEMI, Finnish Environment Institute, Helsinki, Finland
T. MAIJALA, Finnish Environment Institute, Helsinki, Finland

SYNOPSIS. Some 480 dams in Finland are covered by dam safety legislation and of these, some 50 dams are government-owned. In spite of shortcomings and a few incidents there has been no complete dam failure in Finland affecting water storage dams that have a significant damage potential in case of failure. To unify the safety level of government-owned dams and to prioritise future maintenance work, the environment administration has decided to carry out condition assessments of dams that have a significant damage potential in case of failure.

INTRODUCTION

Finnish state-owned dams have been built over the last 40 years, and their history is still recent. Sufficient accurate data from different tests is available for many assessment aspects. The data consists of : soil investigations from the planning period, quality control tests from the period of construction, monitoring frost depth, phreatic surface level and seepage flow rate during the period of operation.

Nonetheless, some of the abovementioned data is inadequate or incomplete. Consequently, new testing, monitoring and supervision are necessary in order to obtain proper data for the condition assessment process.

DAM SAFETY IN FINLAND

In Finland, dams have been built mainly for flood control, hydroelectric power production, water supply, aquaculture and for storing waste that is detrimental to the health or to the environment. Most of Finland's dams were built after World War II. Regular monitoring of dam safety by the state-owned power companies began in 1962 and that of state-owned dams (the environment administration) in 1972.

The Act and Decree on Dam Safety were enacted in 1984 to improve the safety of all dams, waste dams included. In 1985, a Dam Safety Code of

Practice was issued to apply the statutory regulations as a practical guideline. This improved the maintenance situation considerably, due to the fact that a basic inspection had to be carried out and a safety monitoring programme created for each dam subject to the Dam Safety Act. The third revised Dam Safety Code of Practice was issued in 1997.

Some 480 of Finland's dams are covered by the legislation. Of these 85% are water storage dams and 15% waste dams. The experts calculate that in the event of an accident, 37 of the dams would endanger human life or health or cause considerable damage to the environment or property (so-called P dams). Most of the dams are embankment dams, and a few are concrete gravity dams. Concrete structures have been used for water regulating structures. Some dams are provided with an overflow structure for high flood situations.

Finland differs markedly from many other countries in topography, soil and climate. Finland is a rather flat country characterised by glacial formations. Typical features of the climate are the long, cold winters, the freezing of the soil and the spring thaw. The ground is seismically tranquil, and there are no earthquakes on a scale to threaten dams.

The emphasis of Finnish dam safety is on the prevention of dam accidents and on the effective reduction of hazards should it not be possible to prevent an accident. Careful design, construction and monitoring of dams and their appropriate maintenance play a key role in preventing dam damage. Long-term changes in conditions and the ageing of structures can be taken into account with regular safety monitoring. Rare exceptional physical conditions, human error or other causes (e.g. internal erosion) may, nonetheless, still lead to dam failure. The objective of the Finnish dam safety system is to restrict any damage that might be caused by dam failure and to prevent loss of human life in the event of an accident. To achieve this we must maintain our dams to a very high standard, have a regular monitoring and emergency action plans designed for P dams to activate the warning function, evacuation and rescuing of the downstream population.

REPAIR WORK ON STATE-OWNED EARTH DAMS

There are some 50 dams owned by the environment administration covered by the dam safety legislation. Eleven of these dams are class P dams (Fig. 1). The basic inspections and further inspections incorporated in the safety monitoring programmes revealed several shortcomings e.g. the following:

- the flood discharge capacity of some dams has been inadequate
- seepage problems

- wet areas and springs behind some dams
- inadequate freeboard against frost in some dam crests
- trees on the dam contrary to the code of practice
- drainage system does not work
- bedrock of some dams needed grouting
- facing of wet slopes needed repair work.

In spite of shortcomings and a few incidents there has been no complete dam failure in Finland affecting water storage dams that have a significant damage potential in case of failure. To unify the safety level of state-owned dams and to prioritise future maintenance work, the environment administration has decided to carry out the condition assessments of its P dams.

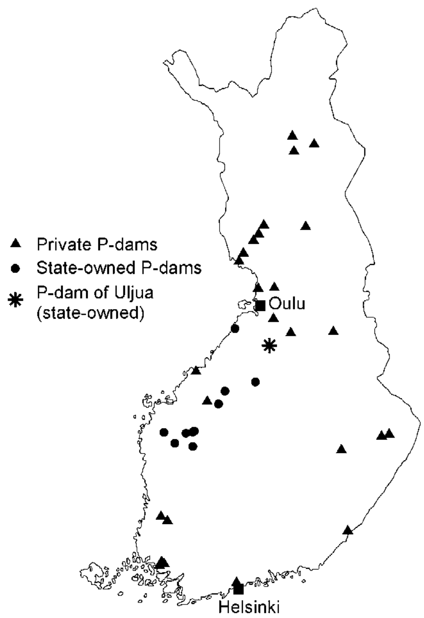

Figure 1: Location of P dams in Finland.

PRINCIPLES OF CONDITION ASSESSMENT

Assessment data

Finnish state-owned dams have been built over the last 40 years, and their history is still recent. Sufficient accurate data from different tests is available for many assessment aspects. This data consists of e.g.:

- soil investigations from the planning period

- quality control tests from the period of construction
- monitoring frost depth, phreatic surface level and seepage flow rate during operation.

Nonetheless, some of the abovementioned data is inadequate or incomplete. Consequently, new testing, monitoring and supervision are necessary in order to receive proper data for the condition assessment process.

An example of proper soil investigation data is presented in Fig. 2. Similar data on dam core permeability and density is available. Nevertheless, these accurate permeability test results do not contain anisotropy data from the core and subsoil. In order to assess the threat of piping, non-homogeneity as well as anisotropy should be taken into consideration.

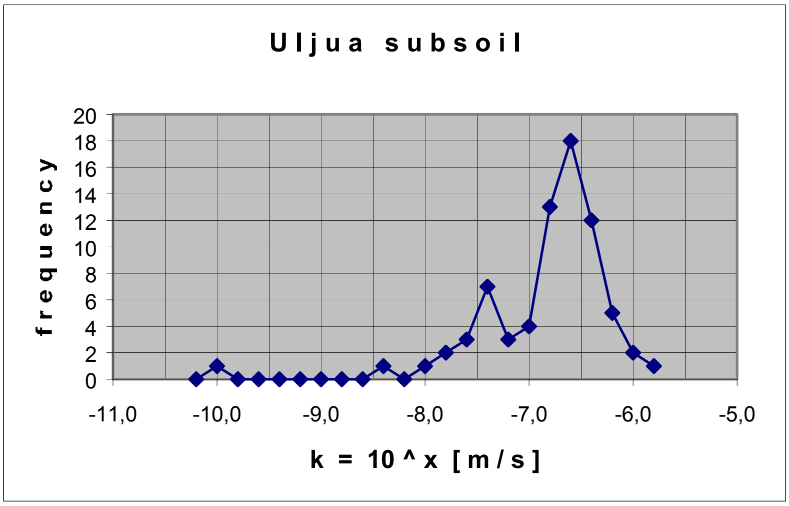

Figure 2: Coefficient of water permeability determined from Uljua subsoil moraine.

As an example, the main cross sections of Uljua dams are presented in Fig. 3. Such designs are typical for many Finnish state-owned dams. The wide core moraine dam construction seems to carry a shortcoming in the shape of poor filtering and drainage on the dry side of the dam. The technical failing of the rock fill dam construction seems to be a core that is too narrow and shallow with a weighted creep ratio that is too low. Both factors lead to an increased risk of piping either through the dam or the subsoil.

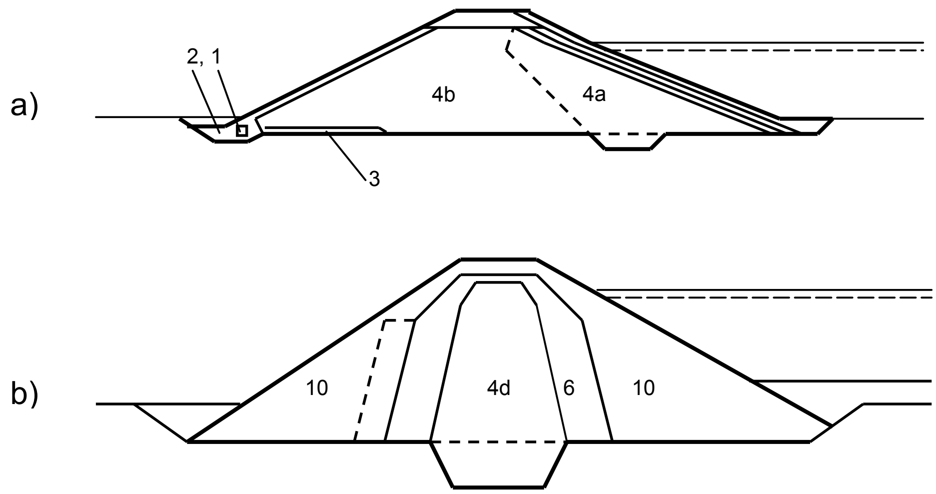

Figure 3: Uljua dams, typical cross sections. a) Arkkusaari 'homogeneous' or wide core moraine dam: 1 = 'stone drain', 2 = sand drainage layer, 3 = bottom drainage layer and filter, 4a and 4b = moraine cores. b) Tulisaari rock fill dam: 4d = moraine core, 6 = filter, 10 = supporting rock fill.

The data we use consists of technical data on one hand, and dam history on the other hand, especially failures. The knowledge of dam history is essential, because the dam itself is a full-scale test. Consequently, a lot of interest is focused on dam behaviour from the period of construction and first reservoir filling until the present. Typical dam incidents include:

- excessive seepage or possibly piping during the first reservoir filling, one in Uljua rock fill dam in the year 1970
- erosion of upstream rock fill blanket during operation
- piping in Uljua rock fill dam in the year 1990 during operation
- inadequate discharge of the drainage system, possibly due to thinness of the bottom filter and clogging of the subsurface drains.

Assessment methods

In order to be able to assess risks, a methodology had to be developed as well as technical criteria. It seems impossible to calculate actual probabilities, and yet the hazard and risk level of different phenomena have to be assessed and compared. Some tools applied or developed for these purposes are:

- application of the Fuller curve to determine the grain size distribution curve of the active portion of soil
- modification of the Foster and Fell filter criteria for practical activity; the principle is presented in Fig. 4

- utilisation of the principle of fuzzy logic; the principle is presented in Fig. 5; in fact Fig. 4 includes the concept of fuzzy logic as well.

Certain tools are considered necessary, because an individual engineering judgment alone may lead to inappropriate deviation in the assessment process. Besides, knowledge of the hazard and risk level is essential when drawing up the repair works schedule.

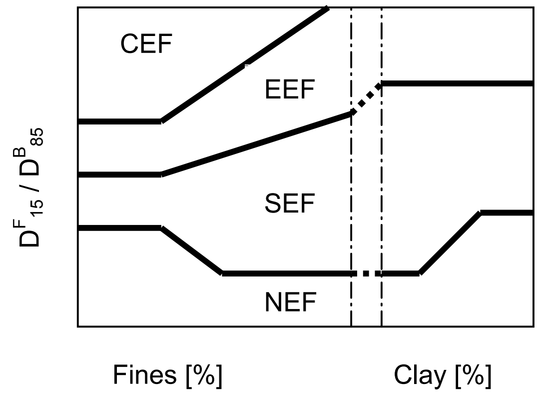

Figure 4: Principle of applied filter criteria chart. NEF = no erosion filter, SEF = some erosion filter, EEF = excessive erosion filter and CEF = continuous erosion filter. All percentages and grain sizes are calculated from corrected grain size distribution curves. D^F_{15} and D^B_{85} represent filter and base material grain size diameters, through which 15 and 85 % respectively, of the material will pass.

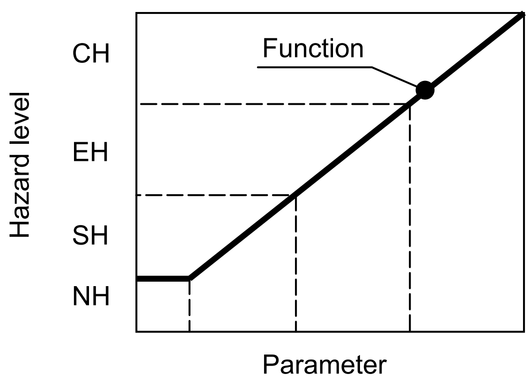

Figure 5: Principle of applied fuzzy logic, based loosely on the terminology used in Fig. 4. NH = negligible hazard, SH = some hazard, EH = excessive hazard, CH = catastrophic hazard.

The aspects to be assessed were classified into four main categories:
a) external erosion, including erosion induced by ice forces
b) internal erosion and subsurface drainage, including particularly:

- internal stability, self filtering and segregation of each layer
- filter criteria on the layer interfaces
- seepage in the dam moraine core, filters and subsoil
- frost action
- flow in pipelines, including clogging by ferruginous precipitation
- adjoining structures

c) slope and subsoil stability
d) additional aspects, including particularly:

- background ditch drainage
- vegetation effect
- supervision and monitoring
- maintenance
- emergency action facilities.

Based on preliminary results, internal erosion and subsurface drainage and additional aspects have major roles in the assessment process, while external erosion is merely a matter of engineering. Stability seems to be of minor interest.

Despite the fact that most aspects occur worldwide, there are certain special phenomena featured in Finnish dams. Apparently these phenomena are typical to a larger area, but they are reported rather seldom in literature. These phenomena are:

- frost action, especially formation of ice lenses, which lead to soil loosening and increasing piping threat
- ferruginous precipitation, apparently suspended hydrated iron oxide precipitation, which clogs the subsurface drainage system.

The result of the condition assessment process will be a document for each dam including presentation of:

- history
- current conditions
- hazard and risk classification
- recommendation for repair action.

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Portfolio Risk Assessment in the UK: a perspective

A.K. HUGHES, KBR, UK
K.D. GARDINER, United Utilities, UK

SYNOPSIS. This paper discusses the merits of Portfolio Risk Assessment (PRA) from the point of view of a practitioner and a dam owner.

INTRODUCTION

The management of reservoir safety in the UK is generally subject to the requirements of the Reservoirs Act 1975 and the assessment methodology applied by Panels of Engineers appointed under that Act. The Health and Safety Executive (HSE) claims jurisdiction over the safety of reservoirs where a business is involved under the powers of the Health and Safety at Work Act 1974, although they defer to Panel Engineers and the inspection system at present. The HSE also claims jurisdiction over non-statutory reservoirs.

Under the Panel Engineer system, the reservoir inspection is generally based on observational techniques supplemented with historical information such as instrumentation data, previous reports and studies, drawings etc. The Panel Engineer tends to focus on technical matters with the intention of maintaining the safety of the public by preventing a dam failure. The system has a good track record with no failure in the UK causing loss of life since 1925. However, the system only considers the safety of individual dams and does not address the justification and prioritisation of recommended works for owners of multiple dams. In addition, it does not consider the tolerability of risk and business drivers for identifying and evaluating options for even higher levels of safety.

WHY WOULD YOU CARRY OUT PORTFOLIO RISK ASSESSMENT?

Portfolio risk assessment is a process which can assist owners to manage reservoir safety in the overall context of their business.

The importance of this approach was recognised in OFWAT document MD 161, 'Maintaining Serviceability to Customers' dated 12 April 2000 addressed to 'The Managing Directors of all Water and Sewerage Companies and Water Only Companies' which stated;

'Each company needs to demonstrate how the flow of services to customers can be maintained at least cost in terms of both capital maintenance and operating expenditure, recognising the trade off between cost and risk, whilst ensuring compliance with statutory duties.'

'The Government considers an economic framework related to current and likely future asset performance (serviceability) is likely to provide the best way forward. .... As the (Environmental Audit) Committee recommends , it will be important for this work to investigate the practicability of approaches that are forward looking, taking account of the risk of asset failure (probability and consequences) as well as past historical trends.'

The PRA process specifically addresses the trade off between cost and risk and the compliance with statutory duties through an approach that takes account of the risk of asset failure accounting for both probability of failure and consequences of failure. The PRA approach does not replace or supplant the role of the Panel Engineers, but builds on the Panel Engineers' technical assessments and other information available to an owner. The approach seeks to use estimates of the likelihood of various failure modes, estimates of life and economic losses, and preliminary evaluations against tolerable risk guidelines (HSE 2001) and the owner's business criticality considerations, to identify opportunities for improved dam safety through investigations, and risk reduction brought about by carrying out works at the dam and improved reservoir safety management. Improvements in the effectiveness of detection and response to dam safety incidents by owners and the effectiveness of emergency response by local authorities can also be considered.

THE PORTFOLIO RISK ASSESSMENT PROCESS

PRA is a logical, auditable method of sytematically assessing a stock of dams in its current condition and assessing and prioritising the works required to be done and other measures that would improve reservoir safety, but may not be required under current practice. Some water companies have used this technique, and the prioritised lists and resulting spend profile that comes from it, as the basis of their submission to OFWAT (the regulatory body for the privatized UK water industry). OFWAT had asked that risk assessment be used in the companies funding submissions and therefore the submissions that used these techniques were generally well received.

A risk assessment carried out for a portfolio of dams typically uses data from historic incidents, accidents and failures, together with estimates of the probability of occurrence of extreme floods and earthquakes, to obtain estimates of the probabilities of failures for the failure modes considered. In addition, information from dam break analyses is used to estimate life loss and economic consequences for each failure mode. Remedial measures are defined for each mode of failure to meet UK Reservoir Safety practice and to reduce the probability of failure. Additional measures can be considered to exceed current UK Reservoir Safety practice. An evaluation may then be carried out, including cost benefit analysis, to provide information on the strength of justification for each remedial measure relative to tolerable risk guidelines such as those by the HSE (2001). This also provides data for the prioritisation of these remedial works based on alternative approaches discussed in the next section of this paper. The dam owner must then decide how this information will be used for the reduction of risk.

A number of PRA studies carried out for owners have shown that the process promotes a strengthening of the management of reservoir safety and its integration into all areas of the owner's business such as, the licence to operate, asset management, asset operation and maintenance, risk management, legal and insurance areas.

ISSUES IN USING THE RESULTS FROM A PORTFOLIO RISK ASSESSMENT

Once a Portfolio Risk Assessment has been carried out, many questions arise that can only be answered by the owner. These questions have implications that go far beyond the technical issues that a reservoir safety group typically deals with and therefore representatives from a wide range of departments in the owner's organisation should be involved. The discussion of these questions and some of the suggested answers form the major part of the rest of this paper.

1. **How should the PRA be used to prioritise the remedial works that have been determined should be carried out?**

    - **By probability of failure?** – should the owner take the view that any failure is unacceptable and therefore the dams most likely to fail should be dealt with first?
    - **By consequence of failure? –** some dams, should they fail, might only frighten a few sheep, whereas others might threaten large numbers of people or major elements of infrastructure. It might therefore be prudent to spend money on the dams which have the highest consequence of failure first.

- **By maximising the cost effectiveness of risk reduction?** – the estimated risk (considering by probability and consequences of failure) reduction and cost for all remedial measures can be estimated and the most cost effective remedial works given the highest priority.
- **Using an evaluation against HSE (2001) Tolerability of Risk Guidelines**? - The Health and Safety Executive (HSE 2001) have published guidelines for assessing in the tolerability of risks to individuals and to groups. A risk is sometimes said to be 'broadly acceptable' if it is lower than one in a million per annum. However, the key to evaluating the tolerability of risks is whether the risks have been reduced to be ALARP, or 'as low as reasonably practicable'. The ALARP Principle is an expression of the undertaker's duty of care under common law. The HSE (2001) refers to the satisfaction of the ALARP Principle as requiring a "gross disproportion" test applied to individual risks and societal concerns, including societal risks. The gross disproportion, which should be sought in deciding how far to pursue risk reduction, is between the cost of an additional risk reduction measure and the estimated risk reduction benefit for that measure. HSE (2002) refers to this disproportion as "the bias on the side of safety", "erring on the side of safety", and "compensating to some extent for imprecision in the comparison of costs and the benefits"
- **By some hybrid of the above?** – A suggested hybrid method is shown in Figure 1.

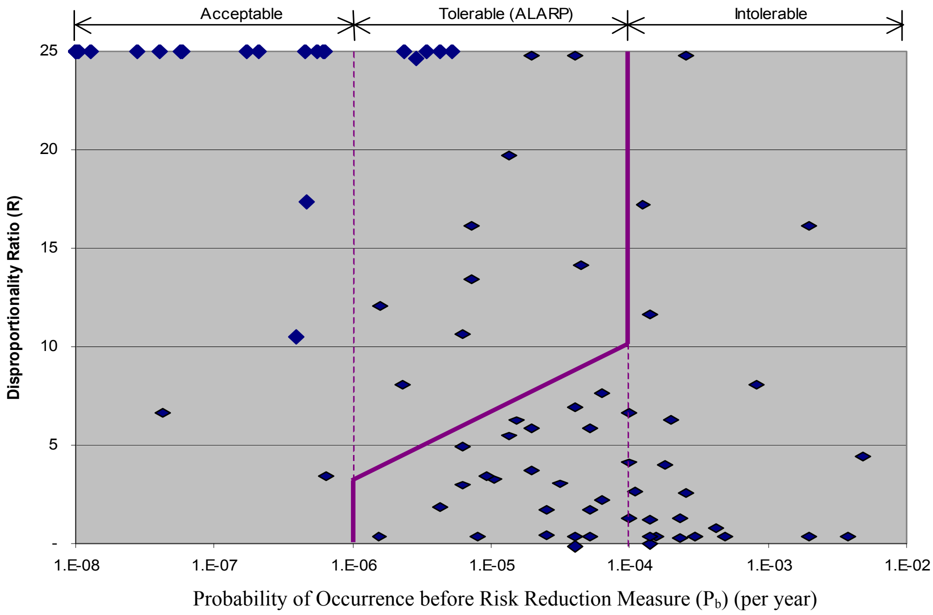

Figure 1. Risk Reduction Measures plotted against. HSE Tolerable Risk Guidelines

This sets limits of tolerability based on HSE guidelines and uses a disproportionality (cost/benefit) ratio and the risk of occurrence before the remedial measure is carried out to prioritise those measures.

- **By doing works recommended "in the interests of safety" at each dam firs**t – works recommended "in the interests of safety" have to be carried out "as soon as practicable" under the Reservoirs Act 1975 or by the time stipulated by the Inspecting Engineer. The remaining remedial works could then be prioritised by the methods above.

Each approach to prioritisation results in a different rate of risk reduction verses cost relationship. The fastest rate of risk reduction for the investment of funds is achieved by using the cost effectiveness approach, where risk is expressed in average annual terms. However, other factors may be important to consider in establishing a prioritisation. In addition to factors mentioned above, business criticality, or the timing of a capacity expansion construction project, are examples of such factors.

2. **What are the factors that limit the size of the capital programme that can be managed, thus directly influencing the rate of implementation of risk reducing remedial works for a dam owner with a large number of dams?**

- **Limited resources** - Even if the owner had unlimited funds, all works cannot be started at once. Work would be slowed by such things a limited number of site investigation contractors, rigs and engineers, and a limited number of contractors with the relevant experience.
- **Need to maintain water supplies** - Many remedial work projects will require at least a partial drawdown of the reservoir. With the recent history of dry summers many owners would not be prepared to allow work on a number of reservoirs to proceed simultaneously. Equally, if a reservoir is a 'sole source' reservoir, in as much as an area can only be supplied from one reservoir, the owner will wish to wait until the water supply network is reinforced or the risk of losing supply can be minimised in some other way before allowing work to start. It is also often necessary to coordinate works at the reservoir with works at the treatment works.
- **Environmental factors** - Planning approvals, rights of way diversions, the migratory and nesting habits of birds, the presence of toads, newts, badgers, etc., SBA's, SSSI's, Heritage sites, opposition from local inhabitants and landowners and the need and ability to

supply compensation to the river downstream can all affect commencement date and duration of construction works, and thus the priority of the scheme.

3. **Once the prioritised list of works has been agreed upon, how should the Recommendations of the Inspecting Engineer contained in his Report under the Reservoirs Act 1975 be accommodated?**

When the Inspecting Engineer carries out his inspection he is usually unaware of the condition of other reservoirs in the next valley or even in the same valley. Some would say that, traditionally, the Inspecting Engineer has taken the view that his duty is to ensure the safety of the dam that he has been asked to inspect, irrespective of the problems or shortcomings that may exist at other dams in the ownership of the undertaker.

The problem that may arise, following a Portfolio Risk Assessment, is that particular recommendations made "in the interests of safety" by the Inspecting Engineer may not achieve a 'high ranking' and therefore may not be scheduled for a number of years. This may occur because the remedial measure that is responsive to the recommendation "in the interests of safety" may result in only a small reduction in risk relative to its cost, or other words it is not as cost effective as other remedial measures that have been identified for the owner's portfolio of dams. If the undertaker waits too long to act on the Inspecting Engineer's recommendation, this may cause intervention from the Enforcement Authority because the Act states 'as soon as practicable'. The actual 'meaning' of this phrase has not been defined, except that it has been said by some, that money is not a factor to be considered; but it may take a court ruling before it is defined. Certainly, as discussed above, there are other factors that can affect the timing of works from the owner's point of view.

In addition, the recent Water Bill gives powers to the Enforcement Authority to determine what "as soon as practicable" means in certain circumstances. It would seem sensible that owners, and particularly those using a PRA approach, should work with an Inspecting Engineer to determine a time for completion rather than have it imposed on them by the Enforcement Authority.

Thus, the PRA process could produce some conflict or difficulties with the current reporting system unless the Inspecting Engineer 'signs on' to the process. One mechanism to create an understanding is to have a annual briefing of all Inspecting Engineers involved with the owner's portfolio of dams so they understand how the PRA prioritisation lead to the timescales that the owner is proposing for works that are responsive to their recommendations. Inspecting Engineers could then consider this information when setting their timescales or the date of the next inspection. Owing to the way in which the PRA is carried out, it is highly likely that 'recommendations in the interests of safety' will have been identified in advance of the inspection and therefore a risk reduction measure will already have been identified. Any new recommendations by the Inspecting Engineer will themselves have to be assessed and prioritised during an update of the PRA.

Clearly, if there is conflict of any kind, then under the terms of the Reservoirs Act 1975, the owner will be bound to carry out the recommendations "in the interests of safety" irrespective of the fact that the money could be more effectively spent elsewhere to reduce risk to the community based on the PRA.

For example, provision of additional spillway capacity could be recommended "in the interests of safety" for a spillway that will already pass 95% of the design flood without overtopping. The flood that will exceed this capacity could have an annual exceedance probability approaching 1 x 10-6. At the same dam, the PRA may have identified that seepage failure has a 1 x 10-3 per annum probability of occurring, even though there is no recommendation to improve protection against seepage failure in the Inspecting Engineer's report. This raises several questions, including the following:

- Where should the owner spend his limited available funds?
- Would a referee, as defined by the Reservoirs Act 1975, take account of the PRA if an owner appealed against a timescale set by the Inspecting Engineer?
- If a failure occurred, what might the judgment of the enquiry be if the owner had enlarged the spillway and severe seepage had caused the dam to be washed away?

4. Is PRA worth the dilemmas that it spawns? Do the advantages outweigh the disadvantages?

Is the owner's business at greater risk with or without the information provided by the PRA? Should the owner rely solely on the Report and Recommendations of the Inspecting Engineer? Can you hear a barrister in cross examination in court saying would you have carried out work on this dam earlier if you had used a technique called Portfolio Risk Assessment?

Some of the advantages and disadvantages of the PRA methodology are summarised below:

Advantages

1. In the event of a major incident, evidence that the owner had assessed the risks and was carrying out safety measures in a logical sequence may reduce any penalties imposed by the courts when funds had been spent on other dams rather than the dam concerned in the incident.

2. A PRA will allow the risks to the Company and the Community associated with dams to be reduced as quickly as possible.

3. A PRA can provide a persuasive argument to the shareholders and the regulator that increased spending on reservoir safety is justified.

Disadvantages

1. In the event of a major incident, evidence that the owner had assessed the risks at considerable cost, and was carrying out safety measures in a logical sequence, may not be taken into account by the courts, when funds had been spent on other dams rather than the dam concerned in the incident – especially when one considers how the 'expert witness' system works at times.

2. A prioritisation based on a PRA can conflict with recommendations "in the interests of safety" by Inspecting Engineers. Impecunious owners might be put in a position where they have the funds to carry out works that they are obliged to do under the Reservoirs Act 1975 or the high priority items from the PRA but not both.

3. The PRA may reveal unacceptable risks to the owner that they do not have the funds to reduce. Perhaps "ignorance is bliss", but then "ignorance is no excuse" when it comes to the law!

CONCLUSIONS

Despite the issues highlighted in this paper, and the vagaries of the English legal system notwithstanding, the authors conclude that the use of Portfolio Risk Assessment can be strongly recommended as a tool to assist owners to manage reservoir safety in the overall context of their business. The approach follows a logical well thought out process involving evaluation against engineering guidelines and accepted practice, risk analysis, evaluation against tolerable risk guidelines, prioritisation of risk reduction measures, and sometimes prioritisation of investigations to reduce the uncertainties associated with engineering and risk assessments. The process will cause the organisation to think about the relationship of reservoir safety to the business as a whole. Effectively using the information derived from a PRA can result in a corporate reservoir safety management system that is much more effective and efficient, is auditable and more defensible, and is better integrated with other parts of the business, including finance, capital projects, legal and insurance sections.

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Hydraulic and operational safety evaluation of some existing Portuguese large dams

EDUARDO R. SILVA, Institute of Water, Lisbon, Portugal.
JOSÉ ROCHA AFONSO, Institute of Water, Lisbon, Portugal.
JOVELINO MATOS ALMEIDA, Institute of Water, Lisbon, Portugal.

SYNOPSIS. The Portuguese Regulations for Safety of Dams came into force in 1990, after being published as a Decree-law. Since then some rules and guidelines concerning the different stages of the life of dams have also been published, to complete and to help the application of the law.

Following the occurrence of problems during flood events in 1995-96, with the overtopping of a few small dams, and with incidents at some large dams, that could be controlled but, nonetheless, were of great concern, the Portuguese authorities decided to launch a specific program for the safety reassessment of the existing large dams in the country.

For that purpose 11 calls for tenders were made for the study of 38 large dams, concerning all aspects of structural, hydraulic and operational safety, and also including studies of the downstream valleys for dam failure scenarios.

The safety studies were based on all the hydrological data available today, on the original projects and other elements related to dam features, on behaviour records and on site inspections. Some relevant conclusions were reached in these studies. It was also shown that in some cases compliance with current safety regulations had not been met.

The results from the evaluations carried on the hydraulic and operational safety and the actions proposed to lower the risk are presented, where cases of significant hazard at the downstream valley or risk to the structure of the dam are considered to exist. Measures that are currently being undertaken , or will be pursued in near future, are also discussed.

LONG-TERM BENEFITS AND PERFORMANCE OF DAMS

INTRODUCTION

Although dams have an important role in the development of communities they also imply risks, however small, for people and for economical and social activities in the downstream valley that could be affected by the failure of the dam.

The existence of these risks was highlighted in Portugal by the occurrence of problems during flood events in 1995-96, with the overtopping of a few small dams, and with incidents at some large dams, that could be controlled but, nonetheless, were of great concern.

An evaluation of the safety conditions of Portuguese dams is necessary to prevent major accidents due to dam failures or, at least, to mitigate their consequences.

For that matter, due to the lack of human resources within the public administration, a decision for preparing tenders for specialized outsourcing was taken by the Institute of Water (INAG), in 1999. INAG is the Portuguese Authority in dam safety, and has the technical support of National Laboratory of Civil Engineering (LNEC), as defined by dam safety regulations. A total of 11 tenders, concerning 38 large dams, were launched.

As this first group of dam safety studies is concluded, very soon another group of dams will be included in new call for tenders. This plan will continue until all dams of significant or high risk are studied.

PURPOSE OF UNDERTAKEN STUDIES

The major purpose of these studies is to get an accurate revue of the safety conditions of the Portuguese dams regarding the regulation for safety of dams, and to identify the remedial measures that have to be implemented by the owners to improve safety to the new standards.

These studies should include an assessment of the structural and hydraulic-operational safety, a global risk index computation, a possible change of the rules of exploitation of the reservoir, the mapping of the downstream areas affected in case of dam failure, the assessment of downstream risks and the proposal of an alert and warning system.

Also they should propose some immediate measures to be taken to solve simple problems. Major deficiencies or corrective works, including civil works, electric and mechanic equipments, observation systems and alert and warning systems, are identified in the studies but need further analysis and design from the dam owners, to be approved and implemented.

CHOICE OF THE DAMS

The 38 dams that made part of this first group of tenders were chosen after an assessment that included preliminary field inspections. All of these dams had been designed before the new regulations were mandatory, all of them showed several deteriorations and it also was established that for the great majority the associated potential risk was either significant or high.

This group of dams comprised most of the oldest large dams built in the country for irrigation, and also a representative group of more recent dams with that same purpose.

The majority of these dams had shown during the preliminary inspection that there was no observation plan and that no inspections took place regularly, so that the observation activities were very deficient.

Also some of them showed what appeared to be signs of structural problems that needed to be studied to determine and implement the corrective measures.

In some cases the outlet works didn't work and the dams showed lack of maintenance of the equipments and of the structure itself.

The personnel responsible for the exploitation of the dams in some cases had no specific preparation and didn't fully understand how to correctly operate gates and valves.

The chosen dams are mainly situated in the interior northern part of country and in the southern part near the coastline, as can be seen in Figure 1, and their characteristics can be seen in Table 1.

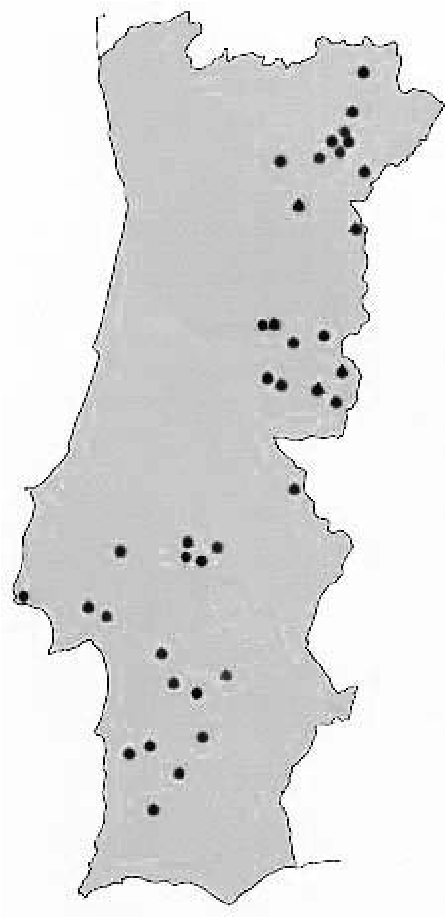

Figure 1. Location of the dams

Table 1: List of studied dams

Dam	End of constru -ction	Age (years)	Type	Use	Height (m)	Reservoir (hm^3)
Alfândega da Fé	1970	33	TE	SI	25	1.60
Alijó	1991	12	TE	S	40	1.74
Alvito	1977	26	TE	SI	49	132.50
Apartadura	1993	10	ER	SI	46	7.50
Azibo	1982	21	TE	SI	56	54.50
Burga	1978	25	TE	I	35	1.80
Camba	1993	10	TE	SI	35	1.10
Campilhas	1954	49	TE	SI	35	21.70
Capinha	1981	22	TE	S	18	0.52
Carviçais	1984	19	TE	S	20	1.20
Cova do Viriato	1982	21	PG	S	24	1.50
Covão do Ferro	1956	47	PG	H	32.5	0.87
Fonte Serne	1977	26	TE	I	18	5.20
Furadouro	1959	44	PG+TE	I	17	0.40
Gameiro	1960	43	PG+TE	IH	20	1.30
Gostei	1993	10	TE	I	35	1.40
Idanha	1949	54	PG	IH	54	77.80
Magos	1938	65	TE	I	17	3.00
Maranhão	1957	46	TE	IH	55	205.00
Marateca	1991	12	TE	SI	23.8	37.20
Meimoa	1985	18	TE	SI	56	40.90
Montargil	1958	45	TE	IH	48	164.00
Monte da Rocha	1972	31	TE	SI	55	104.50
Odivelas	1972	31	MV+TE	I	55	96.00
Pego do Altar	1949	54	ER	IH	63	94.00
Peneireiro	1973	30	TE	S	15	0.80
Penha Garcia	1979	24	PG	SI	25	1.10
Pisco	1968	35	TE	S	24.5	1.40
Ranhados	1986	17	PG	S	41	2.60
Rio da Mula	1969	34	PG+TE	S	17	0.34
Roxo	1967	36	CB+TE	SI	49	96.30
S M Aguiar	1981	22	TE	SI	20	5.40
Salgueiro	1975	28	TE	I	25	1.80
Santa Clara	1968	35	TE	ISH	86	485.00
Toulica	1979	24	TE	IS	16	2.00
Vale das Bicas	1939	64	TE	I	12	2.00
Vale do Gaio	1949	54	TE/ER	IH	51	63.00
Venda Velha	1957	46	TE	I	14	4.64

RESULTS

In Portugal nowadays around 180 large dams according to the ICOLD definition exist, mostly for hydropower and irrigation purposes, many of them more than 30 years old. In the 40's and 50's those that were built for irrigation and water supply were directly promoted by the State, through a specific department that gained a large experience in dam design and construction. More recently, however, we have seen an increasing number of dams constructed as a result of private investment or various public departments and local authorities with a less developed history of dam operation and construction. On the other hand, the operation of irrigation and supply dams has been judged inadequate, with a lack of adequate technical and financial resources identified. As a result a significant number of problems have led to specific direct interventions by dam safety public authorities.

<u>Some cases where safety did not comply with safety regulations</u>

The assessment of the compliance of the hydrologic, hydraulic and operational safety of dam in Portugal has to be made for the return periods imposed by the existing regulations. Those return periods can be seen in Table 2, where it can be seen that "potential risk" has a vital role in defining which one to adopt.

Table 2: Return periods imposed by the RSB

Dam		Potential risk	
Concrete	Embankment	High	Significant
h ≥ 100	H ≥ 50	10,000 to 5,000	5,000 to 1,000
50 ≤ h < 100	15 ≤ h < 50	5,000 to 1,000	1,000
15 ≤ h < 50	h < 15	1,000	1,000
h < 15	-	1,000	500

The potential risk is defined in Portuguese regulations as a measure of the consequences of an accident, not withstanding the probability of its occurrence, and can be sorted by the following levels, according to the loss of human lives and economic damages:

- low, when no lives are in threat and there are few economic damages
- significant, when some human lives can be lost and the economic losses are of some importance
- high, when an important number of lives can be lost an the economic losses can be high

Therefore, to determine which return period to apply to the design flood of spillways one must do the study of the areas affected by the wave resulting of the failure of the dam and determine the number of human lives that could be considered at risk and of the economic losses and infrastructures affected.

In these 38 cases only 2 of them are considered of low potential risk, 7 of significant risk and the rest are considered of high risk. In some cases the results of the studies includes an estimate of the number of lives that could be in danger, the number of homes and a list of other infrastructures that could be affected by the flood wave, such as schools, public services and civil protection structures, roads, railways, bridges and others.

Table 3: Potential risk of the dams

Dam	Scenario	Estimation			Potential risk		
		no. lives	no. homes	Infrastructures	low	significant	high
Alfândega da Fé	overtopping		3	Yes		x	
Alijó	piping	57	22	Yes			x
Azibo	piping	518	192	Yes			x
Burga	overtopping		78	Yes			x
Camba	piping	29	11	Yes			x
Cova do Viriato	sudden breach	175		Yes			x
Covão do Ferro	sudden breach	378	140	Yes			x
Fonte Serne	piping			Yes		x	
Furadouro	sudden breach			Yes	x		
Gameiro	sudden breach			Yes	x		
Gostei	piping	322	119	Yes			x
Maranhão	overtopping			Yes			x
Marateca	piping	216	80	Yes			x
Meimoa	overtopping	1566	580	Yes			x
Peneireiro	overtopping		87	Yes			x
Penha Garcia	sudden breach			Yes			x
Pisco	overtopping			Yes		x	
Ranhados	sudden breach	57	21	Yes			x
Salgueiro	overtopping		58	Yes			x
Toulica	piping	4		Yes		x	
Vale das Bicas	piping	35	13	Yes			x
Vale do Gaio	overtopping			Yes			x
Venda Velha	piping	105	39	Yes			x

Comparing the return periods in Table 4 we can see that generally those determined in the hydrological studies made are greater than the ones adopted in the original studies. The consequence is that the peak flows that result of hydrological studies should be greater than the original ones. But analysing Table 4 we can see that in some cases the peak inflows are lower and in a considerable number of them the peak inflows are almost unchanged. It was seen that it had mainly to do with the new amount of data available today, the new methodologies that are currently used, considered more accurate, and in some cases with mistakes in the original studies that now have been detected and corrected.

In some cases, however, like in Fonte Serne, Magos, Meimoa and Vale do Gaio dams, the peak inflows were over 100% higher.

Table 4: Results of the hydrological studies

Dam	Catchment area (km^2)	Return period		Peak inflow (m^3/s)		Volume (hm^3)	
		initial	new	initial	new	initial	new
Alvito	212,00	100	1000	1300	598		
Capinha	6,30	1000	5000	32.5		0.334	
Cova do Viriato	2,30	100	1000	34	43	0.106	0.299
Fonte Serne	32,00	500	1000	55	125		
Furadouro	3374,00	500	1000	2300	2415		248.0
Gameiro	3255,00	500	1000	2800	2390		240.0
Idanha	362,00		5000	700	1168	43.20	48.40
Magos	105,00		1000	110	279		11.50
Meimoa	61,00	1000	5000	228	505	4.840	14.00
Montargil	1182,00	500	5000	1200	1764	80.00	197.0
Pisco	13,95	?	1000	100.6	105.9	0.362	0.666
Rio da Mula	3,00		1000	22	35	0.060	0.194
Roxo	350,00	1000	1000	740	1232	18.30	35.00
S M Aguiar	128,60		1000		218.6		7.700
Santa Clara	520,00	1000	5000	2000	2482	65.00	100.0
Toulica	26,00	100	1000	80	100	0.614	2.395
Vale do Gaio	509,00		5000	750	1762		
Venda Velha	174,00	100	1000	300	327		18.63

In some other cases the peak inflows remained almost unchanged presenting only variations of about 10%. This happened in 11 dams for which either the design was recent or the studies then showed the cautiousness of the designer.

Looking at the performance of the dams we can see that 30 % of the spillways do not present a discharge evacuation capacity that complies to the new regulation. In these cases construction of a new spillway or modifications of the existing spillway or dam operational constraints are required for re-establishing compliance with current statutory constraints and guidelines.

Toulica dam, for instance, is overtopped in all the studied scenarios, even for 100 years return period flood with 3tc, where tc is the time of concentration of the dam drainage basin. This fact led to a restriction being imposed on the level of the reservoir 2 meters below NPL so it can deal with a 100 year flood with 1tc.

But there are several other cases of insufficient spillway capacity. Montargil, Fonte Serne, Cova do Viriato, Roxo, Meimoa, Magos, Rio da Mula, SM Aguiar, Vale do Gaio, Venda Velha and Pisco dams showed this problem, although the magnitude of it varies significantly.

Table 5: Performance of the spillways

Dam	Spillway type	Gates (y/n)	Spillway capacity (m^3/s)		Discharge evaluation (y/n)	
			Initial	Revised	Satisf-actory	Over-topped
Camba	Surface	no	40	39	yes	no
Carviçais	Surface	no	45	17	yes	no
Cova do Viriato	Surface	no	3.8	18	yes	no
Covão do Ferro	Surface	no	7	20	yes	no
Fonte Serne	Surface	no	36	68	no	no
Magos	Surface	yes	110	195	no	no
Maranhão	Shaft	yes	1600	1987	yes	no
Marateca	Surface	yes	60	77	yes	no
Meimoa	Surface	yes	124	240.5	no	no
Montargil	Shaft	yes	765	1022	no	no
Pisco	Surface	no	43	77.5	no	no
Ranhados	Surface	no	215	140	yes	no
Rio da Mula	Surface	no	7.8	26	no	no
Roxo	Surface	no	64	161	no	no
S M Aguiar	Surface	no	155	200	no	no
Salgueiro	Surface	no	29	20	yes	no
Santa Clara	M glory	no	208	213	no	no
Toulica	Surface	no	17.6		no	yes
Vale das Bicas	Surface	no		107.9	yes	no
Vale do Gaio	Shaft	yes	1000	1200	no	no
Venda Velha	Surface	no	140	236	no	no

In some cases like the Marateca dam and Camba dam the spillways expected performance is near acceptable, with the anticipation of some damages for the revised design floods but without any kind of danger to the structure of the dam.

Results from the evaluation undertaken on hydraulic and operational safety of dams

One of the main conclusions of these studies relates to some features that the actual law imposes on hydraulic and operational safety, namely the need for the gates to be operated locally and from a distance, and to have two different energy sources available, besides being manoeuvred also manually.

Those requirements apply also to bottom outlets, which are sometimes too demanding and make it very difficult for existing dams to comply.

The legislation imposes the need for operational manuals at each dam, which should namely include guides for the reservoir exploitation, as well as rules related to all the equipment operation and the necessary measures for maintenance and conservation. The manuals were found to be lacking on the studied dams. In these studies this lack of information was highlighted, procedures were drafted and proposed for implementation as soon as possible.

The operational procedures are of great importance to dam safety because the operation personnel in most of the studied dams revealed lack of understanding of the equipment installed and of the right procedures to operate them, in response to reservoir conditions. This is more dangerous in cases where spillway gates exist, because it can endanger the dam itself.

The bottom outlets in some cases like Penha Garcia, Cova do Viriato and Pisco dams were out of order and so, in case of an emergency, it would be impossible to lower the reservoir. In other cases like Venda Velha, Vale das Bicas, Toulica or Magos dams the bottom oulets were operating poorly but allowing some kind of control of the reservoir.

The amount of financial resources needed in some cases makes it difficult for owners to comply with the legislation.

Actions proposed to lower the risk

As indicated by the studies, measures to lower the risk in some dams led to restrictions imposed on the operation of the reservoirs such as lowering normal storage levels, and alternative design of solutions for spillways and other elements.

This was the case of Meimoa, Fonte Serne, SM Aguiar and Toulica dams, where reservoir levels were conditioned to prevent damages. Those levels were determined in each case after discharge evaluations were made for the chosen design floods and the consequences were assessed.

In other cases, when there were serious problems of reliability and performance of the spillways, it was decided that it was necessary to improve their discharge capacity by modifying the existing one or by designing an auxiliary spillway. This was the case of Capinha, Montargil and Roxo dams.

Some cases of rehabilitations underway

Due to heavy rainfall in December 2000 the spillway of Pisco dam suffered huge damages that threatened the dam itself and motivated emergency intervention. After some remedial work was performed in the spillway, so as to make it endure a small flood, a designed for a new spillway and bottom outlet was made by the consultants involved in the safety studies. Afterwards works were awarded to a contractor and construction now is completed.
Fig. 2 depicts an intermediate phase of the works, with the new spillway completed alongside the old one. Afterwards, a new intake tower and intake and bottom discharge tunnel were constructed at the old spillway section, and the earth fill was remade.

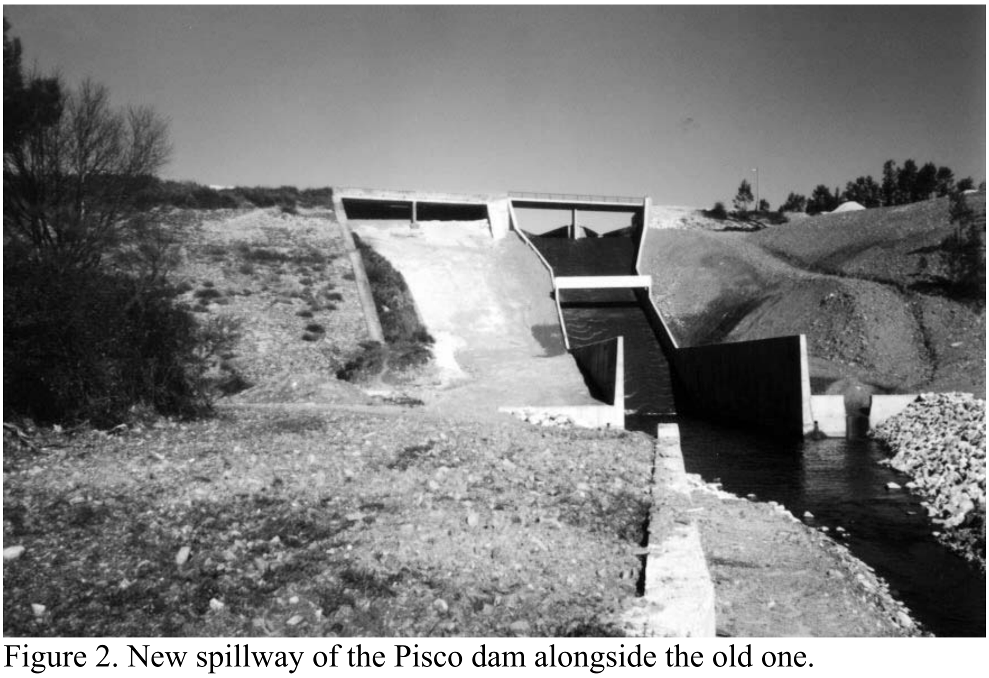

Figure 2. New spillway of the Pisco dam alongside the old one.

Cova do Viriato dam is being subjected to several interventions destined to install a new bottom outlet and a new stilling basin, due to accommodate the increased spillway discharge capacity, and to benefit the water intakes and other supply equipments. Also the gates and valves will be operated locally and from a distance, and they will have two different energy sources for operation, besides manual operation.

Due to the insufficient spillway capacity of Fonte Serne dam a new spillway design for the studied flood was prepared. It will be implemented as soon the owner can call a tender.

Other designs were made to improve safety conditions in hydraulic structures or equipments that will be implemented by the owners as soon as resources are available for that purpose.

<u>Measures initiated and to be continued in the near future</u>

The immediate actions necessary to increase safety resulting from these studies are recommended for implementation as soon as possible to prevent, accidents and avoid endangering lives.

Once the studies have been completed, meetings will take place with owners to discuss all the new available information and to decide on measures to be undertaken.

Most of the concerned owners for the studied dams are irrigation associations, which have some difficulty in obtaining funds to perform necessary interventions, because the amount of money needed to fully and immediately comply with regulations is beyond their current available resource. For this reason interventions have to be sorted in order of risk and programmed in a structured manner.

CONCLUSIONS

The results of the safety studies made for this first group of dams showed that, in spite of the amount of work that needs to be done so that the dams comply with existing safety regulations, the global picture is nonetheless of moderate concern. It is however essential that corrective measures in some structures and hydraulic equipments are undertaken.

It is necessary that dam owners comply with their legal responsibilities, being the Authority's role to guarantee that they do it. For dam owners, and Engineers who are responsible for supervising dam operation and safety, it is fundamental to acquire the knowledge of the problems and implications related to their dams. They require to have the resources in place to implement safety and operation procedures to ensure that the necessary interventions and tasks can be carried out in a phased approach.

To protect lives and to prevent economic losses in the valleys downstream it is also necessary to develop and implement Emergency Plans. These plans are divided, in Portuguese regulations, into the “Internal Emergency Plans”, that concern the dams operation and the downstream nearby areas, where the owners may be responsible for the first actions and warnings, and the “External Emergency Plans”, directed by the Civil Protection Departments.

New studies will be launched, aiming at improving the Portuguese large dams’ safety, especially for those private and public owned dams in which owners don’t have the demanded expertise.

To implement studies recommendations, an increase both in the Authority’s organization and in dam owners’ safety efforts will be needed. This will also imply an increase in new investments by all entities involved.

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Reliability principles for spillway gates and bottom outlets

G.M. BALLARD, Consultant, UK
J. LEWIN, Consultant, UK

SYNOPSIS. Reliability analysis of spillway gate installations, and to a lesser extent bottom outlets of reservoirs, has been increasingly used in risk assessments of dams. As a result there is now considerable collected experience of the design and operation of different types of components and systems, both qualitative and quantitative. The qualitative experience has led to general acceptance of some fundamental principles of design and operation in order to achieve good reliability. The paper discusses some of the more important principles, using examples from spillway gates which have been assessed for reliability by the authors. A common approach to attaining reliability is the provision of redundant equipment, yet the occurrence of common cause failures (CCF) – and the need to provide adequate defences against them – is less frequently considered. Attention is drawn to the types of events leading to CCFs and to some potentially effective design defences.

DESIGN

For a system that is required to have a high reliability, the design features of the system can have as much effect on the achieved reliability as the specific reliability of the individual components that comprise the system. This section briefly discusses some of the more important aspects of system design, using examples from existing spillway gate designs as illustrations.

Well Proven Equipment

Where a system is intended to perform an important safety function it is not generally appropriate to use newly developed types of equipment or technologies. The failure experience of newly developed components is limited and the failure modes of the equipment are likely to be imperfectly understood. If the equipment has not previously been used in similar applications or environments then there may be unpredicted problems which cause the component to fail in an unexpected manner. This may lead to further failures as a result of unpredicted interactions between components. Also, components based on new technology suffer from the absence of improvements which accrue as that technology matures and benefits from manufacturing and operating experience.

These factors can have a major impact where an individual component is used many times in an installation.

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

When updating or replacing equipment on an existing spillway gate installation, particular areas of concern include bearings and bearing materials, PLC control equipment, and lubricants.

Single Failure Criterion

A safety critical system should be designed so that, if possible, the failure of any single component will not prevent the system performing its function when required. This principle is based on the relatively high probability of a single failure occurring compared to the significantly lower probability of two or more concurrent component failures.

While this may be relatively easy to achieve with electronic, electrical and, to some extent, mechanical systems, it is more difficult or impossible to achieve with structural and civil aspects. This difference is mitigated by the respective failure characteristics of the different system types. Electronic and electrical equipment is prone to sudden failure which cannot easily be prevented by condition monitoring or preventive maintenance. Structural and some mechanical systems may be expected to exhibit failure modes which involve progressive degradation mechanisms that, in principle, should be amenable to prevention by monitoring and preventive maintenance. Therefore the single failure criterion is less critical for structural and some mechanical systems than for electronic and electrical systems.

When a component does comprise a single failure point for a system then special care has to be applied to the design, quality assurance and performance monitoring of that component. The principle of using well proven equipment becomes even more important. Equally, the ability to monitor the component to ensure continuing satisfactory performance is essential. In addition consideration should be given to the existence of any sudden failure modes that may arise for that component and how these failure modes can be mitigated by good design or operating practice.

For an existing spillway gate installation of typical design, the situation assessed against this principle may resemble the following:

- The electrical power system is partly duplicated but there are a few single failure points
- The gate control system has a number of components that are single failure points, e.g. control transformer, rectifier, limit switches, etc.
- The single brake is an example of an electro-mechanical component that mostly has degradation type failure modes but may also have sudden failure modes due to loss of electrical power
- The drive train is almost exclusively a series system, with any single component failure leading to failure of the whole system

- The gate itself is a structural system with no redundancy, as are the spillway piers and other civil structures

Judged against this principle, the design clearly has serious deficiencies.

<u>"Fail Safe" Design</u>
The failure of any component within the system should, if possible, move the system towards a "safe" state. For many protection systems there is a "safe" state which is acceptable and component failures should cause the system to move towards that condition.

For spillway gates the situation is significantly more complicated. The purpose of the gate is both to retain the reservoir water level and to pass the water depending on the situation that arises. Neither state – "gates open" or "gates closed" – can be considered "safe". The gate control system has some features that are used to protect the gates from damage but these may inhibit opening of the gates if they fail to operate as intended. Again there is no unambiguous "safe" state, although in a flooding emergency the requirement to open the gates may be more important than safeguarding them from damage.

A specific example involves the limit switches that control gate travel. Overtravel limits are provided to prevent equipment damage. However if one of the limit switches fail in a specific mode, open or closed depending on the logic of the control circuit, then the gate cannot be moved unless the interlock can be overridden. The other failure mode of the switch is "safe" for gate operation but may lead to equipment damage. Two alternative design strategies might be appropriate in this situation. The first would be to provide a redundant arrangement of limit switches such that no single failure would lead to either potentially "unsafe" state. The second (less preferred) would be to provide duplicated switches to prevent equipment damage, but offer an override facility which could be used if the gates need to be opened in an emergency.

<u>Redundancy and Diversity</u>
The main protection for any system against failure of individual components is the use of redundancy and/or diversity. Frequently this takes the form of providing two or more identical parallel lines, each of which can perform the required function on its own. Thus the electrical system on a typical spillway gate installation may have two parallel electrical feeders from the main 440V switchboard all the way through to the gate breakers. Either circuit will provide power to the hoist motors should the other fail. All that is required is a manual changeover of supply breaker on the gate control panel. An automatic changeover system could be implemented by use of

appropriate sensors if required. Further examples are the use of an alternative drive motor (not frequent in practice) should the main drive motor for a gate fail, and the provision of a standby diesel generator to maintain electrical power on failure of the commercial grid supply.

The basic effectiveness of redundancy in improving reliability performance arises because of the failure logic of such systems. If the probability of failure of either one of two duplicate channels is p, then the probability of concurrent failure of both channels is p^2, e.g. if $p=10^{-2}$ per demand for one channel then the system failure probability is $p^2=10^{-2}\times10^{-2}=10^{-4}$ per demand.

In redundant circuits the mode of operation may follow a variety of patterns depending on the exact system type and operation. Where only a single channel can operate at any one time there needs to be provision for an automatic or manual changeover to a standby channel in the event of failure of the first channel. For monitoring or control systems all channels can operate simultaneously and a voting logic can be used to determine how the various channel outputs will be used to define the system output. For example, the parallel gate limit switches are both fully operational at all times and the voting logic is that either limit switch tripping trips the hoist system. For more complex systems involving three or more parallel channels then 2 out of 3 voting arrangements can be used to reduce the occurrence of spurious control/alarm action due to component faults while maintaining a high reliability.

Identical parallel channels can be susceptible to common cause failures, so the use of diverse parallel channels should be considered. In this arrangement, both channels provide a route for the system to function but they use different equipment and/or operating methods to achieve the end result. A simple example would be the use of, say, a vane type limit switch in a parallel channel while a lever arm switch is used on the primary channel. The use of diverse equipment in redundant channels makes it less likely that multiple failures of equipment, affecting both redundant channels, will occur concurrently.

<u>Common Cause Failure (CCF)</u>

The use of redundancy to improve reliability relies on the fact that failure of the individual redundant channels is independent. That is, if one channel fails then the probability of failure of the other channel remains at p, the value it was before the first channel failure. This is not an unreasonable assumption and satisfactorily represents many failure events. However the assumption breaks down when the same cause, a common cause, leads to failure of multiple parallel channels.

To illustrate the effect, suppose that an individual channel has a probability of failure on demand of $p=10^{-2}$ and that p divides into two components, p_I the proportion of random failure modes and p_C the proportion of common cause failure modes. Then the failure probability for a two channel redundant system is not p^2 but $p_I^2+p_C$. If p_C is only of order 5% then the reliability of the parallel system is not 10^{-4}, assuming independent failures, but $0.95\times10^{-2}\times0.95\times10^{-2}+0.05\times10^{-2}=5.9\times10^{-4}$, that is, worse by a factor of ~6. Even if p_C is only 1% then the system failure probability is still worse by a factor of ~2 compared to the fully independent case.

Analysis of many CCF events in the past has suggested that a reasonable working estimate for p_C for a well designed redundant system is approximately 10%, and that specific CCF defence measures will be required if this proportion is to be reduced to any significant extent.

Consideration of the mechanisms that lead to common cause failure (CCF) events indicates that the two most common problems are design errors that have led to unintended interactions between channels or create common weaknesses, and operational errors – particularly in maintenance – that have instigated multiple failures. Other causes, perhaps more widely recognised, are common adverse environmental conditions and external hazards such as fire, lightning or explosion.

A typical spillway gate design is susceptible to a range of common cause failure events including environmental and external hazards, maintenance errors and design interactions. Defences against the causes of CCF events that should be considered when designing and operating systems include:

(1) Design

- Review all stages of the design with the specific target of identifying potential CCF interactions and eliminating or protecting against them
- Equipment or functional diversity such that different equipment or operating principles are used in the redundant channels
- Fail-safe design to ensure that there are no failure modes which can lead to a dangerous CCF
- Well proven equipment so that the failure modes of equipment are well understood
- Protection and segregation of redundant channels to reduce the potential for environmental or external hazards affecting multiple channels
- Derating and simplicity to ensure that equipment is not operating at the limits of its design specification and that the performance of the overall system is capable of comprehensive analysis

(2) Operations

- Comprehensive commissioning trials in order to fully verify equipment performance; comprehensive monitoring, recording and analysis of operating experience
- Ergonomic interfaces to reduce the potential for both simple operational errors and misunderstanding as to the state of the system
- Well thought out and presented procedures for all important activities
- Thorough training and regular practice in realistic exercises

(3) Maintenance and Testing

- Equipment designed to facilitate full testing of all functions without undue interference with the state of the equipment
- Well assessed and presented procedures that can act as a checklist for all relevant important actions
- Staggered maintenance of parallel channels so that redundant equipment is not maintained at the same time

Most of these features are common to the specification for the design of any reliable system, but the potential for CCFs may require special consideration. Examples from typical spillway gate installations illustrate the issues involved:

(1) Environmental CCF

Most of the equipment on a spillway was protected from the weather by sealed enclosures; electrical cables ran to and from these enclosures in steel conduits. If the seals on the enclosure are poorly designed or deteriorate with age then moisture can enter the enclosures and the cabling conduits. There was significant evidence of cable failure due to conduit corrosion and cable degradation as a result of moisture ingress. While concurrent failure of the parallel cabling on the power feeders was not thought likely, at least two factors were of concern. Firstly, the gates were typically all connected to one power feeder and the other feeder was tested infrequently, so one of the feeders could be in a failed state for a significant period of time. Secondly, the gate tests typically involved moving gates under a normal motor load, whereas in an emergency the motor currents could be significantly higher.

The defences in this case could include the following:

- Improved design of water seal; regular preventive maintenance of seals
- Gland seals on all cable entry and exits to reduce the ingress of moisture to the conduits
- Segregation of the control cabinet power feeders so that the failure of one water seal would not affect both power feeders

- Regular and staggered testing of both power feeders both electrically and operationally so that the operating state of both feeders was regularly confirmed
- Occasional testing of the motors with a dummy load that more closely represented the worst conditions of emergency use

(2) External Hazard CCF

Duplicated power feeders run in steel conduit from the 440V switchboard to the spillway gate control cabinets. The conduits run close together over extended distances, crossing structural expansion joints and metal walkways. The conduits did not appear to have any heat protection or slack when crossing structural joints, earthing of the conduits and equipment was often not to modern standards and no lightning protection was installed. If any one of the feeders was damaged due to mechanical interference, fire, seismic shearing, lightning, etc., it is probable that the other feeder would be damaged at the same time.

The defences in this case could include the following:

- Spatial segregation of the cable runs so that the two power feeders would be unlikely to suffer from the same physical event
- Improved protection of the conduits from external events
- Provision of a diverse means of operating the gates, e.g. a portable diesel driven engine that could be connected to the gate drive train

(3) Design CCF

On some spillway installations the motors drive the hoist gear train via worm reduction gearboxes. Some of these boxes, which operate at quite high speed, are small and get very hot during operation. They have breather vents, which are simply holes in the top of the boxes, and water ingress has been a recurrent problem. The water both degrades the lubrication of the gears and has led to significant problems with the shaft oil seals and bearings. Both the main drive motor for any gate and the alternative drive motor operate through identical types of worm reduction gearbox and a systematic problem with this type of box could lead to failure of both alternative drive trains. On one project 4 out of 14 gates had been tagged out for emergency use only because of degraded worm reduction boxes.

The defences in this case could include the following:

- Derating of the worm gearboxes to ensure that they operate well within their design capacity and are thus more tolerant of poor conditions
- Improved attention to environmental protection by fitting breathers with desiccant filters to reduce water ingress
- Prompt action on observed degradation so that the concurrent existence of degraded equipment can be minimised

- An alternative design of redundant motor arrangement that does not share common types of equipment

(4) Design CCF
The design of the spillway gates on some projects incorporated a gate bottom flange which would make the gate prone to severe vibration under certain opening conditions. The operators were not aware of the potential gate vibration problem and were unsure how to react to the occurrence of severe vibration. On one project where vibration had occurred it was attributed to water hammer and not thought to be significant. Continuing severe vibration could lead to failure of the gate hoisting cables or anchorage points, and possibly structural failure of the gates. The condition could affect all the gates if they had to be opened during a major emergency.

The defences include:
- Use of well proven equipment which has a recorded experience in the relevant application and environment
- Design review at project inception to identify potential weaknesses in design or operation of the equipment
- Monitoring, recording and analysis of operating experience to identify potential problems, followed by effective action to remedy them

(5) Operational CCF
In an emergency, spillway gates must be opened to prevent the dam being overtopped. Generally operational staff will receive instructions about the extent and timing of gate opening. However if communication is lost staff will be expected to open the gates themselves using a set of emergency procedures. Interviews with staff at some projects revealed that they had little understanding of these procedures, had in most cases never used them in any training or emergency exercise, and had a number of misconceptions about the correct operation of the gates. If communications were lost in a real emergency, a significant delay in opening the gates could prove critical. The performance of operational staff could affect all gates at the installation and could have breached any redundancy provisions in the design.

The defences that may be relevant to this situation include:
- Provision of clear, well presented emergency procedures and a requirement that these be practised on a regular basis
- Performance of regular emergency exercises simulating a range of emergency scenarios to which project staff must respond appropriately
- Training and certification of operating staff at all projects; regular re-certification requiring demonstration of adequate knowledge and experience

Revealed Faults

The design intent should be for any component failure to become apparent to the operators as soon as possible after it occurs. The objective is to minimise the time for which a system remains in a failed state without any repair action being initiated. For normally operating systems this requirement may be straightforward, but for protective systems operating in a standby mode it requires more consideration. The most common technique is to employ monitoring and alarm systems such that appropriate sensors will detect anomalous conditions and alert the operator.

For spillway gates much of the equipment is deactivated between tests and is therefore not amenable to monitoring. However the electrical supply systems can be monitored and alarmed, particularly where the supply to the gates is separate from the supply to the dam offices and the staff may be unaware of a power trip.

Despite the difficulty of continuous monitoring there is value in considering a monitoring system which is activated when power is applied to the gates for a test. Not all features of the gates may be exercised during testing and a monitoring system could alert the operator to potentially degraded conditions such as low oil levels, high gearbox temperatures, or high earth leakage currents which could be indicators of incipient failures. The electrical continuity of all the circuits could be checked, as could some aspects of the integrity of equipment such as limit switches, protection devices and controls.

Testing

Standby protective systems such as spillway gates may be idle for extended periods. In the absence of fault monitoring systems, component degradation and failure only becomes apparent at the time of an actual demand. Assuming that component failures occur randomly over time, the probability of the system being in a failed state increases approximately linearly with elapsed time since the last demand.

Regular testing ensures that the operability of the system is checked on a much shorter timescale and that system repair can be carried out before an actual demand on the system. An effective test programme must provide for testing all aspects of the system at appropriate intervals. The test interval should reflect the likelihood of potential failure modes, as represented by the failure rate for that part of the system. Care should be taken to ensure that the test programme examines aspects of the system that may have unrevealed failures, where components are not used on a routine basis but comprise a back-up or protection function for use only in specific situations.

With reference to a typical spillway gate installation:

- The test programme should include standby provisions such as an alternative motor arrangement
- If bypass features exist to protect against failure of, e.g., limit switches, then these should be tested regularly; similarly the correct functioning of items such as reset buttons on current overload trip should be verified
- Alternative power supplies such as diesel generators or trailer mounted emergency power supplies should be tested by operating a number of gates; where relevant, it is particularly important to test the interface arrangements for coupling the generator into the power supply circuits

OPERATION

Ergonomic Design

While spillway gate equipment is designed to operate effectively and reliably, it must also be designed to be operated easily. On installations which are manually operated, with no automatic control, the equipment and especially the control systems should reflect good ergonomic practice.

Major design elements for control systems include:

- Controls should be systematically laid out and clearly and unambiguously labelled; controls arranged on a mimic diagram of the system are often effective
- The controls should show clearly the state of the system using lights or other displays as appropriate
- If the system has interlocks, inhibits, protection etc. which can disable the system operation, the state of these should be clearly shown
- If a piece of equipment is in a failed state then this fact should be made clear to the operator by appropriate sensors/alarms/displays
- Any overrides or bypasses intended for irregular use should be protected from accidental use by appropriate means such as key operated switches
- The actual state of the equipment, rather than the state of its control element, should be shown wherever possible (a motor running light should be based on measured rpm, current drawn etc. rather than inferred just from voltage to the motor terminals)
- The operation of the controls must reflect the physical limitations of operating staff; e.g. displays should be visible and easily readable when the relevant controls are being operated, controls should be easily and comfortably accessible and well illuminated where appropriate, manual operations should be within normal manual strength limits

These features are required in order that staff can operate gates reliably, often under stressful conditions when it is easy to make slips and mistakes.

On some existing spillway gate installations the following issues arise:

- The gate controls are generally simple and the layout is therefore straightforward, but on some older plant the labels on control buttons can be illegible, causing a major problem for inexperienced staff
- The control panels may have no indication of the current state of the hoisting system; there may be no indication of electrical power to and from the breakers, no indication of power to the motor or the brake, and no indication of the position of any of the limit switches
- Gate hoist mechanisms incorporate protection systems related to the gate and the electrical equipment, but control panels often provide no information on the status of these interlocks or protective devices (if a gate, when last closed, tripped out on the overtravel limit switch it would have to be backed out using an override button until the overtravel limit switch has cleared, but the operator would have no indication of this)
- There may be no condition monitoring in the form of alarms or sensors, so the operator may have no indication of equipment failure other than lack of response from the system

Operating Procedures

All significant operating tasks, especially those performed infrequently or under stressful conditions, should have clear, well-written procedures to guide the operating staff. The procedure should be simple and straightforward, containing only essential text and diagrams.

The procedure should:

- Explain simply under what circumstances it is to be used and how the operator can determine the relevant circumstances, e.g. what readings to take, how to find them, who to communicate with, etc.
- Explain simply what it aims to achieve, e.g. why the procedure is being performed, how its success or failure can be measured, what data the operator can use to assess the procedure, etc.
- Lay out in flow sheets the sequence of actions required. At each stage the state of the equipment should be specified, with instrument readings if appropriate. References should indicate where ancillary information can be found, addressing issues such as what may go wrong during the action, how it can be identified and how to recover the situation. If there are several separate objectives these should be clearly distinguished.
- Where diagrams or graphs are required the procedure should state simply and clearly how they are to be used, what data is required as input and where it is available, what value should be read from the graph and how it should be used
- Where communications are required the procedure should identify who is the contact, how to reach him/her, what information will need to be given, and what information/instructions need to be received

- Instructions should be in large type, visible in poor light, encapsulated for use outdoors in inclement weather conditions; a copy should be kept in the action location in addition to a clearly identified central location

While much of the above may seem obvious, the authors have visited many projects where operating procedures failed to conform to these guidelines.

Training

All staff who are expected to operate the gates during an emergency should be trained and should regularly practice gate operation. They should be certified as competent to operate the gates after initial training and re-certified on a 3–5 year basis to ensure that they maintain their competence. Re-certification should be conditional on demonstrating a good level of practical experience in routine gate operations and participation in a reasonable number of emergency exercises.

Emergency exercises could vary in scope from simply practising the use of various standby facilities such as the alternative motor drive or the diesel generator, to a larger scale exercise in which a full scenario is simulated and staff have to act in real time. A full scale emergency exercise should be undertaken at least once every three years, and should involve practising both communications with the administrative control centre and the independent action that could be necessary if such communication is lost.

CONCLUSIONS

The benefits of reliability assessment are both qualitative and quantitative. There are clear principles of design and operation which will lead to improved reliability in practice. As a broad generalisation for systems intended to provide some type of standby function, where the appropriate reliability measure is probability of failure on demand, a well designed and operated system should be able to achieve a reliability of $\sim 10^{-3}$, a high integrity system intended for a safety critical function should aim to achieve a standard of $\sim 10^{-4}$, and only an exceptionally carefully engineered, designed and operated system is likely to achieve a reliability of $\sim 10^{-5}$.

Spillway gate installations are safety critical structures. A number of gate systems assessed by the authors have not achieved a reliability standard of 10^{-3}. Sometimes they have been an order of magnitude or more worse. This might be expected from installations that were designed and constructed 30–50 years ago, but the same trend has been found in gates commissioned in the last 15 years. While certain design and operation principles may appear self-evident, many of the installations visited by the authors have fallen far short of the recommendations laid out in this paper.

FMECA of the Ajaure Dam - A Methodology Stydy

M. BARTSCH, SwedPower AB, Stockholm, Sweden

SYNOPSIS. In 1998 Vattenfall decided to introduce the use of risk analysis in dam safety in Sweden, by issuing two pilot studies on the Seitevare and Ajaure embankment dams. The objective of these studies was to demonstrate methods to be applied for risk analysis on dams. SwedPower performed the Ajaure study in collaboration with BC Hydro International. Incorporated into this assignment were also a number of technical investigations in order to improve the knowledge base of the dam.

In 2000-2001 a second study was performed focusing on development of the application of FMEA/FMECA and other available methods and on staff training, while still relying on the information gathered during the 1998-1999 study. This "Methodology" study is summarised in this document.

The initial step of the FMECA of the Ajaure Facility was to set up a system model and break it down into subsystems and components by the use of block diagrams. The component failure modes their root causes and effects were analysed and documented using fault trees and pathway diagrams. The FMEA was extended to an FMECA for a few components to demonstrate the proposed technique for criticality analysis. The analysis was summarised in FMECA tables complemented by more extensive component data sheets.

The study concludes that the FMECA framework provides a suitable framework for working with dam safety issues at dams. Other methods, such as, functional modelling, pathway diagrams, event and fault tree analysis should be integrated as considered necessary with regard to the characteristics of the sub-system at hand. In fact, coupling of various methods can be looked upon as a promising direction for further development in the area.

It is envisaged that studies of this type will be performed for a limited number of dams in the Vattenfall portfolio.

LONG-TERM BENEFITS AND PERFORMANCE OF DAMS

BACKGROUND

General

Ajaure is a high consequence dam according to the Swedish dam safety guidelines. The 50 m high rock-fill dam is situated in the upper part of Ume River and was constructed 1964 to 1967. The dam has exhibited a number of unanticipated performance characteristics since construction, which include progressive horizontal downstream deformation, and overtopping of the spillway walls. Also, with regard to a revision of the Inflow Design Flood it has been concluded that Ajaure at present has insufficient spillway or surcharge capacity. Therefore the decision has been taken to raise the dam, which also would be beneficial for dams downstream. (The design of the raising of the dam has been performed in parallel to the risk analysis and is presented in the adjacent paper by A Nilsson and I Ekstrom, SwedPower.)

The dam owner Vattenfall (the former State Power Board) decided to consider the issues within a risk management framework and sought the assistance of BC Hydro International (BCHIL). BCHIL assisted Vattenfall and SwedPower (consulting engineers within the Vattenfall Group) by providing guidance on the application of a version of its evolving failure modes and effects analysis (FMEA) process to the Ajaure Dam risk management issue.

A preliminary FMECA was performed in1998-1999. The study included some technical investigations in order to improve the knowledge base of the dam. The present study performed in 2000-2001 relies on the information gathered during the first study. Focus has instead been on methodology and staff training issues. BCHIL was again sub-contracted by SwedPower to provide assistance to accomplish this Methodology Study.

The Ajaure assignment was one part of a two-part initiative by Vattenfall to introduce the use of risk analysis in the dam safety discipline in Sweden.

Problem Characterisation and Method of Problem Analysis

The task has been to characterise and evaluate the risk posed by Ajaure Dam with the view to develop a safety management system, which demonstrates that the risks are being effectively controlled. The risk characterisation process should permit the identification of the relative contribution of different hazards and deficiencies to the overall risk. The process should also permit the assessment of the changes in risk profile associated with modifications to the dam and/or risk reduction alternatives.

Essentially this project involves:

- a methodical approach to hazard and risk identification and their characterisation;

- modelling the ways in which hazards may be realised with resulting harm;
- identification of how the hazard sequence might be arrested or the effects mitigated.

In principle, the risk can be characterised in a relative sense in terms of a criticality index comprised of three indices that reflect the potential for a failure mode to initiate, the sequence progressing to failure; and the consequences of failure. Also, and again in principle, uncertainty can be characterised by assigning ranges to the indices instead of individual values as appropriate.

Objectives

An important objective in Vattenfall authorising a second risk based analysis for Ajaure Facility is further training of its engineering staff (SwedPower) in emerging methodologies. Another focus of the FMECA analysis of Ajaure Dam is characterisation and evaluation of the risks that have been identified in the Ajaure SEED by monitoring and surveillance and through operating experience.

FMEA, general

Failure Modes and Effects Analysis (FMEA) is a method of analysis whereby the effects or consequences of individual component failure modes are systematically identified and analysed. While the actual analysis is inductive, i.e. is based on the question "*What happens if a component or element fails?*", it is first necessary to 'break the dam system down' into its individual components or elements. Once the system has been de-aggregated the failure modes of each of the fundamental elements can be identified.

Once the failure modes and/or root causes have been identified, the effects of the failure mode on other components of the subsystem and on the system as a whole are systematically identified. The analysis is usually descriptive and information is normally presented in tabular and/or spreadsheet form. FMEA clearly relates component failure modes and their causative factors to the effects on the system and presents them in an easily readable format. A thorough understanding of the system under analysis is essential prior to undertaking an FMEA.

APPLICATION OF FMEA AND FMECA ON AJAURE FACILITY

General

The application on the Ajaure facility comprised the parts where the principles of FMEA were the primary focus of the study.

- The FMEA, in which the facility was broken down and analysed in a structured manner
- The FMECA, in which criticality ratings were assessed for a few components, and
- Derivation of global failure modes related to the Water Retaining Structures, the Discharge Facilities and the Spillway Gate Control.

FMEA process

General
In this application the FMEA process can be said to consist of three basic parts:

- System and subsystem breakdown
- Component details
- Failure modes and effects

The FMEA process was extended to FMECA by adding a fourth part:

- Criticality ratings and criticality index

The analysis has been documented on FMECA worksheets, where each of the four basic parts listed above is found as column headings. Under the heading "System and subsystem details" the functional subsystems were broken down into their physical parts, i.e. from subsystems stepwise down to components.

Under the heading "Component details" the design function(s), the design and performance parameters and the performance details have been listed. For each component the design parameters that characterise its performance have been identified. Input has been collected from designers and design data. The next step has been to collect information on the performance details with the intent to map out the design and construction adequacy. Important input has been gathered from the SEED report, performance records and complementary investigations.

In the third section with the heading "Failure modes and effects" the first step was to list the functional failure modes for each component. Here the failure mode of a design function is identical to the loss of the design function. Fault trees have been used to document the relation between root causes and the failure mode.

For each primary failure mode the potential failure sequences, i.e. the pathways to dam breach, have been explored. Also the possibilities to stop the failure sequence from progressing all the way to dam breach, the ultimate effect, have been documented.

As described above the FMEA findings are documented in FMEA tables in a worksheet format. More exhaustive information on each component is compiled in a "component data sheet". On the component data sheet each of the headings are identical to those of the FMEA table are listed. To illustrate the failure sequences graphical pathways showing the chain of events from component failure mode to dam failure are included. Fault trees have been used to illustrate the interrelationships of root causes to component failure modes.

FMEA application to the Ajaure dam

In a system context the Ajaure facility belongs to the "Super System" of Ume River. Upstream of Ajaure the systems of Överuman Regulation Dam and Klippen Power station are situated. Downstream Ajaure there are 14 hydropower facilities, of which the Gardiken Facility is situated immediately downstream. This is illustrated in Figure 1 below.

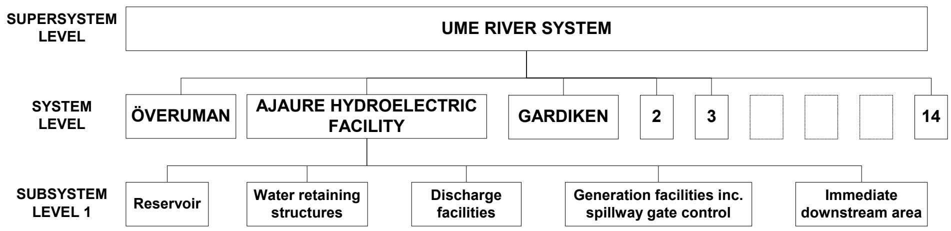


Figure 1. Logical Model of Supersystem, System and Subsystem Level 1

The function of the Ajaure facility (global system) was defined as to "retain water in the reservoir with control of the outflows". It's ability to generate power has been omitted from the study. The motivation is that the focus has been purely on dam safety. As an effect of this the study of the Subsystem Generation facilities has been limited to the Spillway Gate Control.

The "global system" failure mode to be analysed has been defined as "dam breach and release of reservoir water". Component failure modes that cannot initiate a sequence of events that may lead to dam breach have not been covered in this analysis.

In the FMEA the Ajaure facility was broken down into five principal sub-systems; Water Retaining Structures, Discharge Facilities, Spillway Gate Control, Reservoir and Immediate Downstream Area. The focus of the analysis was on the first three subsystems. Since they have great differences regarding their structure (continuous versus discrete components, man made versus geological formations, etc) and functioning (continuous loading

versus work on demand, etc) slight differences in the methodology have been used for the three subsystems.
Spatial and functional models were developed to facilitate the analysis, see example in Figures 2 and 3.

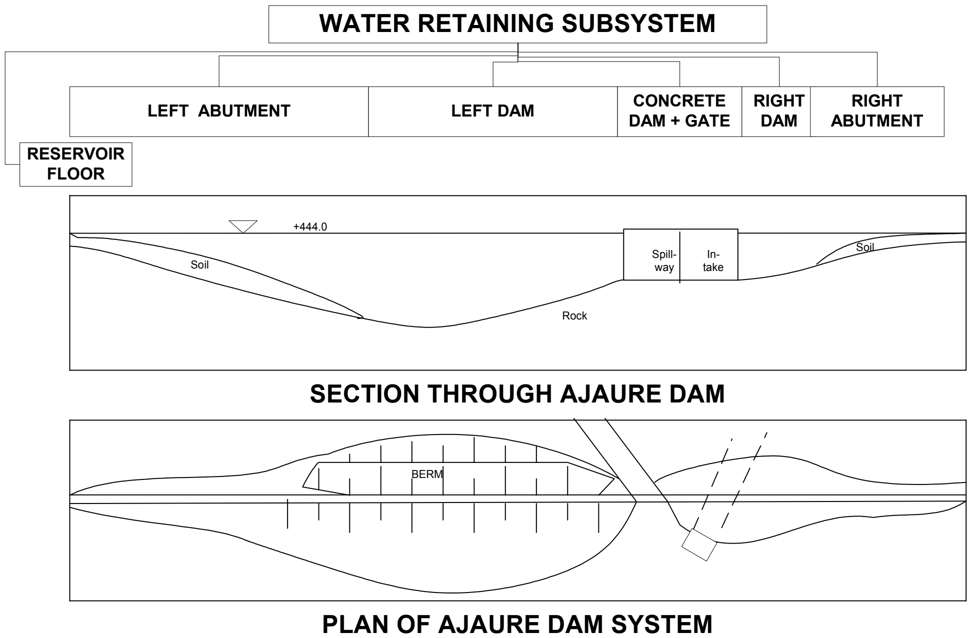
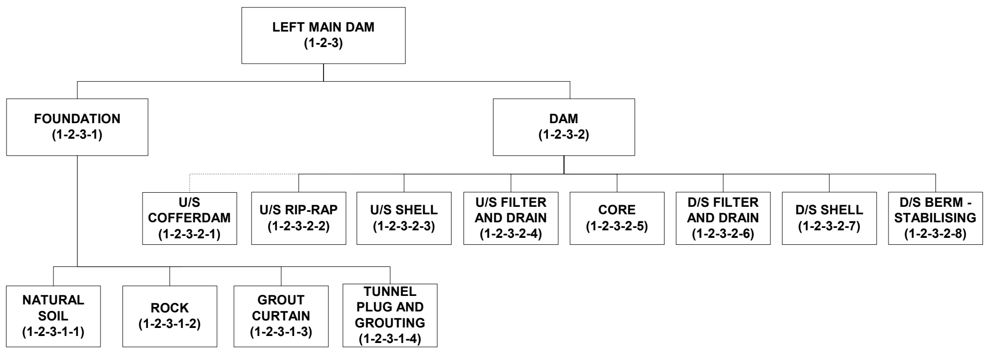


Figure 2. Plan and section of the Ajaure Dam



Block diagram of the component level of the Left Main Dam

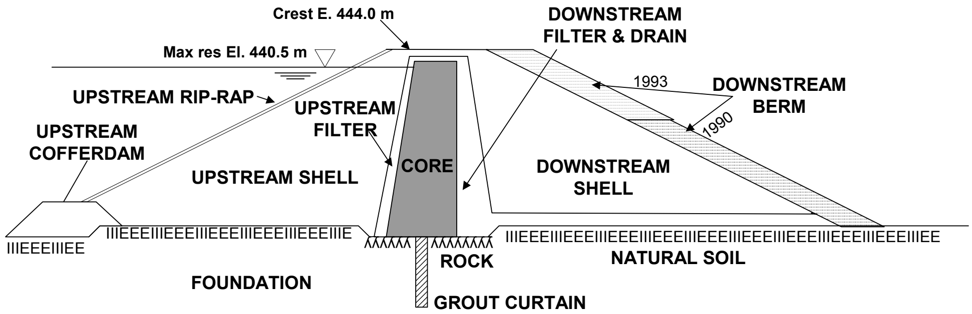


Figure 3. Spatial Model of Left Main Dam

The subsystems were broken down to the component level. Detailed component data sheets including pathway diagrams for identified failure sequences were elaborated for a number of components. Such a sheet for the downstream shell is summarised in Figure 4.

Primary Function (1)
P1: Provide structural support for core and D/S filter.
Design/performance parameters
Compressive strength, shear strength, Los Angeles-value, rock type, specific weight – not specified in design but investigated due to malperformance
Material and construction specifications, see Chapter 4. The rock fill consists of schists and gneiss with a high content of mica.
Performance details
During the second half of the 1980's, it was established that section 0/640 of the left embankment dam was moving abnormally in horizontal downstream direction….etc.
Functional Failure Mode
Failure to provide structural support for core (loss of structural integrity of D/S shell)
Immediate Effects
Deformation of core
Failure Sequence - Pathway Diagram

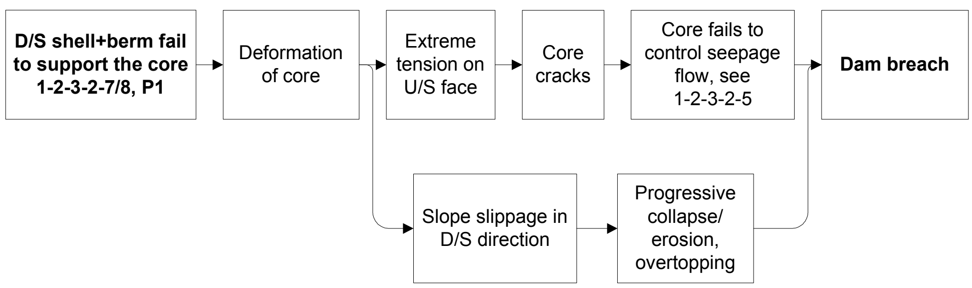


Figure 4. Summary of the Component Data Sheet for the D/S Shell

The design function of the subsystem "Water retaining structures" has been defined as to "retain water in the Ajaure reservoir with a controlled (small) seepage flow and with controlled discharges as required". Every element that has significance in making the system act as a continuous water barrier has been considered to be part of the water retaining structures. However the study was limited to one of the subsystems, the “Left Main Dam”. Further, gaps in the present knowledge of the mechanics of the functioning of embankment dams and in the available information on site specific data such as material properties and performance characteristics render this case study is primarily a demonstration of how the principles of the FMEA methodology can be applied.

The design function of the subsystem "Discharge facilities" has been defined as to "convey water in a safe way from the upstream reservoir, through the dam, and to the river downstream of the dam". All elements of significance in making the system perform the spillway function are included in the sub-system.

The design function of subsystem “Spillway Gate Control” has been defined as to “be able to activate spillway gates in a controlled manner given a requirement to pass flows”. Every element that has significance in making the system activation of the spillway gates possible has been considered to be part of the spillway gate control. The system components can be grouped in three overall aspects of the spillway gate control, for which functional models were developed

- Information flow and means of activation
- Power supply for spillway gate motors
- Power supply for measuring equipment, remote control, and station control equipment

The availability in many systems is influenced by human intervention (such as design, operation, test, maintenance etc.). There is therefore a logical connection between human reliability and technical reliability. Both human and technical availability is also determined from factors that lie outside the direct work situation. The organisation design is such an overall context and has therefore both direct and indirect influence on the basis for human and technical availability.

FMECA process

The FMEA process has been extended to FMECA by addition to the FMEA tabulation of:

- Criticality ratings and criticality index

The criticality analysis allows us to rank the importance of the failure modes by assigning criticality indices for the probability of occurrence of failure and the severity of the failure consequences. Here a qualitative approach, that does not require detailed frequency data, has been chosen. A relative index scale with five steps 1-5 has been put up. Here a set of three criticality indices has been assigned for each failure mode. They represent:

- Failure mode initiation - the potential for the failure mode to occur
- Failure sequence progression - the potential for the failure sequence to progress to ultimate failure
- Failure consequences - the severity of the consequences caused by ultimate failure.

Based on the three "criticality indices" a risk index has been calculated by multiplying them together. This risk index can be used to rank the potential failure modes according to the combined influence of their index of vulnerability and the severity of their failure consequences.

However, in order to cover differences in component function "demand" a fourth column has been added to provide context to the "criticality indices, e.g.:

- Event likelihood - frequency (1/year) of event that requires the component to function.

The process of assigning criticality indices involves weighing of evidence that supports a postulated failure mode (hypothesis) against evidence that contradicts the postulated hypothesis. Where the available information/evidence is incomplete a range has been assigned to the index. A wide range indicates that there are large uncertainties in the analysis due to lack of information/evidence. Here it is important to point out that a high number does not necessarily mean than that there is a weakness in the dam. It may also mean that there is a great lack of knowledge about the phenomenon in question, suggesting actions such as further investigations and/or a continued analysis. The "weight of evidence" explaining and motivating the assigned criticality indices has been documented.

Global Failure Modes

In the FMEA the system has been broken down into manageable bits and analysed. As an extension of the FMEA, an attempt is made to put the bits back together again, and return to the overall function of the Ajaure facility. This is done by working backwards in the pathways to failure, from dam breach towards the component failure modes. The end-branches (just before dam breach) of the pathways to failure interfaces with a global failure mode. Grouping together of the pathways' end-branches results in a few principal types of global failure modes, with connection to the three primary subsystems:

- Failure by slope instability, crest collapse and leakage/internal erosion, originating from deficiencies in the left main dam in the water retaining structures

- Erosional failure of D/S slope, originating from unsafe passage of discharge flow past the dam, initiated by deficiencies in the Discharge facilities or the Spillway gate control
- Overtopping, originating from failure to control the reservoir water level by discharge, due to deficiencies in the Discharge facilities or the Spillway gate control

For the identified global failure modes the global pathways, or when more appropriate the global fault trees, have been derived from the pathways used to model the effects of the component failure modes.

CONCLUSIONS AND LESSONS LEARNED

The training component of the SwedPower staff is deemed to have been successful, regarding methodologies with regard to risk analysis of dams, as well as training in sound engineering practices in general.

The applied FMEA methodology is regarded to provide a suitable framework for working with safety issues at dams. However, FMEA do not provide a stand-alone method or procedure but other methods such as pathway diagrams and fault tree analysis should be integrated in the application. Further development of the coupling of various methods and the criticality analysis would be beneficial to make the application more straightforward.

The elaboration of global failure modes provides a means of joining the results from the more disciplinary analysis of the various sub-systems. The global failure mode diagrams serve as logical maps displaying the relationship between various component functions and their role along the failure pathways.

The criticality ratings provide insights into what the engineers consider to be the principal issues concerning seriousness of issues and extent of uncertainty. The outputs from the criticality analysis process serve well as a basis for reasoning concerning the management of the risks.

Another conclusion is that complementary technical investigations providing site-specific data are often required to make the FMEA meaningful.

Agent-based dam monitoring

V. BETTZIECHE, Ruhrverband (Ruhr River Association), Essen, GER

SYNOPSIS. The monitoring of security relevant structures is a task of growing importance in civil engineering. Large structures such as bridges and dams demand the use of precise measuring systems and the collaborative work of engineers, geologists and geodesists. Considering the time and labour consumed by the acquisition, processing and analysis of measured data, concerned authorities, operators and companies are trying to automate these operational procedures. The existing computer-based solutions focus on remote monitoring and neglect a collaborative analysis of measured data. However, an appropriate and effective monitoring system must conduct all of the tasks performed by experts involved in monitoring.
The Institute of Computational Engineering of the University of Bochum, in co-operation with the Ruhrverband (Ruhr River Association), is developing a dam monitoring system based on software agents. The nucleus of the system's conceptual design is based upon the autonomous and collaborative analysis of measured data, associated with intelligent agents adopting the part of the experts generally involved in dam monitoring.

INTRODUCTION

Dam monitoring is based on precise measuring systems and the collaborative work of engineers, geologists and geodesists. Considering time and costs of acquisition, processing and analysis of measured data, an automated management of these procedures is desirable. Most of the existing computer-based solutions focus on remote monitoring, presentation and electronic transfer of measured data. To this end, they do not consider the cooperation between the experts involved in monitoring. However, an appropriate and effective monitoring system has to pay attention to the individual tasks performed by the experts. Furthermore, the distributed collaborative data analysis and safety assessment has to be captured through the system established.

The Institute of Computational Engineering of the University of Bochum, in cooperation with the Ruhrverband (Ruhr River Association), is currently

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

developing a dam monitoring system based on software agents. Software agents represent an innovative, powerful as well as robust software technology allowing not only the implementation of distributed applications but also complex interactions. Consequently, the agent-based dam monitoring system is capable of supporting the collaborative work of the involved experts and incorporates the distributed work flow of data analysis and safety assessment. Thus, the complete work flow of dam monitoring is mapped onto a multi-agent system: regularly performed tasks (i.e. measuring at specified locations at the dam) are carried out by specialist agents. By contrast, the involved human experts are assisted by means of personal agents, which support these experts in performing their specific tasks and allow a direct communication with the multi-agent system.

Software agents - autonomous, mobile and intelligent software programs - provide all the necessary characteristics to innovate and accelerate the development of distributed applications. They represent powerful and robust software technology for implementing distributed-collaborative work flows and complex interaction.

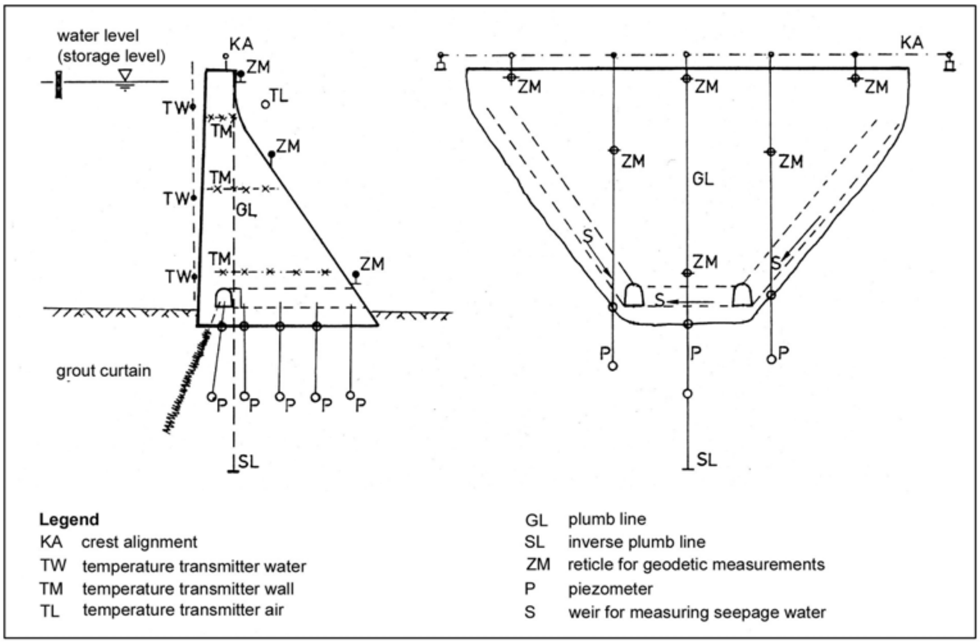


Figure 1: Example for the configuration of measuring devices [1]

DAM MONITORING - TECHNICAL ASPECTS

The aim of dam monitoring is to provide indicators for anomalous structure behaviour in order to be able to take necessary countermeasures in due time and without any reduction in safety. In Germany, the legal basis of dam monitoring is found in the German Code E DIN 19700 (2001). Further, recommendations for measuring devices have been published by the German Association for Water Resources and Land Improvement (DVWK) [1]. An example for the configuration of measuring devices is shown in Figure 1.

The concept of dam monitoring is based on the systematic acquisition of all the relevant parameters, which concern static, hydrologic and operational safety. Therefore, each dam structure must be provided with a measuring and control system, which, then, has to be adapted to the type, size and location of the structure.
The conceptual design of a monitoring system has to consider the following principles:

- Dam and bedrock form a unity, which is embedded in a natural environment.
- An anomalous structure behaviour can occur either gradually or quickly.
- When an anomalous behaviour occurs, the origin should be identifiable by an analysis of the measured parameters.
- Inspection by qualified personnel is indispensable.

In addition, the monitoring system must be adapted to the characteristics of the dam structure and take into consideration the corresponding measuring categories. At arch dams it is important to monitor displacements, and at gravity dams pore pressures are of particular importance in addition to displacements.
An automatic monitoring system rests on extensive electronic measuring equipment. The equipment consists of two essential components: transmitters (sensors) and data recorders (data loggers). Recommended transmitters are i.e.:

- temperature sensors,
- ultrasonic sensors for measuring seepage water,
- laser for measuring displacements,
- vibrating wire piezometers for measuring pore pressure.

The sensors are installed at specified positions (figure 1) inside the structure or the bedrock and they are controlled by electronic equipment (e.g. data loggers) sending electronic impulses. After having received an impulse, the sensors return a signal which can be a measurement of voltage, resistance or frequency. The electronic equipment scales the signal into a value, and either stores it in an internal memory or transfers it to a local database. Data stored in an internal memory can normally be received via a COMMS port (RS232). This interface also allows that the electronic equipment can be programmed from a host computer. An automatic monitoring system is customarily completed with a local computer, usually placed in a control room near the dam. As the redundant data storage is essential in dam monitoring, measured data is stored in a local database and additionally transferred to a central database [4,5].

DAM MONITORING - ASPECTS OF ORGANISATION

Dam monitoring is not only based on instrumental supervision. Several experts have to take care of the data, i.e. they have to analyse the data. The experts view on the monitoring data may be very different, based on their profession and job. For example, a geologist may view at these data differently than a geodesist or a civil engineer.

At the Ruhr River Association the monitoring data have to pass several states of controls as it is shown in figure 2 (left side). Different experts have their view on the data, while on one hand the processing frequency decreases with every processing step, from temporal intervals of one day up to one year, on the other hand the time interval of the viewed data also decreases from an short interval to the whole existing data.

Each step can be briefly described as follows:

1. Data acquisition:

   At the reservoir the crew supervised the dam according to the monitoring plan. This includes daily measurement (manual or automatic) of the relevant parameters, in particular the rate of flow, water level, water pressures, displacements, changes of temperature and others.

2. Check of plausibility:

   Just in time, the manual or automatic measured data are checked with respect to their plausibility. These checks are based on the data of the measurement of the day before or on alarm values and are done by the measuring crew itself.

3. Check of short-time behaviour:

   In the week of the measurement the data are checked by the responsible engineer at the reservoir-administration. He compares the data with the measurement of i.e. the last week to find out anomalies in the short-time behaviour of the dam. After this the data are transferred to the dam safety department of the company.

4. Check of long-time behaviour:
   At the head office of the company several specialist have their own view at the data. At the geological department the data concerning groundwater flow and seepage are checked. Geodesists and Engineers will inspect the movement data. This investigation will be done once a month, in order to find abnormal behaviour in a long-time view of the data.
5. Safety assessment:
   Once a year the responsible engineer has a view over all the data collected. His task is to supervise the measurements and to analyse the data by using statistical tools and computer models. At last he has to compose the annual report, documenting the safety of the dam, not least for the surveillance authorities.

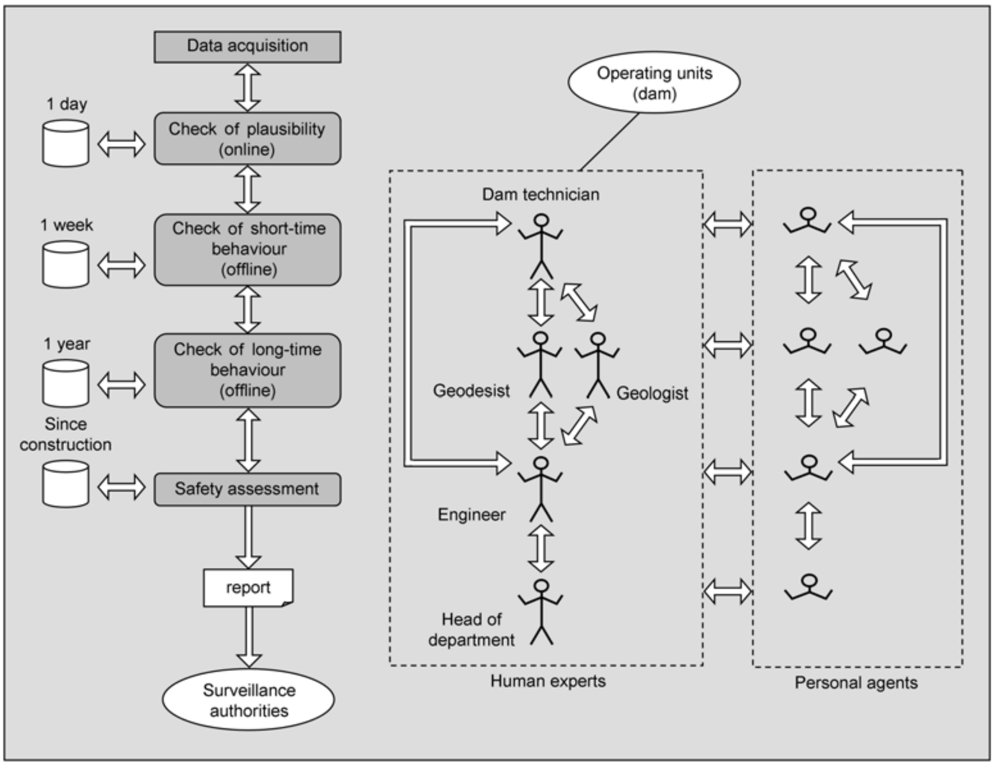


Figure 2: Conceptual design of dam monitoring

CONCEPTUAL DESIGN OF THE DAM MONITORING SYSTEM

The analysis of the described work flow applied by the Ruhrverband indicated that there is a chain of five tasks regularly performed by the responsible experts or in collaboration with other experts. Thus, the basic principle of the conceptual design is to map the regular performed tasks, the individual experts and the interaction between themselves onto a multi-agent system. By that, the software agents can be divided into two categories: specialist agents mapping the regularly performed tasks and personal agents mapping the experts involved in dam monitoring. The conceptual design for the organisation of the agents is shown in Figure 2 (right side).

In order to provide smooth communication between the human experts and the multi-agent system (MAS), each human expert involved in dam monitoring is allocated with a personal agent. This software agent represents the interface "human/MAS" and has to be proactive. A proactive agent is able to realise its environment, to recognise the situation represented by the data and to identify the human user. Depending upon the situation it informs the human user or contacts to other agents, in order to request further information (see Figure 3).
The corresponding agents are organised using the same relationships as the human experts do (see Figure 2).

Figure 3: Informing the dam technician by mobile phone

IMPLEMENTATION OF THE DAM MONITORING SYSTEM

Considering the agents to be applied in the dam monitoring system, there are some basic requirements to be met by the conceptual design of the agent architecture. In the following an appropriate agent architecture is developed by focusing on the basic requirements of agent-based applications.

Interaction, and in particular its basis, **communication**, is an essential element of the networked and collaborative systems of the present time and future. Capable solutions must provide several communication protocols for different requirements. For example, in some environments the HTTP protocol is required in order to avoid firewall problems.

The inter-agent communication within the MAS is to be realised according to FIPA specifications [8], since FIPA is one of the central standards in the agent world. Furthermore, this approach allows inter-platform communication with other FIPA-compliant agents on various platforms.

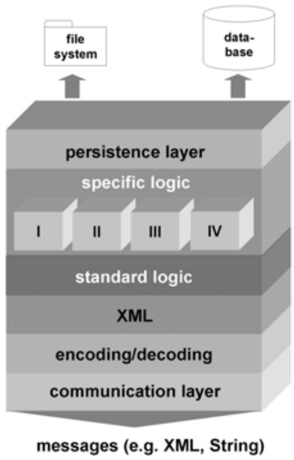


Figure 4: Conceptual design of the agent architecture

When dealing with complex problems, the agents have to be provided with logic. In the current architecture, the logic elements are divided into two categories: **standard logic** and **specific logic** (knowledge). In this particular case the standard logic contains the ontology of the domain “dam monitoring”, by which the agents possess the required vocabulary and basic knowledge in order to communicate and to execute simple tasks.

Via modules the individual knowledge of the involved experts can be integrated very easily. This approach enables the user to adapt the agent to new tasks, goals or environments, too. In other words, the agent becomes more “intelligent” [6,7].

The last layer of the given architecture is a **persistence layer** to keep the state of the agent persistent. In case of a system crash this layer helps to identify the actual state of the agent and to continue the work without any loss of time.

Control of automatic measuring devices - Logger API

As an important factor, a capable computer-based monitoring system must cover the applied electronic equipment. In order to control the measuring devices installed within the structure, there are two popular solutions: systems based on process control systems and systems based on data loggers. In the following, only data loggers are discussed. From an objective point of view, they are the better and more transparent solution for dam operators in planning, use and maintenance.

Since the control of the data loggers depends on the specific communication protocol and the instruction set predetermined by the specific manufacturer, a Java-based programming interface, called Logger API, was developed to encapsulate specific loggers. Specific loggers can be added to the developed library without expenditure.

Data processing and visualization – the evaluation module

Data processing and visualization are provided by an evaluation module which has been conceived thus far with a web-based front end. The web-based paradigm has been chosen such that an acceptance test could be performed in practice in a simple manner and so that no further client-sided software would be necessary.

The task of this web-based evaluation module is to read the acquired data of the dam monitoring from the database and to evaluate, edit and prepare the data in a user-oriented way, graphically and/or tabularly [3].

• *Visualization component*

The visualization component (**view**) acts as a graphical user interface which allows database inquiries, administration of users, etc. (*inputs*) on the one hand and visualizes the requested result quantities in different data formats (*outputs*) on the other hand

An additional task of the visualization component is the representation of the requested data in the format indicated by the user. Output objects are instantiated in order to produce the appropriate outputs depending on the desired format (see Figure 5).

• *Database adapter*

In order to be able to attach several (replaceable) databases, the **model** is realised as an exchangeable database adapter. The assigned tasks are to generate a connection between the database(s) and the controller component, to pass on inquiries which concern measured data to the database, and to return the received results to the controller component

Due to the modularity and expandability of the evaluation module developed, this module can be used in a multi-agent system, for example as a wrapper agent, in order to read measured data from a database. A further possibility is the employment of the module as an interface agent, i.e. as an interface between a human and a multi-agent system which converts "clicked" mouse events into messages understandable for agents.

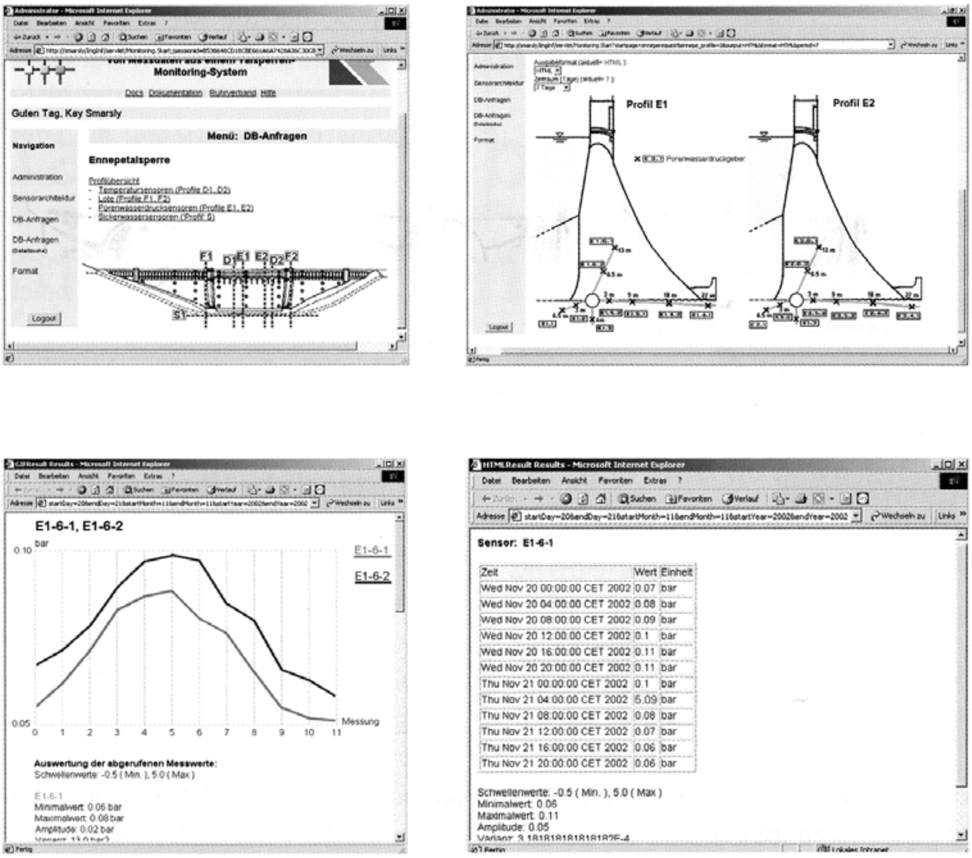


Figure 5: User-specific visualization of the measured data

CONCLUSIONS

Applying software agents, the Institute of Computational Engineering, in co-operation with the Ruhrverband (Ruhr River Association) is taking an innovative approach to developing a modern dam monitoring system, which is capable of supporting the collaborative work of experts involved in monitoring.

The conceptual design of the organisation and the architecture of the agents to be applied in the multi-agent system have been shown. By substantiation, the implementation of two important modules - the logger API and the evaluation module - has been explained.

Actually, these two modules represent a conventional, web-based monitoring system. The measuring devices installed within a dam can be controlled online, and measured data can be read out of the databases and processed according to user preferences.

The multi-agent system is designed to map the distributive-collaborative work of the concerned experts and to integrate their specific knowledge about dam monitoring and dam behaviour. This conceptual design differs significantly from conventional monitoring systems and represents an innovative approach which is capable of demonstrating the enormous potential of agent-based applications.

ACKNOWLEDGEMENT

The author would like to thank Prof. Dr. D. Hartmann, I. Mittrup and K. Smarsley of the Ruhr-University of Bochum, Germany, who developed the computational solution for the collaborative analysis of dam monitoring data.

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Armenia Dam Safety Project

JOHN SAWYER, Jacobs Ltd, UK
LAURENCE ATTEWILL, Jacobs Ltd, UK

SYNOPSIS. The Armenian dam safety project involves the technical investigation of 64 dams during the period June 2002 to July 2003. The scope of work includes:

- Fieldwork: Dam inspections, Site investigations (4000m of drilling), Topographic survey, microseismic survey
- Studies: Hydrology, Flood routing, Dam break, Stability analysis, Seismic hazard assessment, seismic analysis
- Risk assessment
- Rehabilitation preliminary design and costing
- Dam safety plans (Operation & Maintenance, instrumentation, early warning systems and Emergency Preparedness Plan)

The dams include irrigation, water transfer and hydropower schemes and range from 1.5m to 83m high with both embankment and concrete gravity structures.

The paper gives an overview of the project and its challenges. Particular project issues include working across national and engineering cultural boundaries, obtaining information on existing schemes, and using a risk based assessment procedure for prioritising rehabilitation works. Particular technical issues include the refurbishment of neglected mechanical equipment and the rehabilitation of a 65m high dam that collapsed during construction.

INTRODUCTION

The Project Implementation Unit (PIU) of the Committee on Water Economy Management of the Republic of Armenia is implementing a national Dam Safety Project to increase utilisation of the present water reservoirs and to protect the downstream population and infrastructure in the case of a dam break. The safety assessment of 24 large reservoirs was completed during 1999 – 2000, and a preliminary Rapid Investigation of a further 60 dams was carried out in 2000 by Hydroenegetica Ltd of Armenia.

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

LONG-TERM BENEFITS AND PERFORMANCE OF DAMS

This paper considers the follow up project to the 'Rapid Investigation', which studied a total of 64 reservoirs between June 2002 and July 2003. The project is funded by an IDA loan to the Armenian Government and has been carried out by Jacobs Ltd of the UK with the support of Hydroenergetica and Georisk of Armenia.

The importance of dams in Armenia is very high. Some 24% of National electricity demand is generated by hydropower stations. The remaining balance is generated from thermal stations powered by both nuclear reactors (31%) and fossil fuels (45%), all the fuel must be imported. Hydropower is important therefore not only because it is cheap and clean but also because it provides a secure source of power. The water stored in the reservoirs irrigates 2,870km^2 which reduces Armenia's dependency on food imports with consequential security, social and economical benefits. Dam safety is therefore of national significance, and not just to the population living immediately downstream of the dams.

The majority of the dams have been in operation since the 1960's and 1970's, with some in use since 1940. Based on several factors that include the dam height and the reservoir storage capacity, the reservoirs have been divided into the following groups:

- Large reservoirs (12 dams, 15m to 85m high)
- Small Reservoirs (33 dams, 1.5m to 20m high)
- Artificial lakes (17 dams, 0 to 5m high)
- Partially constructed (2 dams 14m to 21m high)

Six of the large reservoirs are hydropower dams and are under authority of the Ministry of Energy. Two large dams were originally built for mining organizations and are not in operation, the other dams are irrigation or multi purpose dams and are owned by Jrambar CJSC, which is a state organisation responsible for irrigation facilities.

SCOPE OF THE PROJECT

The scope of the Consultant services is as follows:

1. Dam Investigations: reveal the structural and non - structural defects based on dam inspections, topographical and geotechnical site investigation results as well as hydrological, geotechnical and seismic studies.
2. Determine the degree of risk for each dam.
3. Recommend rehabilitation measures.
4. Prepare dam safety plans, which include instrumentation, operation and maintenance (O&M) plans and emergency preparedness plans (EPP).
5. Recommend early warning systems where appropriate.

The project therefore covers not only all the technical issues relating to the reservoirs, but also the interface with the operators, owners, emergency services and general public. The investigations and studies into the 'artificial lakes' were more limited than those for the remainder of the reservoirs due to their low hazard, but covered the same general scope.

DAM INVESTIGATIONS

Field Investigations

Only limited information exists regarding the construction of each dam, and typically the information available is design data rather than construction records. For many of the smaller dams no records were found at all. Thus, although an archive search was carried out, it was necessary to carry out field investigations on most of the reservoirs including field inspections, topographic survey and mapping, and geotechnical site investigations.

The field inspections were generally carried out by expatriate dam specialists accompanied by local technical staff and where possible by the operators. An inspection report was produced for each reservoir, and this was then used to establish the requirements for further investigations, particularly the geotechnical site investigations. Topographic survey was carried out by local contractors.

The site investigation involved almost 4000m depth of boreholes and trial pits. Both disturbed and undisturbed samples were taken for characterisation and strength testing in local soil mechanics laboratories. Two local contractors worked under the supervision of local and expatriate geologists.

The terrain of Armenia is very mountainous and the winter is severe, making access to remote areas impossible for several months. The most remote reservoirs are only accessible in the late summer. So far as possible all reservoirs were inspected and the site investigations completed in the Autumn of 2002. Some follow-up work was carried out in late spring of 2003. Security concerns limited access to some border reservoirs. The Turkish border of Armenia is manned by Russian troops and the border with Azerbaijan is unstable, so access to major dams on these borders was restricted. Inspections were carried out on these dams but site investigations were not possible.

Hydrology

Two methods were been used to analyse the flood inflows into the reservoirs. The first, the SNIP method, is based on standard Russian techniques and is in general use in the country. The second, a statistical method using all annual maxima flow data recorded in Armenia, has been used worldwide to check more particular methods (the Regional Method).

The Soviet Norme (SNIP)

This has two approaches, depending on the information available:

1) Applying analytical distribution functions for annual exceedance probabilities where sufficient hydrogeological data is available for the catchments.

2) In the absence of observed data, the peak flood of a given return period is calculated using a formula in terms of m^3 per km^2 which has terms for basin area, rainfall, geographic characteristics and vegetation.

The Regional Method

The basic hydrological records available for analysis in Armenia comprise the annual maximum flows for 102 gauging stations. The average record of over 40 years ensures that a reasonable sample of floods is available at these sites. By combining the records at different sites it is possible to estimate relations between basin characteristics and the mean annual flood, and also a relation between the mean annual flood and the flood of a rare frequency or long return period.

The relationship between mean annual flood (MAF) and the flood for a given return period (Q_T) was determined to be:

Return Period, yrs.	100	500	1,000	2,000	5,000	10,000
Q_T/MAF	3.23	4.7	5.47	6.33	7.65	8.79

A regression between mean annual flood, (MAF), and basin area (AREA) and annual rainfall (AAR) provides a significant relation between the variables:

$$MAF = 2.53 \times 10^{-6} (AREA)^{0.782} (AAR)^{1.764}$$

These two relationships were then used to assess the MAF and Q_T for each reservoir at the relevant return periods.

Comparison of the SNIP and the Regional method

The Armenian Standard (SNIP) was found to give higher estimates of peak flow for smaller catchments (up to $100km^2$). For very large catchments ($100,000km^2$) the regional Method gave a slightly larger estimate, with reasonable agreement between the two methods in the middle range. See figure 1 below which compares the 1000 year flood estimates.

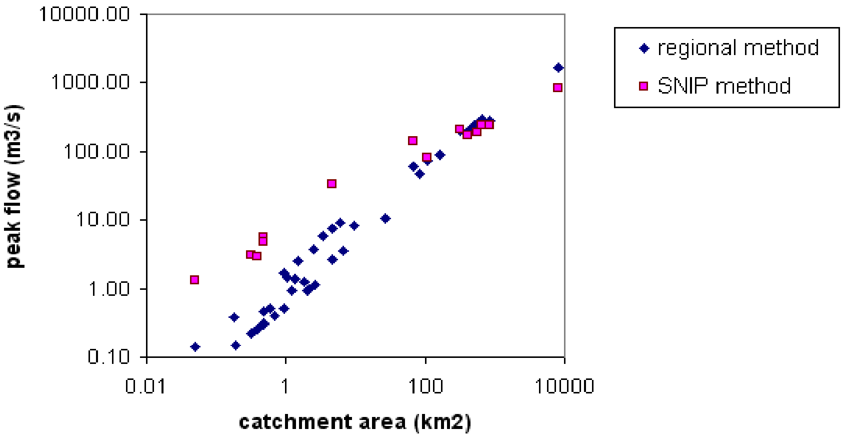


Figure 1: Comparison of 1:1000 year flood estimates

Flood Routing

Flood routing studies were carried out making use of either inflow hydrographs based on SNIP hydrology and SNIP rules for the return periods to be considered, or inflow hydrographs based on Regional Method hydrology and ICOLD recommendations for return periods where this gave larger floods [only the large reservoirs were affected].

Dam Break

Dam-break modeling was used in this project both for input to the Risk Assessment and the Emergency Preparedness Plan (EPP). The dam-break assessment was carried out in three steps:

i.) Initial screening carried out by identifying the potential flood paths on 1:100,000 scale mapping. In the case of some small reservoirs this indicated that the flood wave presents no hazard, passing through no populated areas and joining river channels which are large relative to the size of flood. In this case no further study is needed. In most cases this initial phase defines the extent of flood route which requires further study.

ii.) 'Quick Dambreak'. This is a spreadsheet based method of analysis which predicts the flood size and characteristics and from which inundation mapping is prepared. The approach was developed from the methodology given in CIRIA Guide C542, Risk Management for UK Reservoirs. For this analysis 1:25,000 and 1:50,000 mapping has been used as this is all that was available to the project.

iii.) BOSS DAMBRK. This is commercial software using more sophisticated analysis methods. For this project it was used for the analysis of the most critical reservoirs and to calibrate the results of the 'Quick Dambreak'.

The output from the Quick Dambreak analyses were inundation maps, coloured to show the flood damage parameter velocity x depth, with tables showing flood depth and width, and the time to peak flow at points along the flood path. The analysis has the great advantages of simplicity and ease of use. It has enabled the assessment of all the dams within the project to an adequate level.

The results of DAMBRK were compared with the Quick Dambreak results and demonstrated that within the tolerances of the mapping available the output was satisfactory for risk assessment and emergency planning.

Geophysical Investigations

Seismic refraction survey was carried out at Marmarik dam. The results were used for the assessment of seismic intensity magnification due to the site specific soil conditions.

Electrical resistivity was measured along two profiles at the Landslide N4 at Marmarik dam. The results were used, together with the drilling results, to determine the thickness of the landslide material.

Landslide hazard studies

Desk studies were carried out of potential landslides around Marmarik and Bartsrouni reservoirs. The work involved analyses of satellite images and aerial photos that were taken in 1948, 1976 and 1986.

Four potentially hazardous seismogenic landslides were identified within the Marmarik reservoir area that may influence the dam safety. The impact of the landslides onto the dam safety was assessed and special design provisions were made as a part of the rehabilitation works. They are described in detail in the paper on Marmarik dam.

Bartsrouni dam was constructed on a large, ancient landslide. Recent landslide activities have been demonstrated by numerous scarps. The dam has already been partially destroyed by landslide movements and it is anticipated that future movements will continue to damage the dam.

Seismic Studies

Seismic studies for the dams include the assessment of the seismic stability and assessment of liquefaction potential of fill and the foundation material.

Seismic stability analysis has been carried out using the methodology given in the Seismic Design Standards of Republic of Armenia (SDSRA) –, II.2.02-94 for all dams.

The susceptibility of loose, saturated sands and silty sands in the foundation and dam body to liquefy during an earthquake was carried out according to the methodology given in the Japanese standard.

Seismic design parameters have been selected based on the SDSRA for all dams, and on a Site Specific Seismic Hazard Assessment (SSSHA) for seven critical dams. The selection of dams was based on the level of acceleration assessed in the SDSRA, dam height and the results of the site investigations. The SSSHA was carried out using both a probabilistic and a deterministic approach. The results are given in Table 1 below, and indicate the significant seismic hazard in Armenia.

Table 1. Site Specific Seismic Hazard Assessment (SSSHA) – Design Accelerations

	Design Peak Horizontal Acceleration, g			
	OBE		MDE	
	Ground	Crest	Ground	Crest
Marmarik	0.32	0.6	0.44	0.82
Shenik	0.12	0.30	0.25	0.61
Tsilkar	0.34	0.49	0.49	0.65
Landjaghbiur –1	0.22	0.25	0.68	0.74
Hors	0.24	0.39	0.69	0.71
Gekhi			0.35	0.675
Akhuryan (concrete)	0.4		0.7	

<u>Stability Analyses</u>
Stability analyses for the embankment dams were carried out using the computer programme SLOPEW (GEO- SLOPE International) based on data from the topographical survey and on the site investigation. The load cases analysed are in accordance with SNIP standards. They include consideration of the upstream and downstream slope under static and seismic loading; and full supply level, maximum flood level and rapid drawdown cases.

For all except four of the dams, the factors of safety obtained in the stability analyses for the static condition were higher than the minimum required. Stabilistation works were designed for the four sub-standard dams. For some of the dams, factors of safety obtained for the seismic condition were less than unity. However, the displacements that could be generated were assessed to be negligible.

The concrete gravity dams were assessed by using a spreadsheet based analysis. Static and dynamic stability cases were assessed under a range of water levels and uplift assumptions. The dams were generally shown to have satisfactory stability under static conditions, but were liable to some local overstress in seismic events. One dam, which had an unauthorised spillway raising, was shown to have inadequate safety margins unless the spillway was restored.

Summary of Defects

A wide range of defects relating to design, construction, operation and maintenance were identified. In many cases these could be attributed at least in part to the results of the break up of the Soviet Union. Typical defects included:

- Deliberate blockage of the spillway to increase freeboard.
- Inadequate spillway capacity / freeboard.
- Structural repairs required to spillway or outlets.
- Damaged or deficient riprap or wave protection.
- Outlet valve refurbishment required.
- Slope stability inadequate.
- Leakage through embankment.
- Leakage through reservoir floor.
- Unsafe access to equipment.
- Refurbishment required to hydromechanical equipment.

On the basis of the assessment of defects, remedial works were recommended and outline designs prepared. Detailed design is to be carried out by Armenian consultants. In a limited number of cases ‘emergency works’ were recommended immediately following the inspection. One reservoir was recommended to be drawn down and abandoned (Bartsrouni, built on a landslide), others were recommended to be maintained at a low water level pending remedial works.

RISK ASSESSMENT

Methodology

The approach that has been used in the assessment of risk of all the dams is a semi-quantitative method in which both the probability and the consequences of an event are ranked from low to high and the relative risk levels indicated by the position on a matrix. This method has been adapted from CIRIA Report C542. The following stages are required:

i) identification of failure modes (instability erosion etc.).

ii) comparative assessment of probability of failure (probability of event x probability of this leading to failure).
iii) comparative assessment of consequence or impact of failure (population at risk and economic loss).

All factors are quantified on scales of 1 to 5 or 0 to 4, leading to semi-quantitative assessments. The risk index is the product of the total impact score and the risk score. A comparison of this score for all dams will provide a ranking showing where the priorities for remedial works lies. In addition, if the risk assessment is repeated for the case where it is assumed that the recommended remedial works have been carried out, the reduction in the combined score will enable a quantitative assessment of the benefit of the remedial works to be made.

The risk profile of the dams, as measured by the risk index, is presented in Figure 2. This Figure also shows the reduction in risk that will be achieved by the implementation of the Emergency Preparedness Plans and the remedial works.

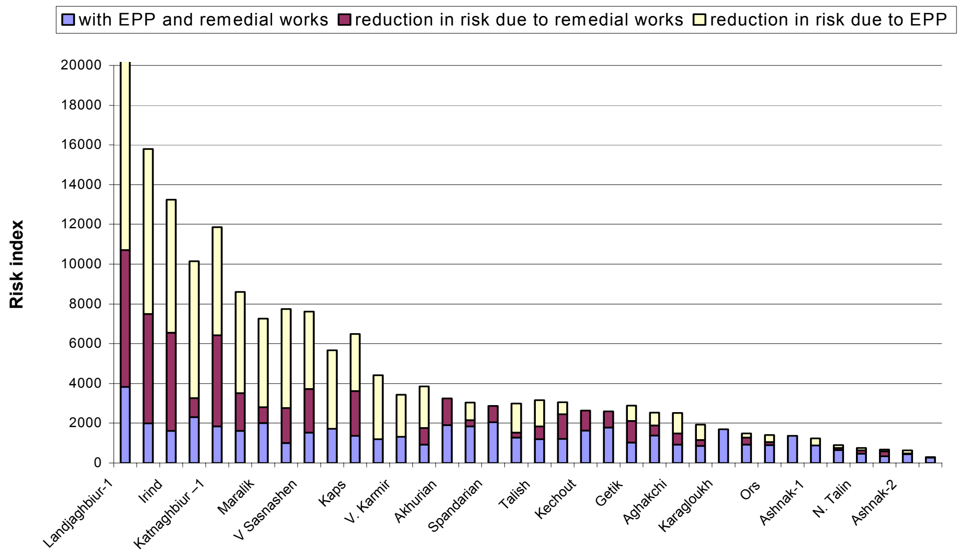


Figure 2: Risk Profile

<u>Cost effectiveness</u>
As a means of assessing cost effectiveness, the reduction in risk index has been divided by the corresponding cost for both structural measures (remedial works) and non structural works (safety materials and emergency preparedness plans) to give benefit/cost ratios for structural and non-structural works.
Figure 3 shows the ranking in terms of the benefit/cost ratio of remedial measures. The average benefit cost ratio is 29 and the range is from 128 (V

Sasnashen) to 0.8 (Kechout). One effect of this ranking is to highlight the significant benefit that can be gained from relatively minor works ($17000 at V Sasnashan compared with $1.3 million at Kechout).

Figure 4 shows the ranking of the dams in terms of the benefit/cost ratio of non- structural measures. Not only is the ranking of the dams quite different but the average benefit/cost ratio, 96, is much higher than the remedial measures cost benefit ratio and also the range, from 12 to 427, is more extreme. This indicates that non-structural measures can be regarded as providing better value for money but it is important to bear in mind that this depends on the efficacy of the EPP's which will require commitment and ongoing expenditure to maintain.

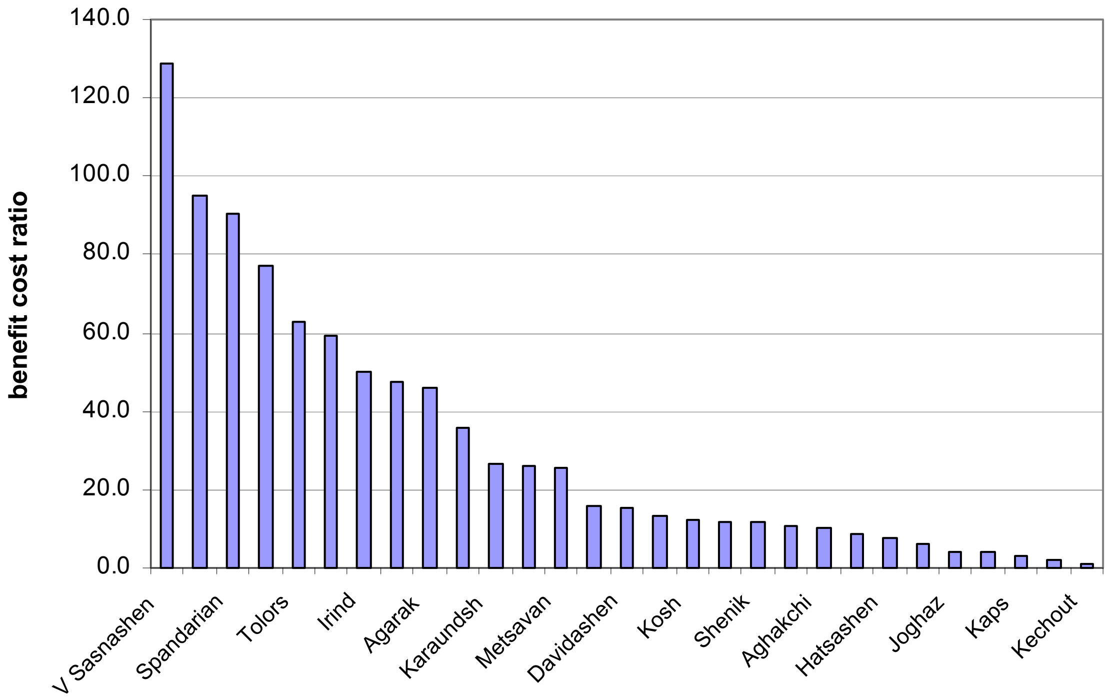
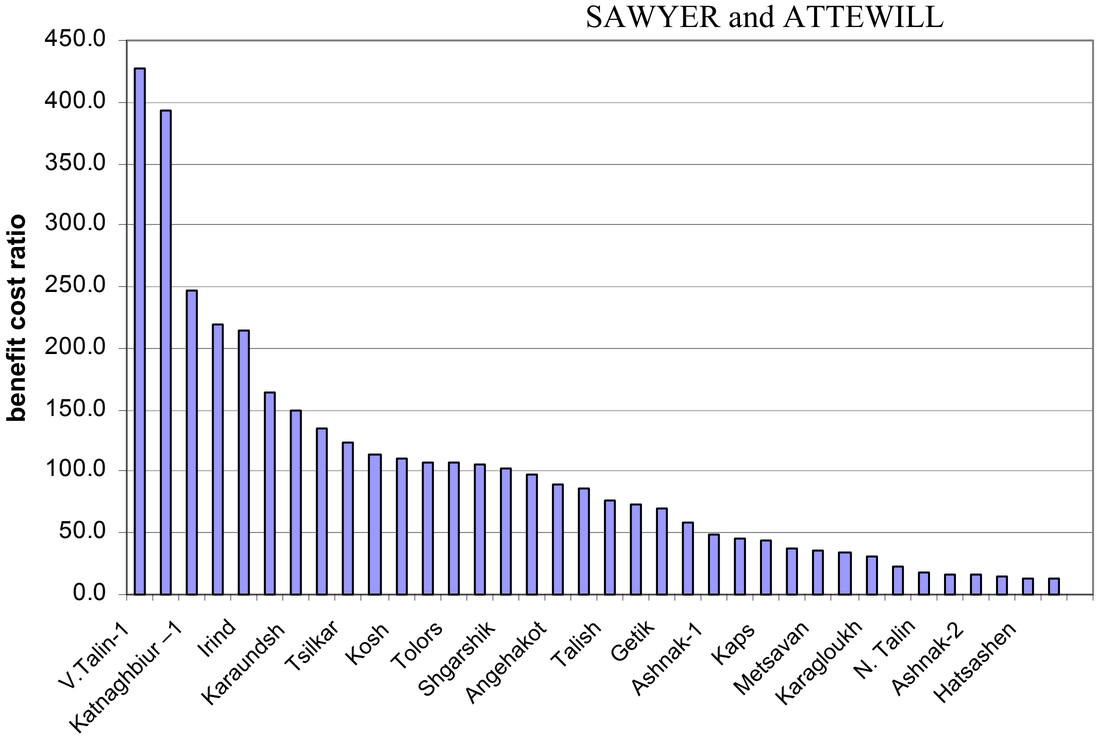


Figure 3: Benefit cost ratio of remedial measures
Figure 4: Benefit cost ratio of non-structural measures



DAM SAFETY PLANS

Dam Safety Plans were prepared for each dam. These include recommendations for instrumentation and monitoring, for operation and maintenance and where relevant an emergency preparedness plan (EPP). The plans were tailored to the particular reservoir, and reflected the size and hazard potential for each dam. The recommendations were generally for simple and robust instruments to monitor reservoir level, leakage and movement, typically just a staff gauge for the water level, V-notch weirs for toe drainage measurement, and survey monuments on the crest for the smaller embankments, with foundation piezometers to measure uplift in the concrete dams. Nine dams presenting a hazard to communities immediately downstream have been identified and an automatic water level alarm recommended to give warning in the event of the spillway discharge exceeding the design capacity. Equipment and materials for emergency works have been identified, to be maintained at each regional depot and each major dam. The proposals have been costed, including the requirements for routine supervision and inspection of the reservoirs, to allow the owners to budget for the long term implementation of the Safety Plans.

The EPP for each dam makes use of the technical studies, particularly the dambreak and inundation mapping, and then relates this to the emergency services and civil authorities. Local specialist consultants were used for these aspects as they require particular knowledge of local organizations.

PROJECT CHALLENGES

The project involved considerable challenges, most of which in some way related to communication. Particular issues included:

- Access to remote sites in difficult terrain and an extreme climate.
- Language: the Armenian engineers work in the Armenian and Russian languages, but technical vocabulary is primarily Russian.
- Engineering culture: the Armenians have historically worked within a tightly regulated system of Soviet Normes (SNIP), rather than to Western approaches. This affects not only design philosophy but also practical details of site investigation and testing and construction techniques.
- Construction records: it proved impossible to obtain reliable 'as-built' information for the majority of the reservoirs, largely due to the effects of the break up of the Soviet Union.
- Communication between the UK and Armenia: time zones, awkward flights, poor telecommunications and internet connections all add difficulties.

In this context it is essential to have Russian speaking technical staff and to adjust Western technical methodologies to suit the SNIP based designs and investigations. If all the geotechnical testing equipment in the country is to Soviet standards, there is little point in insisting on Western ones. It is also essential to have expatriate staff who will respect and adapt to the local culture, while bringing the benefit of their own experience.

CONCLUSIONS

The study has identified substantial remedial works required to the dams of Armenia. The use of a semi-quantitative risk assessment methodology has given a prioritisation of the remedial works. This has been used to substantiate a request for IDA funding. A programme of remedial works is now in progress based on priorities assessed in this study.

The project also delivered Dam Safety Plans for each reservoir which gave recommendations for instrumentation, monitoring regimes, maintenance and emergency planning. Implementation of these plans will require a significant long term organisational commitment, but will go a long way to limiting the need for future major remedial works programmes.

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Reservoir management, risk and safety considerations

J L HINKS, Halcrow Group Ltd.
J A CHARLES, Consultant

SYNOPSIS. Risk assessment techniques are being increasingly applied to portfolios of reservoirs in the UK and overseas. While hydrological and mechanical/electrical risk can be reliably evaluated using modern techniques, geological and geotechnical risks are more difficult to quantify. The calculation of seismic risk might appear fairly straightforward, but it poses a number of challenges because a severe earthquake may discover weaknesses in the dam or reservoir rim that were not identifed before the event. At larger dams with gated spillways, the probability of mechanical/electrical malfunction can be significant. A simple methodology for the quantification of each major class of risk is described with the aim of calculating a probability of failure for each dam. This can then be multiplied by a figure representing the financial consequences of failure in order to yield an annualised figure of the magnitude of the risk, which can then be used in ranking the portfolio.

INTRODUCTION

Risk analyses have been increasingly used for engineering applications over recent years. In 1982 a House of Lords Select Committee recommended that the techniques should be applied to reservoir safety and this led to the publication, in 2000, of CIRIA Report No C542 entitled "Risk Management for UK Reservoirs".

The paper describes techniques of risk analysis for reservoir safety that have been developed for use in the Balkans, the Caribbean and elsewhere. The methodology has many similarities to that in the CIRIA Report but adopts a definition of risk which is in use in Canada (Hartford, 1997) and Switzerland:

Risk (£/year) = consequences of failure (£) x probability of failure (per year)

The methodology differs from that in the CIRIA Report in that it seeks to quantify likelihood as an annual probability and consequences in terms of £ or $. The advantages of this approach are:

(a) the risk can be expressed in £/year and represents the premium that would be payable in a perfect market to insure the dam
(b) a portfolio of dams can be ranked according to the calculated risk that they pose
(c) account can be taken of all the undesirable consequences of dam failure including interim costs (e.g. provision of temporary water supplies) and the cost of rebuilding the dam.

The disadvantages of the approach include the following:

(i) the difficulties of putting reliable probabilities to certain types of failure (e.g. internal erosion)
(ii) the need to allocate a monetary value to the loss of a human life
(iii) the inability to handle uncertainty other than through sensitivity analyses.

PROBABILITY OF FAILURE

The historical annual probability of failure of large embankment dams up to 1986 is given by Foster et al (2000a) as 4.5 x 10^{-4} per dam-year and this reduces to 4.1 x 10^{-4} per dam-year if construction failures are excluded. This figure should be compared with the statement by Hoeg (1996) that the probability of failure of embankment dams had reduced over a period of 30 or 40 years from 10^{-4} towards 10^{-5} per year. Charles et al (1998) have shown that in the period 1831-1930 in Great Britain the occurrence of a failure causing loss of life was $3x10^{-4}$ per dam-year. However, since the introduction of reservoir safety legislation in 1930 and up to the time of writing, no failures have occurred in Great Britain which have caused loss of life.

Probability of failure may be taken as the sum of the probabilities of failure due to the following causes:

- hydrological failure
- geological/geotechnical failure
- mechanical and electrical failure
- seismic failure

Foster et al (2000b) give the following breakdown for the causes of failure of large embankment dams prior to 1986:

	HINKS AND CHARLES
	% of total failures
Overtopping	46
Piping through embankment	31
Piping through foundation	15
Piping from embankment to foundation	2
Slope instability	4
Earthquake	2

Internal erosion thus accounts for 48 % of the failures of embankment dams. Although the term “piping” is used by Foster et al, 2000a and 2000b, piping is just one particular form of internal erosion and the three categories of piping listed above doubtless include other forms of internal erosion failures that strictly speaking were not piping failures. Where failure has occurred it will often be impossible to determine the precise mechanism of internal erosion.

Although mechanical/electrical failure does not feature in the above list from Foster et al (2000b), a more detailed list in Foster et al (2000a) indicates that 13% of failures are associated with a spillway gate. Where large dams with gated spillways are under study this mode of failure cannot be ignored.

Failures due to earthquakes represent only 2 % of the total, but it should be remembered that there are difficulties in defining failure. Dams are frequently badly damaged in earthquakes without an uncontrolled release of water taking place. This may be partly because irrigation dams are sometimes full for only a couple of weeks per year. For the Nihon-kai-Chubu earthquake in 1983 damage equivalent to failure was defined as follows (Gosschalk et al, 1994)

- sliding of slope
- longitudinal crack more than 50 mm wide
- transverse crack
- crest settlement more than 300 mm
- leakage of water

Hydrological failure

Overtopping is believed to have been responsible for about half of worldwide embankment dam failures and most of the deaths (ICOLD, 1997). This statement is supported by the statistic, quoted by Foster et al (2000b), that 46 % of embankment dam failures are attributable to overtopping.

A relationship will often be needed between return period and percentage of probable maximum flood (PMF). The growth curve in Figure 1 is derived from the figures quoted in "Floods and Reservoir Safety". It is only approximate and should probably not be used overseas without careful checking.

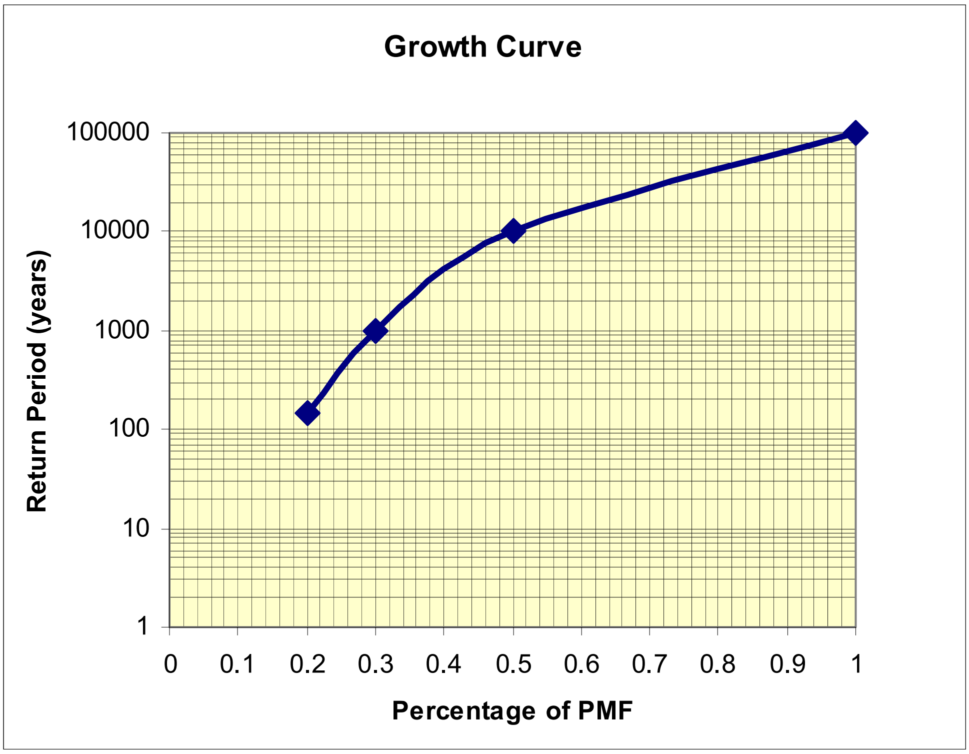

Figure 1. PMF Growth curve for UK (from "Floods and Reservoir Safety")

ICOLD Bulletin 109 argues that where the spillway is designed for, say, the 1,000 year flood the true probability of failure for hydrological reasons will often be an order of magnitude less. This is thought to be for the following reasons:

- the reservoir may not be full at the start of the storm
- wave freeboard may not be taken up by waves
- the dam may be able to withstand some overtopping.

Bearing the above in mind it should be possible to put a probability to overtopping leading to dam failure in a period of risk of, say, 100 years.

Figure 2. Orifice spillway at 51m high dam. The dam is used partly for flood control

Geological/geotechnical risk

Foster et al (2000b) attribute 48 % of embankment dam failures to internal erosion and, when taken across the whole portfolio of dams, the average probability of geological/geotechnical failure will be about the same as the average probability of hydrological failure. About half of all internal erosion failures through the embankment are associated with the presence of conduits. This has been confirmed in a study of internal erosion in European embankment dams where the ICOLD European Working Group on internal erosion in embankment dams found that in almost half the cases where failure occurred, or where failure almost certainly would have occurred very quickly if the reservoir had not been rapidly drawn down, the problem was associated with a structure passing through the embankment (Charles, 2002).

Work by Foster et al (2000b) give the average frequency of failure (during the life of the dam) due to piping through the embankment by dam zoning categories for large dams up to 1986. Some of these figures are reproduced below:

	Average frequency of failure (x 10^{-3})
Homogeneous earthfill	16.0
Puddle core earthfill	9.3
Earthfill with rock toe	8.9
Concrete face earthfill	5.3
Earthfill with filter	1.5
Zoned earthfill	1.2

It should be noted that 49 % of internal erosion failures occurred during first filling of the reservoir, 16 % during the first 5 years of operation and 35 % after 5 years operation.

In areas of steep topography particular account needs to be taken of the risk of landslides into the reservoir such as that which caused the loss of over 2,000 lives at Vaiont in Italy in 1963 (Hinks et al, 2003). This event was particularly disastrous because of the high loss of life (LOL) in the village of Longarone downstream where 94 % of the 1,348 residents perished.

Mechanical and electrical failure

The principal mechanical/electrical risk is the failure of spillway gates to open. However the following also need to be considered under this heading if not elsewhere:

- Non-operation of spillway gates because of human error
- Blocking of spillways with debris
- Non-operation of bottom outlets

During the 1987 floods in south-eastern Norway the percentages of dam owners experiencing problems were reported as follows:

Power failure	50 %
Communication Problems	23 %
Spillways not opened	19 %
Damaged Access Road	17 %
Clogging of spillways	10 %

The above illustrates the high risk of power failures during extreme events; in some environments it may be appropriate to assume that the primary power source will definitely fail. Because of this spillway gates are always provided with a standby power source the reliability of which may itself be questionable. In a recent survey the probability of failure on demand was assessed as between 0.2 % and 1.0 % depending on the details of the particular installations.

For the dam to fail the failure on demand clearly needs to be accompanied by a flood and it may be that the greatest risk to the dam is from the non-operation of all the gates in a flood of relatively modest return period.

Figure 3. 24 metre long by 5 metre high spillway gate. Synchronization between the two ends is not reliable and the gates are at risk of twisting.

Human error in the operation of spillway gates is an important factor since operators will often be reluctant to cause certain flooding downstream. This will particularly be the case if they are subject to high level political pressure not to open the gates. This needs to be factored into the risk calculations.

Blocking of spillways with debris is not strictly a mechanical/electrical problem but there have been a number of serious incidents causing major damage and/or loss of life (Hinks et al, 2003).

The non-operation of a bottom outlet is unlikely to be the main cause of the failure of a dam but it may be an important contributory factor. The problem is often the accumulation of silt or debris in front of the outlet.

Seismic failure
Most of the dams that have failed completely as a result of earthquakes have been small homogeneous dams in Japan, China and India. Another important category of failures are tailings dam, particularly in Chile where there were devastating failures in the earthquakes of 1928 and 1965. For conventional large dams those of greatest concern are those constructed on liquefiable foundations or using liquefiable fill.

CONSEQUENCES OF FAILURE

The methodology provides a mechanism for reducing the consequence of failure to a single number. For the ranking of 33 dams in Albania, Hinks and Dedja (2002) used the number of houses at risk. This worked quite well for relatively small irrigation dams up to 30 m high but is not adequate for large dams where the cost of replacing the dam itself could run into hundreds of millions of pounds. The answer is to calculate the total cost of failure including:

- loss of life.
- loss of housing and commercial property
- agricultural and infrastructure losses
- loss of dam and power station

With the aid of dambreak analyses it should be possible to quantify the above losses, although there may be complications due to uncertainty over the water level in the reservoir at the time of failure.

Loss of life
A particular difficulty arises in determining an appropriate notional cost to allocate to the loss of a human life. It has been suggested that it is inappropriate to put a value on human life and this viewpoint can be readily understood, particularly where the value chosen is much too low. However, it is emphasised that in the context of reservoir risk management, the allocation of a notional cost to the loss of a human life is being done solely to assist in ranking a portfolio of dams by risk and is not meant to reflect on the intrinsic worth of human life.

For overseas work the authors have assigned a notional cost to the loss of a human life by taking the Gross Domestic Product (GDP) per capita of the country concerned and capitalising it at an appropriate rate of interest. In the UK this methodology would give a sum of about £335,000 at 2004 prices assuming capitalisation at 5% rate of interest. This compares with a cost of £1 million to prevent a fatality quoted in the HSE booklet “Reducing Risks, Protecting People” (HSE, 2001). Probably the appropriate notional cost to put on the loss of a life in the UK is somewhere between these two values. However, doubling the assumed cost of human life will often make little difference to the order of ranking by risk.

It is worth noting that priorities for remedial works at a portfolio of dams can be ranked without the need to put a predetermined cost on the loss of a human life. If the cost of remedial works is known at each dam, it is possible to work out what the cost of human life would have to be to justify the expense of those remedial works at each dam. The dams can then be ranked giving the highest priority accorded to the dam where the cost to prevent a fatality is lowest.

In addition to determining the value of each life it is necessary to determine loss of life (LOL) as a proportion of the population at risk (PAR). A number of authors have addressed this issue and various formulae have been proposed which take account of warning time (WT):

- For WT < 15 mins LOL = 0.5 (PAR)
- For 15 mins < WT < 1.5 hrs LOL = $PAR^{0.56}$
- For WT > 1.5 hrs LOL = 0.0002 (PAR)

The data from which the above formulae were obtained were all for developed countries and mostly for the United States. LOL may well be greater in developing countries where there is less personal mobility. DeKay and McClelland (1993) have pointed out some of the limitations of these formulae.

Loss of housing and commercial property

The costs of a dambreak associated with damage to housing can be roughly estimated by taking a standard value for each dwelling. If greater accuracy is required higher values can be put on larger houses and lower values on smaller ones.

For some years various levels of damage have been defined as follows in terms of velocity (m/sec) x depth (m) – see Binnie & Partners, 1991:

V x d < 3 m^2/sec	inundation damage
3 m^2/sec < V x d < 7 m^2/sec	partial structural damage
V x d > 7 m^2/sec	total structural damage

The above relationships may understate the damage caused and it is worth noting that in the 2000 floods when 10,000 properties were flooded, the total damage was estimated at £1.3 billion, ie £130,000 per house (Watts, 2003). This compares with a figure of £ 63,000 per house for flooding in Melton Mowbray in 1998 (Kavanagh, 2003)

Agriculture and infrastructure losses

A dambreak is likely to do permanent damage to fields and agricultural infrastructure near to the dam whereas only temporary damage is likely further downstream. Depending on the season there may, however, be extensive damage to crops. Roads and bridges may also be washed away and financial allowance may need to be made for their replacement as well as for the short-term disruption to commerce whilst the bridges are reconstructed.

Loss of dam and power station

For the valuing of dams and power stations, parametric equations have been developed using dam height, dam length, reservoir capacity, installed capacity of power stations etc. This is, clearly, a very simplified approach but it has proved to be more successful than trying to update figures for the original cost of the facilities. The parametric equation used for 24 large dams in the Caribbean was:

$$\text{Cost (\$m)} = 0.65 \times MW + 0.13 \times Mm^3 + 0.52 \times h + 0.065 \times L$$

Where MW is the installed capacity at the power station in MW
Mm^3 is the capacity of the reservoir in Mm^3
h is the height of the dam in metres
L is the length of the dam crest in metres

Whilst the above equation uses readily available parameters and has proved reasonably successful it cannot be recommended for wider use without careful calibration for the stock of dams to be considered.

Where power stations are underground or a long way downstream of the dam it may be tempting to exclude the cost of their replacement from the estimates on the grounds that they are unlikely to be destroyed. However, if the dam fails, the power station is unlikely to be of much use for several years and expensive alternative generating capacity may have to be installed.

For dams in cascade it will often be necessary to assume that failure of the upstream dam will take those downstream with it.

Other costs

Where dams provide water supply to cities the cost of disruption may be high both in terms of the health of the citizens and in respect of the development of an alternative source. These, and similar costs, need to be taken into account.

CONCLUSIONS

The methodology described in this paper is suitable for the ranking by risk of a portfolio of dams. The accuracy of the probabilities of failure in absolute terms will depend on the care taken in calculating those probabilities and on the budget available for the exercise. This will, in turn, be dictated by the purpose for which the results are required.

In the words of Cummins et al (2001):

Whilst the precise probabilities and consequences will never be known because each dam is unique and there is a lack of applicable data, these risks can be compared with others faced by the community.

This is just one advantage of seeking to calculate absolute probabilities which form a common language with engineers working in disciplines other than dams.

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Development of a probabilistic methodology for slope stability and seismic assessments of UK embankment dams

M. EDDLESTON, MWH, Warrington, UK
L. BEEUWSAERT, System Geotechnique Ltd, St. Helens, UK
J. TAYLOR, MWH, Warrington, UK
K. D. GARDINER, United Utilities, Warrington, UK

SYNOPSIS. The introduction of the “An engineering guide to seismic risk to dams in the UK” in 1991 has led Inspecting Engineers to pay greater attention to the seismic risk of the dams they inspect. For owners of large stocks of dams, such as United Utilities (UU), this has resulted in the need to investigate a large proportion of their dams. In order to proceed in a structured way, UU commissioned a Panel of Experts to advise on a methodology to investigate and analyse their embankment dams and to establish the need for detailed investigation and/or remedial works.

Since the publication of the methodology, which was based on a pilot study of five dams, over 30 further embankment dams have been investigated using the approach. This has not only verified the appropriateness of the initial methodology but has also provided a database of geotechnical information. This information has allowed the methodology to be refined to incorporate probabilistic, in parallel with deterministic analyses. Deterministic analysis suffer from limitations such as the inability to consider variability in the input parameters. Also, there is no direct relationship between factor of safety and probability of failure. Probabilistic slope stability analysis allows for the consideration of variability in the input parameters and it quantifies the probability of failure of a slope. It can be performed using the Monte Carlo method, where a re-running of the analysis is performed using new input parameters estimated from the mean and standard deviation values of the chosen parameters. A distribution of factors of safety is then obtained which can be related to risk of failure. A methodology has been developed to incorporate the results of deterministic and probabilistic analyses, which aligns with current thinking regarding risk assessments.

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

LONG-TERM BENEFITS AND PERFORMANCE OF DAMS

INTRODUCTION

In order to ensure that a consistent and systematic approach was adopted to investigate the seismic stability of its large stock of embankment dams UU commissioned Bechtel to develop a methodology for seismic investigations in conjunction with a Steering Group of eminent dam engineers (Rigby et al, 2002). The methodology was required to comply with recommendations by Inspecting Engineers under the Reservoirs Act 1975 following the publication of "An engineering guide to the seismic risk to dams in the UK" (Charles et al, 1991) and its associated Application Note published by the ICE and DETR(1998). The methodology utilised conventional effective stress testing and classical soil mechanics theory for the development of slip surfaces. It was recognised that there are alternative approaches but it was considered that this approach would provide information suitable for long term use and for comparison with other studies. The original methodology was introduced in 2000 and has since been used as a basis for the analysis of over 30 of UU's embankment dams.

Since the introduction of the methodology the emphasis placed on risk management has increased (Hughes et al, 2000a and 2000b, Kreuzer 2000). This is leading the dam community to consider the methods used to evaluate embankment slope stability risk. For example Johnston in his Binnie Lecture (2002) commented:

"For the past half century the factor of safety calculated by a limit equilibrium analysis has been the accepted method of assessing stability. Now limit equilibrium's role as the sole or even the best method of analysis is being questioned. The factor of safety faces two challenges. Firstly, from finite element analysis which provides the ability to calculate how a dam will settle (or rise) and move upstream/downstream and how the stresses will change as a response to changing loads. The other challenge comes from advocates of probabilistic risk assessment who suggest that the factor of safety approach disguises the fact that even well built dams are a hazard. The probabilistic approach argues that, since failure cannot be completely ruled out, engineers should define and aim for a target probability of failure."

Bridle (2002a) further suggested that:

"Probability is part of the language of risk, much used and understood by managers and non-engineers. Giving them advice using risk language would therefore help them reach the right decisions about dams and dam safety. Use of this language would help us to consider how safe our dams are, which is important when it comes to the fundamental question of 'are they safe enough? It would also overcome the esotericism of our 'factor of safety' language, which means different things in different contexts."

This paper builds on the experiences of applying the UU methodology and explores the possibility of extending it into probabilistic analyses that align more closely to current thinking on risk management of dams.

DETERMINISTIC APPROACH

Deterministic slope stability analyses compute the factor of safety of a slope based on a fixed set of conditions and material parameters. If the factor of safety is greater than unity, the slope is considered to be stable, if the factor of safety is less than unity, the slope is considered to be unstable or susceptible to failure. Guidance on factors of safety for slope design of new embankment dams is given in "An engineering guide to the safety of embankment dams in the UK" (Johnston et. al, 1999). This approach is adopted in the current methodology with the factors of safety varying with the level of confidence in the data available as detailed in Table 1.

Table 1. Factors of safety used in the deterministic approach

Level of information available/Need for remedial action	Factor of Safety
Based on desk study information and decision charts for deep and shallow slips	at least 1.7
Based on assumed conservative parameters	at least 1.6
Based on the analysis of sufficient field and laboratory testing data	at least 1.5
Remedial works for deep slips	less than 1.3
Urgent attention required for deep slips	less than 1.2

Deterministic analyses suffer from limitations such as the failure to consider variability of the input parameters and inability to answer questions like "how stable is the slope?". Also, there is no direct relationship between the factor of safety and the probability of failure. In other words, a slope with a higher factor of safety may be no more stable than a slope with a lower factor of safety, depending on the nature and variability of the slope materials. For example, a slope with a factor of safety of 1.5, with a standard deviation of 0.5^{o} on the angle of shearing resistance used in the analysis, could have a much higher probability of failure than a slope with a factor of safety of 1.2 with a standard deviation of 0.1^{o} on angle of shearing resistance. The effect of variations in soil properties is illustrated in Figure 1.

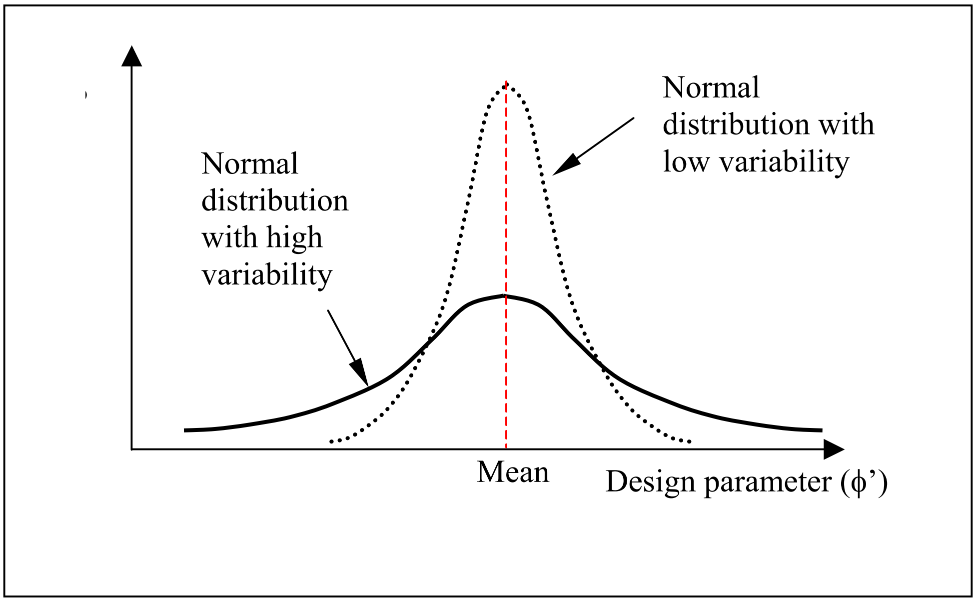
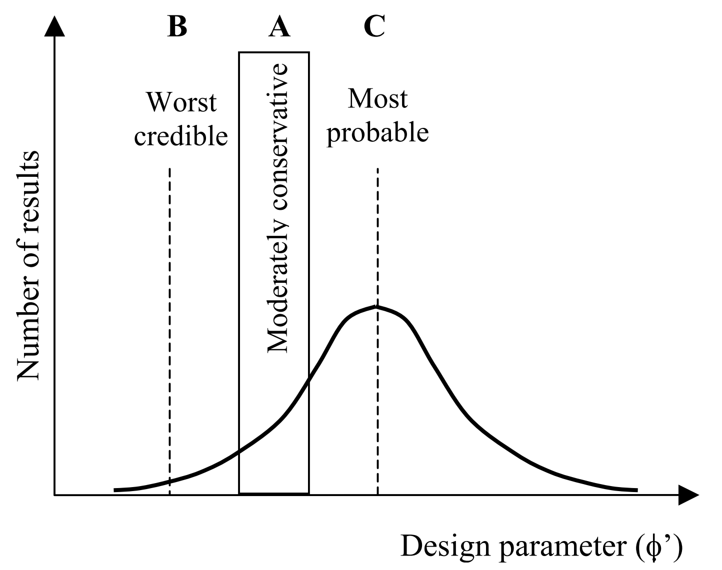


Figure 1. Variability in soil parameters

In the original methodology "worst" credible soil parameters are used in the analyses. The choice of parameters used needs to be considered in relation to the design methodology adopted. CIRIA Reports C580 and 104 (Gaba et al, 2003 and Padfield and Mair, 1984) dealing with retaining wall design define three levels of design parameters for different situations as indicated in Figure 2. As will be discussed later the probabilistic approach generally uses most probable parameters.

Recent investigations, undertaken on UU embankment dams, have allowed an assessment to be made of the effective stress shear strength parameters of a variety of embankment materials. A summary of the results for 10 dams is presented in Table 2. It should, however, be noted that whilst this is useful data, in statistical terms it still only represents a relatively small population. The selection of appropriate parameters is key to the use of both deterministic and probabilistic design methods.



A - The term Moderately Conservative is a conservative best estimate. Experienced engineers most often use this approach in practice.
B - The Worst Credible value is the worst that a designer could realistically believe might occur.
C - The Most Probable value is essentially the mean value excluding obviously anomalous values.

Figure 2. Definition of design parameters as defined CIRIA Reports C580 and 104

Table 2. Soil parameters from selected embankment dams

DAM	Material	Mean	Standard Deviation	No. of samples	Worst Credible Value
	Core	30.8	5.2	10	22
1	Shoulder (clay)	33.5	2.9	17	29
	Foundation	32.4	3.1	11	27
	Core (clay)	30.0	0.8	6	29
2	Shoulder (granular)	32.8	N/A	1	N/A
	Foundation	26.9	1.8	14	24
	Core	32.3	4.5	9	25
Cascade 1	Shoulder (clay)	30.0	3.8	23	24
(3 dams)	Shoulder (gravelly clay)	40.2	2.8	4	36
	Foundation	27.9	2.4	17	24
	Core	28.0	2.4	9	25
6	Shoulder (clay)	28.4	2.4	79	25
	Foundation	27.8	1.8	59	25

DAM	Material	Mean	Standard Deviation	No. of samples	Worst Credible Value
7	Core	32.7	3.7	6	27
	Shoulder (clay)	35.0	3.9	9	29
	Shoulder (gravelly clay)	37.2	3.0	5	32
	Foundation	27.6	3.4	9	22
8	Core	31.5	3.3	6	26
	Shoulder (clay)	31.5	4.1	2	25
	Shoulder (gravelly clay)	42.0	4.3	11	35
	Foundation	34.2	4.4	3	27
9	Core	27.6	1.7	4	25
	Shoulder (gravelly clay)	37.5	2.6	10	33
	Foundation	31.2	4.5	7	24
10	Core	31.8	1.8	4	29
	Shoulder (gravelly clay)	40.8	1.8	3	38
	Foundation	37.2	2.0	2	34

PROBABILISTIC APPROACH

Probabilistic slope stability analysis allows for the consideration of variability in the input parameters and it quantifies the probability of failure of a slope. Probabilistic slope stability analysis can be performed using the Monte Carlo method. Basically, the method consists of re-running the analysis many times by inputting new parameters estimated from the mean and standard deviation values of the chosen parameters. A distribution of factors of safety is then obtained as indicated in Figure 3.

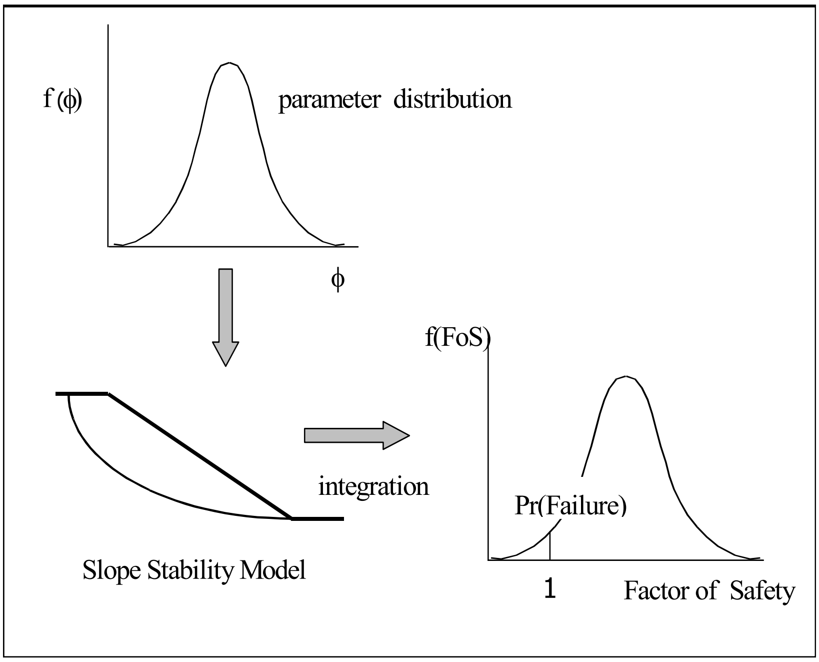


Figure 3. Summary of probabilistic approach

Probabilistic analysis can be performed on proprietary slope stability software such as GEOSLOPE, SLOPE/W. When employing such software the following considerations apply:

i. The use of a probabilistic analysis will not affect the deterministic solution. The software computes the factor of safety of all slip surfaces first and determines the critical slip surface with mean parameters as if no probabilistic analysis is chosen.

ii. A probabilistic analysis is performed on the critical slip surface only.

iii. When the analysis is completed, the factors of safety presented are the minimum, mean and maximum factor of safety of all Monte Carlo trials.

iv. In a probabilistic analysis, the input value of a parameter represents the mean value and the variability of the parameter is assumed to be normally distributed with a known standard deviation.

v. During each Monte Carlo trial, the input parameters are updated based on a normalised random number. The factors of safety are then computed based on these updated parameters. By assuming that the factors of safety are also normally distributed, the software determines the mean and the standard deviations of the factors of safety. A probability distribution function for the factor of safety can then be generated.

vi. The number of Monte Carlo trials required is dependent on the level of confidence and amount of variability in the input parameters. Theoretically, the greater the number of trials, the more accurate the solution. It is important that a sufficient number of trials be carried out. One way to check this is to re-run the analysis with the same number of trials; if the two solutions are different, the number of trials should be increased until the difference becomes insignificant (minimum number of trials is likely to be of the order of 5000).

vii. The probability of failure is the probability of obtaining a factor of safety less than 1.0 and is obtained from the probability distribution function (PDF).

Typical outputs are shown in Figure 4. Figure 4a) shows a situation of a low factor of safety and high probability of failure typical of a pseudostatic analysis of a downstream embankment slope where the analysis is used to estimate deformations using Ambraseys (1972), Ambrayseys and Menu (1988) and Swannell (1994). Figure 4c) shows the situation of a slope with an acceptable factor of safety and a very low probability of failure. Figure 4b) however gives a borderline factor of safety. The question that needs to be addressed is whether a probability of failure of 1 in 2000 is acceptable in relation to the consequence of failure.

ACCEPTABILITY CRITERIA

A number of acceptability criteria based on probability of failure have been found in the literature (based on mean parameters) as detailed in tables 3 to 7.

Table 3. Acceptability Criteria - Smith (1986)

Conditions	Criteria for Probability of Failure	Equivalent Event
Earthworks	10^{-2}	1 in 100
Earth retaining structures	10^{-3}	1 in 1,000
Onshore foundations	10^{-3}	1 in 1,000
Offshore foundations	10^{-4}	1 in 10,000

Table 4. Acceptability Criteria - Santa Marina et al. (1992)

Conditions	Criteria for Probability of Failure	Equivalent Event
Temporary structures with low repair cost	10^{-1}	1 in 10
Existing large cut on interstate highway	10^{-2}	1 in 100
Acceptable in most cases except if lives may be lost	10^{-3}	1 in 1,000
Acceptable for all slopes	10^{-4}	1 in 10,000
Unnecessarily low	10^{-5}	1 in 100,000

Table 5. Acceptability Criteria - Rettemeiere et al.(2000)

Conditions	Criteria for Probability of Failure	Equivalent Event
Likely	10^{-1}	1 in 10
Possible	10^{-2}	1 in 100
Not Impossible	10^{-3}	1 in 1,000
Unlikely	10^{-4}	1 in 10,000
With a degree of probability verging on certainly unlikely	10^{-5}	1 in 100,000
Totally Unlikely	10^{-6}	1 in 1,000,000

Bridle (2000b) related Probability of Failure to the ALARP principle ("as low as reasonably practical") where risks are considered acceptable only if all reasonable practical measures have been taken to reduce risk.

Table 6. ALARP Criteria - Bridle (2000b)

Conditions	Criteria for Probability of Failure	Equivalent Event
Unacceptable	10^{-3}	1 in 1000
ALARP	10^{-3} - 10^{-6}	1 in 1000 to 1 in 1,000,000
Negligible	10^{-6}	1 in 1,000,000

Table 7. ALARP Criteria - HSE framework tolerability of risk, (2001)

Conditions	Criteria for Probability of Failure	Equivalent Event
Intolerable	10^{-4}	1 in 10000
Tolerable (ALARP)	10^{-4} - 10^{-6}	1 in 10,000 to 1 in 1,000,000
Broadly acceptable	10^{-6}	1 in 1,000,000

The published data indicates a considerable range of values where a balance is needed between both the probability of failure and consequence of failure using for assessment techniques, such as Failure Modes, Effects and Criticality Analysis (FMECA) or Location Cause and Indication methods (LCI) as outlined in the CIRIA report on "Risk management for UK Reservoirs" (Hughes et al, 2000a).

There is some consensus that a probability of failure of 10^{-4} (1 in 10,000) is considered a generally acceptable criterion for slopes where there is a potential for loss of life. Alonso (1976) equates this to the commonly accepted deterministic factor of safety of 1.5 for new build embankment dams. However Christian et al (1994) report probabilities approaching 1 in 1000 for a factor of safety of 1.5.

For a general and conservative approach, which could be considered in parallel with consequence of failure considerations, it is proposed that more stringent criteria be used in preliminary analyses as detailed in Table 8.

Table 8. Suggested acceptable values of Probability of Slope Failure

	Suggested Acceptable Probability of Failure
From desk study information	Less than 2×10^{-6} (1 in 500,000)
Measured dam specific parameters	Less than 1×10^{-5} (1 in 100,000)
Remedial works required	Greater than 1×10^{-4} (1 in 10,000)
Urgent attention required	Greater than 2×10^{-4} (1 in 5000)

These are currently suggested values only and are being evaluated along side the conventional deterministic factors of safety already in use in the existing methodology. It must also be borne in mind that shear strength is not the only parameter that should be considered when using probabilistic methods. Variations in groundwater conditions, inundation of downstream slope due to heavy rainfall, poor drainage or overtopping and the effects of climate change will all need to be taken into account.

PROPOSED METHODOLOGY FOR PROBABILISTIC SLOPE STABILITY ANALYSES

In order to evaluate the possible advantages of the use of probabilistic methods of slope stability analyses of embankment dams, a hybrid deterministic/probabilistic approach is being evaluated for the embankment dams currently under investigation as detailed below.

Choice of parameters

For each parameter (ϕ' and others as required) determine the mean and standard deviation from available testing information.

Probabilistic analysis (mean and standard deviation parameters)

Carry out slope stability analysis including the probabilistic approach to determine the Factor of Safety based on mean parameters.

<u>Deterministic analysis (worst credible parameters)</u>
For each parameter determine the worst credible value. As a guide the worst credible value is sometimes defined as:

mean – (1.64 x standard deviation).

This means that 5% of values are potentially lower than the selected worst credible value. This is similar to the approach used in structural design, in particular for concrete structures e.g. characteristic strength, and also discussed in Eurocode 7 (Driscoll and Simpson, 2001, Cardoso and Fernnandes, 2001, Hicks and Samy, 2002, Samy and Hicks 2002). It should be noted that the choice of 5% is arbitrary and should reflect the risk the designer is prepared to accept on the statistical parameters value, and a degree of engineering judgement is therefore required. Perform deterministic analysis for worst credible parameters and report factor of safety based on worse credible values.

<u>Check slip surface between probabilistic and deterministic analyses</u>
The slip surface geometry obtained from worst credible parameters could potentially be different to that obtained with the mean parameters. If so, re-run the probabilistic analysis with mean parameters on that particular slip.

<u>Report Probabilities of failure and Factors of Safety</u>
Compare and report results obtained.

- Probability of failure from Monte Carlo analysis
- Factor of safety based on worse credible values based on deterministic analysis

A flowchart summarising the proposed methodology is given in Figure 5.

CONCLUSION

The adoption by UU of a rigorous methodology for the seismic investigation of their embankment dams has afforded the opportunity to accumulate and collate a significant common data set for some of its stock of older embankment dams. This has allowed for a detailed comparison of the properties and performance of its assets to enable it to begin to align the findings of conventional deterministic slope stability analyses with probabilistic risk assessment methods. Such an approach allows dam owners to evaluate how safe their dams are in terms of probability of failure. If this is considered in conjunction with the consequence of failure, it will also allow a more rigorous review of the trade off between cost and risk which should improve dam safety management using techniques such as Portfolio Risk Assessments, as described by Hughes and Gardiner (2004).

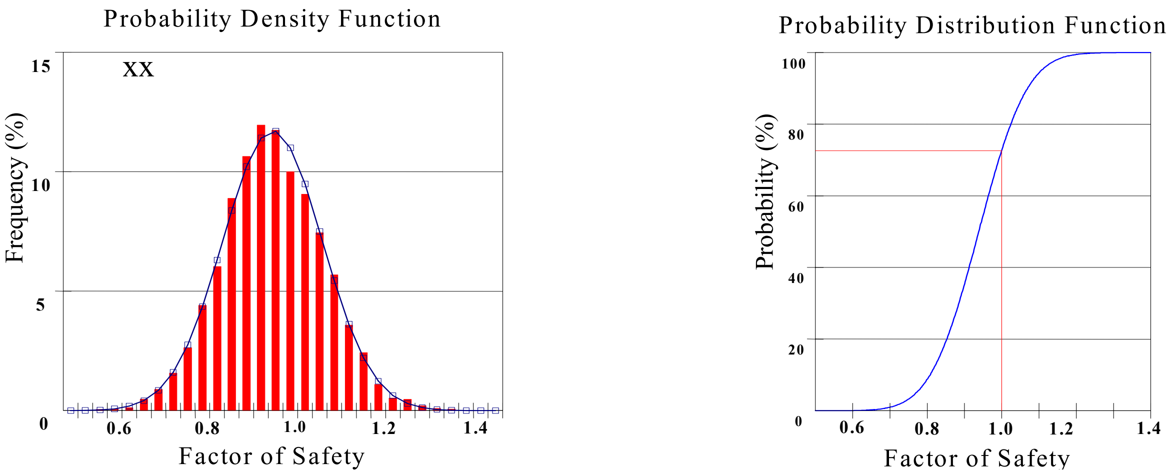


Figure 4a). Probability density/distribution function
Factor of Safety of 0.9, Probability of Failure Less than 1 in 1.4 (70%)

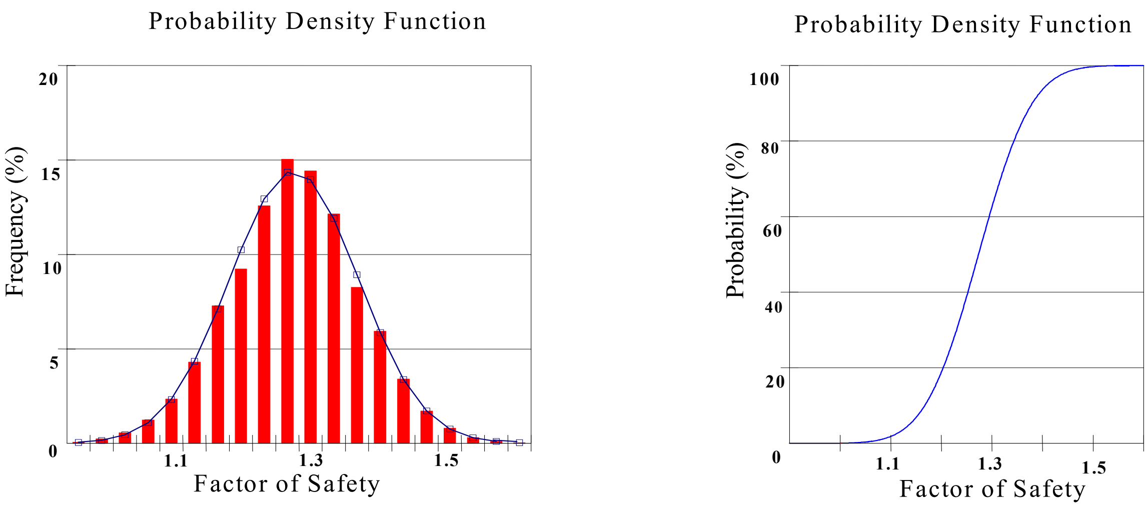


Figure 4b) Probability density/distribution function
Factor of Safety 1.3, Probability of Failure Less than 1 in 2000

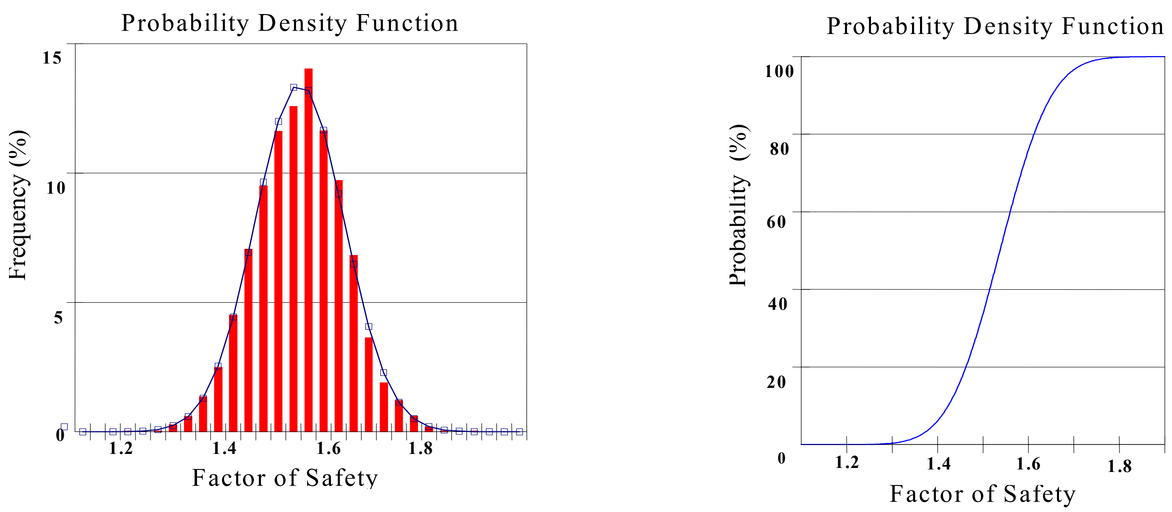
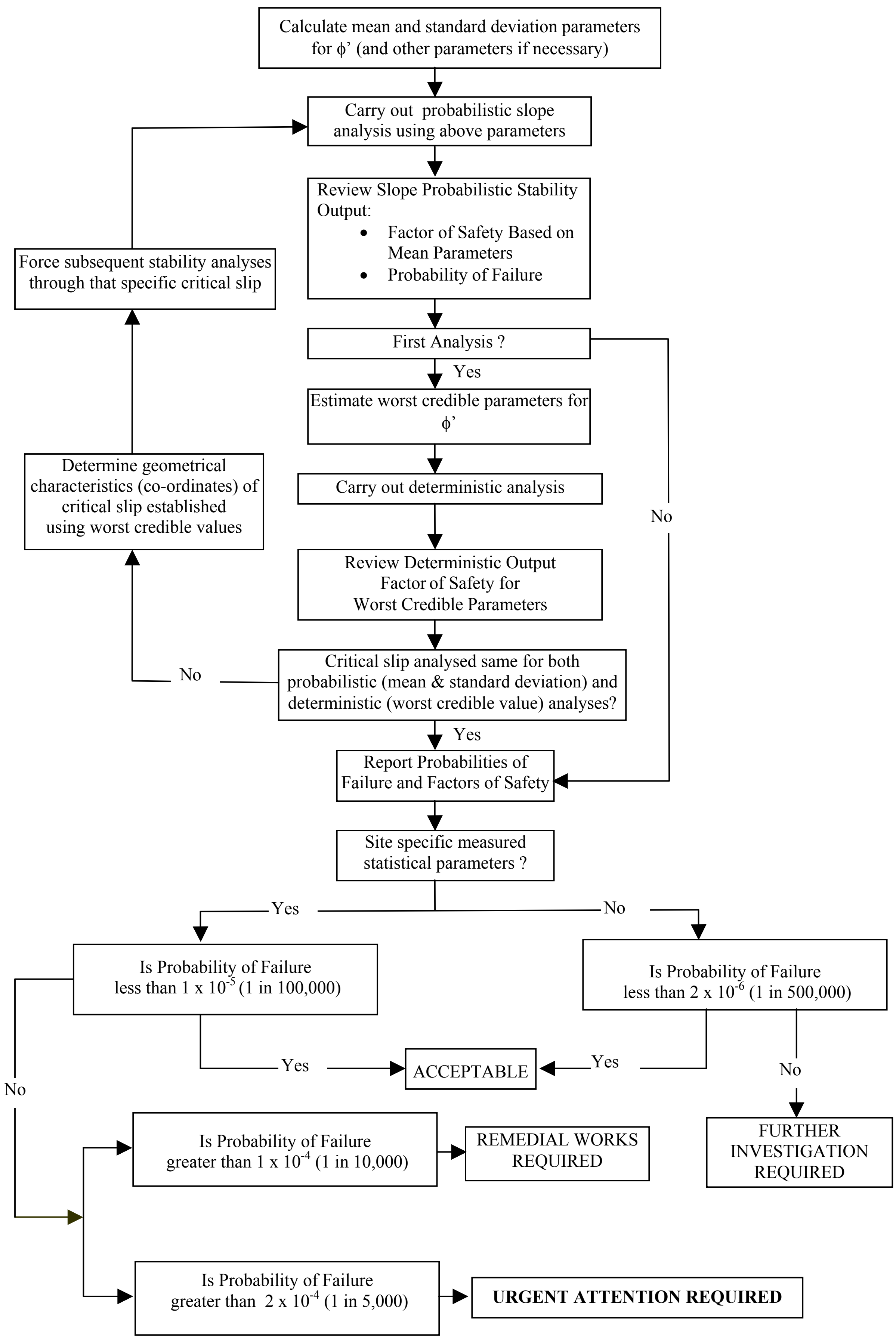


Figure 4c) Probability density/distribution function
Factor of Safety 1.5, Probability of Failure Less than 1 in 10,000,000

Figure 4 Typical Probability density/distribution functions


Calculate mean and standard deviation parameters for ϕ' (and other parameters if necessary)
Carry out probabilistic slope analysis using above parameters
Review Slope Probabilistic Stability Output:
Factor of Safety Based on Mean Parameters
Probability of Failure
Force subsequent stability analyses through that specific critical slip
First Analysis ?
Yes
No
Estimate worst credible parameters for ϕ'
Determine geometrical characteristics (co-ordinates) of critical slip established using worst credible values
Carry out deterministic analysis
Review Deterministic Output Factor of Safety for Worst Credible Parameters
No
Critical slip analysed same for both probabilistic (mean & standard deviation) and deterministic (worst credible value) analyses?
Yes
Report Probabilities of Failure and Factors of Safety
Site specific measured statistical parameters ?
Yes
No
Is Probability of Failure less than 1 x 10-5 (1 in 100,000)
Is Probability of Failure less than 2 x 10-6 (1 in 500,000)
Yes
ACCEPTABLE
Yes
No
No
FURTHER INVESTIGATION REQUIRED
Is Probability of Failure greater than 1 x 10-4 (1 in 10,000)
REMEDIAL WORKS REQUIRED
Is Probability of Failure greater than 2 x 10-4 (1 in 5,000)
URGENT ATTENTION REQUIRED

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Ridracoli Dam: surveillance and safety evaluation reported on internet page

P.P. MARINI; P. BALDONI; F. FARINA; F. CORTEZZI - Romagna Acque, Forlì, Italy
A. MASERA - Enel.Hydro, ISMES Division, Bergamo, Italy

SYNOPSIS. During a period of several seismic events that took place in January 2003 in the valley downstream of the Ridracoli arch gravity dam, inhabitants and local Authorities requested information about the safety conditions of this important structure. To satisfy such an expectation, the Manager of the Romagna Acque, owner of the dam, launched a project aimed at providing such information. Communication through the Internet web was decided and an Internet page was prepared, reporting the safety conditions of the dam, with respect to hydrologic, hydraulic, static and seismic aspects and the resulting surveillance activities.
Methodologies and operative techniques are today mature and available for an effective evaluation and surveillance of dam safety, and for presentation to the resident population living downstream of the dam. Data collected at the Ridracoli dam site by several monitoring systems are in fact automatically processed and interpreted in order to evaluate the different aspects affecting the safety of the dam and the protection of the downstream valley.

The experience gained using automatic monitoring and a knowledge based support system is used to obtain on-line evaluation, explanation and interpretation of dam's behaviour, identifying surveillance activities to manage anomalous trends or to minimize critical situations due to flooding.
All information are summarized and presented on the Internet page. In addition, for the people living in the downstream area, the presentation is available on a video, located at the City Hall.

INTRODUCTION

The selected approach and the methodology takes advantage of the automatic monitoring systems (which encompass hydrologic-hydraulic, static and seismic structural aspects) and of the on-line analysis of structural dam behaviour, compared to theoretical models, in order to identify safety

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

anomalies, if any. From these analyses the management of surveillance is defined requiring *ad hoc* inspections, collection and analysis of further information in order to define the safety condition of the dam.
The operational procedures for surveillance management have been evaluated by the National Board Authorities for Dams and by the Protezione Civile (Department of Civil Protection), defining the conditions and the thresholds that could induce alert conditions for the dam and for the downstream valley.

RIDRACOLI DAM

The Ridracoli arch-gravity concrete dam (height 103.5 m and crest length 432 m) closes a very wide U-shaped valley in the Tuscan-Romagna Apennines in Italy. The storage reservoir is intended for water supply to 37 communities in the Forlì and Ravenna Provinces, including the main towns and the San Marino Republic.

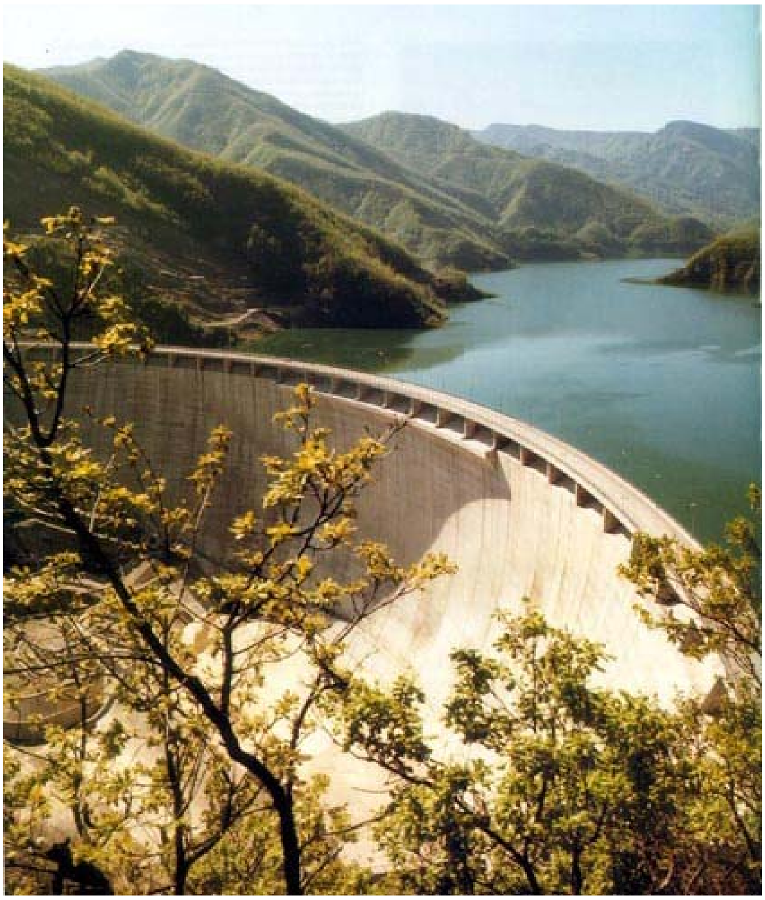

Figure 1: Ridracoli dam

The reservoir was filled completely for the first time in 1986 and nowadays the dam is commissioned for normal operation.

MONITORING SYSTEM

To control the Ridracoli dam site, that is the catchment area, the structure, the foundation, the reservoir banks and the slopes of the downstream rocky formation, a large monitoring network has been installed during the construction of the dam. An automatic monitoring system, centralized in the warden house via cable, reads most of the measurements (259 sensors are automatically recorded, on a total of 971). Many instruments were installed for a detailed monitoring of the structure's behaviour during construction and the first filling phase. In the current normal operation, the on-line surveillance of dam performance is based on a subset of measurements.

In parallel to the on-line system, the off-line surveillance activities performs analysis of the measurements, automatically or manually recorded, verifying the dam's behaviour, by the comparison to the prediction of the three-dimensional F.E. model.

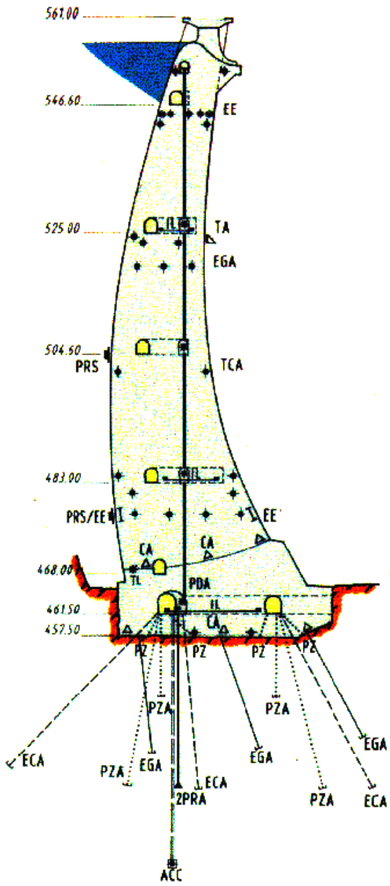

Figure 2: Ridracoli dam: monitoring system of the crown section

HYDROLOGICAL AND HYDRAULIC ASPECTS

Hydrological and hydraulic aspects are fundamental with respect to the safety of a dam. The reservoir capacity is 33.06 Mm^3, the catchment area is about 37 km^2. At the Ridracoli dam site a monitoring system has been installed for reservoir monitoring and management, in particular for the management of the water supply and to foresee flood events. On the basis of the measured data and of the water balance in the reservoir, the inflow and the outflow are computed and both displayed in the Internet page.

If high floods are expected and, in any case, if the outflow is excess of 50 m^3/sec (that corresponds to 10% of the spillway capacity) those responsible for the dam have to start up the extraordinary surveillance and alert the Civil Protection Dept. The surveillance condition and the dam safety conditions is reported on Internet.

STATIC STRUCTURAL BEHAVIOUR ANALYSIS

A decision support system (named MISTRAL) was installed in 1992 on a personal computer connected to the automatic monitoring system in the acquisition Centre, located in the warden house near the dam.

Mistral is a decision system for evaluating, explaining and filtering the information collected by the most important instruments connected to the automatic monitoring system, providing on-line interpretation of the behaviour of the structure in order to support the activity of the personnel responsible of the safety surveillance, requiring his intervention in case of anomalous situation, if any.

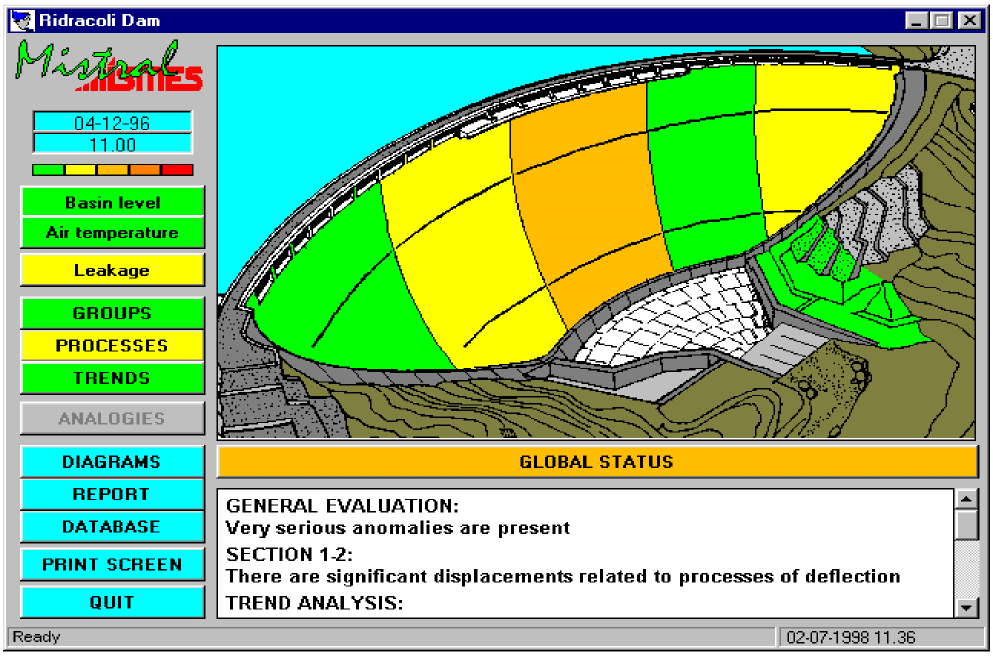

Figure 3: Mistral Interface: General state of the dam (test situation)

The on-line system makes it possible to verify the state of each measurement with respect to threshold levels (physical threshold, measured rate of variation and reference structural model), using knowledge about the significance and, reliability of each instrument, and evaluates the current state of the dam and of any elementary structural part, identifying any anomalous process and verifying the reliability of the measurements by consistency checks. The Mistral system currently operates taking into account the data collected hourly by 40 instruments.

Mistral displays the results of the analysis through a colour-based graphical interface that represents the state of the measurements, of the processes, of each section and of the entire structure under evaluation giving relevant explanations.

If the processed "global status" of the dam corresponds to alert conditions, (level 5 or red colour in the Mistral interface) the extraordinary surveillance enters in force and the Civil Protection Dept is alerted. The surveillance and the dam safety conditions are reported on the Internet page.

SEISMIC STRUCTURAL BEHAVIOUR ANALYSIS

The seismic monitoring system is made of four accelerometric stations and by one seismic station (each station has instruments installed in the three directions). The system allows to measure both the input ground motion and the structural answer of the dam.

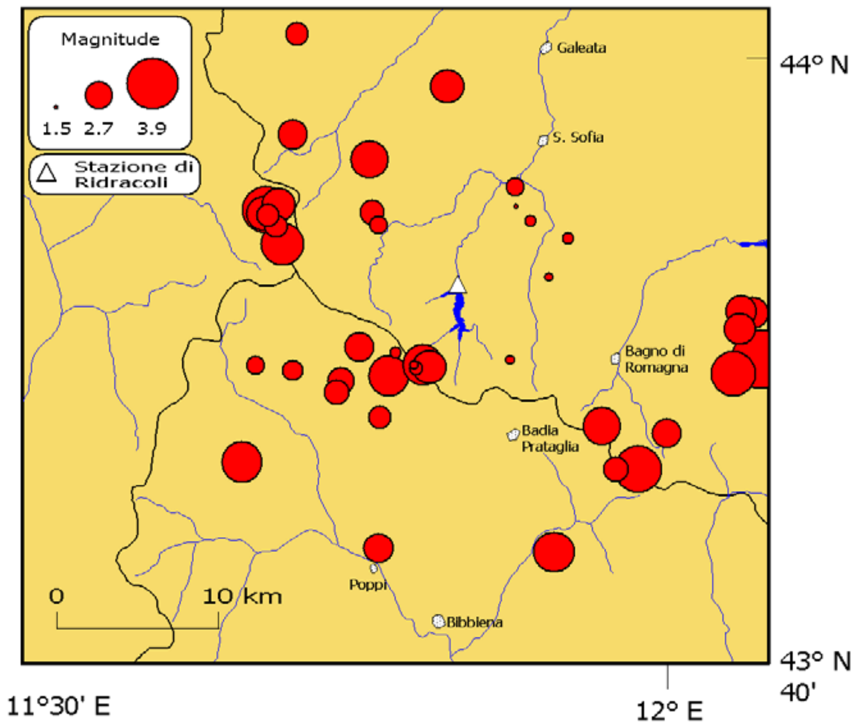

Figure 4: Local earthquakes collected by the seismic monitoring system

In the last period (1995-January 2003) the system collected 128 earthquakes that exceeded the trigger threshold. 63 were far from the dam site and 65 local (epicenter distance nearby 25 km from the dam site, as suggested by Dam's Authorities).

If the peak ground acceleration of the earthquake, measured at the base of the dam, is higher than 0.20 g (that corresponds to the seismic value obtained by the physical model that shows the beginning of cracks in the upper part of the dam, near the spillway sill), those responsible for the dam have to start up extraordinary surveillance (such as *ad hoc* inspection and collection of the whole measurements) and alert the Civil Protection Dept. The surveillance condition and the dam safety condition is reported on the Internet page.

The recorded seismic measurements, are periodically stored into the historical data base and processed to analyze the dam's behaviour, in comparison to the calculated one by a three-dimensional F.E. model and to the dynamic response retrieved from the vibrating test data.

INTERNET PRESENTATION

In the Internet home page of Romagna Acque much information is available relevant to the company, the water supply system and the dam.

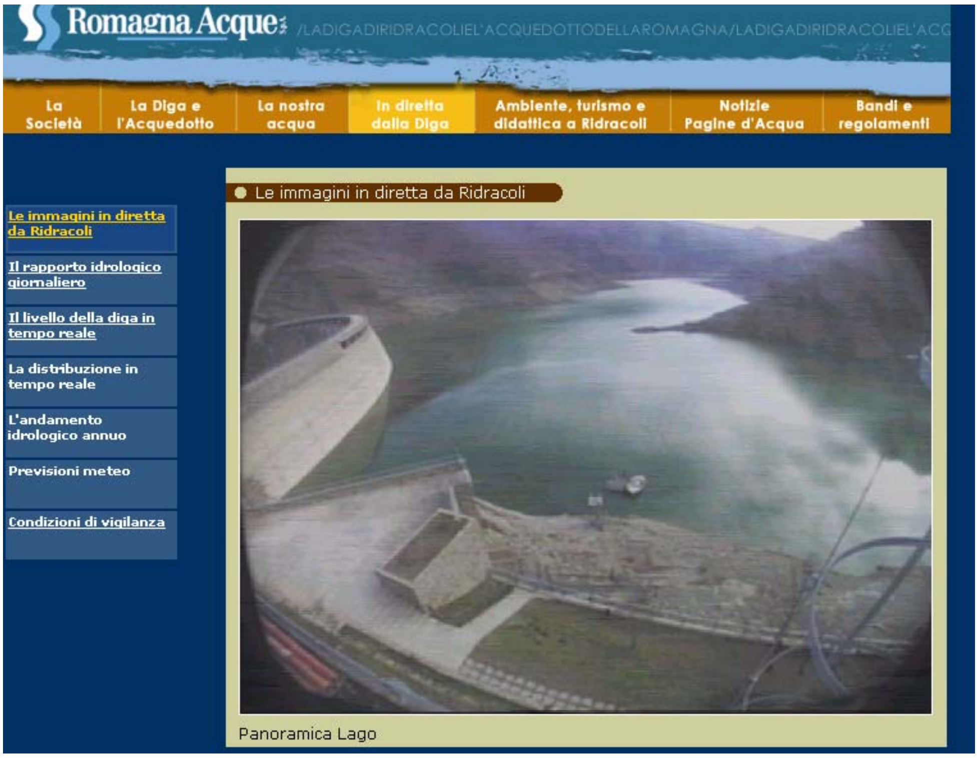

Figure 5: On-line images from the dam

In addition to the quality parameters of the water, the production and distribution of drinkable water, many data about the dam are reported, as illustrated in the following figures. The information reported is up-dated every hour.

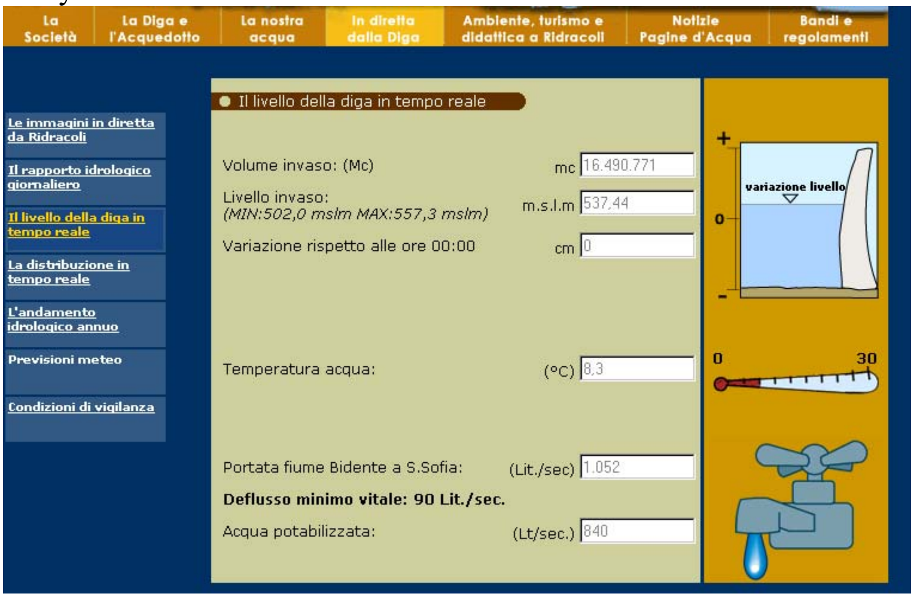

Figure 6: On-line water level in the reservoir

Figure 7: Water supply distribution

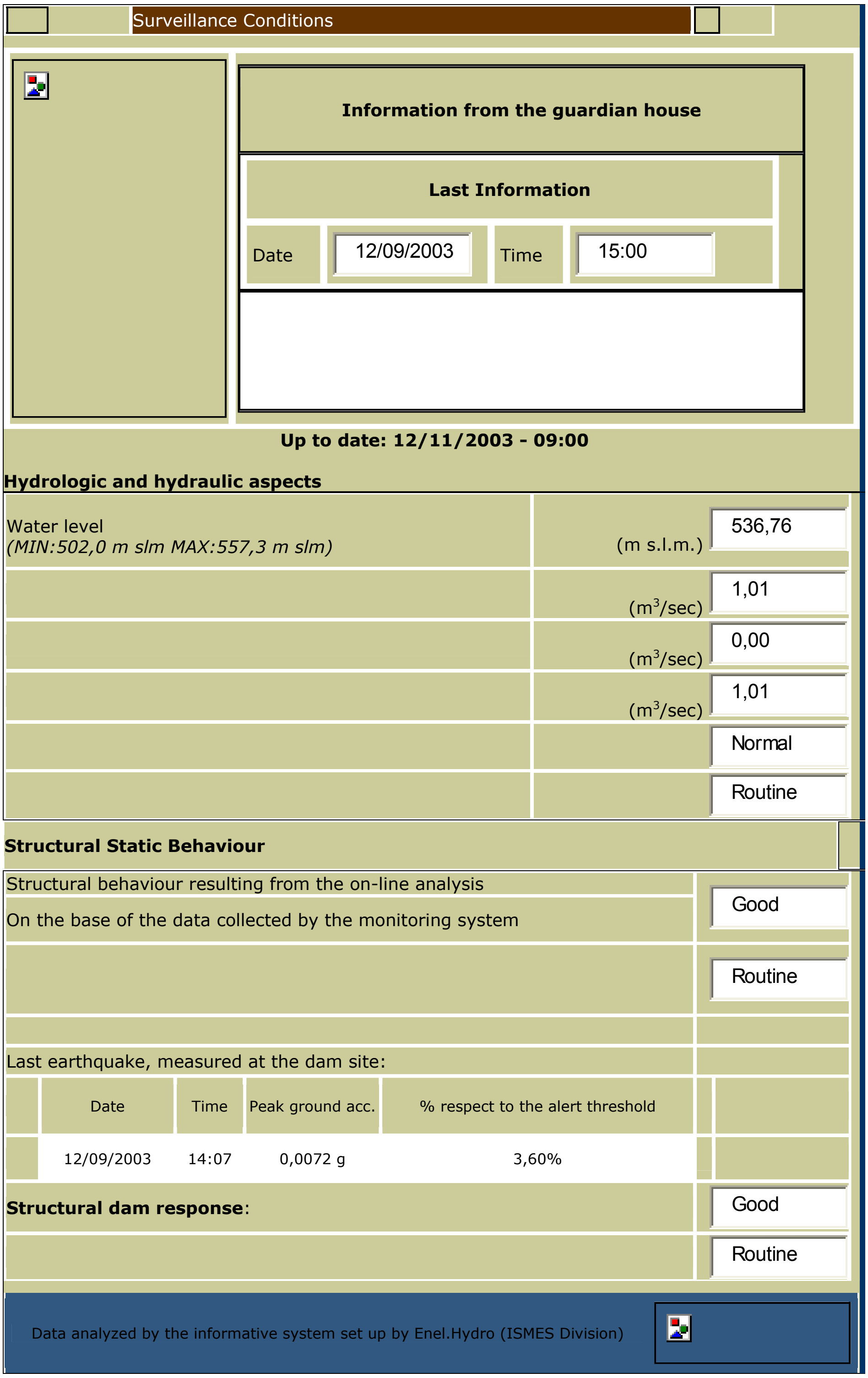

Figure 8: Safety and Surveillance Conditions (translated from Italian)

In the previous figure, the dam surveillance condition, together with the safety evaluation, is reported with respect to hydraulic, static and seismic safety assessment.
On average, the website is visited 40-50 times each day.
The local administration and residents downstream of the dam have given positive indications even though they report that some of the information provided is not always easy to interpret. In particular, reference is made to the difficulty of interpreting the definitions of *Surveillance Conditions.* In view of this feedback, the website Introductory Page is now in the process of revision by the incorporation of additional explanatory notes.

CONCLUSION

Monitoring and data analysis are primary parts in managing the safety of dams by risk assessment methodology. At the Ridracoli dam the on-line data analysis and the surveillance management have became a part of the safety procedures of the dam. The results of such activities are available to the population living in the downstream valley, by Internet network and by video installed in each City Hall.

This is the first time in Italy that the results of risk assessment methodology has been used on-line and available on the Internet.

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Reservoirs Act 1975 - Progress on the implementation of the Environment Agency as Enforcement Authority

I.M. HOPE, Environment Agency
A.K. HUGHES, KBR

SYNOPSIS. The Water Act 2003 has established a new role for the Environment Agency (the Agency); that of the Enforcement Authority for the Reservoirs Act 1975 in England and Wales. Currently some 140 Local Authorities fulfill this role.

The Agency is preparing to commence this new role from 1st October 2004 and this paper describes the process being followed and progress to transfer this new duty. It also sets the scene for the subsequent increase in the role of the Enforcement Authority driven by the Water Act 2003, namely the requirement for Undertakers to produce Flood Plans for reservoirs.

INTRODUCTION

The Reservoirs Act 1975 was implemented between 1986 and 1987, (Charles, 2002) and only applies to 'large raised reservoirs' with a capacity greater than 25,000 cubic metres of water that do not fall within the scope of the Mines and Quarries (Tips) Act 1969.

The Act covers some 2600 reservoirs in the United Kingdom, 2000 of which lie in England and Wales. However, the jurisdiction of the Agency is confined to England and Wales. The Water Act 2003 has not affected the 600 reservoirs that will continue to be regulated by the 32 Enforcement Authorities in Scotland.

In England and Wales some 140 Local Authorities (Unitary Authorities, County Councils and Metropolitan Boroughs) are currently responsible as Enforcement Authority for 2000 reservoirs. For local authorities this role has attracted a varying response, often co-ordinated by differing departments. This has led to an inconsistent application of the Act and has ultimately driven the need for consistency led by one body. This requirement was recognised in a review of the Reservoirs Act 1975 and reported to the British Dam Society (BDS) by Simms and Parr (1998) at the 10th BDS Conference held in Bangor in September 1998.

THE WATER ACT 2003
The Water Act 2003 transfers the responsibility for Enforcement to the Agency. It also establishes the requirement for Undertakers to prepare Flood Plans when directed by the Secretary of State. In addition the provisions of the Reservoirs Act 1975 are to apply to the Crown. Further details can be viewed on the Defra website www.defra.gov.uk.

THE ENVIRONMENT AGENCY
The Environment Agency is a 'Non Departmental Public Body' that reports to the Department for Environment Food and Rural Affairs (Defra). Its vision is for 'A better Environment in England and Wales for present and future generations'. Its role is to be an efficient operator, modern regulator, influential advisor, effective communicator and champion of the environment. These are underpinned by its Values which include an outcome driven approach, being firm and fair and open to change.

The Agency's functions are extensive and its main operating role is Flood Risk Management. Part of its massive Flood Risk Management infrastructure includes 119 flood storage reservoirs that come under the remit of the Reservoirs Act 1975. It also has considerable regulatory powers, responsibility and experience. For example it is responsible for over 1600 authorisations in process industries, more than 100,000 consents to discharge and over 7500 waste management licences. Further details on the Agency can be found on its website:- www.environment-agency.gov.uk.

PRINCIPLES OF MODERN REGULATION
Society demands high environmental and safety standards. The business world rightly expects greater regulatory efficiency, whilst minimising bureaucracy so that compliance costs are kept to a minimum. These potentially conflicting demands can be met by a modern regulatory regime.

Five principles have been set out by the Better Regulation Task Force (2003) to achieve this aim and they are:-

- **transparent** - rules and processes which are clear to businesses and local communities
- **accountable** - by reporting regularly on actions and performance
- **consistent** - by applying the same approach and standards within and between sectors and over time

- **proportionate (or risk based)** - by allocating resources according to risks involved and scale of outcomes which can be achieved
- **targeted (or outcome focused)** - the outcome must be central to the planning and assessment of performance

The Agency has included a sixth principle:-

- **practicable** - to provide clarity to business on how they comply

Through the application of the principles of Modern Regulation the Agency aims to be perceived as an effective regulator and to achieve a high degree of public confidence in its activities. The Agency believes in firm but fair regulation and has developed an Enforcement and Prosecution Policy to reflect this. Included in this policy are the factors to be considered in deciding whether or not to prosecute. The Reservoirs Act 1975 empowers the Enforcement Authority to take both Civil and Criminal proceedings. In preparing for this new role the Agency will apply its Enforcement and Prosecution Policy which enshrines the principles of Modern Regulation and apply them to the enforcement of the Reservoirs Act 1975.

ROLES UNDER THE RESERVOIRS ACT 1975

The Reservoirs Act 1975 is principally designed to be self regulating with the onus on the Undertaker to keep records, manage the dam and its infrastructure to a specified operating regime, and procure all necessary services and works. This is in line with the role of a regulated party defined by the Principles of Modern Regulation. The Reservoirs Act 1975 clearly establishes the role of the Undertaker and defines its responsibilities. The term ‘Undertaker’ has been specifically adopted in preference to ‘Owner’ as the role of Undertaker, i.e. person or persons that use and control the reservoir, may not always be the owner.

The Reservoirs Act 1975 also recognises distinct roles of engineer (Panel Engineers),each of which are required to be re-appointed to their respective panels every five years. Only a qualified civil engineer who is a member of the appropriate panel can carry out the statutory requirements of the Act relating to engineering aspects of construction, on-going supervision and inspection.

ROLE OF THE ENFORCEMENT AUTHORITY

The Enforcement Authority has a legal duty to ensure that the Undertakers’ self regulatory regime is fully compliant (i.e. effectively a compliance audit role) and can take necessary actions to secure compliance. The main duties of the Enforcement Authority include:-

- Maintaining a register of reservoirs, and making this information available to the public.
- Ensuring that the Undertaker has appointed a Supervising Engineer.
- Ensuring that the Undertaker commissions regular inspections of the dam by an Inspecting Engineer.
- Enforcing the Act by influencing, warning, cautioning and ultimately prosecuting non-compliant Undertakers.
- Commissioning essential works required in the ‘Interests of Safety’ in the event of non-compliance and recouping full costs incurred from the Undertaker.
- Acting in an emergency if the Undertaker cannot be found.
- Producing a Biennial Report to Defra and to the Welsh Assembly Government (WAG) of enforcement actions taken.

PROJECT MANAGEMENT OF NEW DUTY

The Agency has fully embraced the principles of project management to introduce all new duties to its business. This ensures that business aims are fully delivered to the specified time, cost and quality. For the introduction of this new enforcement role a Project Board has been established chaired by the Head of Flood Risk Management. The Project Board comprises key Agency personnel, a representative from: Defra, the British Dam Society (who is also an A.R. Panel Engineer), the Reservoirs Committee of the Institution of Civil Engineers; a current Enforcement Authority, and the Technical Manager – Reservoir Safety.

A project team, led by a Project Manager, reports regularly to the Project Board. The team, all of whom are part time consultees to the project, represent key elements of the Agency’s business which include the following:-

CIS (Corporate Information Systems)	Finance
Legal	Customer Services
Enforcement Processes	Personnel
Records Management	Media Relations
Debt Recovery	Emergency Management
Procurement	Planning Guidance

A comprehensive approach to project implementation has been adopted because of the impact that this change project will have across the Agency business.

PROJECT PLAN

The Project Plan has four elements supported by a comprehensive communications strategy:

1. Process definition
2. Delivery of suitable information technology
3. Acquisition of existing records
4. Recruitment of permanent staff

Process definition includes definition of the new duty, development of a Vision, statements of policy, business processes and work instructions supported by guidance and training.

A business case is currently under review for suitable information technology software termed the Reservoir Enforcement and Surveillance System. The acquisition of existing records is dealt with in more detail below, as is the proposed permanent structure.

VISION FOR RESERVOIR SAFETY

The Project Board has endorsed the following Vision for the overall guiding principles for the execution of the new duty:

"We will assure Reservoir Safety by robustly applying the principles of Modern Regulation in our enforcement of the Reservoirs Act 1975"

The Project Board have received proposals defining the strategic objectives for Reservoir Safety and how these objectives will be translated into performance measures.

The next stage of this process will witness the new team owning these strategic objectives. These objectives will define their business plans and training plans, which will be underpinned by the core values of the Agency.

Crucially, performance monitoring will be instigated against objectives set. The new performance measures derived for the team will also feed into and ultimately be evaluated against the Agency's Water Management Directorate's Balanced Business Scorecard. The Scorecard is designed to provide a high level summary of performance for use principally at Director level and provide early warning of under performance.

ELECTRONIC DOCUMENT MANAGEMENT

The business world is making increased use of electronic document management. This was for example reflected in a paper by Stewart (2002) where he expanded on a system developed for Severn Trent Water to hold all documentation electronically. Increased transfer to Electronic Document Management (EDM) is also reflected in the Agency's EDM strategy, which in part is driven by the targets set by the Modernising Government White Paper in 1999. EDM is also regarded as the most effective way to manage reservoir records in the future. It is planned that the prime method of receipt of notifications, certificates, etc., will be electronically. This contrasts with the current method of the majority of reservoir record retention - paper files. When all the current paper records are amalgamated they will require some 30 filing cabinets to retain them, hence the need for EDM.

TRANSFER OF DATA & INFORMATION

In order to establish the quantum of work and resources required to transfer data and information several Enforcement Authorities were visited at the commencement of the project. The visits were hosted by the lead officer for the authority and register and files reviewed.

Following review, a 3 phase approach to the process of transfer of data and information was adopted:

Phase I	A trial of the process based upon 10% of the total volume (which was completed by December 2003)
Phase II	The capture of the remaining 90% of records (refined by learning from Phase I) and due for completion by July 2004
Phase III	The 'Mop Up' of documents created/filed by existing Enforcement Authorities after Phases I & II.

This approach was designed to ensure that:-

1. From the 'go live date' of 1 October 2004 all necessary information would be electronically available to the Agency.
2. Potential issues would be considered and resolved, and important knowledge would be acquired at the earliest possible date.
3. All enforcement processes would be in place, trialed and operable before the duty commenced.

A questionnaire was despatched to existing Enforcement Authorities to determine:-

- confirmation of contact and reservoir details
- how records were held
- what processes, and computerised systems, if any, were in use
- advice and guidance that should be passed to the Agency

The questionnaire also made it clear that the Agency would not commence its role until 1st October 2004, but wished to ensure it was fully sighted on emerging enforcement issues.

Currently there is no single, comprehensive register of reservoirs for England and Wales. The process of transferring the individual registers from the existing Enforcement Authorities and subsequent checking is enabling this to be compiled.

RESERVOIR ENFORCEMENT AND SURVEILLANCE SYSTEM (RESS)

A consistent, national and effective business tool is required to enable the Agency to effectively undertake the enforcement role.

The system adopted needs to achieve the following four key business needs:-

- A reservoir register to hold structured information about reservoirs (i.e. inspections, actions, etc.)
- Electronic Document Storage and Management
- Standard letter generation
- Workflow support for Regulation business processes

Five options have been appraised that range from a manual process wholly reliant on paper records and increased staff numbers to the adoption of an existing Agency Permit Administration System (P.A.S.) which incorporates automated workflow. A standalone Electronic Document Management (EDM) has also been considered. The options have been assessed against a range of criteria that include:-

- Agency Environmental Vision and Technical Strategies
- Modernising Regulation
- Business Risk
- Wholelife costs (i.e. development, maintenance and operating activities)

The foundation for all the options considered is the processes that are defined by the legislation. It is from these processes that an automated system will be designed or a manually based team trained and managed.

BUSINESS PROCESSES

A Guide to the Reservoirs Act 1975 (ICE, 2000) defines six core procedures for compliance and enforcement. By fundamentally reviewing the Reservoirs Act 1975 some 18 distinct procedures have been established to resolve potential non-compliant acts or offences.

From these procedures (or business processes) the activities and performance objectives of each Agency department can be defined and interaction with outside parties, e.g. Inspecting Engineers, consistently managed.

The Agency Management System (AMS) provides a standard structure for all business processes. Once business processes are developed and approved, they are published and available on the Agency's Intranet. The types of AMS business processes that already exist range from guidance on the resource allocation for waste licence pre-application to the process to be adopted in managing and maintaining the Agency's own reservoirs. The application of AMS to all business processes defined by the Reservoirs Act 1975 will ensure a consistent and transparent approach.

COMMUNICATIONS AND STAKEHOLDER MANAGEMENT

The management of the interface with key reservoir industry organisations is regarded as crucial to the successes of this project and to the future effectiveness of the role. It is essential that the Agency project the profile that meets both the aspirations of the reservoir industry and Government. At an early stage of the project, Stakeholder Mapping was employed as a tool to define and manage the communication strategy for both internal and external stakeholders. To date, constructive working relationships have been established with:-

- Government – including Defra, WAG and the Scottish Executive
- The Health and Safety Executive
- Panel Engineers
- Key Undertakers
- Institution of Civil Engineers (ICE) and the British Dam Society

Comprehensive engagement with key Agency departments is in the process of being developed. An intranet site has been established and an internet site is planned before October 2004.

This paper later reflects on the increased profile to the reservoir industry and wider interest groups that the Agency will have with Reservoirs. The Agency is currently developing a National Customer Contact Centre (NCCC) based in Rotherham which will be fully briefed to handle routine enquiries from the public, for example educational enquiries.

As an active Enforcement Authority, the Agency will be pro-actively engaging with the profession and wider reservoir community in seeking both compliance with the Reservoirs Act 1975 and fostering improvements in approach.

As with any change management process the need for effective communication throughout the process is paramount. In establishing the pro-active relationship with the reservoir industry, the Agency is keen to ensure that changes are well forecast and a ‘no surprises’ culture engendered. The proposed automated workflow system will establish a continued dialogue with respective parties at relevant stages, for example: checking that a periodical inspection has been arranged, checking that measures in the interests of safety have been completed or checking the appointment of the Supervising Engineer. For some Undertakers this will represent a significantly different approach as they establish an ongoing relationship with the new Enforcement Authority.

NEW TEAM STRUCTURE

In undertaking this new duty, the Agency will build on its existing strengths which include significant enforcement expertise and local awareness through Flood Risk Management. A core team will be formed in Exeter to provide the routine surveillance and the enforcement capability. This will provide a ‘One stop shop’ approach to the compliance monitoring and enforcement role. The Technical Manager – Reservoir Safety will provide leadership and management to the team that will comprise two key elements:

1. Surveillance
2. Enforcement

The surveillance team will manage the reservoirs register, initiate all routine correspondence, and populate the RESS and handle detailed enquiries. The enforcement team will co-ordinate all enforcement across England and Wales and manage the portfolio of enforcement cases. They will take over from the influencing element of enforcement led by the surveillance team and be responsible for the warning, cautioning and prosecuting stages. The services of Panel Engineers will be procured to advise and work with the Agency in order to achieve the appropriate regulatory outcome in accordance with the Reservoirs Act 1975. The Enforcement process will be assisted by a representative from the Agency’s Area Flood Risk Management Regulation Team. This local representative will provide the essential ‘eyes and ears’ on the ground. One of their first roles will be to check that the Register of Reservoirs is complete for their Area.

TRAINING AND DEVELOPMENT

A key element of the project will be the provision of training for all staff with a role to play in the enforcement of the Reservoirs Act 1975. The Agency is progressing towards Investors in People (IiP) accreditation and thorough training and development for its staff is seen as crucial.

To properly enforce such a comprehensive Act all potential scenarios are being worked through as part of design of training. As an illustration, Powers of Entry, and Police and Criminal Evidence Act (PACE) training will be provided to ensure that local staff are fully able to apply Section 17 of the Reservoirs Act 1975 which states a person duly authorised in writing by an Enforcement Authority may at any reasonable time enter upon the land on which a reservoir is situated. This is also particularly important in view of the potential recourse to compensation that could arise from a 3rd party by virtue of Section 18 of the Reservoirs Act 1975. Section 18 deals with compensation to third parties where the Enforcement Authority exercises any powers conferred on it by Section 17. Compensation is payable by the Enforcement Authority where damage is caused. Such compensation is deemed to be a reasonable expense incurred by the Enforcement Authority and is recoverable from the Undertaker.

FLOOD PLANS

The Water Act 2003 establishes the requirement for Undertakers to provide Flood Plans when directed to by the Secretary of State. Reference is made to this requirement in the Defra letter to Water Company Chief Executives reported in Dams & Reservoirs June 2003. It is proposed that these plans will have to be produced from April 2005 and industry provided with a five year rolling programme for their production. In order for Defra to establish how these plans are to be prepared, their constituent parts, the consultees and their respective roles, a research and development (R&D) project had been let to Kellogg Brown & Root (KBR). By the end of 2003 a proposed format had been established based on the Control of Major Accident Hazard Regulations 1999, together with proposed prioritisation criteria for preparation of plans. Defra propose to embark on a major consultation process with all affected parties (i.e. Undertakers, Panel Engineers, Emergency Planners, etc.) in 2004. This programme fits with the development of the Civil Contingencies Bill.

INCIDENT REPORTING SYSTEM

A further R & D project let by Defra to KBR has been to develop an incident reporting (and investigation) system for UK dams. The outcome from this contract was presented to the BDS on 27th October 2003 when an industry wide consultation process was initiated. The aim of the system is to improve the safety of UK dams by promoting awareness of safety issues, learning from experience of others and identifying research needs. A targeted questionnaire to key representatives of the UK dam industry had produced support for the Enforcement Authority to co-ordinate this role. Currently it is planned that the Agency commence this new role from June 2005.

THE FUTURE

The scene is set for an interesting and increasingly important new role for the Agency as it takes on its responsibilities as the Enforcement Authority. This will bring with it considerable opportunities for improved regulatory efficiency and partnership activities establishing closer links with the reservoir community. For example the Agency will be working closely with Defra and WAG, together with the wider reservoir community, to determine new policies on the application of the Reservoirs Act and influence future policy changes. Through the transfer of enforcement for reservoir safety to just one body, the Agency will achieve a consistent, systematic approach to achieving compliance with the Reservoirs Act 1975 and thus accomplish the Vision established for Reservoir Safety.

ACKNOWLEDGEMENTS

The authors wish to thank the Environment Agency for permission to publish this paper.

APPENDIX

Information Sources

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Developments in management of reservoir safety in UK

A. J. BROWN, KBR, Leatherhead, UK.
J. D. GOSDEN, KBR, Leatherhead, UK .

SYNOPSIS. The UK government funds a continuing programme of research and development on issues related to the safety of large raised reservoirs in the UK. This paper describes three recent projects carried out by KBR which are likely to have a significant effect on the way reservoir safety is managed in the UK.

The first project was to devise and trial a system for quantitative risk assessment of dams, to allow comparison of threats such as inadequate spillway capacity with other threats to the safety of a dam. This system is to be published in early 2004 as an Interim engineering guide for extended trial by dam owners and dam professionals. The second project arose out of the realisation that in UK there are typically about three incidents a year where emergency drawdown of a reservoir is required to avert failure. The project comprised a feasibility study into the content of an incident reporting and investigation system and how this might be established. The third project comprised a feasibility study to identify practicable means of early identification of internal erosion in old dams.

INTRODUCTION

There have been no dam failures involving loss of life in the United Kingdom since enactment of the first Reservoirs Act in 1930. One of the contributions to ensuring that this situation continues is a research and development programme funded by the UK government (Department of environment, food and rural affairs, Defra), to both carry out original research and disseminate current good practice to all those involved in the management of dam safety.

This paper describes three research projects carried out by KBR for Defra, and comments on how UK dam safety management practice may develop in future.

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

THE INTEGRATED SYSTEM

The prototype Integrated System of Quantitative Risk Assessment for dams (KBR, 2002) is summarized in Figure 1. The system is intended to be a rapid screening level assessment, suitable for use as part of the ten yearly safety review carried out under the Reservoirs Act 1975 or for a portfolio risk assessment.

The definitions used form the cornerstone of the system, and unfortunately there is currently no agreed common framework of definitions used in the dam industry. Some of the key definitions of the processes used in the System are shown in Table 1.

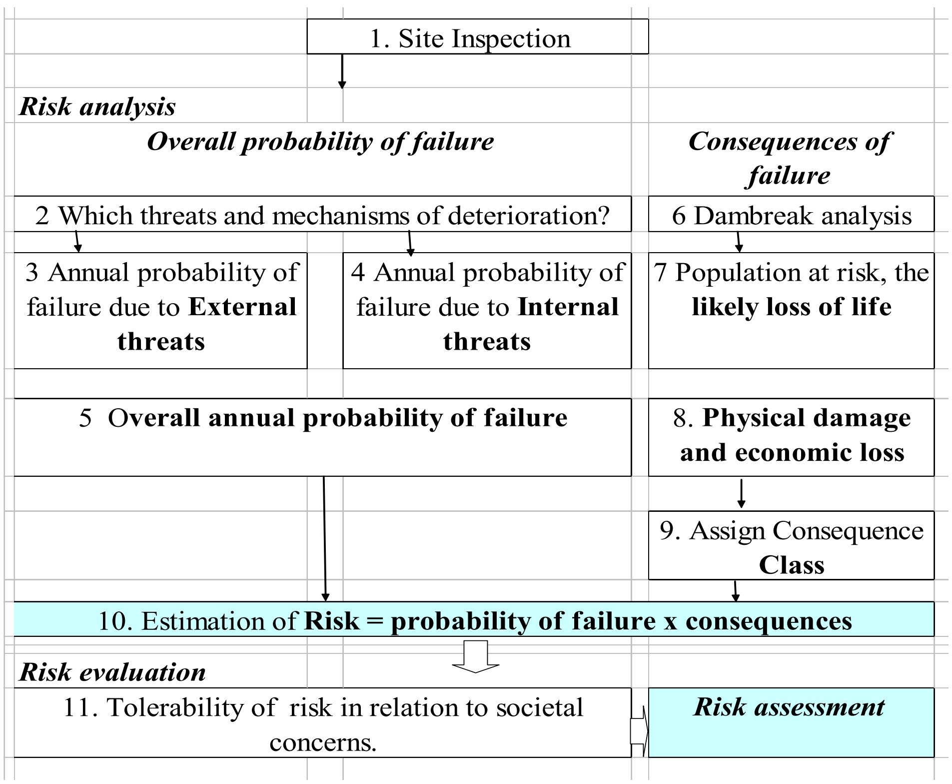

Figure 1: Process comprising the Integrated System

The selection of threats to quantify is one of the most difficult yet important steps. At the feasibility stage the System contains a methodology for estimating the AP of failure due to the most common threats (namely floods, upstream reservoirs, seismic, wind and internal threats), although it includes a requirement for the user to evaluate the significance of other threats at a particular dam and a facility to add these into the estimate of the overall probability of failure. This is carried out using an event tree similar to the Failure Modes and Effects analysis (FMEA) in BS 5760-5:1991.

Table 1: Key definitions used in the Integrated System

Term	Definition
Current Condition	Condition of a dam at a particular date as assessed from visual inspection and in some cases physical investigation
Indicators	Measurable outcome from the application of a mechanism of deterioration e.g. deformation, seepage, instrumentation results.
Intrinsic condition	Current physical property or dimension of the dam which can be measured and which affects the outcome of the application of a mechanism of deterioration. Although initially determined by design and construction details; this may change with time due to ageing, neglect, maintenance or upgrading.
Mode of failure	Means by which a failure (uncontrolled sudden large release of water) may occur; four modes are differentiated in the System namely external erosion (including overtopping), internal erosion, sliding and appurtenant works.
Mechanism of deterioration	Process by which the integrity of the dam is undermined. The mechanism can have a quantitative threshold above which deterioration is likely to occur e.g. slope protection designed to withstand waves due to 100 year wind
Threat	Random Event (External threat, such as floods and earthquake) or Potential Internal Instability (Internal threat) that poses a threat to the integrity of the dam.

Annual Probability of Failure

For external threats such as floods the system uses analysis, by adopting the concept of a “Critical” external event, which is an external loading of sufficient magnitude to just cause failure of the dam. The annual probability (return period) of this event is estimated from the relationship between magnitude and return period.

Estimating the probability of failure due to internal threats is difficult, as internal threats do not occur as independent events and it is often difficult to measure the occurrence of the threat. The preferred system for evaluating the probability of failure due to internal threats is to relate the dam condition, in terms of a Current Condition score of 0 to 10, to the annual probability of failure. The annual probability of failure of the worst condition dams due to internal threats is based on performance over the last 25 years (Brown & Tedd, 2003), while it is assumed that the best condition dams have an annual probability of failure due to internal threats of $1x10^{-7}$.

A critical element of this methodology is the system for assigning the Current Condition score, which is assessed from indicators of poor performance (e.g. seepage and settlement); the quality of ongoing surveillance; the ability to lower the reservoir rapidly in an emergency and the reservoir operating regime.

Consequences of Failure

It is necessary to quantify the consequences if the dam failed, firstly in terms of areas of inundation and structural damage, and then in terms of the likely loss of life and damage to infrastructure. The system uses published rapid methods of estimating the peak breach flow at the dam (Froehlich, 1995), and how this attenuates down the valley (CIRIA, 2000).

The relationship between the likely loss of life (LLOL) and PAR derived from dam failures and flash floods in the United States was used (Bureau of Reclamation, 1999, which includes allowance for the "forcefulness" of the flood wave and warning time.

The estimation of physical damage is as far as possible based on systems used by the Environment Agency for evaluating potential flood defence schemes; albeit some adjustment is required to take into account the higher velocities and thus greater destruction from a dam breach flood.

Tolerability of Risk

The System plots the probability of failure and LLOL on an FN chart, as both one technique for evaluating the tolerability of risk, and as a means of prioritising dams where several are being considered together (e.g. in a cascade). It also provides a spreadsheet to allow the user to carry out ALARP assessment. This estimates the cost to save a statistical life for a package of works. This value can be compared with the cost of the package of works to assess whether the expenditure is proportionate to the reduction in risk achieved.

Benefits

The following benefits are anticipated on application of the prototype system:

- Explicit consideration of the likely threshold of dam failure can help provide a more considered basis for decision making. It will assist understanding of the margin of safety that is available
- For the first time internal threats can be evaluated in a similar format to external threats
- Permits investment to be targeted where it will do most good i.e. achieve the largest reduction in risk
- ALARP analysis can be a useful tool in identifying the value obtained from proposed investments

An interim engineering guide to an integrated approach to reservoir safety will be issued in 2004 for an extended trial as a screening tool over a period of 5 years. Feedback should be provided to the authors or Defra who intend to carry out a review of the approach at the end of that period.

INCIDENT REPORTING AND INVESTIGATION SYSTEM

One of the contributions to managing dam safety is to learn as much as practicable from near miss incidents, which might have become a failure in different circumstances, and this is the objective of the proposed incident reporting and investigation system (Gosden & Brown, 2004).

Other industries were drawn on in defining the system for dams, where systems for reporting near miss incidents are well established although normally being a statutory requirement.

As part of devising a incident system for UK dams, questionnaires were sent out to a selection of dam owners and panel engineers to obtain their views on the various issues relating to such a system. A questionnaire was also sent out for the third research project described in this paper; devising a method for early detection of internal erosion.

Possible objectives and combinations of output and incident level

There is a wide range of possible combinations of level of detail of analysis and output from the data, and the level of seriousness of an incident which could be included in an incident database, as summarised in Table 2.

The levels of incident that were adopted are as shown in Table 3, being based on those used previously in the BRE database (Tedd et al, 1992) although with some tightening of definitions. The current best estimate of the likely average number of each level of incident per year is also included; being derived from the response to the questionnaire (other than Level 6 incident which is derived as shown).

The practicable options considered are shown in Figure 2, with selection of the preferred option based on the views of UK dam industry obtained from the questionnaire, the likely completeness of reporting, the cost of data collection and processing, and the value of the output in improving dam safety.

Table 2: Possible objectives and outputs from incident system

Objective	Output	Feedback from questionnaire to UK dam industry
Ensure best possible practice is applied to ensure the continuing safety of UK dams	II Lessons learnt	Highest support in principle, 69% of dam owners and 35% of others were prepared to contribute to cost.
	II Trends III Cause and feature of each incident	High support in principle but willingness to pay not tested explicitly
	IV Historic Annual probability	70% of dam owners and 30% of others were prepared to contribute to cost.
Minimise whole life cost of asset	VA Cost and duration of incident	62% of owners were prepared to pay for information on cost, but only 39% for the disruption arising from the incident
	VB Reliability database	44% of dam owners and 33% of others were prepared to contribute to the cost. Only 7% of dam owners strongly agreed that it was worthwhile
Data collection	VI Number of extreme events/yr	Low priority.

Table 3: Estimated number of incidents a year in UK, with 2600 large dams

Incident Level	Definition	Estimated No/ yr
1	Failure (uncontrolled sudden large release)	0
2	Emergency drawdown or works; serious operational failure in emergency	3
3	Precautionary drawdown, unplanned visit by Inspecting Eng, unplanned works; serious human error	10
4	Works in the interests of safety (Section 10 of Reservoirs Act)	60
5	Physical works not under a higher incident level. Investigation arising out of periodic safety review	30
6	Extreme natural event > 1% annual probability (1 in a 100 year return period)	78 (1% of UK dams/yr. x 3 threats)
7	Other e.g. operational failure	na

<table>
<tr><td>Output Table 2</td><td colspan="7">Incident level (Table 3) -Y is combination which is practical, other combinations are not practical</td></tr>
<tr><td></td><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td><td>6</td><td>7</td></tr>
<tr><td>I</td><td colspan="3" rowspan="2">Option A</td><td>-</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>II</td><td colspan="2" rowspan="3">Option C</td><td rowspan="3">Option D</td><td>Y</td></tr>
<tr><td>III</td><td colspan="3" rowspan="2">Option B</td><td>Y</td></tr>
<tr><td>IV</td><td>Y</td></tr>
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<tr><td>VI</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td><td>Y</td><td>Y</td></tr>
</table>

Figure 2: Options considered for combination of Incident level and output

A critical issue is the likely effectiveness of a voluntary reporting system. This was assessed from the responses to the questionnaire sent out to the dam industry. Of the 117 questionnaires, 43% responded to the questionnaire on the incident system and 34% to the questionnaire on early detection of internal erosion, although only 16% of recipients provided case history data for the latter. Of those that responded to the questionnaire on the incident system, 77% considered they would achieve a completeness ≥80% for a Level 3 incident (Precautionary drawdown of the reservoir) and 13% considered they would achieve a completeness ≥80% for Level 6 (Floods> 100yr).

It was concluded that a voluntary system would only attract a proportion of actual incidents, and that based on the response to the questionnaire the likely completeness of reporting of Level 2 and 3 incidents could be between 35% and 85%. Thus depending on the level of reporting, it may be difficult to reliably differentiate trends in safety from changes in reporting completeness. Hence any statistical analysis may be of uncertain value for Outputs 2 and 4, and biased for Output 3. Initially the system will be voluntary. However, depending on the effectiveness it may be appropriate that the system should become mandatory through new legislation.

It was concluded that, based on both the willingness to pay and likely completion of reporting, there is reasonable support in principle from the UK dam industry for Options A and B, but less so for Option C and none for Option D. Option B (which includes Option A) is taken forward as the information to be obtained from the incident reporting system.

Investigation of near miss incidents

For serious near miss incidents it is of value to investigate the incident to maximise what can be learnt, rather than just relying on an incident report. It is proposed that the purpose of the investigation is the same as for the various accident investigation bodies under the Department of Transport; namely to look for the root causes of accidents without apportioning blame or liability.

It was concluded (Gosden & Brown, 2004) that

- The system should investigate all Level 1 and 2 incidents, but the database manager will be given discretion to investigate other incidents that he believes merit investigation
- the investigator should be appointed by, and report to, an independent body. It is proposed that the independent body would not carry out the investigation themselves but appoint a civil engineer, qualified in accordance with the Reservoirs Act, to carry out the investigation

EARLY DETECTION OF INTERNAL EROSION

The objective of this research was to develop techniques for the early detection of progressive internal erosion (Brown & Gosden, 2004). Drivers for this research included recommendations from a recent research project into the feasibility of an Integrated System to assess all threats to dams (KBR, 2000), and a recent serious near miss incident involving an unprotected masonry culvert through an older embankment dam.

The project builds on the work of the European Working Group (Charles, 2001) as well as others (e.g. Vaughan, 2000a, 2000b). The project comprised data collection through both a questionnaire to dam professionals to obtain data on internal erosion incidents, and the use of expert elicitation to quantify parameters which are not readily measurable (Brown & Aspinall, 2004).

Long term strategy

The overall purpose of a strategy for the early detection of internal erosion is to obtain time

- in which mitigation actions can be taken to avert failure (which could include physical upgrading works), and
- if failure cannot be prevented, to warn and evacuate people from the dam break inundation zone

It is implicit that the importance of early warning is greater where the risk of loss of life and/ or damage resulting from a failure is high; namely that the amount of advance warning time should be greatest and the reliability of detection of defects highest where the risk to the public is greatest. This suggests that the strategy for early detection of internal erosion should be risk based. It is considered that in the long term detection should be one of a suite of three risk control measures to reduce risk from progressive internal erosion, namely

a) surveillance (detection);
b) planning of measures to be taken in the event that internal erosion is detected (emergency planning) and
c) the reduction of vulnerability through physical upgrades

<u>Rate of deterioration</u>

Data on the rate of deterioration is available from the questionnaire and expert elicitation (Brown & Aspinall, 2004); with the key variable being T_f, the estimated time from detection of the incident to failure if there had been no intervention. Figure 3 shows T_f by the location of the incident or the type of dam from the questionnaire. This figure shows that the respondents to the questionnaire considered

a) T_f varies by several orders of magnitude, from 1 to over 100 days,
b) incidents associated with culverts and pipes were much more likely to lead to a rapid failure. The median T_f (50% of incidents) for incidents at appurtenant works was 5 days, whilst the median for incidents in the body of puddle core dams was in excess of 365 days (a year).

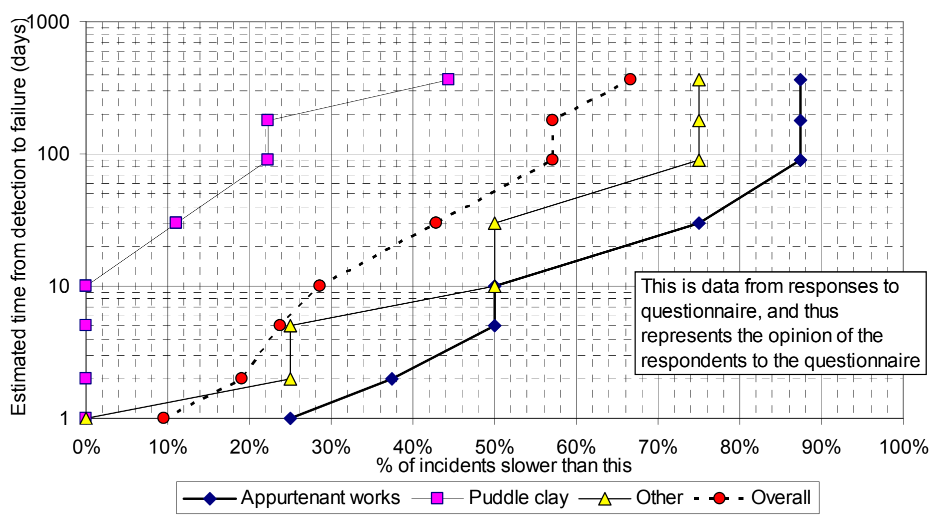

Figure 3: Variation of estimated time from detection of incident to failure (T_f) with incident location or embankment type

Further results from the project are given in Brown & Gosden (2004); with the overarching conclusion being that the understanding of internal erosion processes is still immature. Detailed conclusions include that the rate of deterioration due to internal erosion can be very variable, that there is a threshold leakage for erosion to commence and thus that leakage may occur without internal erosion, depending on issues such as the soil type and magnitude of leakage.

Interim Strategy

Currently there are significant uncertainties in relation to the proposed control measures. For example there are significant uncertainties in estimating the annual probability of failure due to progressive (rapid) internal erosion. Similarly there are a number of arguments against applying the approach of physical upgrades as a default at the present time (except for very high consequence dams):-

a) Currently it is not possible to reliably predict those dams where internal erosion would be rapidly progressive, rather than steady
b) Pipes and culverts appear to be the largest risk; it is more difficult to upgrade these than the body of the embankment
c) If the mechanisms of deterioration and singularities (e.g. construction features) present at a dam cannot be fully quantified, then upgrades could lead to a false sense of security if they were incomplete in not addressing all potential failure modes. (e.g. if carrying out an upgrade led to a reduction in surveillance this could increase the probability of failure due to progressive erosion)

It is therefore concluded that at present it is more appropriate to concentrate on surveillance, and to link the risk control measures to the consequences of failure, rather than risk, albeit with some provision for adjustment on the basis of an assessment of the vulnerability of a dam to failure. Those dams with higher consequences would justify higher expenditure than those dams where the consequences are limited.

Frequency of monitoring

Four general monitoring regimes are proposed to be applied as shown in Table 4. The proposed “Matrix” to define the monitoring regime, which depends on the consequence class and condition of the dam, is shown in Table 5, whilst the Consequence Class is shown on Figure 4.

The latter is based on the Dam Category for defining the design flood as given in Table 1 of Floods and Reservoir Safety (ICE, 1996); but made more quantitative by changing “could endanger life” to “likely loss of life” and requiring that damage be quantified in £M. It is recognised that the accuracy of the latter should be appropriate to the intended use and generally would only be an order of magnitude estimate.

Table 4: Suggested Guide for in-service dam base monitoring frequency

Parameter	Monitoring regime (Note 1)			
	α	β	γ	δ
Visual surveillance				
Exterior; including Exterior of culverts/ shafts (and Interior where no confined space)	Daily	Daily to Tri-Weekly	Twice Weekly to Weekly	Monthly
Interior of culverts/ shafts, where confined space	Weekly to monthly	Monthly to 3 monthly	3-Monthly to 6-Monthly	Ten yearly
Instrumentation				
Flow of water incl turbidity (Note 2)	As for visual surveillance of exterior			
Telemetry	Recommended	Recommended	Consider	Not applicable
Surface Movement	Yearly	2-Yearly	Consider	Consider
Pre-existing instruments	*For manual reading; where automated readings are available more frequent reading would be appropriate.*			
Piezometers	Monthly to 3 monthly	Monthly to 6-Monthly	3-Monthly to 6-Monthly	Consider
Internal movement/ stresses	Yearly	2-Yearly	Consider	Consider
Parameters required to adjust trigger level				
Rainfall	As for flow of water			
Reservoir level	As for flow of water			

1. These frequencies may need to be varied according to the conditions at, and the type, and size of the dam; these should be determined by the dam owner and his Supervising and Inspecting Engineers.
2. This applies to any flow of water that might be emanating from the reservoir. Where there is concern over the behaviour of the dam then periodic measurements of temperature and/or chemical analysis of the water may be helpful in improving the understanding of the sources of the water.

Table 5: Proposed "Risk Matrix" to define monitoring regime

Condition of dam	Consequence class of dam (From Figure 4)			
	A1	A2	B	C/D
Poor	α	β	β	γ
Average	β	β	γ	δ
Good	γ	γ	γ	δ

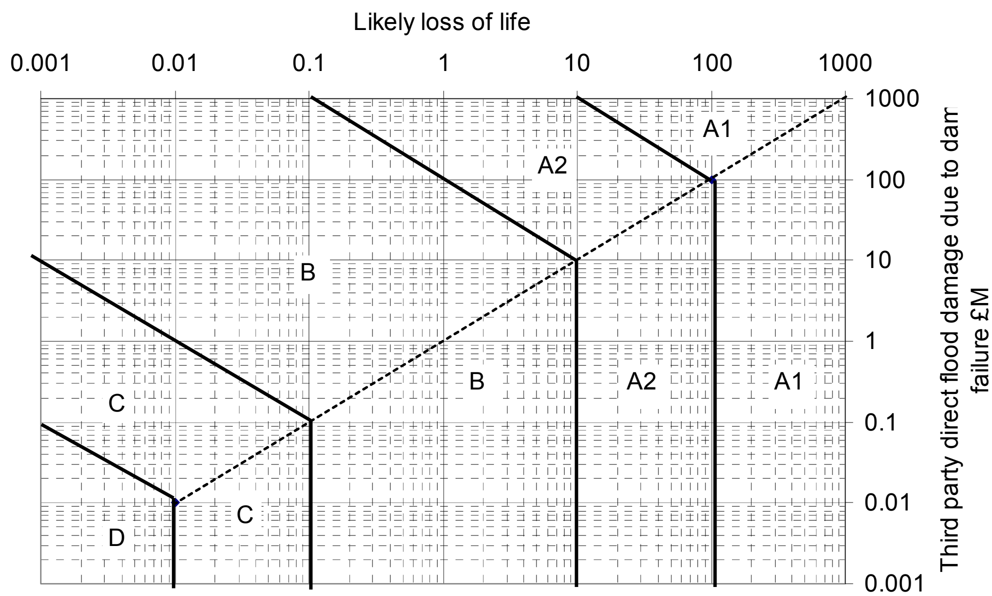

Figure 4: Proposed Consequence diagram for UK dams

DISCUSSION – THE FUTURE FOR DAM SAFETY MANAGEMENT IN THE UK

There is no reason to be complacent about the good public safety record of dams in the UK, and the projects described will contribute to continuous improvements in the safety regime. Quantitative risk assessment (QRA) is still in the early stages as a management technique, but is likely to have far reaching effects on how risk and uncertainty are perceived and managed, and thus on the nature and extent of physical upgrading works.

In a society which is becoming increasingly litigious it is important that safety management becomes more transparent, and that its application to dams is consistent with the approach in other high hazard industries. QRA should assist in informing the debate on these issues.

New legislation passed in 2003 (The Water Act) will change the enforcement of the Reservoirs Act in England and Wales to a single body, the Environment Agency, and also introduce the requirement for emergency plans for higher risk dams.

Implementation of the incident reporting and investigation system described in this paper should lead to more informed understanding of both the frequency and type of serious near miss incidents and prioritisation of areas for future research.

CONCLUSIONS

The UK government programme of research and development in relation to dam safety continues and provides useful output in terms of how the safety of UK dams is managed. Several recent research contracts have been described and a description of how safety management may change in future given. Further information on the projects described is given on both the Defra and British Dam Society websites. Feedback on the Interim Guide to QRA is welcomed and should be addressed to Defra. Readers are encouraged to use the Incident Reporting System, once in place. Similarly suggestions for future research are always welcomed and may be addressed to Defra.

ACKNOWLEDGEMENTS

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Use of expert opinion elicitation to quantify the internal erosion process in dams

A. J. BROWN, KBR, Leatherhead, UK
W. P. ASPINALL, Aspinall & Associates, Beaconsfield, UK.

SYNOPSIS. Expert Opinion Elicitation is a generic term for a number of similar techniques that have been developed to provide quantitative estimates of parameters which cannot readily be quantified through direct measurement or other sampling techniques. The initial motivation for their development was the 1986 Challenger Shuttle disaster in the space industry, and subsequent applications have spread into many other areas: the techniques have been widely used in the nuclear industry, for instance. One particular procedure consists of obtaining responses to a set of quantitative questions from a number of experts, including the range of uncertainty in each response, and then combining these through a weighting procedure to obtain a pooled best estimate of the parameters of interest.

This paper describes an application of that procedure as part of a research contract to improve methods of early detection of progressive internal erosion in UK embankment dams. For some of the parameters, information is also available from a questionnaire circulated to British dam professionals, and the paper compares the outcomes produced by the two approaches. The paper concludes with comments on the future role that expert opinion elicitation could play in providing a better understanding of dam safety issues, in particular in the determination of relevant uncertainties.

INTRODUCTION

KBR are currently undertaking a research contract for the UK government (Department of environment, food and rural affairs, Defra) to "identify a cost effective means of early detection of progressive internal erosion in embankment dams". The terms of reference entail major emphasis on embankment dams which pre-date modern geotechnical engineering (no filters or instrumentation), and that the hazards posed by unprotected pipes and culverts require particular attention. The final output from the project is to be Technical Guidance on the management of internal erosion.

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The approach adopted to respond to the terms of reference comprised a questionnaire to dam owners and panel engineers to identify recent case histories of internal erosion, a literature review and expert opinion elicitation. This paper describes the latter from the parameters selected for quantification, through the results it gave, lessons learned and where the technique could be of value in other areas relating to the management of high hazard industries.

EXPERT JUDGMENT AND ELICITATION OF EXPERT OPINIONS

General

In recent years, important changes have occurred in engineering which affect the way in which many safety-related decisions are made. These changes have resulted mainly from the development of risk-based methods for the design and appraisal of engineered systems. One feature of these methods is the objective of quantifying the level of safety in order to estimate the likelihood of engineering failure. The introduction of probabilistic concepts for treating uncertainty requires an engineer to exercise a form of judgment which differs from the conventional professional judgment that he (or she) may have developed during his career through training and practical experience. This alternative form of judgment, which surfaces in all attempts at estimating probabilities, in whatever domain, is generically termed 'expert judgment', and involves enumerating subjective probabilities that reflect an expert's degrees of belief. Hitherto, this subjective element in assigning probabilities has often been treated informally, or ignored altogether, but methodological advances, such as that reported here, are bringing this form of judgment increasingly to the fore.

Various approaches for combining expert opinions are possible (see, e.g., Cooke,1991; Meyer & Booker, 2001), including: *simple averaging, decision conferencing (the committee), the Delphi method, expert 'self-weighting', and the mathematical theory of scoring rules*. It is the latter that has been most refined by Cooke (1991), with his "Classical model" for expert judgment pooling (designated 'classical' because there is a close relationship with hypothesis testing in classical statistics). Cooke's scheme has been extensively tested and used in many areas of science and engineering, including the aerospace industry, nuclear industry, meteorology, hydrology (in the Netherlands), earthquake engineering and volcanology.

Examples of the use of expert elicitations in UK include:

a) O'Hagan (1998), where a consensus approach was used to address future capital investment needs of a major water company, and also in assessing the rock mass permeability at a possible nuclear waste repository at Sellafield
b) Aspinall & Cooke (1998), who describe the use of the structured elicitation methodology and decision-support procedure based on the "classical model" during the Montserrat volcanic eruption crisis, and
c) unpublished work on flight operations safety for British Airways (W.P. Aspinall, pers. comm.).

Classical method

The basis of Cooke's method is that the experts are posed a number of "seed" questions for which the answer is known (or knowable). Their responses are then assessed to obtain scores and individual weights, as defined in Table 1 and illustrated in Table 2; full mathematical details can be found in Cooke (1991). The procedure can be used to greatest benefit when the opinions of several experts (say, five or more) have to be elicited efficiently and promptly - for smaller groups, it may not be justified.

There are some important explanatory remarks in relation to Table 2. Firstly with only two seed questions, the number of degrees of freedom in the Chi-square test for the calibration statistic are too few to obtain results reflecting the accuracy of individual experts – hence Experts 1 & 2 have the same calibration score even though, in this example, one was more 'accurate' in his predictions than the other. Expert 3 falls between Experts 1 and 2 for informativeness, but falls below the threshold level for calibration (with Expert 4) when, as here, the DM's performance is optimised. Expert 4 is highly opinionated, and always fails to make his confidence limits wide enough to score any hits, but there is still a non-zero probability (0.007) that he is actually well-calibrated.

The fully-optimised DM has the highest calibration score, (when it is added to the group, as a virtual expert) but its Informativeness score appears poor because it amalgamates the spreads of all (positively weighted) experts. The DM's overall normalised weight is, therefore, slightly less good than the best real expert in this example, but then the DM's range reflects the collective spread of opinions. When optimised, the DM's 50%ile estimates for both seed questions are very close to the actual realizations, notwithstanding the scatter in the four experts' opinions.

In a real exercise, more seed questions are used for scoring the experts, and different combinations of statistical test power and significance level can be set to constrain relative performance scores across the group and DM.

Table 1. Basis of 'classical model' for combining experts' opinions – terms, scores, weights and factors

Term	Explanation / basis
Item	A 'seed' variable (for calibration purposes) or a question of interest for which an evaluation is sought from a group of experts
Calibration score	Test the hypothesis "This expert is well calibrated" with respect to his peers, on the basis of his estimates for a set of 'seed' variables. The score is the significance level in a chi-square test at which the hypothesis would be just rejected
Informativeness (Inverse is Entropy score)	a) Quantify the individual's 'informativeness' by indexing his cumulative information distribution function for all seed items relative to a uniform 'background' distribution (strictly, an inverse of a chi-square test statistic for closeness of correspondence); b) this 'background' distribution is either uniform linear (suitably truncated) or log normally distributed between quantiles; the latter is typically used when the range of possible values can vary over two orders of magnitude or more
Synthetic decision-maker (DM)	a) constructed from a weighted sum of the experts' responses to the items of interest, item-by-item. b) extracting the DM's distributions for each seed variable, the DM can be treated as a 'virtual expert' and scored against the seed items at different significance levels; the opinion of this virtual expert then can be iteratively re-combined with the real experts.
Expert weights	a) For each expert, the product of his calibration multiplied by informativeness scores across all seed items, normalized so that the sum of all expert weights, including that of the DM, is unity b) The 'classical model' software allows adjustment to the power of the chi-square test and the related significance level setting, which determines the threshold calibration score at which experts are given a non-zero weighting.

Table 2 : Illustration of scores and weights for 4 experts answering (only) two seed questions.

Expert	Experts' opinion ranges	Calibration Score	Inform. score	Normalized wt., incl opt. DM
1	*10, 35, 90* *15, 35, 80*	0.36	0.12	0.05
2	*40, 50, 60* *45, 52, 58*	0.36	1.27	0.52
3	*10, 25, 45* *15, 30, 55*	0.18	0.60	0
4	*80, 90, 95* *75, 80, 85*	0.007	1.60	0
DM		0.94	0.41	0.43
Results	Actual Seed values	5%ile	50%ile	95%ile
DM soln 1	50	*22.8*	*49.7*	*72.3*
DM soln 2	50	*26.4*	*51.8*	*66.8*

The rational mathematical basis for the 'synthetic decision-maker' is one feature of the method which makes it superior to other schemes for pooling judgments, making use of expertise weighted according to the quality of response to the whole set of seed variables. Usually, but not invariably, the DM ends up with a heavier weight than most, if not all, of the 'real' experts. Thus, the concept of the DM can also be described as the creation of a 'rational consensus', for the problem of combining a range of opinions (as opposed to reaching a simple average, democratic compromise or some other variant of egalitarian consensus). That said, in some applications, where suitable seed data are sparse or repeated tests are not possible, the scoring power of the calibration scheme may be weak, and its impact on individual weightings may have to be constrained.

Nonetheless, Cooke's method has at its heart a basis which replicates the formal scientific method, and one of its most valuable attributes is the scope it provides for quantifying realistically the spread of scientific or engineering uncertainty in relation to any parameter of interest. Thus, the procedure is usually framed to elicit suitable lower and upper percentile confidence estimates from the experts (in the present case 5%ile and 95%ile values), as well as a central or 'best' estimate value (which can be the mode, mean or median, depending on the distributional properties being sought). This aspect of the structured elicitation procedure is especially important for those variables for which adequate data do not exist for conventional statistical analysis - where the need for precise differentiation between engineering judgment and expert judgment comes into play.

APPROACH USED ON THIS PROJECT

The approach used on this project was based on that formulated by Cooke (1991), with the best estimate and 5% and 95% uncertainty distribution quantified for each item. To avoid peer pressure biases, the responses of the individual experts are provided independently by each directly to the facilitator, everyone remaining anonymous when the results are reported back to the group of experts. In the present project, the full set of questions had to be completed during the workshop, to avoid compromising the calibration seed questions used to evaluate the 'accuracy' and 'informativeness' of the experts' judgments (given time and opportunity, the experts could have looked up the relevant answers from published papers).

On certain questions of interest for the Defra study, some significant or systematic differences emerged amongst the experts, and the elicitation process was repeated a second time, partly in order that it could be preceded by more extended discussion of the technical issues, but also to further widen the base of experts to include two academics. Eleven experts took part in the second workshop, comprising two owner's representatives (who are both Supervising Engineers), two academics, and seven consultants' staff (six Panel AR and one Supervising Engineer); conduct of the workshop was overseen by the independent facilitator.

PARAMETERS SELECTED FOR QUANTIFICATION

The primary objective was to obtain a separate view from that in the questionnaire on the rate of deterioration of embankment dams due to internal erosion, and thus inform the output from the research project in terms of recommendations of the frequency of surveillance.

One of the key issues was devising a model of internal erosion that could be quantified using both the elicitation and questionnaire. Such a model should ideally include the effect of time, the indicators that internal erosion is occurring (indicators), those factors that determine both the predisposition to internal erosion (intrinsic condition) and how events may progress at a particular dam (event trees). It proved impossible to devise one model that satisfied all these requirements, so three models were constructed, as presented in Brown & Gosden (2004). The questions were devised to quantify elements in each of these models, with the variables of most concern being summarized in Table 3, and issues to be addressed in devising the detailed text of the questions included in Table 4.

Table 3. Groups of variables selected for expert opinion elicitation

		No. of questions
1	Seed questions	11
2	Prevalence of leakage and internal erosion	16
3	Average leakage and erosion rates	4
4	Minimum detectable leakage rate, dam critical flow	5
5	Rate of deterioration i.e. how long from detection to failure	10
6	Contributory factors to rate of progression	14
7	Chance nodes in event tree; i.e. what are the likely proportions of possible types of behaviour?	14
	Total	74

Table 4. Issues in devising questions for expert opinion elicitation

Issue	Adopted
For which dam type(s) the question should be posed	The UK populations of puddle clay core, and homogenous dams. This was on the basis that the data in the BRE database shows that these are the most common types; together comprising 84 % of the UK embankment dam population.
To which dam(s) does the question apply?	Questions were generally posed to apply to the whole UK population of that type of dam.
Clarity of question	The question should be unambiguous. The draft questions were subject to external review by (non-dam) experts familiar with expert elicitation.
How many questions can be included	The first workshop had 11 calibration and 63 elicitation questions, as shown in Table 3. Although this is towards the upper limit of a number for one session, it was achieved, partly, by including a break in the elicitation session.
Content of seed questions	A minimum of 11 questions were required to calibrate the experts. There was some difficulty in finding suitable questions, i.e. those which covered the relevant subject area and for which the majority of experts would not know the answer.

In retrospect it has been realized that the term “vertical puddle clay core” actually describes three separate facets of a dam core, for example a dam which is homogenous in terms of material can have a puddle core (i.e. a core zone where the fill is placed by puddling). Although this issue was raised in discussion during the elicitation, the wording of the questions was not formally updated to reflect this need for precision.

RESULTS OF ELICITATION

Weighting of experts

Although in the results of the first workshop every expert had a non-zero weighting (i.e. contributed to the synthetic DM), it was decided for the second workshop that the weight of the synthetic DM should be allowed to increase towards a maximum, subject to the constraint that a majority of the group (*i.e.* for no less than six of the experts) must retain non-zero weights (see Figure 2 below for an example). This point was reached for a calibration power of 0.5, and a chi-squared significance level of 1%. The net effect of excluding the five lowest scoring experts is to raise the normalized relative weight of the synthetic DM to 0.44, from 0.15 for the first workshop (no non-zero weights). The six surviving (non-zero weighting) experts have weights ranging from 0.19 down to 0.02 (equivalent to a highest-to-lowest weight ratio of 9*x*). The synthetic DM would now have more than twice the weight of the best positively weighted individual expert, and 22*x* the weight of the lowest, positively weighted expert.

As a comparison with the weighting from the elicitation, based on performance with the known seed questions, a mutual weighting of colleagues in the group was carried out in the first workshop. There are some significant changes in ranking between the two, for example some experts scoring significantly less well on the performance-based measure than their colleagues might anticipate, while others do much better. This is not an uncommon pattern of ranking in groups of specialists of any discipline: some experts are well-regarded but tend to be strongly opinionated, while other more reflective individuals, who may be considered indecisive or diffident are, in fact, better estimators of uncertainty. In the present case, where the quantification of model parameter uncertainties is one of the main objectives, it is appropriate that the latter experts gain credit for their ability to judge these things well.

Output from process

The 5%, 50% and 95% estimates provided by each of the eleven experts were combined numerically in a computer code version of the classical model to provide a pooled uncertainty assessment for each query variable, using each individual's weight as derived from his calibration and informativeness on the known seed questions.

A typical result is shown in Figure 1 in the form of the experts' range graphs. Figure 2 illustrates both a question with significant variations between experts and also the effect on the synthetic DM results when its weight is allowed to increase by raising the significance level of the calibration test. Figure 3 shows a sequence of how the combined results of the elicitation for one item changed:

- between the first and second workshops,
- after the second workshop, when one outlying expert reconsidered his responses,
- when a change was made to the way in which the synthetic decision maker's effective score was constrained.

Features of note are the significant differences in widths of ranges between experts, and also the commonly wide ranges spanning the pooled 5% and 95% responses, reflecting the significant uncertainty in some of the parameters of interest. For some questions there is a failure of some experts' confidence limits to overlap with others, suggesting significant discrepancies of opinion. This is as illustrated on Figure 2, where the maximum number of experts who overlap at any one value is only four out of the total of eleven experts; additionally there are two groups of opinion about what the appropriate scaling of the value should be. One of the reasons for repeating the elicitation was that the results of the first workshop had produced some items where responses clustered in two disjoint groups in this way, representing 'high' and 'low' schools of thought. This effect had generally disappeared in the results of the second workshop, leaving only marginal instances, as shown on Figure 2.

In Figures 1 and 2, the 5% to 95% confidence spread of the synthetic decision maker spans the whole range of 50% estimates that are provided by the experts when each has a non-zero weight in the analysis. As a result, the DM encompasses the full extent of opinion but then, inevitably, exhibits a much wider confidence range than that of any one expert.

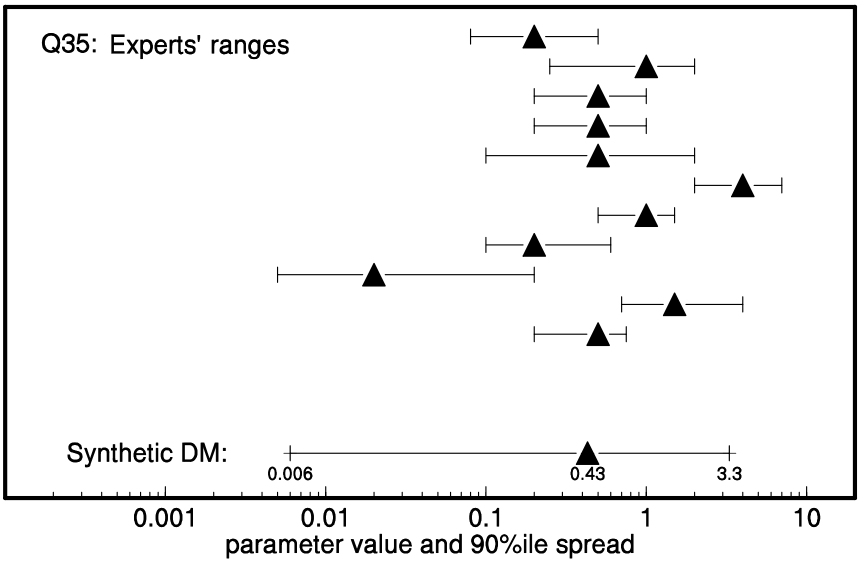

Figure 1. Typical range graph (Q35, median value for population of all UK embankment dams of dam critical flow i.e. uncontrolled erosion flow at which control of the reservoir has been lost)

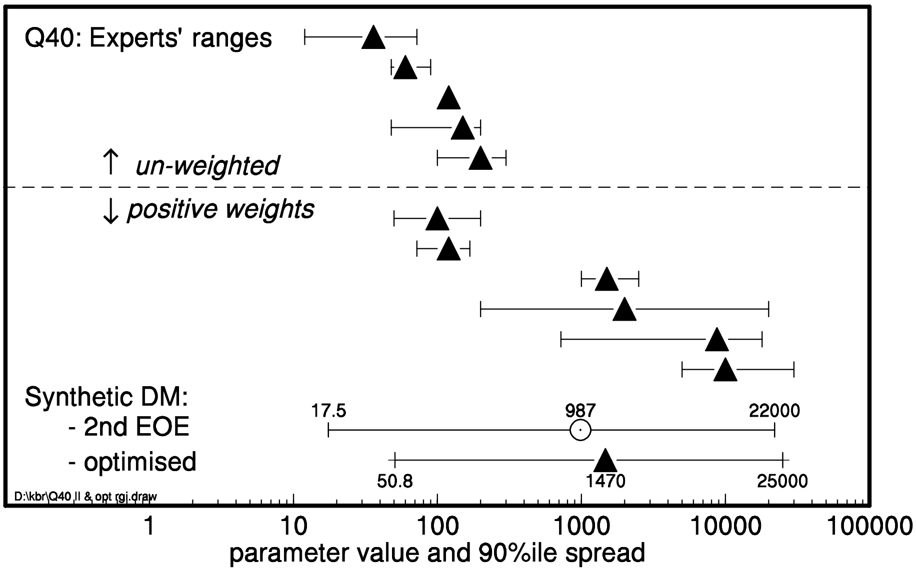

Figure 2. Range graph for Q40 (the time from detection to failure of puddle clay dams due to concentrated leak, in hours; for which only 10% of incidents are slower than this). Note for optimised DM the five lowest scoring experts, above the dashed line, are discounted – note their relatively high opinionation.

Steps can be taken to moderate this effect. If the synthetic decision maker is treated as a virtual expert, and included in the analysis, the calibration test significance level can be chosen so as to optimise the DM's distribution. While reducing the significance level enables all experts to receive positive weight, it does so at the expense of degrading the DM's calibration and entropy scores. Thus, an uncritical combination of expert assessments generally results in very large confidence bounds for the DM, as evinced in Figure 1. In the present case, the significance level was adjusted to the point at which there was still, overall, a majority of real experts with positive scores, as described earlier, thereby reducing the 'noise' of diverging opinions and improving the DM's calibration at the same time. Figure 2 illustrates how the DM's range is reduced slightly, and its 50% value more closely reflects the views the better-weighted experts; however, while some experts are discounted by this decision, similar views survive amongst those with positive weights, so such opinions remain represented in the elicitation.

It can be argued that, even though the DM's 5% - 95% range is typically larger than that of any individual, the spread is more representative of the proper scientific or engineering uncertainty for the variable in question. This is not implausible as some of the experts also present spreads in belief of similar magnitude.

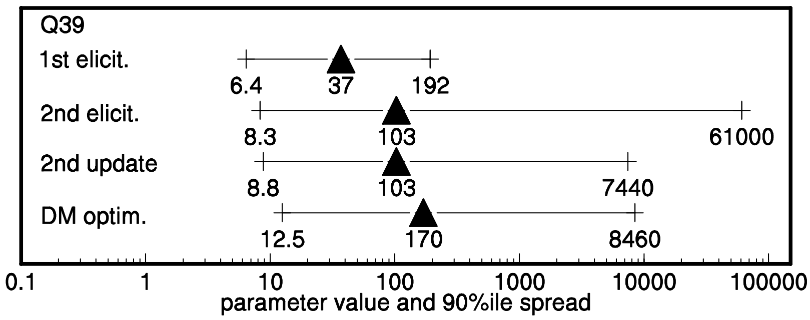

Figure 3. Example of changes between first and second elicitation

The way in which in which the synthetic decision maker's results changed through the various stages of the present elicitation process is illustrated in Figure 3. In this instance, the most marked change arose at the time of the second workshop, when technical issues were re-visited in detail and additional experts added to the panel. A few participants, who gave extreme or discordant values, were then given the opportunity to review their responses, resulting in the revised '2nd update' results. These outcomes were not greatly modified when the DM's weight was allowed to increase at the expense of a minority of the group ('DM optim.'), as just described, above.

Lessons learned

The elicitation process itself was new to all those who took part, and the key aspect that could be improved in future exercises of this kind is to increase ownership of the questions and issues by those taking part. This could be achieved by a longer workshop where the experts themselves assisted in setting the questions to be evaluated. Additionally, discussion could be stimulated by appointing protagonists to argue the case for extremes of possible responses (in some cases, it has been found effective to ask people holding opposing views to play 'devil's advocate', to argue the case for a particular position they themselves don't adhere to - this often reduces strongly-held dichotomies of opinion!).

ASSESSMENT OF RESULTS: ACCURACY AND PREDICTION

This section compares the elicitation responses with data available from elsewhere, and comments on the predictions made by the experts.

Questionnaire to UK dam industry

In parallel with the elicitation, a separate questionnaire was sent to 117 respondents, comprising all owners of more than 15 dams (20 number), a sample of 15 owners of one or two dams, all Panel AR Engineers (56 number), 10% of Supervising Engineers (24 number) and two research bodies. As well as questions relating to personal experience of internal erosion and opinion of the effectiveness of surveillance, requests were made for specific case histories of serious near miss incidents relating to internal erosion. This produced a total of 34 incidents from 19 respondents, and the data obtained are used here for comparison with the results of the elicitation exercise. It should be noted that these data were not available at the time of the first workshop, but a preliminary assessment was available by the time of the second.

Prevalence of leakage

The best estimate, from the elicitation, was that about 10% of puddle clay dams had ongoing steady leakage at each of the body of the dam, along an interface with appurtenant works and through the foundation, with 7% have leakage from the body of the dam into the foundation. Where leakage was occurring it was considered that ongoing internal erosion was occurring at about 10 to 17% of these locations. For homogenous dams steady leakage was judged as less likely (3 to 11% of dams, depending on location), with 7 to 17% of the leakages having ongoing internal erosion.

The questionnaire only provides data on serious progressive (deteriorating) internal erosion, which is likely to be less prevalent than steady ongoing erosion. This reported on average, for the period 1992-2002 three emergency drawdowns and ten precautionary drawdowns a year due to concern about internal erosion. This represents 0.2% and 0.5% of the stock of British embankment dams per year. These confirm that internal erosion is a serious threat.

Erosion and leakage rates

Figure 4 shows the results from three elicitation questions superimposed on a sensitivity study of how concentrated leakage might be expected to vary with crack width for a given crack height and length. The three points for each question represent 5, 50 and 95% uncertainty values. Flow in the crack is laminar up to 0.6mm, then turbulent. The experts' responses appear reasonable when compared with the sensitivity study.

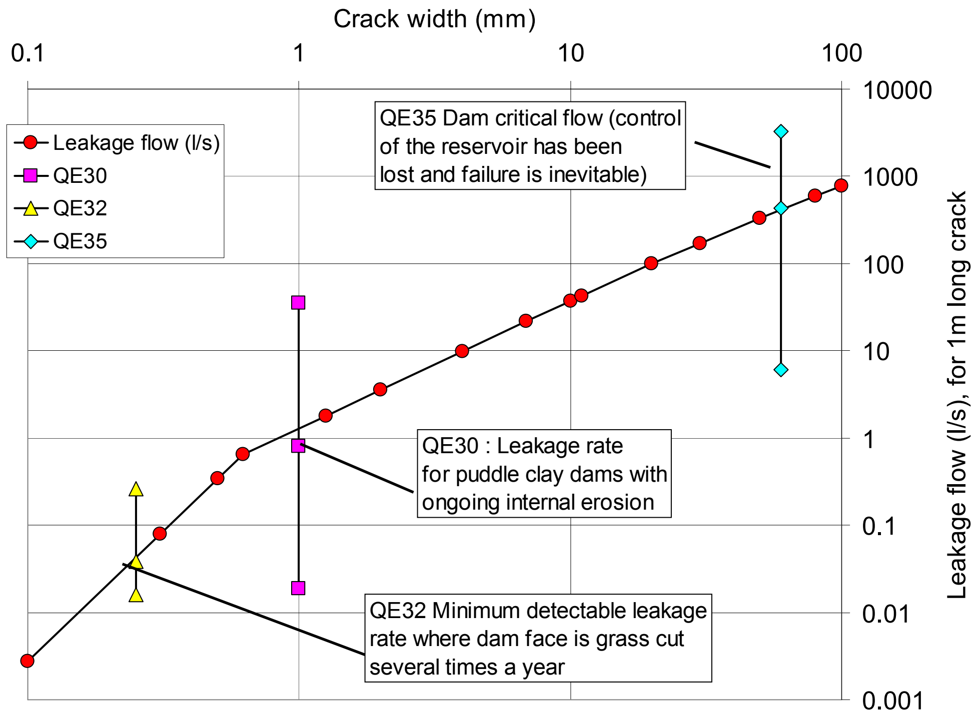

Figure 4. Sensitivity study of concentrated leakage flow to crack width (for flow through a 1m high 3m long crack under 10m head)

Rate of deterioration

Figure 5 shows the experts' opinion of the distribution of the time-to-failure for the whole population of UK puddle clay dams, if progressive internal erosion commenced at every dam, the time-to-failure being defined as that from the moment internal erosion was detected at a level of concern sufficient to call in an Inspecting Engineer to the time at which the dam critical flow rate was reached. Also shown on the figure is the distribution of the questionnaire respondent's opinions on how long before the dam would have failed in that incident, if there had been no intervention.

The significant range for the best estimate is noted, ranging from quicker than a day for 2% of dams to about 4 months for the slowest 2%. However, the response to the questionnaire suggests that the time to failure would have been much slower, with 75% of dams taking longer than 4 months. The significant uncertainty bands for the expert's opinion are also noted.

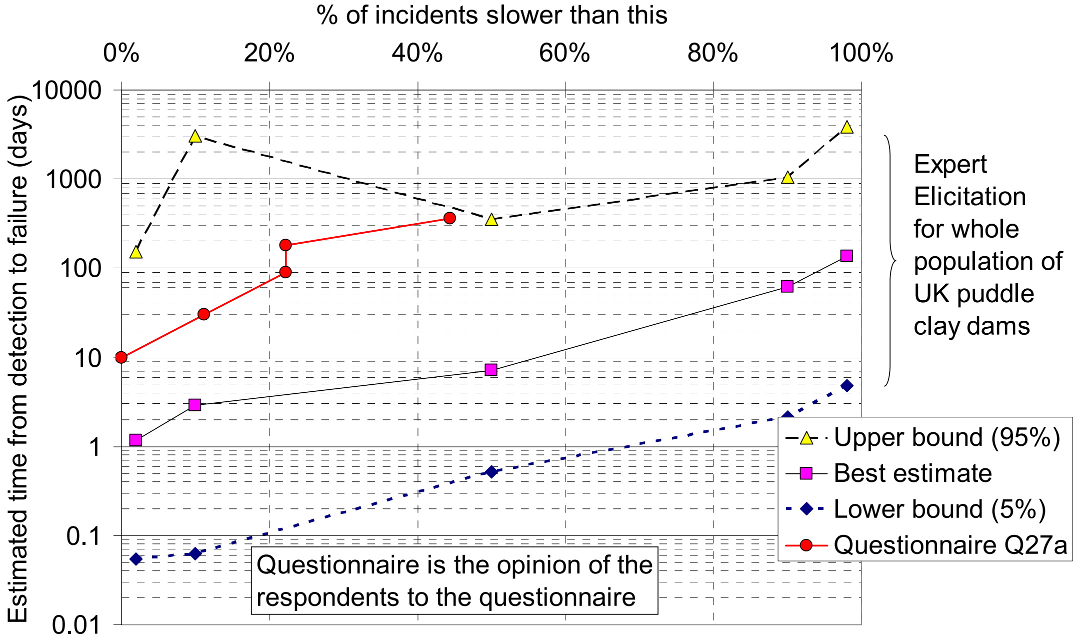

Figure 5. Distribution of time to failure for puddle clay dams

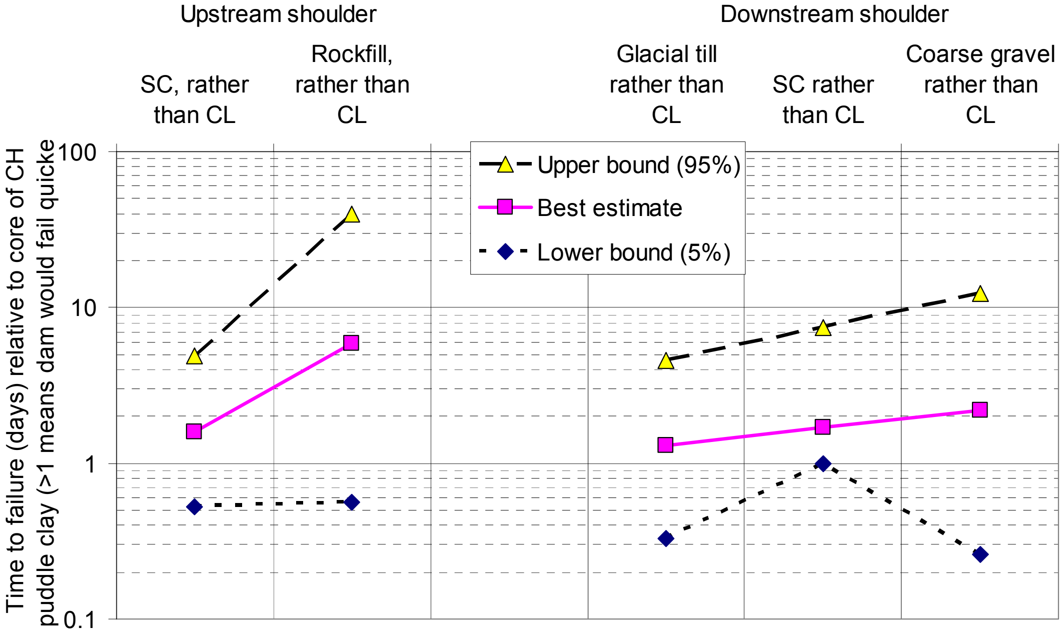

Figure 6. Effect of characteristics of dam shoulders on time to failure

Contributory factors to rate of erosion

The elicitation questions included the effect of factors such as the hydraulic gradient, the plasticity and degree of compaction of core material and properties of the shoulder materials on the time to failure. Typical output is shown in Figure 6. The expert opinion typically gave changes in rate of deterioration of up to 10; this may be low when compared to the ranges in rate of deterioration of several orders of magnitude.

DEBATABLE ISSUES

The understanding of internal erosion processes is still immature, with quantitative methods only available for limited elements. Tools that can help in either quantitatively capturing existing knowledge and experience, or in probing unexplored areas are therefore of value. The elicitation process set out by Cooke is of value in providing rational consensus, in that the opinions of the quiet reflective expert are considered, with appropriate weightings, just as much as those of more dominant personalities.

Elicitation has proved of value in making the wide spread of uncertainty explicit, and in capturing knowledge. The process adopted for this research contract did not fully explore the reasons for the wide discrepancy of results, but this could be pursued in future exercises. Debatable issues raised include:

a) most of the dam experts appear to give uncertainty bounds which are narrower than the true uncertainty, particularly where the uncertainty covers orders of magnitude - however, this trait has been found to be true of technical experts of all kinds;
b) the validity of questions which ask for the spread of a variable over the whole population of a particular dam type. It could be argued that for some of the dams the question is irrelevant, or inappropriate; however, to advance the knowledge of internal erosion further work is required at both a detailed level on specific dams and in understanding of the behaviour of groups of dams;
c) the validity of questions which simplify a complex problem down to focus on only one aspect of the problem, assuming "all other things being equal". For issues governed by two (or more) important interdependent variables this may be an over-simplification.

Possible applications of the technique include research into parameters which cannot readily be quantified, for example floods with an annual probability of less than 10^{-4}/ annum. Additionally in increasingly litigious times the underlying structured basis of the method can provide a valuable record of the way a decision was reached, the impartiality of which could offer both a significant shield against personal liability to individual experts providing critical advice and a transparent decision process for major organisations.

CONCLUSIONS

Expert Opinion Elicitation, a technique first developed for the space industry, was one of the techniques used in an ongoing research contract for Defra to explore current knowledge of internal erosion. It provided a useful set of judgments and insights, including explicit confidence limits, broadly consistent with the findings from the questionnaire to the wider UK dam industry. Significant advantages of the technique are the encouragement which the procedure gives to all participants to express their true engineering beliefs (unbiased by peer pressure). In addition, the combined output from the procedure (the synthetic decision maker) generally provides values for the complete set of questions that are, overall, more coherent and closer to reality than those that would be obtained from any one individual expert, however good.

It is concluded that expert elicitation provides a valuable technique for quantifying those variables that cannot be determined by direct measurement, and for evaluating realistic likely spreads of scientific or engineering uncertainty on engineering parameters.

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Dam Accident Data Base DADB - The Web Based Data Collection of ICOLD

J-J. FRY, EDF CIH, Le Bourget du Lac, France
A. VOGEL, Risk Assessment International, Vienna, Austria
J-R. COURIVAUD, EDF LNHE, Chatou, France
J-P. BLAIS, EDF CIH, Le Bourget du Lac, France

SYNOPSIS
This paper describes a database (DADB) that includes all information about dam failures which are necessary for the evaluation and the assessment of failure modes and hazards. The DADB currently includes about 900 events, all individually observed and investigated.

INTRODUCTION

Risk estimations associated with dam failures based on statistical studies had been difficult to carry out, because either the information of different data base were contradictory or no data were available. The comparison of different failure rates also faces difficulties, because some failure listings define "failure" as an accident that destroys a dam and renders it useless, while others mean a catastrophic accident, which releases most or all of the impounded water. In 1974 ICOLD published a first failure list, which presented 202 dam failures [2]. 5 years later the results of another investigation showed only 129 dam failures [3].

In 1995 ICOLD updated this compendium [4] by defining a failure as a collapse or movement of a part of a dam or its foundations so that the dam cannot retain the stored water. Accidents during construction were considered to be failures when a large amount of water was released downstream by a river flood which caused the partial or total destruction of the dam, whereby the height of the dam in construction when the overtopping began should have a height of at least 15m or reservoir filling had commenced before dam completion. According to these definitions 179 failure cases were determined, which all concerned large dams, according to ICOLD's definition from 1973 [1].

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

Therefore no catastrophic failures of dams during construction are considered, as long as the reservoir was empty and also no large slope stability failures during construction, which often led to critical situations for the workers. Not only reservoirs, which impound water, but also tailings dams, impounding tailings or toxic fluids have caused extensive damage in previous failures. The failures of the tailings dams of Buffalo Creek in 1972 caused 125 deaths and in 1985 in the Stava valley, Italy, 268 people died after a similar catastrophe, not to mention the contamination after the failure of the uranium tailings dam Key Lake in Canada in 1984 or the recent release of 100,000m^3 of contaminated cyanide liquid after the failure of a tailings dam in Romania in January 2000 and the subsequent poisoning of drinking water of more than 2 million people in Hungary.

ICOLD recognized the need for a compendium on failure data of such constructions and published for the first time in 2001 a bulletin concerning failure events of tailings dams [5].

Failure causes must be investigated irrespective of the dimensions of a dam or the extent of its hazard. The failure in 1972 of the Canyon Lake dam in the USA, which was only 6 m high, caused the death of 300 persons [6]. Data on failures of small dams include valuable contributions for the assessment of failure modes and causes, as well as for those of large dams [7]. The proposed DADB will be web based and include data on failures of small and large dams as well as failures of tailings dams (Figure 1).

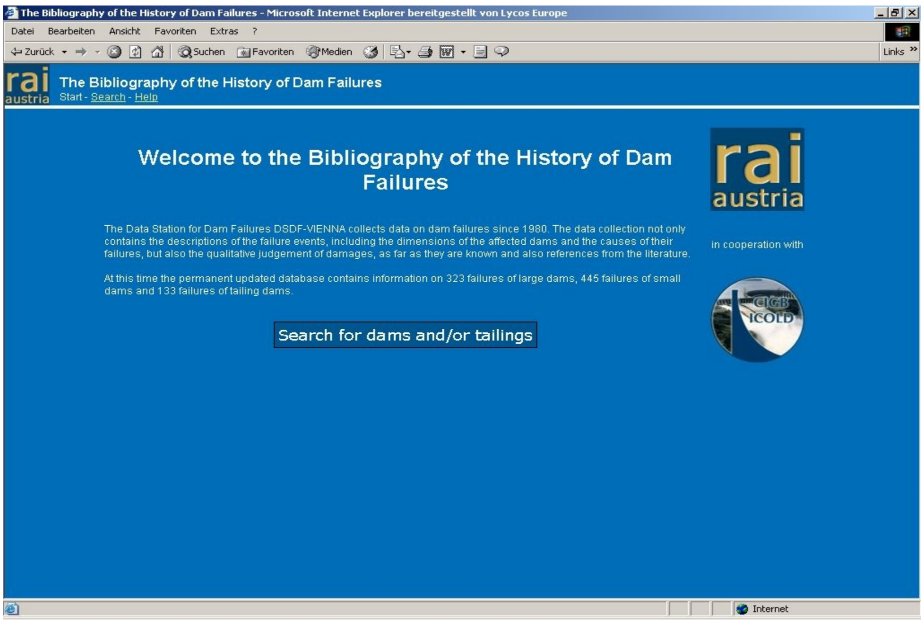

Figure 1: Front page of DADB

CONTENTS OF DADB

Dam information

The opponents of statistical studies based on historical records of dam failures criticise the fact that data of the past would be not homogeneous and therefore the dam failure information not directly comparable. The proposed DADB sweeps away these arguments and offers information about the name of the dam, the country, the date of its construction its purpose, the date of failure, the type of the dam, its height (above ground level and lowest foundation), crest length, crest width, base width, volume, upstream and downstream slope geometry. The type of material (watertightness, upstream shoulder, downstream shoulder, downstream protection), type of spillway (type, width, height, design flood), information about foundation (type, thickness) and reservoir (capacity, normal water level, maximum water level) will also be given. In cases of tailings dams the kind of impoundment is also available.

DADB will relate the failures exactly to all known current dam types. It was therefore necessary to distinguish between 20 different types of dams for water storage and 7 other special kinds of types of tailings dams, according to international regulations and their particular methods of construction.

DADB also provides the user with 7 different uses of the failed dams, which are the storage of tailings, for hydroelectric, flood control, irrigation, water supply, for wood transport or unknown purposes (Figure 2).

Failure information

To avoid probabilistic techniques to estimate dam failure risks and structural reliabilities it was stated that dams can fail through an infinite number of modes, which cannot be fully enumerated [8]. DADB contains the primary failure causes, which were investigated after the dam failures. 13 different failure causes, including the sensitive ones caused by construction or calculation errors or hostile failures are distinguishable (Figure 2).

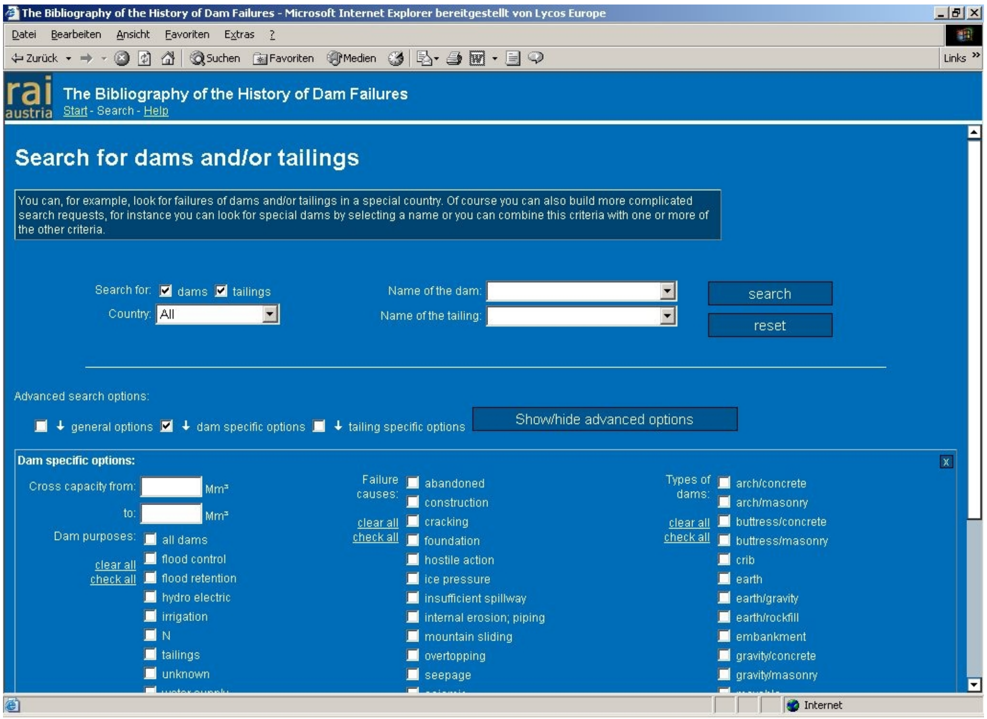

Figure 2: Advanced search page of DADB

The database will include (if known):

- information about breach initiation
- maximum depth above breach
- volume stored above breach invert
- evolution in time of overtopping
- breach height
- breach top width
- breach bottom width
- breach average width
- breach side slope
- breach and empty time
- breach peak outflow
- breach outflow hydrograph
- method of determining peak outflow
- flood peak entering in the reservoir
- flood hydrograph entering in the reservoir
- eroded volume
- outflow volume

Supplementary information

DADB also gives information about the human and the economic damage caused by a dam failure, as far as it was reported. In cases of tailings dam failures the volume of the outflowed tailings or contents and the travel distance is additionally available. Pictures of some events are also available, which show the dimensions of the damage to the dam construction. The pictures of the photo gallery can be enlarged to full size. (Figure 3).

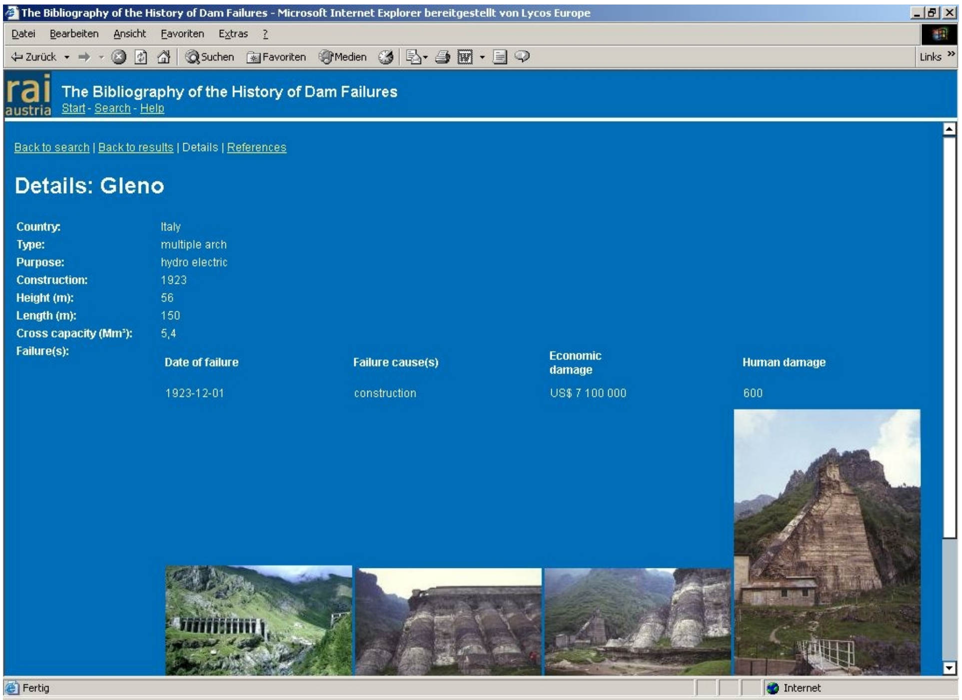

Figure 3: Example of a result page of DADB

Reference information

To verify the origin of the data, a list of references is included for each dam failure, to enable the user to get additional information to that presented on every result page (Figure 4). Most of the references will be also available in form of pdf - files

SEARCH OPPORTUNITIES

On the search page (Figure 2) it is possible to search for every single parameter which is mentioned, but also for all in every combination. The search for height, length and for the storage capacity or for the impoundment is possible for a special rate or in intervals. A click to one of the names of the dams in the summit list of every search operation leads the user back to the failure sheet for this dam, to provide him with the accompanying references, the photos and all the other parameters.

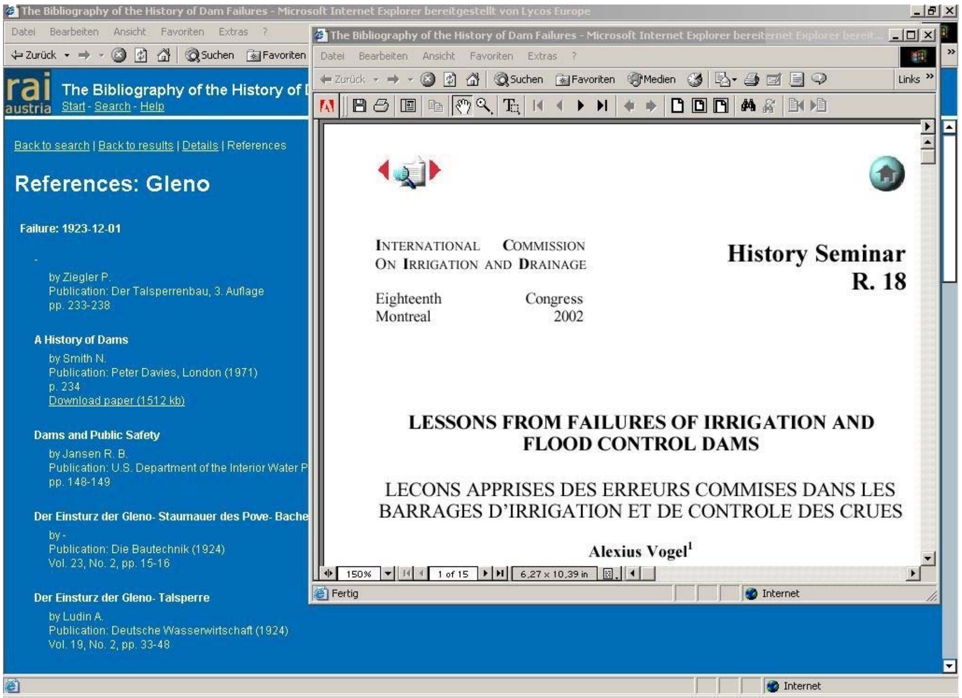

Figure 4: Example of a reference page of DADB

RESULTS

The number of all reservoirs impounding water, which are a standing menace to life and property will be today in the order of 400,000. DADB documents now more than 900 dam failures and 132 of those of tailings dams and will be updated permanent.

CONCLUSION

DADB includes all information about failures of water storage and tailings dams which are necessary for the evaluation and the assessment of failure modes and hazards. Today it includes about 900 events, all individually observed and investigated. The data are also usable for the assessment of failure behaviours and for the investigation of a probable existing failure-cause-specific break-mechanism.

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Comparison of some European guidelines for the seismic assessment of dams

N.REILLY, Consulting Engineer

SYNOPSIS. Following the publication of the Application Note to An Engineering Guide to Seismic Risk to Dams in the United Kingdom in 1998, a seismic working group was set up by the Euroclub of ICOLD. The purpose of this was to present and compare the approach to seismic appraisal of dams across Europe. To date guidelines for five countries (Austria, Italy, Switzerland, Romania and the United Kingdom) have been made available. The paper presents the key concepts of these and compares them.

INTRODUCTION

The document "An engineering guide to seismic risk to dams in the United Kingdom" (the British seismic guide) was published by the Building Research Establishment in 1991 as part of a large suite of guidance documents for the design and assessment of dams in that country. There are some sixteen similar semi-official guides applicable to dams in the UK but they are not codes of practice and have no formal legal force. Nevertheless they are widely followed, albeit tempered by engineering judgement in specific cases.

The British seismic guide was received as a very useful advance but there were many who thought its provisions were rather severe in terms of the magnitude of risk that dams were to be tested against. As a result a peer review was set up and this resulted in an additional document, the Application Note to the guide, being published by the Institution of Civil Engineers in 1998. This modified the seismic guide as described below.

In the course of the peer review it was suggested that a working group of the Euroclub of ICOLD be formed to prepare a comparison of practice across Europe in relation to the seismic assessment of dams. This was done and copies of guidance documents (codes in some cases) from five countries have been received and reviewed. This paper presents a brief outline of each

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and compares them. The key features are summarised in a comparative table (Table 1).

UNITED KINGDOM

In the UK the key document (Charles et al 1991) was published in 1991 and contains in Part A a brief but comprehensive overview of seismic risk and hazard, drawing parallels with flood risk. It presents a summary of the parameters used to describe earthquakes and reviews the historical seismicity of Britain. The guide goes on to propose the standards to be adopted for the safety evaluation of dams in the UK, both existing and new. The **Safety Evaluation Earthquake (SEE)** is defined as the earthquake which will produce the most severe level of ground motion under which the safety of the dam against catastrophic failure should be ensured. The **Operational Basis Earthquake (OBE)** is also defined but the guide does not concern itself with this.

Dams are allocated a hazard category using the method of ICOLD bulletin 72 (ICOLD 1989) which takes into account reservoir capacity, dam height, number of persons at risk and potential downstream damage. This yields a classification number which puts a dam into one of four categories designated I to IV, IV representing the highest hazard. The guide recommends that category IV dams be tested against a 30,000 year return period event. Alternatively the maximum credible earthquake (MCE) estimated by a site specific study could be used. The MCE is defined as the earthquake that would cause the most severe level of ground motion at the site concerned which appears possible for the geological conditions. The other three categories are to be tested against events of return period 10,000, 3,000 and 1,000 years in descending order. For cases where a site specific study of seismicity was not justified, the guide presented a zone map dividing the country into areas A, B and C and tabulated indicative peak ground accelerations for the range of return periods. For zone A (the most seismically active) the recommended peak ground accelerations (PGA) range from 0.375g for 30,000 years return period, 0.25g for 10,000 years, down to 0.1g for 1000 years.

Part B of the guide contains three chapters dealing with embankment dams. The first chapter (Chap 5) outlines the effects of earthquakes on embankment dams and quotes some examples of UK dams which have been subjected to minor events. (This is supplemented in an appendix by a similar review of world wide incidents). The next chapter outlines the methods of analysis available and the final chapter in this part presents recommendations regarding which methods to apply as a function of height and hazard category.

Table 1: Key features of seismic safety assessments

CHARACTERISTIC	**UK**	**AUSTRIA**	**ITALY**	**ROMANIA**	**SWITZERLAND**
Status of document	Guide	Guide	Guide	Statutory	Statutory
Hazard designation	ICOLD Bulletin 72	Dam ht, capacity	ICOLD Bulletin 72	Not stated	Dam ht, capacity
Seismic variation	1991: zone map 1998: contour map	Zone map & contour map	Zone map	Zone map	Contour map
Maximum PGA	1991:0.375g 1998: 0.32g	MCE: 0.3g OBE: 0.14g	>0.6g	0.32g	0.03 to 0.16g (for 475 years)
Return periods:					
Cat IV	10,000 yrs/MCE	)Where	>2500 yrs	Top cat: MCE	Not applicable
Cat III	10,000 yrs	)applicable	2500 yrs	or 800 years	(I) 10,000 yrs
Cat II	3000 yrs	)use	1000 yrs		(II) 5,000 years
Cat I	1000 yrs	)MCE	500 yrs		(III) 1000 yrs
OBE	Not stated	200 yrs	Not stated, see text	100 yrs	Not stated
PGA analysis factor*	0.67	Not stated	0.5 to 0.67	Not stated	Not stated
Site specific study	No recommendation	Recommended	Mandatory for cat IV	Recommended	
Seismicity	Very low	Very low	Moderate	High	Very low

*Reduction factor to be applied to PGA for purposes of analysis

Part C deals in the same manner with concrete dams and the quoted appendix reviews worldwide events.

The foreword to the guide stressed that it was provisional in character and would need to be reviewed in the light of experience. As a result of a general view that the risk criteria were unduly severe, a review started almost straightaway, culminating in the Application Note to the guide published in 1998 (ICE 1998). This introduced two main changes. Firstly the zone map was replaced by a contour map giving PGA's for 10,000 year return period events as a result of a nation wide study of seismicity (Musson and Winter 1996). This gives a maximum PGA (in zone A) of 0.32g,which is rather higher than given in the original guide. Secondly the return period for category IV dams was reduced to 10,000 years or MCE.

The Application Note also presents some new information. In the period since the introduction of the seismic guide two large owners of dams had carried out site specific assessments of seismicity for all their damsites. The results of these were summarised and presented. These in general agreed with the Musson and Winter contour map of PGA. The Application Note also presented summary results of a number of seismic assessments of a wide variety of dams, both of concrete and embankment types. It is notable that, to date, despite the great age of many UK dams, no dam has yet had to be strengthened solely for reasons of resistance to earthquake.

AUSTRIA

The Austrian seismic guide is published by the Reservoir Commission of the Federal Ministry of Agriculture and Forestry and is dated 1996. It appears to be part of a broader range of guidelines for dam design. The guide is specifically not a standard but there is provision for its application, procedures and criteria, to be discussed with the authorities. It applies equally to existing and new dams.

The Austrian guide is appreciably shorter than the British guide but it follows similar principles. It follows ICOLD Bulletin 72 in terms of differentiating between OBE and MCE cases but it does not specifically use the bulletin's system of hazard categorisation. Instead it states that for dams >15 m high or capacity >500,000 m^3 then both OBE and MCE should be checked. This would also apply for smaller dams in potentially dangerous circumstances. Otherwise only the OBE case need be considered.

For the OBE a contour map of PGA is presented which has a maximum PGA of 0.14g. The minimum to be considered is 0.06g. For the MCE the guide contains a zone map with PGA varying from 0.11g to 0.3g. However it suggests that in general a site specific study should be carried out.

The guide goes on to give some advice relating to material properties, methods of calculation and factors of safety. It also presents response spectra and time histories for use in analysis and gives guidance on post earthquake inspection.

ITALY

The Italian seismic guide was published by the Dipartimento per I Servizi Tecnici Nazionali of the Presidenza del Consiglio dei Ministri in March 2001 and applies specifically to existing dams. New dams are subject to statutory regulations which since 1959 have included seismic criteria. The seismic guide may be used where it is not possible to apply the current criteria to an existing dam.

In format and philosophy it follows the UK guide quite closely but there are some significant differences which are outlined below.

The system of hazard categorisation follows ICOLD Bulletin 72 but the return period of the events for each category differ markedly. For category IV the return period of the SEE event is specified as not less than 2,500 years or MCE, the definition of the latter being as defined above. For categories III, II and I the return periods are respectively 2500, 1000, and 500 years.

In an appendix, the guide gives some advice on the definitions of high, moderate and low downstream damage. It suggests that high is greater than 1% of gross domestic product (GDP), moderate is 0.1 to 1% and low is 0.01 to 0.1%. Damage less than 0.01% is regarded as none or negligible.

The SEE to be applied is defined by the PGA and there is a legally established map of the country which identifies three seismically active zones and an unclassified zone. For a return period of 2500 years the maximum PGA is given as 0.6g and the minimum (applying in the unclassified zones) is 0.2g. It should be noted that these are the minimum values for category IV dams because of the “not less than 2500 years” criterion mentioned above.

The guide defines the available methods of analysis in a similar way to the UK guide but is more prescriptive in relation to category IV dams which must be subjected to field investigation and dynamic analysis. It also gives more detailed recommendations with regard to material parameters and safety factors and has a section on appurtenant structures.

For the OBE case, the guide recommends using the appropriate zone PGA for category I dams divided by two.

When a dam has been subjected to an earthquake an inspection must be carried out and a report submitted to the authorities. Dams in categories III and IV, as well as those more than 45 m high or retaining more than 10 Mm^3 must be equipped with a seismic monitoring system comprising two strong motion instruments, one at the base and one on the crest.

ROMANIA

The Romanian practice in relation to seismic safety of dams is defined in the "Code for design and seismic safety assessment of dams and hydraulic structures", 3rd edition of March 2002. An English language translation is not available and the following is based on an English precis, hence the level of detail is less than for the other countries' guides. The document comprises a mandatory code plus a detailed advisory guide. It has to be read in conjunction with a code for dams (PE729) first introduced in 1979 by the Ministry of Energy. The latest edition is dated 2001.

Romania differs from the other countries reviewed in that it is seismically very active and a large magnitude event occurred as recently as 1977 (M_L 7.2). The guide contains a useful survey of historical earthquakes in Romania and, despite some very strong events, there has been relatively little damage to hydraulic structures.

The code makes use of two systems of classifying dams which are defined in other documents. The first is "class of importance" (STAS-4273/83) which relates to the economic and social value of the works. There are five classes designated I to V, I being the most important. The other system is "category of importance" (NTHL-021) which relates to the hazard posed by the facility. This grading has four categories, A to D, A being the highest hazard. From the documents available it is not clear how these are derived nor how they are used in combination. However the SEE for categories I/A and II/B appears to be derived by a site specific study with a return period between 475 and 800 years depending on the source of the event. For the lower categories (III, IV, V and C/D) only the OBE case is considered using zone maps giving PGA values for return periods of 100 years. Across the country the PGA varies between 0.08 and 0.32g.

The guide contains detailed recommendations regarding methods of analysis, material parameters and earthquake parameters (response spectra etc). It also addresses appurtenant structures, construction in seismic zones, instrumentation and rehabilitation of dams damaged by earthquakes.

SWITZERLAND

The Swiss seismic guide was published in 2003 as the "Directives relating to the safety assessment of reservoirs subjected to earthquakes" under the authority of the ordinance on the safety of reservoirs (OSOA) dated 1998. It applies equally to new and existing reservoirs.

In format and philosophy it follows the foregoing guides but is appreciably more comprehensive in its treatment of the subject and contains a great deal of theoretical background and bibliography. It also defines in general terms the qualifications and experience required of the engineers who lead the safety evaluation. These are more onerous for the highest hazard category of dam than for the lower hazard ones.

The system of hazard categorisation is based mainly on dam height and, to a lesser extent, reservoir capacity. There are three categories, I (the highest hazard) to III. Categorisation is done by reference to a simple chart of height against capacity. The main determinant is dam height and, broadly, any dam higher than 40 m is in category I and below 10 m is in category III but very large or very small reservoir volumes modify this. For category I the return period of the SEE event is specified as 10,000 years, for category II it is 5,000 years and for category III it is 1,000 years.

The appropriate PGA for the site and return period are given by a series of statutory contour maps for the country and these are supported by response spectra for three types of foundation taken from Eurocode 8. For a return period of 475 years the PGA varies from 0.03 to 0.16g.

The guide defines the available methods of analysis but is generally more prescriptive than the other guides reviewed. Category I dams must be analysed by dynamic methods with material properties obtained by field investigation.

In addition to sections on embankment and concrete/masonry dams the guide has a section on barrages, ie dams containing a preponderance of movable elements. There are also sections on instrumentation and post earthquake inspection. All category I dams are required to have strong motion instruments. Inspections and reports to the authorities are mandatory for all dams following events of specified severity, the threshold event levels being lowest for the highest hazard dams.

CONCLUSIONS

Seismic guidance documents for dams for a range of countries in Europe have been compared. The general approach is similar but there is a divergence on the degree of risk to be accepted for similar categories of dam. This is particularly true of MCE where, despite accepting the ICOLD definition, some countries use a probabilistic approach with a relatively low return period.

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SESSION 3
RISK ASSESSMENT AND RESERVOIR MANAGEMENT (PART 1)

Chairman Ian Carter
Technical Reporter Jon Troke

Papers Presented

1. Sri Lanka dam safety and reservoir conservation programme –
   L Attewill, L Spasic Gril& J Penman

2. Condition assessment of Government-owned dams in Finland
   P Vuola, R Kuusiniemi & T Maijala

3. Hydraulic and operational safety evaluation of some existing Portugese large dams
   E.R Silva, J.R Afonso & J.M Almeida

4. Reliability principles for spillway gates and bottom outlets
   G Ballard & J Lewin

Papers not Presented

5. Portfolio risk assessment in the UK: a perspective
   A Hughes & K Gardiner

6. FMECA of the Ajaure Dam – a methodology study
   M Bartsch

7. Agent-based dam monitoring
   V Bettzieche

8. Armenia dam safety project
   J Sawyer & L Attewill

9. Reservoir management, risk & safety considerations
   J.L Hinks & J.A Charles

Jonathan Hinks (Halcrow)
This is a question to James Penman and his co-authors although I admit that it is a rather loaded question. I see from the paper on work in Sri Lanka that they use both quantitative and semi-quantitative risk analyses. Now, I'm very enthusiastic about quantitative risk analyses but sceptical about semi-quantitative methods. Why score likelihood of failure from one to five rather than putting an annual probability to the failure? Similarly, why grade consequences as a failure from one to five? Why not express the consequences in some meaningful units like number of houses at risk or estimated cost of failure?

Professor David Bowles who is the director of the Institute for Dam Safety Risk Management at the Utah State University says that there is a need to use a proper risk metric rather than an index system. Further, that "folks think they are doing risk assessment because they multiply a "probability index" by a "consequence index". However, these simplistic approaches distort the true picture and, worse still, can direct a dam safety program in the wrong direction or leave it without the justification needed to move in any direction at all. The "opportunity cost" of index approaches is that they do not provide the justification to convince owners in the private and public sectors that dam safety work is needed by placing the justification on a cost effectiveness and risk-based scale that can be compared with other risks in other sectors of a business or a national economy."

I have now estimated actual probabilities of failure for 89 dams which I've inspected overseas and the clients have been happy with the work and have appreciated having the results expressed in real units and as mentioned by James the method facilitates the preparation of economic analyses for remedial works.

So having told James the answer I would like to hear, I will ask my question: How does he rate the comparative usefulness of quantitative and semi-quantitative methods?

James Penman (Jacobs GIBB Ltd.)
Well, I must say I'd agree with you on that. You see that things had actually moved on a bit between the presentation I gave and the paper that was written. In our final assessment on Sri Lanka the conclusions were based on the quantitative assessment rather than the qualitative. The qualitative was useful in the early part of the project where there were subjective judgements. For example, if you were looking at a dam trying to assess the probability of a piping failure, you would be able to initially just score that in a ranking based on individual assessment rather than to assign a probability at that phase. Thereafter, for the overall analysis (when it was combined) we did it on a probabilistic method.

Christine McCulloch (University of Oxford)
How do you ensure that your method of cost/benefit analysis does not reinforce the disparity between the rich and the poor?

James Penman (Jacobs GIBB Ltd.)
The analysis we did in terms of the impacts of the dams was looking at the area inundated. We worked out the value of the property that was damaged, the impact on the industry and impact on infrastructure. Everything was valued according to its true value.

Christine McCulloch (University of Oxford)
Surely that would privilege the wealthy people with the valuable property over the damage that might be done to many poor people whose property would not be of high economic value?

James Penman (Jacobs GIBB Ltd.)
Yes, you're right, viewing it in economic terms. We had to adopt some criteria for our work and it was done purely on economic terms and to that extent you're correct.

Jonathan Hinks
I think Christine McCulloch's question about reinforcing the disparities between rich and poor is a very important question and I think it needs more thought than I've been able to give it in the last couple of minutes.

We need to consider how risk analyses are going to be used. Are they going to be used to rank dams by priority for remedial works within a country or to compare investments in different countries?

Within an individual country I have tended to use a flat rate for a home regardless of whether it is a mansion or a shack. Likewise I have always used a single value for a life regardless of whether it is the life of a rich man or of a poor man. If you do this I do not think that there is an in-built bias.

I would use a different value of human life in a rich country than in a poor country to reflect perceptions on the ground. However our analyses are unlikely to be used to compare investments in different countries. When discussing the cost of remedial works it is worth remembering that they may be cheaper in countries where labour rates are low.

Alan Brown (KBR)
In response to the question by Christine McCulloch, it should be noted that the measure of tolerability of risk preferred by HSE in Reducing Risk, Protect People (HSE, 2001) is the "as low as reasonably practicable" (ALARP) approach, which quantifies the cost to save a statistical life. Use of the term "statistical life" is deliberate, as this does not differentiate in value of life between rich or poor or age or other characteristics of the person at risk.

The second point is question for James: How was the annual probability of failure due to internal erosion estimated?

James Penman (Jacobs GIBB Ltd.)
We split it into three categories, between whether it was low, medium or high risk, based on the assessment of the dam, how much seepage was coming through, the condition of the seepage and whether it was being monitored. Then the probabilities we assigned to those were inevitably rather arbitrary but were really based on our perception of the level of risk compared with other modes of failure. A low probability of piping had an annual probability of about 10^{-4} going up to about 10^{-2} for a high probability.

Francoise Lemperiere (Hydrocoop)
One question to Mr Almeida and possibly to all others. How do you link the probability of failure with the probability of overtopping of dam crests?

I have studied 100 dam failures due to floods. It is often considered that any overtopping can destroy embankment dams, and that concrete dams (and possibly masonry dams) may tolerate a greater amount of overtopping. However, this may not be true. Maybe earth filled dams have tolerated up to fifty centimetres of overtopping over an hour, concrete dams have tolerated one metre of overtopping over an hour and a number of masonry dams (which may be the most dangerous) can fail before overtopping occurs. The list of overtopping for low concrete gravity dams may be higher than for high gravity dams because the impact of two-three metres overtopping is relatively much more for a low dam than for a high dam. It may be possible for concrete gravity dams higher than 20m to shake when a 10-15m high concrete gravity dam may have failed. So the link between overtopping and failure should be according to the dam height.

Juvelino Almeida (Institute of Water, Portugal)
In fact in Portugal there is big discussion because some people think that they should act according to the effective risk. As you know, the effective risk is the potential risk times the probability of failure but our regulations around the world tend to work with the potential risk. In Portugal we work with the potential risk in total terms. In some countries they work with the same amount of potential risk related to the natural conditions.

What do you think it is we need to study? The possibility? The potential risk is the potential possibility, so is it possible? It doesn't matter very much which probability. Is it possible? No? One thousand in ten years? That's very dangerous. One thousand in a million years? That's not so dangerous but what if it happens if I am in that place at that moment? So, to the public in general the potential risk is not very easy to accept. We also had an overtopping recently in those storms I spoke about. We had an overtopping of a dam and a failure didn't occur and with some overtopping of small dams, failures did occur, happily with no fatal accidents. But the discussion goes on in Portugal – must we work or not with effective risk?

Most of the time the most dangerous occurrence is the overtopping and so we study what really happens to the downstream valley if overtopping occurs and with that we make emergency plans and we are trying now to implement those emergency plans.

Jim Clayton (Yorkshire Water)
A question for Mr Almeida about external emergency plans. Have any of these plans been published and, if so, what has been the reaction of the Portuguese public?

Juvelino Almeida (Institute of Water – Portugal)
Your question is about emergency plans and public acceptance. Well, as a matter of fact I must confess to you that our work is not as difficult as we may wish to think but there are some interesting points of view. We did some interviews with the local population living in the valley downstream of one dam that is around ten or twelve years old. It's a concrete dam 50 metres high and it's very interesting to hear the views of the public. They say that places where they have earthfill dams are very dangerous but that here they are very safe because there is a big wall of concrete and can now live in peace.

Your question is about public acceptance, another problem is not actually public acceptance but that when we try to do something more with local authorities such as small exercises it's not very easy because the Portuguese think an exercise is what they see in the movies, with emergency services etc.

We need to explain to them that this is not necessarily what exercising is. Exercising begins as five different steps and the first steps are some people around a table discussing small problems and the fourth level is discussions with all the staff, firemen, the owner of the dam, the authority and so on. But as a matter of fact I can't give you a very good answer because we are in the beginning of those plans.

We are doing internal and external emergency plans. Internal refers to an area where you have no time to advise the local authority (who could then advise the population). In such a case, if a failure occurs, it's the owner of the dam that needs to take actions protecting the population in the valley downstream. An internal emergency plan is developed for areas where the water will take half an hour to arrive and after that external emergency plans belonging to the civil defence authority are used. External plans have not been addressed as yet, and we are mainly working still on the internal plans. Perhaps at the next opportunity I could give you more details.

Chris Binnie (Independent Consultant)
James; you talked about a lot of instrumentation data at some of the dams you were at. My experience is that designers put a lot of instrumentation into the dams in order to be able to confirm that the dam is performing in the way that they had designed it. But, that quite a lot of those instruments are not necessary for the long term checking of the operation of a dam. My experience is that you can leave the people to collect a lot of instrumentation data but they don't really know what that instrumentation data is for and you finish up with files and files of numbers. I have found that about ten years after the dam has been completed the operator can cease collecting probably two-thirds of the instrumentation data because it's no longer required as the dam design parameters have been proved.

The second point is that I have found that with instruments like piezometers it may be advisable to provide a trigger level at which the safety of the dam might be compromised. This means that someone collecting the data can readily recognise when there might be a problem with the dam and call someone more experienced.

Did you come across those aspects in the dams that you were looking at in Sri Lanka?

James Penman (Jacobs GIBB Ltd.)
On your first point I would agree with you. It's exactly the problem we found that the dams had been heavily instrumented for construction and had really served their use on that purpose. I think the issue there is that you never know when the instrumentation might be needed in the long term if something does go wrong and it's really quite a bold move to discontinue it. There's a good chance you might regret it later when you did need that data and if you don't continue reading it, albeit at a reduced frequency, there is a chance then that it does go into disuse and won't be there when you need it. So our advice on that on the Sri Lanka dams was to continue reading all of it but on a reduced frequency.

On your second point, what we were getting them to do with the instrumentation data on things like seepage was to have plots of the seepage through the dam not plotted against time but plotted against reservoir level. There would, therefore, be a normal band of readings where you would expect the seepage reading to fall and then anything on the high side of that normal band could act as the trigger level for them to go and investigate further.

Jean-Pierre Blasé (EDF-CIH, France)
To Pekka Vuola: You gave two filter criteria, the classical one by Terzaghi and a second one, is it the criteria by Fell & Foster or another? Did you choose it through experience that showed it to be good criteria to use?

Pekka Vuola (Finnish Environment Institute)
The criteria is based exactly upon the criteria of Foster & Fell but our opinion is that their presentation or concept is a bit complicated for practical use and the one that I presented is right for practical engineers but should be similar to the one by Foster & Fell.

Rod Bridle (Rodney Bridle Ltd)
The perfect filter approach does offer the opportunity to understand the mechanisms of internal erosion failure better. I have to say that I haven't yet figured how to work out the probability of failure when viewed against perfect filter criteria but I would recommend to our colleague from Finland to have a look at the paper and see if he can apply it.

SESSION 4
RISK ASSESSMENT AND RESERVOIR MANAGEMENT (PART II)

Chairman Henry Hewlett
Technical Reporter John Falkingham

Papers presented

1. Implementation of a probabilistic methodology for slope stability and seismic assessment of UK embankment dams
M Eddleston, L Beeuwsaert, J Taylor & K.D Gardiner

2. Ridracoli Dam; surveillance and safety evaluation reported on internet page
P Marini, P Baldoni, F Farina, F Cortezzi & A Masera

3. Developments in management of reservoir safety in the UK
A.J Brown & J.D Gosden

4. Reservoirs Act 1975: progress on implementation of the Environment Agency as Enforcement Authority
I.M Hope & A.K Hughes

Papers not presented

5. Use of satellite images in monitoring of hydroelectric generation plants: recent developments
G Franchioni, P Federici & A Tamburini

6. Use of expert elicitation to quantify the internal erosion process in dams
A.J Brown & W.P Aspinall

7. Dam accident data base – the web based data collection of ICOLD.
J.J Fry, J.R Courivaud & A Vogel

8. Comparison of some European guidelines for the seismic assessment of dams
N Reilly

Iulian Asman (Romanian National Water Administration)
I'd like to give you an abstract of my paper entitled 'Main Aspects of the Romanian Dam Safety Legislation – An Approach based on Risk Management'.

Under the present Romanian legislation concerning dam safety risk management is covered by regular dam safety evaluation, by continuous monitoring of dam behaviour, by state control and by emergency preparedness. The term 'risk' is included for the first time in the recently issued dam safety law. The paper deals with the basic principles of the new law including the concept of risk management. The first Romanian legislation was issued in November 2000 and it represents a joint effort of the Romanian National Committee on Large Dams (RNCLD) and of the National Dam Safety Commission. The RNCLD includes representatives from the Technical University of Civil Engineering and the two main owners of large dams in Romania, namely the Water Power Company and Romanian Water National Administration.

The legislation has 5 chapters and 31 articles that deal with general provisions, dam operating conditions, dam safety and risk management. The dam safety requirements are mandatory in all stages of a dam's life starting with design of the dam and ending with its decommissioning. Dam safety requirements cover water retaining dams, tailings dams and tailings disposal facilities, power stations, locks and above ground large channels.

In Chapter 1, General Provisions, dams are rated into categories of importance on the basis of a quantitative evaluation of their associated risk (DAR), a system of criteria and indices concerning the dam characteristics (DCS), the dam behaviour and dam condition (DB), and the dam failure consequences (FC). Dam rating in the categories of importance is used for dam monitoring level, prioritisation of dam safety assessment within a dam portfolio and the level of dam safety evaluation. The dam safety assessment is made by dam experts with appropriate qualifications and experience in applying best engineering practice and guidelines in the field of dams. Overseeing of the implementation of the technical provisions of the law is the responsibility of the National Dam Safety Commission whilst it is the dam owners who are responsible for observing and maintaining the safety requirements provided by the current legislation.

In Chapter 2, Dam Operating Conditions, the main elements relate to permits for the construction of a dam, licensing of dam operation and the monitoring of dams.

Permits for construction are issued only if the Minister of Water Affairs and Environment endorses the dam's safety taking into account the category of importance of the dam and compliance with state standards.

A license to operate the dam is issued only after assessment by an authorized expert of the dam's safety. Operating licenses are valid for a maximum of ten years and are renewed at intervals decided by the National Dam Safety Commission.

Dam monitoring is a strict obligation of the owner. Assessment of the condition of the dam and, in particular, of its behaviour must be made systematically, aimed at an early detection of a threat. Safety surveillance of dams that belong to Categories A and B, has to rely on monitoring instruments, regular technical inspections and periodical tests of equipment. Surveillance of dams within Categories C and D can be based on visual checks and regular inspections.

The law states that dam behaviour monitoring must be organised on three levels. The first and lowest level, involves the dam owner's certified personnel who carry out visual checks, measurements, primary evaluation and testing of equipment. For the second level, an experienced engineering team has to be employed to analyse monitoring data, carry out periodical inspections and prepare safety reports usually annually. At the third level a dam surveillance commission is involved which carries out site inspections and analyses safety assessment reports and approves normal or restricted operation and decisions for remedial works. Sanctions and penalties can be enforced on owners for any actions or negligence in monitoring which compromise dam safety.

Romanian legislation entrusts safety assessments to dam experts placing responsibility on the expert for his actions. The owner is legally responsible to follow the provisions for dam safety and he faces financial and legal penalties for non-compliance. It is also compulsory for an owner to develop emergency and evacuation plans for his dam.

Jonathan Hinks (Halcrow Group Ltd)
I would like to give a very warm welcome to the 'Interim Guide to Quantitative Risk Assessment' written by Alan Brown and John Gosden and published today. I obtained an advance copy yesterday and read it last night.

It looks an excellent treatment of the subject and my only question is to ask why the authors do not suggest a value for human life which would allow the consequences of failure to be expressed as a single number. Putting a value on human life is not easy but it would allow the risk to be expressed in £/year equivalent to the insurance premium that would be payable on the dam in a perfect market.

Alan Brown (KBR)
You refer to the 'value to prevent a fatality' in terms of deciding when the cost of risk reduction measures is proportionate to the reduction in the risk. Section 11.4.3 of the Guide notes the values used in other industries, and also that it's a difficult issue. If carrying out road improvements would save life, the value is about a million pounds per life but in the railway industry they are now having to spend a lot more than that per life. The argument is that going on a railway is an involuntary risk, you're putting yourself in the control of the train driver and the system, whereas in a car you are in control of the car. It's a developing area and the aim of the guide is to give guidance and identify some of the issues but not always give a hard and fast rule.

Peter Kite (Peter Kite Associates)
Question for Ian Hope. One of the requirements in the Water Act 2003 was that in the interests of National Security the Secretary of State may serve notice on an undertaker not to publish and withhold access to flood plans. What proposals are being considered on the level of security required for the storage and handling of documents and the level of security screening that will be required for people involved in drawing up flood plans?

Ian Hope (Environment Agency)
As I stressed in my presentation we are in the early stages of working with Defra to develop proposals for flood plans. We've got an open consultation process next summer, which is a critical opportunity for each of you to register your views. At this stage of the project I would probably say there are more questions than answers and Peter's highlighted one of the potential issues that we need to address. We are actively working through Defra with other government departments that will have an interest in flood plans and obviously toward the summer of next year we will be in a position then to release our proposals.

Neil Williams (Severn Trent Water Ltd)
This is a question to Ian Hope again relating to a flood plan. As a dam owner, we're concerned that the definition of a flood plan would be prescriptive and may not consider the investment that has already been made by some responsible owners. Could an assurance be given that in defining a flood plan that consideration be made of owners already significant investment in this area?

Ian Hope (Environment Agency)
I certainly appreciate the concerns – they've been registered from more than one quarter. The opportunity is there, Neil, for you today to write formally to Defra to express, firstly the concern you mention and also outline the extent of your current plans. We do need early engagement with the industry, to help shape our final proposals.

James Penman (Jacobs)
This is a question for Joanne. I can see the Monte Carlo analysis type approach you describe is quite an elegant way of working out probability of the factor of safety being left from one based in the standard deviation of soil parameters. Can you explain how you deal with variations in the position of the phreatic surface within the dam, because in my experience that is equally as important as the parameters themselves?

Joanne Taylor (MWH)
Currently we use a number of different scenarios depending on the information we have and you'll all know it can be very difficult to find the ground water regime within an embankment. So where we have sufficient piezometric information we model the piezometric surface as we perceive it, where we don't have that level of information we often use the concept of an r_u value to create an equivalent condition.

John Laing (Arup)
A question for Ian Hope. In the Reservoirs Act 1975, there is no time limit for the time from an inspection by an Inspecting Engineer or Supervising Engineer to the submission of the report to the owner. What is your opinion of an acceptable timescale and do you think that a formal timescale will be introduced in the future and that it will become part of performance monitoring for all Panel Engineers?

Ian Hope (Environment Agency)
I outlined the software system currently under development in my presentation. Firstly, I would stress that it's a very proactive system. 28 days before an inspection is due, the undertaker will receive a letter seeking notification of the proposed Inspecting Engineer. Once we get the response, the system will automatically check this against the Defra database to ensure that the engineer is properly appointed. Following on from that, once we've got a date for the inspection we'll be logging that into our system. There is an adjustable time scale for subsequent follow up. So, for example, if it's a Category A dam then we would be seeking follow up in 6 months' time. I would add that a 6 month period is an absolute maximum that we'd be working to initially for all risk categories and we will review this. Timescales are adjustable in the system and we will be adopting a risk-based approach to our work. I would stress that there will be a proactive response from the enforcement authority if we've heard nothing. I suppose the sub-question that you asked concerns legislation. I think it's quite important that when we get the experience of being the enforcement authority, say over the next 12-18 months there's bound to be issues that we do have to contend with that we would see better resolved through legislation. We would then hope to start to influence any changes in legislation we see necessary, particularly loopholes in the Act.

Rod Bridle (Rodney Bridle Ltd)
I am inspired by being quoted at length in Eddleston et al's paper (p 232) to raise another fundamental question, although first I would like to say how good it is to see how much progress has been made on probabilistic risk assessment in the four years since our conference at Bath.

My new fundamental question relates to 'acceptable' and 'tolerable' risk mentioned by several presenters. The question of imposing probability of death, however low the probability, by dam failure on communities downstream is one which society at large should consider and reach reasonable conclusions about. Society should decide what downstream communities should tolerate or find acceptable on the basis of information we engineers provide, bearing in mind that the benefiting communities bear the cost of making dams acceptably safe. My view is that our elected leaders represent 'society' in this context, and the Secretary of State's new powers, under the Water Act 2003, to order flood plans puts the Secretary of State in a position to make decisions about acceptable risks. Do the presenters and others agree that this is the proper approach, or do they, or anyone else, have different ideas on what are acceptable or tolerable risks or on how they should be imposed?

Geoff Ballard
Just a follow up to that last question of Rod Bridle's. If we take the example of tolerability of risk levels in other industries, HSE have explicitly said that it's their job to interpret public opinion and set the levels. It seems to me the Environment Agency is an enforcement agency exactly parallel to HSE in that situation and their job is to interpret public opinion and set the levels.

Alan Brown (KBR)
The following contribution with his thoughts on the issue was submitted, as a written contribution, after the conference

1. **Tolerable is defined** as "a willingness to live with a risk so as to secure certain benefits and in the confidence that the risk is one that is worth taking and that it is being properly controlled" (Reducing risk, protecting people, HSE, 2001, page 3). **The balance between risk and benefits (tolerability) is ultimately determined by society**, including for examples balancing the cost of water against the risk posed by water supply dams. Society's views are voiced through representation in parliament and executive government.
2. Nevertheless **responsibility for managing the risk** lies firmly with the owner of the hazardous installation and the duty of care they owe to everyone who is put at risk by the existence of that that hazard. This follows, for example the common law case of Rylands v Fletcher (1868) LR 3 HL 330, and also Principles 3 and 6 of permissioning regimes (Policy Statement by HSC, available at www.hse.gov.uk/enforce/permissioning.pdf). This will apply irrespective of any standard or guide that may be defined by Government or anyone as to tolerability levels. The reasonableness of the actions of the owner in managing any risk would in the last resort be tested and determined through courts of law.
3. Government is responsible for the **legislative framework** which seeks to ensure public safety through certain requirements on owners. For dams this is through the Reservoirs Act 1975.
4. **Assessment of safety at individual reservoirs** is through periodic inspections by qualified civil engineers. These are appointed to panels following Section 4 of the Reservoirs Act 1975 by the Secretary of State after consultation with of the President of the Institution of Civil Engineers (The "Reservoirs Committee"). These engineers use their judgement as informed by guidance/ technical standards which have evolved from collective experience and research.
5. The **enforcement authority** has an executive role in ensuring that safety works are executed. The suggestion that the Environment Agency should determine what is

tolerable is inappropriate for a number of reasons, including that their function as Enforcement Authority as defined in Section 2(3) of the Reservoirs Act 1975 is limited to enforcement of process rather than determining technical standards, and also that this would have the potential for the Agency to take on liability.

6. **Defra,** along with other agencies, **in its role as regulator**, promotes guidance on technical standards through promotion of research and Engineering Guides. Defra, liaising with Scottish and Welsh Government bodies, would look to the Reservoir Safety Working Group (RSWG), appointed by the Institution of Civil Engineers to advise it on the appropriateness of issuing new guidance to panel engineers (as was carried out recently on extreme rainfall). The RSWG is representative of the dam industry in that it comprises panel engineers (with links to Reservoirs Committee and British Dam Society), owners and enforcement authority. Advice can also be obtained from technical research contractor(s), either in place or appointed to advise on specific issues.
7. **Government Ministers** can therefore satisfy themselves that the guidance and other information issued to the engineers they have appointed stands up to contemporary technical scrutiny and is appropriate.
8. With regard to the wider issues of **education of the public and others to appreciate the risk from dams and measures being taken to manage these** this is the responsibility of all those involved in management of dam safety. This is necessary if societal decisions on tolerability of risk are to be informed decisions rather than knee jerk reactions, for example in the event a dam failed (which statistically will happen one day, albeit possibly not for many decades).

Ian Hope (Environment Agency)
The introduction of flood plans raises numerous issues that we need to work through over the next 12 months. Whilst the risks of an uncontrolled release of water is significantly low, this has to be placed in context. There has to be a structured strategic communications strategy in place ahead of the release of any information. We should not be alarmist, but it is important that risks are appropriately raised in people's minds, and they are not oblivious to the risk until an event happens.

Alan Johnston (Babtie Group)
The paper on Ridracoli Dam has a number of particularly interesting aspects but I would like to concentrate on the measures taken to make information on the safety of the dam freely available on the internet.

Dam engineers have been criticised for a reluctance to communicate in a transparent fashion with interested parties and the general public. This initiative by ENEL proves that the technology is available and the number of hits on the website is proof that it was fulfilling a role in disseminating useful information.

The authors have indicated that there have been difficulties in making the significance of the technical data understandable to a non-technical audience and this is not surprising. Accordingly it would be interesting to know how the dam owner is tackling this problem.

Our colleagues in Italy appear to be leading the field in developing techniques for informing the public on detailed matters of dam safety. Are there plans to extend internet coverage to other dams?

Roberto Menga (Enel.New Hydro)
- The internet presentation is reported in the web site www.romagnacque.it .
- The internet presentation is up-dated automatically every hour.
- The Internet presentation relevant to "Safety and Surveillance Conditions" is under final approval by the National Board Authorities for Dams and by the Civil Protection Dept. and actually is used for inner information inside the Company, as a part of the safety procedure of the dam surveillance.

Richard Guimond (Electrowatt Ekono Ltd)
For existing schemes in the UK and Internationally, if the risk is now quantified to a value much higher than what was previously assessed, who is responsible for the higher risk coverage? Is it the Government or the insurance companies?

Alan Brown (KBR)
Neither. Normally it would be the dam owner, as owner of the hazard.