

DSC3D

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RELIABILITY OF SPILLWAY FLOW CONTROL SYSTEMS

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1. INTRODUCTION

The normal requirements of the NSW Dams Safety Committee (DSC) are set out in its guidance sheets with its principal guidance sheet, *DSC Background, Functions and Operations - DSC1A*, outlining the DSC's general operations and authority.

The DSC has statutory functions under the *Dams Safety Act, 1978* to ensure that all prescribed dams in NSW are designed, constructed, maintained and operated to a standard where risks to the community are tolerably low. The level of risk is determined by the likelihood and consequences of failure. The reliable operation of spillway control systems is an inextricable component in the risk profile of any dam with these features. Their reliable operation is a critical factor in the flood capacity of a dam.

Dam owners, and their professional advisers, have full responsibility for ensuring the reliable operation of their spillway control systems, each with their own individual and specific issues. However, the DSC also has a responsibility to draw owners' attention to any DSC requirements (see section 2.2) for spillway control systems, as well as general issues or findings that may provide guidance to assist owners in their operational responsibilities. Accordingly the DSC has prepared this guidance sheet (with the assistance of Mr. Glen Hobbs – greatly appreciated by the DSC) outlining relevant matters required to achieve *good practice* for spillway control systems.

This sheet applies to all prescribed dams in NSW with spillway control systems (e.g. various types of gates and bulkheads, earthen fuseplugs, proprietary fusible spillway controls and their operating systems etc). It does not address the design and construction of these systems per se but rather the issues that directly affect their maintenance and their reliable operation during flood events.

For spillway gates this sheet adopts a systems approach, emphasizing that all components must perform adequately if reliability is to be achieved. It draws on the results of a recent survey of spillway gate systems and operations (Hobbs, 2003).

The DSC Spillway Control Safety Goals and Key Requirements (Section 2) at the start of the sheet are a summary - the whole sheet is to be read for a proper understanding of DSC considerations on the reliability of spillway flow control systems.

2. DSC SPILLWAY CONTROL SAFETY GOALS & KEY REQUIREMENTS

2.1 DSC Flood Capacity Safety Goals

The goals of the DSC regarding spillway control structures are:

- to ensure that dams have adequate flood capacity to result in tolerable risks to community interests;
- to ensure that the risks posed by the unplanned operation of the spillway control systems themselves, to community interests, are tolerable.

These goals have shaped the DSC's approach to the regulation of spillway control systems, as set out in Table 1. Subject to achievement of these goals, the DSC does not regulate the planned

operation of spillway control systems. Apart from the adequacy of flood capacity, it is the failure of spillway control systems, whether structural or operational, that potentially concerns the DSC.

It is for the dam owner to determine how the goals (including DSC requirements) will be achieved and to demonstrate to the DSC that the goals are achieved or will be achieved following safety improvements. The following sheet sections aim to provide guidance to assist dam owners in achieving these DSC goals.

2.2 DSC Key Requirements

This section summarises the DSC requirements outlined in this sheet.

7. Guidelines for Fusible Spillway Control Components

Under its current policy, the DSC does not regulate the planned operation of fusible elements but only regulates against unplanned operation or failures (see Table 1).

A fusible spillway should be designed and constructed as a dam in its own right. The following are key design criteria that need to be considered when designing a fusible system where breaching could adversely affect community interests:

- the fusible element is to be safe during normal load conditions;
- the consequences of the failure of the fusible element are to be tolerable in terms of community interests;
- there is to be a means of limiting downwards erosion – such as a properly designed concrete base slab;
- there are to be adequate trigger mechanisms to guarantee that the fusible element will fail at the required headwater level;
- there is to be a means of preventing premature fusing due to wave action;
- the design is to prevent premature fusing due to piping;
- there is to be adequate accessibility for surveillance and maintenance;
- the fusible elements are to be regularly inspected and maintained to ensure their operational systems are not adversely impacted;
- the breach is to progress in an orderly and predictable manner.

8. Reliable Gate Systems Operations

For prescribed dams with spillway gates, there shall be an easily updated and transmitted operations log (or software system database) to not only record normal operation and maintenance matters undertaken but record gate incidents and near misses and other relevant information that may impact on gate operation. The incidents should be reported immediately to the DSC if they relate to the potential for serious impact on dam safety. In any event, the incident log summary is to be included in each Surveillance Report (see DSC2C).

For prescribed dams with spillway gates, test procedures are to be developed to ensure all power systems, controls and limit switches, hoist equipment and the gate structures are regularly checked and maintained in as new condition.

Maintenance manuals are to be kept up-to-date and particularly need to be reviewed after equipment upgrades or modification to maintenance procedures.

Training formats are to include:

- formal training, including refresher training, often in a workshop or group environment;
- on the job training, including hands-on operation and basic maintenance procedures; and
- operation under simulated events.

DSC2C stipulates mandatory surveillance requirements that dam owners must meet at a maximum of five yearly intervals.

3. BACKGROUND

The reliable operation of spillway gates and other control systems is critical to the safety of many dam structures where they are required to release water during a flood event or an incident that may threaten the integrity of the dam. The need for reliable operation of spillway control systems has received increasing attention in recent years especially following some highly publicised and well documented failures of gate systems.

Dam owners are particularly becoming increasingly aware of spillway gate reliability and the serious consequences, both upstream and downstream, that may result from gate failure. Also financial constraints are forcing them to minimise their costs through optimizing their operations. Therefore the need to ensure that gates are properly designed, maintained and operated is paramount.

Table 1 - DSC Approach to Spillway Control Systems

Regulated by DSC		Not regulated by DSC	
Design to avoid inadvertent failure of spillway control system with significant consequences for community interests	Operations aspects that reduce the dam's flood capacity	Inadvertent failure of spillway control system without significant consequences for community interests	Operations aspects that increase or do not affect the dam's flood capacity
Examples: 1. structural failure of gate 2. piping failure of fuse-plug embankment 3. unintended opening of gates releasing a large flood	Examples: 1. failure of gates to open 2. failure of fusible elements to breach 3. gates or fusible elements opening too slowly or late	Examples: 1. failure of gates to close 2. structural failure of gate causing only a small flood	Examples: 1. gate opening rules - sequence, timing, steps 2. frequency of breach of fusible elements 3. downstream surge effects not related to unintended failures

Reports of spillway control failures, and discussions with dam owners and operators, have revealed that a combination of factors generally lead to an incident. Typical factors include human error, equipment failure, poor design, poor management direction and inadequate maintenance policy.

In all cases, no one event can be highlighted as the sole cause of the incident. To optimize reliability the complete system must be considered including:

- Hardware: from data input devices through power supplies, hoist units to gate and other control components;
- Software: operational instructions, PLC programs and control systems; and
- Liveware: management, flood routing staff, dam operators and maintainers.

4. CRITICAL ISSUES AFFECTING RELIABLE OPERATION

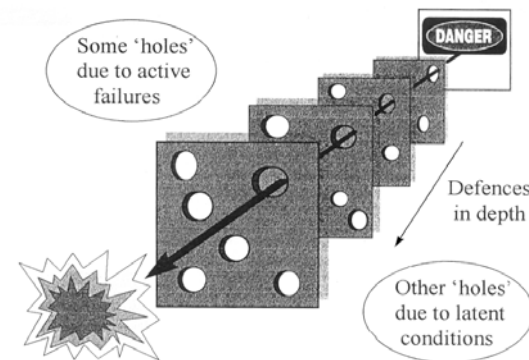
4.1 General

Whilst a spillway gate failure may seem unforeseen and totally unpredictable, a *post-mortem* will often reveal a series of events which led to the failure. In his book *Managing the Risks of Organisational Accidents* (Reason, 1997), James Reason argues that various defences or barriers must be breached for an accident to occur as illustrated in Figure 1. During normal operation one or a number of these barriers may stop a failure occurring.

4.2 Gate Failure Histories

There are numerous examples of spillway gate failures. Table 2 gives details of six gate failures and it can be seen that in each case there are at least two significant events which contributed to the gates' failure. Had one of these events been prevented, the system would probably have operated satisfactorily.

FIGURE 1 (from Reason 1997)



Gate operation involves the reliable interaction of the total system: from the collection of meteorological and inflow data to the gate movement, and then *ramping down* at the tail of the flood.

TABLE 2

DAM GATE FAILURE EXAMPLES (Hobbs 2000)

DAM	CONTRIBUTING EVENTS					RESULT
	1	2	3	4	5	
BELCI Romania	Heavy silting of dam	Poor operating instructions for extreme events	Mains power failure	Gate motors flooded due to poor location & failed to operate	Manual opening failed due to gate blockage	Dam overtopped & failed. 17 deaths
MAVICI Slovenia	Condensed moisture on contact terminals	Redundant relay activated (design fault)				Gates Open unexpectedly, flood wave downstream
ORD Diversion Australia	Gate transmitter failure	Control contactor failure				Gates fail to open and overtopped
MACHHU II DAM India	Under capacity spillway	Mains power failure				Delayed opening of gates. Dam failed. Hundreds killed
FOLSOM USA	Reduced bearing maintenance	Reduced structural maintenance	Poor gate design			Gate failed, uncontrolled discharge
TARBELA Pakistan	High ambient temperature (gate expansion)	Dramatically reduced seal clamp to side plate clearance	No slack rope switch provided on gates			Gate jammed then dropped, snapping ropes and damaging gate

4.3 Review of Gate Failure Database

In a recent international survey (Hobbs, 2003) dam owners were asked to identify incidents that occurred with spillway gate components. These incidents did not necessarily lead to gate failure but, as shown above in Table 2, a combination of such incidents could easily result in catastrophe.

The incidents are grouped under six categories as shown in Table 3.

TABLE 3
GATE FAILURE INCIDENTS

CATEGORY	RECORDED INCIDENTS (From a total of 60 incidents)	PERCENTAGE CONTRIBUTION
Human Factors	Maintenance related (10) Human error during gate operation (3)	22
Loss of Motive Power	Loss of mains (5) Motor failure (2) Failure of back-up power (2)	14
Control and Communication	Failure of limit switches (7) Position indicators (3) Controls failure (3)	22
Gates	Rollers or bearing failure (4) Rope failure (3) Miscellaneous (3)	17
Hoist Units	Screw thread nut failure/problems (2) Mechanical failure of hoist equipment (including keyways etc) (3)	8
Miscellaneous	De-Icing/heater failure (4) Operation manuals (1) Concrete movement/deterioration (incl AAR) (2) Trunnion anchor inspection problems (1) Float-well design/control issue (1) Truck loses load damaging hoist units (1)	17

Human factors and the failure of protection systems (limit switches, controls, position indicators, etc) account for the highest number of incidents, whereas hoist units, which are often seen as a source of failure, have surprisingly few incidents. Whilst the small data base does not give a strong statistical basis for extrapolating the results it provides an indicator of potential problems and unexpected incidents that may occur. It also highlights the fact that a holistic approach must be adopted when considering gate reliability.

4.4 Radial Gate Trunnion Bearings

One issue that has recently received close attention by dam owners world-wide is that of radial gate trunnion bearing failure. This follows the well publicized and dramatic failure of a radial gate at Folsom Dam in the USA. Since this failure there have been other reports of trunnion bearing failure or deterioration in radial gates (ref. 10) at other dams.

Whilst these failures are rare they can be catastrophic. The failures have involved both greased journal bearings and self-lubricated bearings. In response, many dam owners world-wide have

undertaken a check of their trunnion bearings. They have generally adopted one of three approaches:

- Replace suspect bearings-a very costly exercise;
- Monitor bearing condition and deterioration by checking friction (e.g. strain gauging of gate struts to determine friction induced stress or laser monitoring of strut deflection). Note, monitoring motor current draw is considered not to be sufficiently sensitive; or
- Determine the susceptibility of the gate structure and trunnion attachments to failure from high bearing friction, and, if the probability is very low, take no further action.

4.5 Individual Failures & Common Cause Events

Whilst failure of individual components is relatively common and may result in the loss of a gate, reliability studies have regularly shown that the greatest threat to spillway capacity results from *common cause* failure events (i.e. events that disable the complete spillway system or a large segment of the system). These failures are typically:

- Loss of power supply to site where there is limited backup supply, or back-up systems cannot raise all the gates in sufficient time. Common cause power supply problems may include contaminated common diesel fuel supplies, transformer or mains switchboard failure or mains cable failure;
- Communication failure such as between data collection and control systems or flood routing staff off-site, decision-makers off-site and dam operations staff;
- Human factors such as operational errors resulting in incorrect or delayed gate operation or operator injury;
- Systemic maintenance errors;
- Design faults (e.g. incorrect level monitoring devices, structural deficiency); and
- System control faults (e.g. PLC faults) or programming errors.

5. KEY FACTORS IN RELIABLE SPILLWAY GATE OPERATION

5.1 Reliability, Availability and Maintainability

Reliability is the common term that is used in relation to spillway gate operation. It is defined as the number of successful operations out of the total number of gate operations and is related to the failure rate of the gate components. However a dam owner is ultimately concerned with *availability* (i.e. the percentage of time that a spillway gate is operable) which is a function of reliability and maintainability as follows:

RELIABILITY + MAINTAINABILITY → AVAILABILITY

Maintainability determines the time that a system is out of operation, and is a function of preventative maintenance and corrective maintenance. It must be designed into a system. For instance, ease of access for maintenance of critical components, or the provision of

a bulkhead gate that can close into flow ensuring that a partially jammed spillway gate can be quickly isolated and repairs commenced rather than waiting for the storage level to drop. Maintainability is discussed further in Section 8.5.

Likewise reliability should be considered during the design phase such as selection of quality materials and components, appropriate design criteria and facility configuration, etc. Reliability assessment is discussed further in Section 8.8.

5.2 Reliability and Dam Safety Risk

The reliability of the spillway gate system should be seen in the context of a dam's overall safety risk assessment. The following factors should be considered:

- The greater the number of gates, the less significant is the effect of individual gate failure on the overall capacity of the spillway and hence the likelihood of a flood failure of the dam is lower than for a system with few gates;
- The greater the ratio of volume of maximum flood storage to maximum discharge capacity, the greater the storage margin (actually the time available for a successful response to a problem) in the event of gate failure. Hence the lower relative increase in the probability of dam failure in the event of gate failure (Lewin, 2003); and
- The greater the warning time between the initiation of a rainfall event and the requirement to open gates, the greater the chance of successful gate operation.

5.3 Processes and Components

A spillway gate system comprises seven main components:

- The data acquisition system including meteorological information, rainfall, river flow and storage level measuring devices and the data transmission system;
- Data processing systems and equipment including analysis by flood routing staff, dam operators and computer system;
- Communication and control systems both between dam site and remote offices and within the dam site;
- gate control systems including computer controllers;
- Power supply systems including backup systems and fuel supplies;
- Hoist units;
- Spillway gates and embedded steel work such as seal seats and guides, and
- Support structures including piers, hoist bridges, trunnion beams, etc.

To optimize spillway gate operation each of these components must meet acceptable standards of design and construction, and undergo regular maintenance, inspection and testing procedures, with clearly defined operational procedures and regular training of staff, as shown in Table 4.

TABLE 4

SPILLWAY GATE RELIABILITY PROCESSES AND COMPONENTS

		SPILLWAY GATE COMPONENTS						
		Data System Acquisition	Data Processing	Control& Comm.	Power Supply	Hoist Unit	Gates	Support Structures
KEY PROCESSES	Design	Ensure designed to a standard for the acceptable level of risk						
	Supply & Construction	Is in accordance with design drawings and to an adequate standard of quality						
	Maintenance	Regular preventative maintenance						
	Inspection	Periodic audit of equipment						
	Operation	Gate operation in accordance with clearly defined procedures						
	Testing	Periodic testing of all equipment and systems						
	Training	Regular training of all staff involved in gate operation						

6. Design Standards

Inspections and testing alone will not reveal all deficiencies and spillway control systems should meet modern operational requirements either:

- through ensuring they meet current design standards by appropriate design review or condition assessment; or
- identifying the risks and ensuring programs, back-up equipment and/or monitoring systems are in place to reduce the likelihood of failure to an acceptable level.

Critical areas include:

- Earthquake loadings and capacity for fuse-plugs, fuse-gates, spillway gates, hoist bridges and structures, and control system components;
- High confidence in operation of fusible spillway control components;
- Radial gates to withstand increased moments resulting from deteriorated trunnion bearings (eg the Federal Energy Regulatory Commission-FERC-in the US specifies gates should withstand a trunnion bearing friction coefficient of at least 0.3 (Tjomas, 2001); and
- Gate hoist structures, components and gates to withstand or be protected against high torque due to jams which take motors or hydraulic systems to stall load (USACE, 2000).

7. Guidelines for Fusible Spillway Control Components

7.1 General

A fusible spillway includes a component – such as a zoned embankment dam – that is designed to washout in a predictable and controlled manner.

Fusible spillway structures are unique in terms of their operational criteria in that they are required to be safe during the majority of the structure's design life and yet fail at a very specific load level. Thus the safety of the dam depends on achieving a load capacity to a precise factor of safety as any conservatism may cause a failure elsewhere in the dam. Similarly any under-design or poor maintenance may result in a failure of the fuse section during normal conditions, as has happened in several cases around the world (e.g. Lyell Dam-Lithgow, NSW & Hadlock Pond-USA).

Under its current policy, the DSC does not regulate the planned operation of fusible elements but only regulates against unplanned operation or failures (see Table 1). For example, a risk of failure of a fusible element to operate when intended could endanger the dam and would then be regulated by the DSC. Also, fusible elements are themselves dams and, as for any prescribed dam, the DSC does regulate the safety of the fusible element to ensure that it will not endanger downstream residents and interests by inadvertent failure and release of an unexpected flood.

A fusible spillway should be designed and constructed as a dam in its own right with particular attention paid to the matters in the following sub-sections.

7.2 Selection of fusible system

In addition to the normal technical and financial considerations in selecting a fusible system the owner would need to address the site specific factors such as staging of the breaches and the incremental impacts of surge flows downstream. Whilst current DSC policy is that it will not regulate the planned operation of fusible spillways, the owner has a legal duty of care to downstream residents and interests (see DSC2E).

A surge from the intended fuse failure could result in a sudden increase in flood heights for some distance downstream. The scale of any surge effect depends primarily on the type of fusible element and the segment length that breaches at a given flood stage. With earth bank fusible elements, it can be very difficult or impossible to avoid a downstream surge effect, where peak outflow discharge exceeds the peak inflow discharge. This effect needs to be analysed and the fusible system designed to limit adverse impacts to the extent that is practicable. In the United States, a downstream increase in stage of up to 600mm is usually regarded as tolerable (Tjoumas, 1993 – sub-section 2-3.1.6, bottom of page 2-11 and top of page 2-12-ref. 7). In Australia, the corresponding figure is 300mm (see, for example, the Glossary definition of *dam-break affected zone* in the ANCOLD Risk Guidelines - 2003).

Further, where the fusible element stores water at or below Full Supply Level, the owner shall consider the downstream impact of

unintended failure of the fusible section in Sunny Day conditions. The risk of such a failure is regulated by the DSC.

7.3 Design criteria for a fusible system

The following are key design criteria that need to be considered when designing a fusible system which is important to the safety of a prescribed dam or where breaching could adversely affect community interests:

- the fusible element is to be safe during normal load conditions;
- the consequences of the failure of the fusible element are to be tolerable in terms of community interests from loss of storage after the failure event. Where there is no significant impact on community interests, the owner may need to consider any business risks;
- there is to be a means of limiting downwards erosion – such as a properly designed concrete base slab;
- there are to be adequate trigger mechanisms to guarantee that the fusible element will fail at the required headwater level;
- there is to be a means of preventing premature fusing due to wave action;
- the design is to prevent premature fusing due to piping;
- there is to be adequate accessibility for surveillance and maintenance;
- the fusible elements are to be regularly inspected and maintained to ensure their operational systems are not adversely impacted;
- the breach is to progress in an orderly and predictable manner. In that regard the design should predict and verify the lateral erosion rate.

For embankment type fusible elements, the DSC expects that the design will at least comply with USBR's ACER Technical Memorandum No. 10 (USBR, 1987).

8. Reliable Gate Systems Operation

8.1 General

The following Table 5 specifies a listing of key factors that directly affect spillway gate reliability. It presents four levels of achievement for each factor. The DSC expects that prescribed dam owners would review and assess their spillway gate systems in the light of these achievement levels and, where necessary, would take action to move their spillway gate systems to Level 1.

Particular areas for owner's attention under each of these seven key factors are outlined in the following sub-sections.

8.2 Operations Logs

For prescribed dams with spillway gates, there shall be an easily updated and transmitted operations log (or software system database) to not only record normal operation and maintenance matters undertaken but record gate incidents and near misses including hardware problems, procedural issues, power outages, human factors and other relevant information that may impact on gate operation. The log should be accessible to all staff involved in

operation and management of the gates and staff should be encouraged to contribute without fear of reprisal or disciplinary action.

The incidents should be reported immediately to the DSC if they relate to the potential for serious impact on dam safety. In any event, the incident log summary is to be included in each Surveillance Report provided to the DSC (see DSC2C). The DSC will maintain a database of these incidents to assist in providing up-to-date generic safety advice to all NSW dam owners.

8.3 Testing Program

Periodic testing is crucial to ensure reliable spillway gate operations. For prescribed dams with spillway gates, test procedures are to be developed to ensure all power systems, controls and limit switches, hoist equipment and the gate structures are regularly checked and maintained in as new condition.

Checking procedures and operational readiness is best done through operational exercises simulating a hypothetical flood or dam safety emergency. Exercises should include all personnel involved in gate control and operations including hydrologists (flood routers), managers and operators. Some dam owners undertake simulation testing on an annual basis where, besides checking the complete system, it provides a training opportunity for all personnel.

Things to take into account during inspections and testing include:

- Testing of gates should involve the full movement of the gates from the closed position to open to fully closed. Testing gates under full head and flow conditions (i.e. under load) is preferable to no-flow (dry) tests, however there may be provisos to “wet testing” of gates to minimize storage losses and downstream surges;
- Testing periods should be determined in consultation with designers, equipment manufacturers and dam operations staff, and having regard to environmental protection legislation;
- Documenting of inspection and test data and recording site information (e.g. continuously monitor and record performance details such as volts and amperes per phase, hydraulic pressures, undue vibration or noise and check against previous results);
- Pre-inspection work including review of maintenance and repair flow charts and information from field staff;
- Testing procedures and practices should preferably be performed and documented by qualified engineering staff;
- Assessment of condition of embedded items;
- Interviewing operators to test their knowledge;
- Reviewing planned and unplanned maintenance history;

- Testing all systems and power supplies (including auxiliary supplies) and include exercise of remote as well as local / actual read outs. Auxiliary supplies should be checked at least monthly under load;
- Scheduling inspections to gain most information (e.g. outside normal release season);
- Ensuring focused attitude of the inspection team (ie forensic approach);
- Checking availability of O&M Manuals and Dam Safety Emergency Plans on site; and
- Consideration of certifying personnel before permitted to operate emergency discharge equipment.

TABLE 5
FACTORS AFFECTING SPILLWAY GATE SYSTEMS RELIABILITY

LEVEL	OPERATIONS LOG	TESTING PROGRAM	OPERATION MANUAL	MAINTENANCE MANUALS AND PROCEDURES	TRAINING	AUDITING AND CONDITION ASSESSMENT	RELIABILITY ASSESSMENT
1. <i>Excellent (includes Level 2 matters as well)</i>	<i>Log made available to other utilities for development of failure histories and data base.</i>	<i>Annual operation of gates and hoists in a flood simulation exercise involving all personnel involved in flood operations.</i>	<i>Process for staff to identify or suggest changes or procedural improvements. Effect of potential violations clearly stated.</i>	<i>Maintenance programs based on formal failure modes cause and effects analysis (e.g. risk centred maintenance). Process for maintenance staff to identify improvements or suggest changes. Effect of potential violations clearly stated.</i>	<i>Dam operators meet with other operators from other authorities. Rotation of staff between dam sites. Formal procedure for assessing competence of operators. Simulation exercises.</i>	<i>One off check of gate and hoist equipment against modern design standards under current potential loading conditions.</i>	<i>Assessment undertaken by independent assessors. Quantitative assessment of complete system. Results incorporated into overall risk profile for the dam. Broad results of survey made available to other authorities.</i>
2. Good (includes Level 3 matters as well)	Log of all incidents recorded including near misses and human factors. Operators encouraged to note all concerns. Log signed off by management.	Annual operation of the complete spillway gate system and all sub-systems checked, where possible under flow conditions. Performance of equipment recorded and trends noted.	Manuals reviewed yearly and after a flood event, or procedural changes. Photos of key equipment. All procedural steps clearly identified. System in place to ensure up-to-date manuals always available on site and in key offices.	Manuals reviewed periodically or after equipment upgrades. Photos of key equipment. All procedural steps clearly identified. Continuity of maintenance staff ensured (including contractors).	Flood routing and associated staff included in training sessions. Sessions coordinated and regularly revised by trained presenters. Mentoring program set up.	Establish current base line through 'one off' complete inspection of gate and hoist components against drawings. External audit of structures.	Reliability assessment (qualitative or quantitative) of the complete system. Human factor issues addressed. Program to identify critical issues established.
3. Fair	Log of gate and hoist failures.	Gates and hoists operated annually under no flow. Controls checked. Auxiliary power supplies operated monthly under load.	Manuals reviewed occasionally. Certified hard copies retained in key operational areas.	Regular maintenance with manuals reviewed occasionally. Operations staff involved in routine maintenance procedures. Sign off procedure at completion of maintenance task and after equipment checked and returned to normal status. Regular training of maintenance staff.	Dam operations staff regularly undertake training sessions, including formal procedures for 'on the job' training.	Annual condition assessment of structures and electrical and mechanical equipment. Report prepared with photos.	Qualitative assessment of structural, mechanical and electrical equipment. Critical equipment identified.
4. Poor	No log kept.	Ad hoc testing of gates.	Operation manuals not reviewed since commissioning of equipment	Maintenance haphazard and manuals and schedules not reviewed since commissioning of equipment. Operations staff not involved in maintenance	Dam Operations staff given no induction training on equipment and processes.	Nil. Run to failure for all equipment.	Nil Everything is OK (head in the sand approach!).

8.4 Operations Manual

For prescribed dams with spillway gates, test procedures are to be developed to ensure all power systems, controls and limit switches, hoist equipment and the gate structures are regularly checked and maintained in as new condition (see DSC2F). The Standard Operating Procedures and Flood Operation Procedures are critical parts of the Operations Manual that need to be regularly tested, reviewed and updated.

The manuals should be clearly set out with photos to identify critical equipment. The manuals should identify critical steps in a process with cautions and warnings as to what a violation could lead to (e.g. "Allowing the gate to remain at an opening less than the minimum position specified ('x' mm) will result in vibration and possible damage to the lower seal section"). Critical operations, as identified by a reliability assessment, are to be addressed and incorporated into operational procedures.

8.5 Maintenance Manuals (Systems) and Procedures

Maintenance manuals are to be kept up-to-date and particularly need to be reviewed after equipment upgrades or modification to maintenance procedures. The DSC's Guidance Sheet DSC2F has defined its basic requirements regarding Maintenance and Operation Manuals.

The manuals should be clearly set out with photos to identify critical equipment. The manuals should identify and document critical steps in each process with cautions and warnings as to what a violation could lead to (e.g. "over-riding, or disabling, this slack rope switch could lead to the gate dropping and snapping a cable if the gate jams or stops on debris during lowering").

They should include a table for adding suggestions for modified procedures or improvements to processes, or comments, with review and sign-off by management. The manual may incorporate programs based on formal failure modes-cause and effects analysis (e.g. Reliability Centred Maintenance, RCM).

It is suggested that where possible operations staff should be involved in at least basic maintenance procedures, to ensure a reasonable level of familiarity with the equipment. Familiarity of maintenance personnel with the dam equipment is critical (especially electricians), especially where maintenance is contracted out and continuity of personnel may be difficult to ensure. Electrical control circuits should be up-to-date and replacement parts should be readily available.

It is recommended that maintenance manuals incorporate a checking and sign-off procedure, with operation of the equipment at the completion of the maintenance task, to ensure the equipment is fully operational upon completion of maintenance.

Equipment maintainability can be improved through various procedures including:

- Designing equipment for ease of maintenance and ensuring easy, safe access;

- Ensuring correct tools and ample spares of critical components are kept on site;
- Adopting non-destructive and diagnostic techniques where appropriate to determine equipment condition and track deterioration (e.g. non-destructive testing of wire ropes, regular grease and oil sampling, current monitoring of motors);
- Considering formalising equipment inspections through condition indexing (e.g. refer to USACE, 1995); and
- Minimising the opportunity for human error through up-to-date manuals, checking procedures, detection systems etc (for further discussion refer to Reason & Hobbs, 2003).

8.6 Training

Training should encompass the theoretical and practical knowledge for the complete spillway gate system as mentioned in Table 3 above. Unfortunately, from a training perspective, spillway gate operations under flood are generally a rare event in Australia (also sometimes rare to have water ponding against gates) so there is limited opportunity for operators to gain *hands on* experience. Spillway gate operation during a flood event calls not only on technical skills but the ability to make decisions under pressure, manage stressed staff, interface with emergency services (SES, Police, etc), liaise with the public and concerned landholders, and control crowds. Of course this could be happening at night in poor weather conditions with concerns about the welfare of each operator's family.

Therefore training should ensure technical understanding and familiarity with equipment under all operational conditions (not just routine operations) plus ensure operators have acquired the skills necessary to perform under stress in an emergency. Training formats are to include:

- formal training, including refresher training, often in a workshop or group environment;
- on the job training, including hands-on operation and basic maintenance procedures; and
- operation under simulated events.

Some dam owners have instigated a formal assessment of staff competence following a set training program, including certification before the operating personnel are permitted to operate emergency discharge equipment. The dam owner also needs to ensure that appropriate training extends to staff located off site, who may be involved in the routing of the flood or advising operations staff during an emergency.

8.7 Auditing and Condition Assessment

Regular condition assessment of equipment is essential if reliable gate operation is to be maintained. Condition assessment and inspection basically involves two parts.

1. A periodic one-off assessment of the gate structure and hoist components which involves checking the equipment:

- a) against original design drawings to ensure the structures including the hoist equipment, have been manufactured and installed in accordance with the drawings, generally involving a check of component sizes, welds, etc; and
- b) by undertaking a design review and checking the structures and hoists against modern standards, or revised or upgraded loading conditions such as revised earthquake loadings, or structural regulations.

This assessment would normally be undertaken as part of a safety review of a dam (see DSC2D).

2. Regular checking of the structure for corrosion, distortion, damage, wear and deterioration. Ideally inspection check lists should be used, as they provide the basis for a systematic check of equipment and a formalised recording procedure.

In addition, DSC2C stipulates mandatory surveillance requirements that dam owners must meet at a maximum of five yearly intervals. The results of these associated inspections, along with photographic records, should be documented and archived for future reference and as a check for equipment deterioration. Recommendations for any more detailed safety reviews that are considered necessary are to be made in these Surveillance Reports.

Specialist engineers should be engaged where warranted depending on the complexity of the equipment. Critical equipment, as identified by a reliability assessment, should be programmed for regular inspection.

8.8 Reliability Assessment

Reliability (and risk) assessment are regularly used by many authorities to identify critical components and weaknesses in systems, and to identify and prioritise a works program. Any reliability assessment should be linked to the overall risk profile of the dam, including both upstream and downstream effects of gate operation (see DSC3B). Such an assessment should include human factors such as the predicted effectiveness of communication and decision systems, the availability of specialists (e.g. electricians), the training status of personnel and the likelihood of operator error. Another factor receiving increasing attention in recent reliability assessments are security issues including vandalism, sabotage and potential terrorist attacks.

There are broadly two categories of assessment:

- Qualitative only, where the gate system is analysed and gate reliability issues identified, but no analysis undertaken to estimate the probability of operational failure. This is the assessment usually completed and addresses potential failure modes and sometimes an assessment of consequences. A type of formalised assessment is the Failure Modes and Effect Analysis (FMEA), or if consequence is included, Failure Modes Effects and Criticality Analysis (FMECA - ANCOLD, October 2003-App D); and

- Quantitative based, where the gate system is analysed (e.g. using Fault Tree Analysis), reliability issues identified and reliability expressed as a value representing the probability of one or more gates failing to open or close (see ANCOLD, October 2003 - App F). Quantitative reliability is theoretically the estimated number of successful operations out of a total number of operations but, in practice, is our confidence that a gate will operate as planned when required to do so.

Experience has shown that judgments of the reliability of spillway gate systems are unreliable without a systematic, structured analysis of the total system. For this reason, the DSC requires that there be a quantitative risk analysis of the reliability of spillway gate systems in demonstrating dam safety (see DSC2D).

Any assessment should ideally look at the complete system, including hardware, software and liveware (Hobbs, 2000). It should range from the initial receipt of inflow data (rainfall, stream gauging, meteorology etc), through the processing of that data and the associated decision processes, to communication of operational decisions to site, the ability of operators to reach the site under flood or earthquake conditions, power supply, equipment, operation and control. Recent studies have shown that *human factors* (see ANCOLD, October 2003 and Hobbs & Azavedo, 2000) are critical factors in gate reliability, often dominating gate failure results. At the same time an automatic system is not necessarily more reliable.

Studies have also shown that the probability of a gate successfully operating improves if time is available to undertake repairs or correct a wrong decision. Hence for any study it is important to establish the time available to raise the gates in an extreme event, based on hydrological data.

A critical factor in quantitative studies is obtaining relevant data on equipment failures. Information for spillway gate components is very limited and therefore dam owners should be encouraged to share data on component and operational failures. A reliable record of incidents at a dam can also provide data on the frequency of occurrences needed in a reliability study.

Reliability assessments have regularly identified power supplies and actuation as key *common-cause* factors in spillway gate reliability. Therefore the following comments are offered as a guide to dam owners.

- Ideally any decisions regarding power supplies and actuation upgrades should be made following a reliability assessment;
- All emergency operating devices should have protected access for all emergency conditions;
- Dams should have at least one back-up power supply system (e.g. many critical gate installations have up to three independent supplies – Lewin, 1993);

- The need for further back-up systems is a function of a number of factors including reliability of the incoming mains especially in a storm event, site access, the time available to raise the gates in an extreme event, and the consequence of gate failure;
- There is a need to minimise the chance of a single event leading to system failure. Such events could include sabotage, fire, earthquake, landslide, fuel contamination, lightning, communication failure or level control malfunction, etc. Good practice includes:
 - providing separate storage for reserve fuel supplies for multiple back-up units;
 - routing back-up cables or hydraulic lines via alternative routes;
 - locating portable back-up units in a separate location to the main power supply systems;
 - providing back-up input transducers such as storage level indicators; and
 - having alternative communication systems (e.g. satellite phone).
- Hand powered mechanisms should never be viewed as suitable back-up actuation systems except on very small gates; and
- For critical installations an alternative actuation system should be considered. For example if the hoist is electric motor actuated then an alternative system to power the hoist should be provided (e.g. petrol or diesel driven hydraulic or pneumatic motors). Alternative actuation is especially critical where failure of some equipment may completely disable a system such as the loss of a common switchboard or control system. The back-up system should be capable of raising all the gates within the required time taking into account the possibility that the number of available operators may be limited.

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