# The safety of spillway gates

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## 1. Introduction

Large dams store huge amounts of energy: if it is suddenly released, disaster is inevitable. In 1952, Andre Coyne who designed the Malpasset Dam in France said: “Of all the works of mankind, dams are the deadliest.” In 1959, the Malpasset dam failed with a large loss of life.

Many large dams rely on spillway gates to pass floods. If these gates fail to open during a flood, the dam is likely to fail. As it seems that 20 to 30% of dam failures are caused by spillway gate failure, a significant improvement in gate safety is needed.[i]

In many cases all the spillway gates are disabled because of a failure of the control system or the power supply and the dam fails in a moderate flood. In some cases gates fail simply because the operators failed to initiate gate opening.

The paper discusses the safety of various types of gates and discusses what steps need to be taken to achieve a substantial improvement in safety.

The paper also points out that, under modern health and safety regulations, engineers are obliged to establish whether or not there is a risk to human life and, if so, study the options available to minimise this risk. They must make sure that their assessment is properly recorded and, if necessary, peer reviewed. If the health and safety regulations are followed to the letter, there will be a significant improvement in gate safety.

The paper also considers the role of Dam Safety Panels and recommends that their terms of reference include a requirement to review the risks, satisfy themselves that the option chosen by the designer offers the highest possible safety at a reasonable cost and record and publish the results of the analysis.

## 2. Safety considerations

According to Hinks[ii], during the 1987 floods in Norway, 50% of the dam owners experience problems with power failures, 23% had communication problems, 19% had failure of spillways to open and 17% had damage to the access road.

Another paper examined a number of problems related to spillways. It identified the failure of seven dams, the near failure of three more, four structural failures, 13 hoist and three control failures.

Many national dam safety guide lines specify that, for instance, the spillway should be able to pass the design flood with one gate disabled. Some engineers seem to believe that if the guidelines are followed the gate system is automatically safe. In fact gate safety can be guaranteed only if every individual part of the system has been carefully examined to determine the modes of failure and steps are taken to make sure that the risk of failure is extremely low.

According to Bowles[iii], the risk of dam failure from any one incident should be in the region of 1:10,000. Under most circumstances, failure of all the gates will result in dam failure. At a recent conference Micovic[iv] pointed out that the biggest danger to dams is that some or all of the gates will fail to open in a moderate flood, rather than failure of the spillway system to pass an exceptionally high flood. At the very least, the risk of all the gates failing to open should be less than 1:1000 rather than the ~1:100 that is not unusual for many gate installations.

## 3. Spillways

There are a wide range of options for discharging floods. They include:

- Simple ogee weirs
- Labyrinth spillways such as the "piano keys" weir developed by Prof Lemperiere
- Flapgates supported by hydraulic cylinders or air bags
- Tipping gates such as the Hydroplus fusegates
- Float operated gates of various types
- Radial gates with a range of lifting gear
- Vertical lift gates with a range of lifting gear

Modern practice is to also provide emergency spillways that will discharge a significant proportion of the maximum flood if the spillway gates fail or if a flood greater than the predicted maximum flood is encountered. There is a good argument for always providing an emergency spillway if power is needed to open the spillway gates.

Spillways that can pass the maximum flood without human intervention and with out any power supply are always the best option. In the past, they tended to be used on dams with relatively small flood flows because there needs to be a substantial rise in water level to pass a major flood. This means that the dam is higher than it otherwise would have been or that the storage and head available are much less than they would have been for a dam with a gated spillway. Recently labyrinth spillways such as the “piano keys” weir have been developed and will pass three or four times the flow of an ogee weir. The water level rise when passing of flood can be further reduced by using tipping blocks or Hydroplus fuse gates that pass water over the top during a moderate flood and tip over sequentially during a major flood they to allow much bigger flood flows to be passed. As they are normally arranged to tip in a 1:50 or even larger flood, the fact that a considerable amount of stored water is lost is not usually significant.

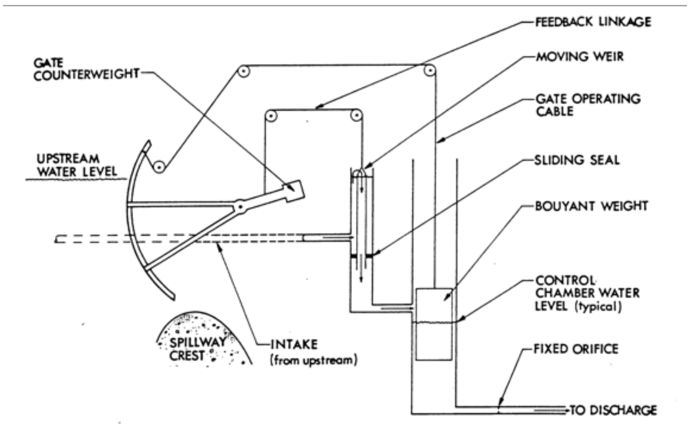
If none of the above options are satisfactory, then gated spillways can be used.

### 1.1. Flapgates

Flapgates are bottom hinged gates that are held up against the pressure of water by hydraulic cylinders or air bags. are ideal for passing moderate floods. Their major – and very significant – advantage is that, although they need power to close them and hold them up, the gates can be lowered without any external power supply and, with clever design, using only the water level to trigger lowering in emergency.

### 1.2. Float operated gates

There are a number of gates operated by floats that open reliably in the event of a flood without human intervention. A typical arrangement is shown in Figure 1. This type of gate is has been service in the Snowy Mountains Hydroelectric scheme for more than 40 years. My own firm designed and commissioned one more than 30 years ago and, as far as I know, it has never given any trouble.



BOUYANT WEIGHT CONTROLLED SPILLING GATE

Figure 1

Although somewhat unfashionable – for reasons that I do not understand – float operated radial gates are a viable option except, possibly, in the largest sizes. Because they do not require any external power supply and they will open if the water level becomes excessive, they are inherently much more reliable than conventional radial gates.

Recently a firm in South Africa developed an innovative gate that, in many situations, supersedes flapgates. The gate and its principle of operation are shown in Figure 2.

Under normal circumstances water in the ballast tank holds the gate closed against the force exerted by the water on the upstream face of the gate. As the lake level rises, the tank fills and maintains equilibrium. When the water level rises above the top of the ballast tank the force exerted by the water on the gate face exceeds the force exerted by the water in the ballast tank and the gate swings open. The rotation of the gate and tank causes water to spill out of the ballast tank thus allowing it to open even further. When the gate is fully open, the ballast tank is completely empty and is floating on the crest of the water passing over the spillway. As the lake water level decreases, the gate comes down and the tank refills causing it to close even further. The major advantage of this gate is that this completely water operated for both closing and opening. One minor disadvantage is that sometimes debris is trapped underneath the gate as it is closing. The debris can be cleared quite easily by cracking the gate by opening the drain valve on the ballast tank.

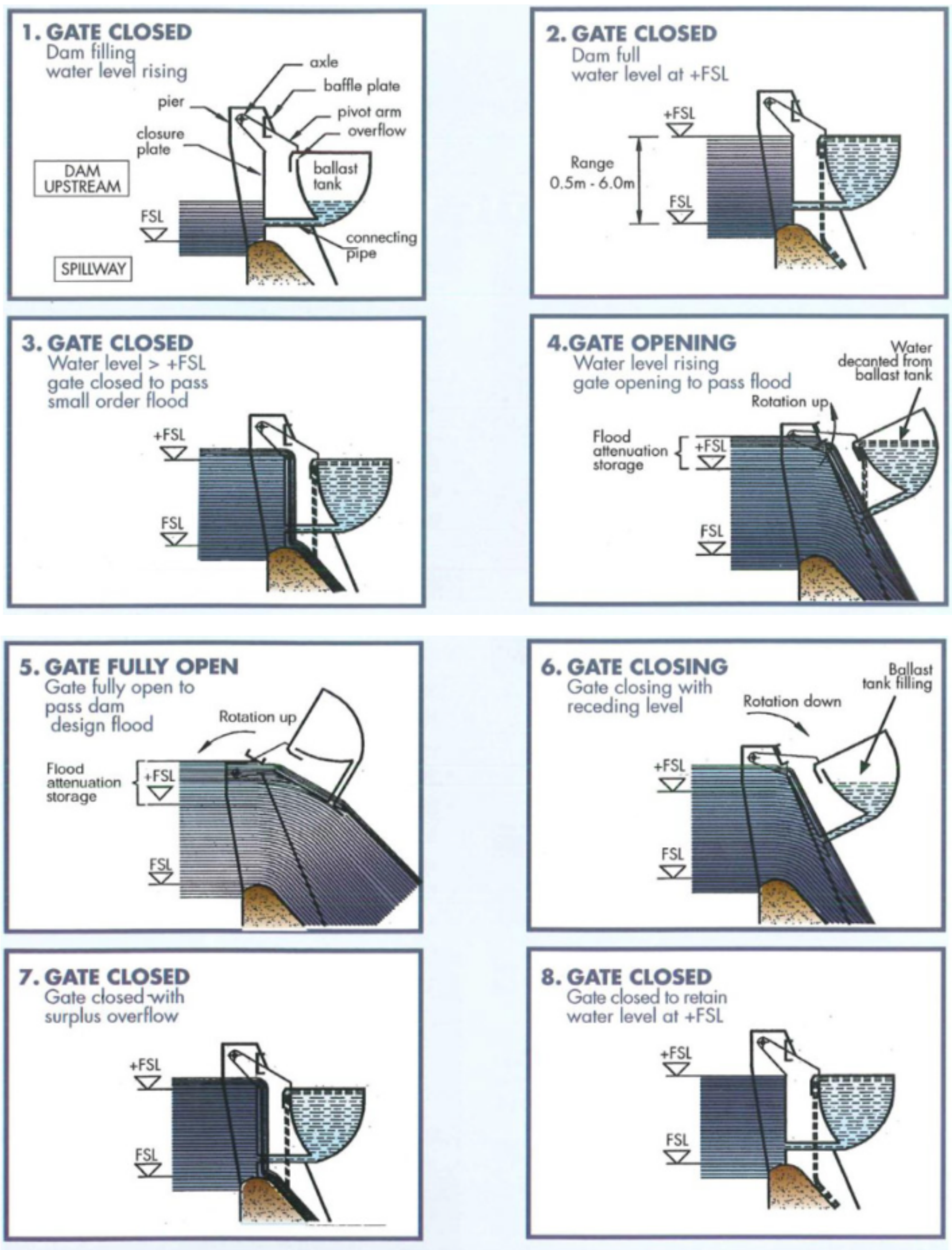



Figure 2

The largest gate that has been built so far is 20 m long and 5 m high so several of these gates can pass quite large floods. I believe that this gate should always be considered whenever flap gates are contemplated.

### 1.3. Radial gates

Most radial gates are lifted by hydraulic cylinders in tension, by chain lifting systems or by winches with wire ropes running down the upstream side of the gate. At some spillways, the gates are lifted by one or more gantry cranes moving from gate to gate. Such an operation requires several experienced operators.

All these systems require a power supply for lifting and if the power supply fails, the gate cannot be lifted. In some cases the designers provide for hand winding gear to be used in an emergency. This cannot be regarded as a credible backup system because no one can guarantee that a sufficient number of fit men will be available and able to get to the dam during the worst storm ever seen.

The gates can also be disabled if the power cable fails, if the control system or cables fail, if the operators do not initiate gate opening and so on. In most cases, the gates are opened by an operator observing that the water level will soon become dangerously high or on instructions from a central operator.

Now that many stations are being converted to remote automatic operation the very considerable additional security provided by the presence of a team of experienced operators can no longer be relied on. Whenever remote control is being considered, the safety of the spillway gates must have a very thorough review. The station should not be de-manned until a highly reliable system for lifting the spillway gates is in place.

In order to minimise the risk of failure to open, no single failure should disable all the gates. In many existing gate installations there are several individual failures that would disable all the gates and comprehensive analyses of gate safety sometimes show that there is a 1:100 chance that all the gates will fail when called upon to open. A safety level of 1:1000 is probably the lowest acceptable value.

### 1.4. Vertical lift spillway gates

Vertical lift spillway gates are even more dangerous than radial gates because of the high risk that the gates will jam while they are being raised. Many of them are raised using one or more gantry cranes moving from gate to gate. Most of them use wheels or caterpillar tracks to reduce friction. If maintenance is neglected, the wheels can seize up on the axles or the chains can break.

## 4. Examples of gate risks

### 1.1. Machhu 2 Dam, India

On August 11, 1979, the Machhu 2 dam in India failed and at least 2000 people were drowned. Investigations showed that the spillway was inadequate and three of the 18 radial gates had jammed and could not be opened using the electric winch system or the backup manual system.

A committee was set up to investigate the causes of the failure but was disbanded before it had completed its report.

### 1.2. Sayano Shusenskaya, Siberia

On 17 August 2009, the power station was flooded due to the catastrophic failure of one of the turbines. As a result of the failure, the power supply to the single gantry crane that lifted the 11 spillway gates at the top of the 200 m high dam was lost. Fortunately, an emergency power supply was organised and the gates were raised before the lake had reached a dangerous level. Had they not been able to open the spillway gates in time, the dam would have been over topped and may have failed. If it failed, 1 million people would have been at risk. There are now two gantry cranes to lift the spillway gates.

### 1.3. Kentucky Dam, USA

This 20 m high dam has a 24 bay spillway designed to pass 30,000 $m^3/s$. The spillway has double leaf vertical lift gates that are lifted out one after the other by one of two gantry cranes. To lift the gates, grabs have to be lowered through flowing water and latch onto the gates. It is often very difficult to latch on to the lower gate and to do so requires a skilled crane operator. Altogether, a team of five is needed.

The fact that there are two gantry cranes does not add much to the overall security because both cranes are parked at the powerhouse end of the spillway and if one fails, then the second crane cannot get past it to open the remaining gates.

Now that the Tennessee Valley Authority is contemplating operating its stations on remote control, it will be more difficult to ensure that a team of five people is always available to lift the gates in severe weather when roads may be flooded and their families may be in danger.

It seems that the Kentucky Dam is not an isolated case. There appear to be many dams in a similar situation throughout the United States and in many other countries.

### 1.4. West African Dam

An important dam now under construction in West Africa needs to pass a flood in excess of 3000 $m^3/s$. The 11km earth fill dam is designed with limited freeboard and there is no allowance for a rise in lake level during a major flood. There was also a saddle dam with rock foundations. No consideration was given to using this dam as an emergency spillway. The estimation of the maximum flood was based on 80 years of record and there was no margin for the uncertainty that such a short record brings. If the dam failed from overtopping then the downstream flood could easily reach 10,000 $m^3/s$ and could drown something like 20,000 people.

The original designers proposed a number of flapgates 6 m high. A different company was selected for final design and, without any explanation, changed to 18 - 6 m x 6 m radial gates using chain lifting gear. The emergency power supply consisted of one 100 kVA diesel generator that could not be tested at full load. All the gates were to be controlled by a single PLC and the specification for the mechanical and electrical equipment did not once mention the critical nature of the system and the need for extremely high security.

I was appointed to the World Bank sponsored Dam Safety Panel as hydro-mechanical engineer. The dam safety panel did not make a formal analysis of the safety of the dam but my own assessment of the safety of the spillway gates was that the system was unacceptably unreliable. I therefore recommended that the flapgates selected by the previous consultant be used. I also pointed out that the design flood was probably under estimated. The President of the Dam Safety Panel disagreed and told the client that the dam was safe. His opinion was accepted. I then had no option but to resign from the Panel.

## 5. The safety of gates that require power to open

Quite clearly, the biggest safety problem lies with radial and vertical lift gates that require an external power supply to open. In many cases, gate operation also depends entirely on the presence of experienced operators. This is not something that can be guaranteed in the long term.

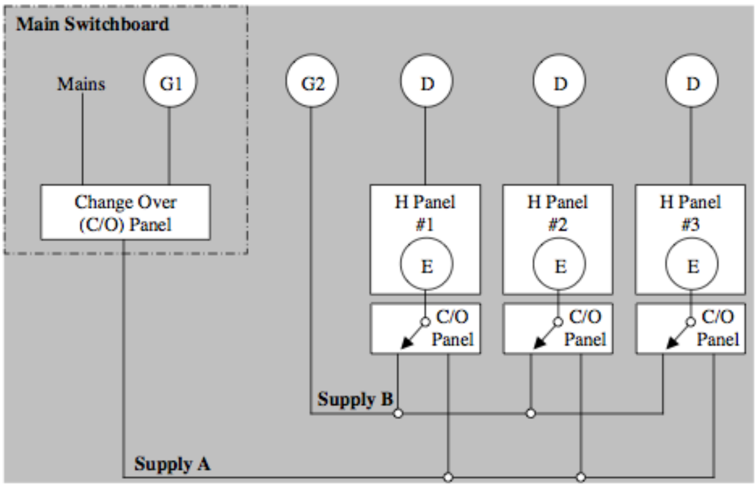



Figure 3

As mentioned in Section 2, hoist failures are a significant factor in gate failures. If the risk of failure is to be substantially reduced, the risk of hoist failure must be reduced.

A few years ago the safety of three spillway gates for a dam in Australia was subject to a critical examination.[v] To provide adequate reliability the reviewers recommended two emergency diesel generators plus one diesel pump for each pumping unit. The proposed arrangement is shown in Figure 3. They also considered the alternative of flap gates but, for reasons that were not fully explained, discarded them.

While it may be satisfactory to have five diesel engines to provide security for three gates in a country where a high level of maintenance and regular testing can be expected, it is not reasonable to expect that, in a dam with 10 or more gates and in a developing country, a diesel pump for each gate is a practical option. It cannot be guaranteed that the diesels will always have adequate clean fuel, a starting battery that is in good condition and fully charged and that each engine will be tested regularly. A much better solution is needed.

I believe that any gates that require an external power supply to open should have two independent gate lifting systems because, with a single lifting system, failure disables the gate. One system should operate without an external power supply – or, perhaps – a completely separate and highly reliable local power supply – and it should open the gates without human intervention.

I described a system that would meet these objectives in a paper published in "Hydropower and Dams in 2008.[vi] It was based on a system installed at a New Zealand hydropower station in the 1980s that, as far as I know, has never given any trouble.

The system relies on hydraulic cylinders that extend to open the gate rather than the conventional alternative of tension cylinders. Using cylinders that extend to lift the gate means that the failure of a cylinder to move will not disable the gate. With a tension cylinder, seizure of the cylinder will make it impossible to open the gate. An additional advantage is that the cylinders are cheaper than tension cylinders. Thousands of them are used in large forklifts and hydraulic cranes and, in many cases, a standard production cylinder will be available.

As shown in Figure 4, the cylinders can be mounted on the bridge deck just upstream of the gate itself. This is a very suitable arrangement when obsolete winch lifting gear is being replaced. The pairs of cylinders can be mounted side-by-side. At the same time the winch wires can be replaced by modern high-strength plastic rope or slings to eliminate the corrosion and other problems encountered with wire ropes. This was done at the Clyde Dam in New Zealand where, in 2008, corroded 44 mm wire ropes lifting 120 tonne gates were replaced by 43mm Dynex rope with complete success.

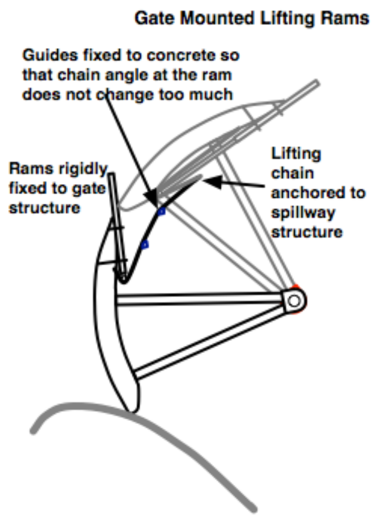



Figure 5

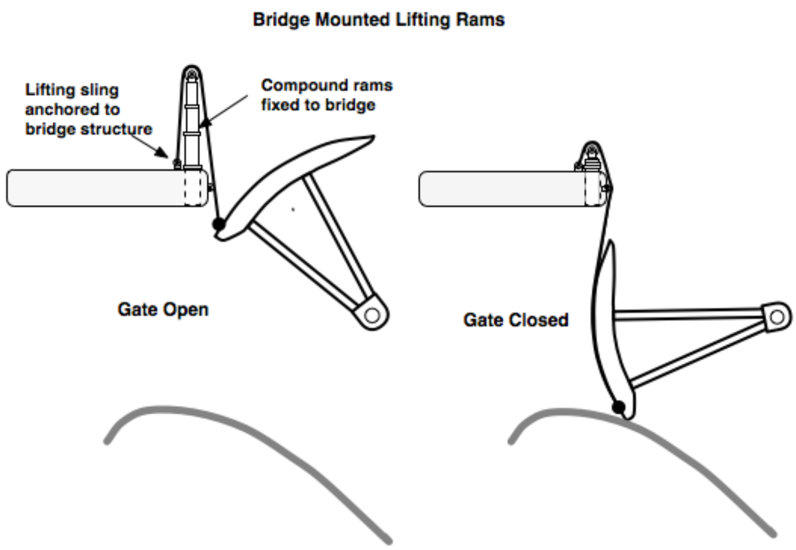



Figure 4

As shown in Figure 5, the cylinders can be mounted on the upper part of the gate itself pushing downwards on a rope that is attached to the gate at one end and the civil works at the other. This system was first installed on some canal regulating gates in Australia 20 years ago and has operated without any problems ever since. The system can be used on new spillway gates or it can be retrofitted on existing radial gates.

If vertical lift gates are used, it should be possible to arrange for the cylinders to be installed vertically just clear of the gate slots and, as before, pushing upwards against a chain or, preferably, plastic rope or sling. As standard slings will lift up to 125 tonnes, it is possible to lift gates weighing 200 tonnes or more.

As shown in Figure 6, each pair of cylinders has its own independent hydraulic oil supply. The first set has a conventional pumping unit with one or two electric motors. Because there is also a backup system, a single unit can be used for several gates. In general this unit would be arranged so that the motors can **also be supplied** from an emergency generator.

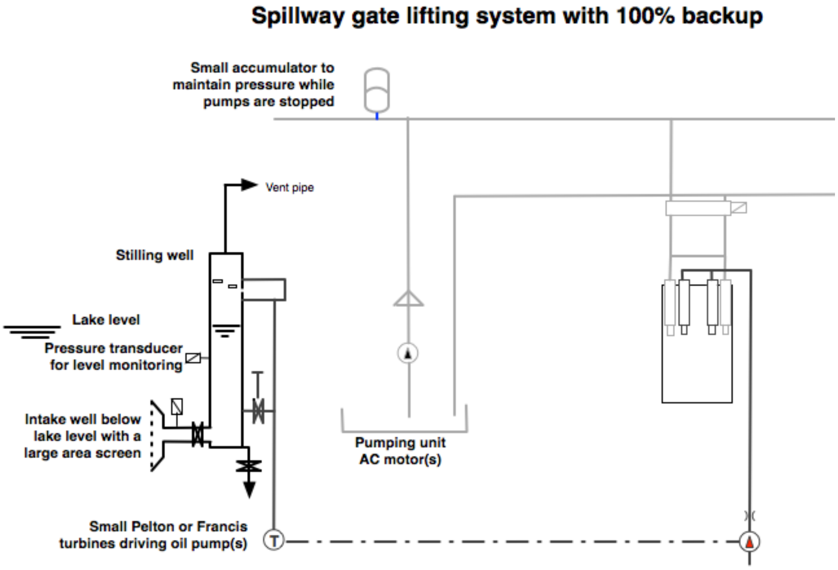



Figure 6

The second pumping set is individual to each gate. A small oil pump is driven by a water turbine driven by water that overflows from a stilling well whenever the lake level is too high. The oil pump supplies pressure oil to the cylinders and slowly opens the gates until the water level starts to drop. The flow through the turbine will slowly decrease and, at some stage, the oil pump will act as a motor and drive the turbine backwards so turning it into a brake and lowering the gate slowly and under control. If the water intake is properly screened and the screen has a very large area, the system will be highly reliable. The system can be tested by means of a bypass valve.

## 6. What needs to be done?

I believe that the hydropower industry needs to take dam and gate safety much more seriously. The standards that apply in the hydropower industry are much less strict than those that apply to, for instance, nuclear power stations even though experience shows that nuclear power stations have not killed nearly as many people as have been killed by large dams.

I think the first thing that should be done is to set up worldwide reporting system for failures, and, most important, failures that could have led to a major disaster. If everyone in the hydropower industry is aware of problems that have arisen at other dams and what needs to be done to avoid them, they will be able to review their own situation and, if necessary, take action. To give one example, the accident at Sayano Shusenskaya was identical to a failure at Grand Rapids in Canada about 20 years before that received very little publicity. It is possible that if the Russians had known about this accident, they would have taken effective action when they discovered fatigue problems with the turbine cover bolts.

The second thing that needs to be done is to ensure that spillway gates systems on every dam are subject to a rigourous risk analysis that considers the gate system as a whole, rather than relying on arbitrary rules to determine whether or not the system can be considered to be safe. The objective of such as analysis should be to demonstrate that no single failure can disable all the gates and the failure of a single gate is extremely unlikely.

We must also consider the liability imposed on engineers responsible for design and operation of dams and spillway systems by modern health and safety regulations. The theme behind all of them is that an engineer involved in a structure or anything else that poses a risk to human life is obliged to assess the risks, consider options for mitigating them and make a record of the assessment. If the risk is significant the assessment must be peer reviewed. If an engineer fails to do this and a fatal accident occurs, the outcome could be a charge of manslaughter.

Engineering institutions also have codes of ethics that apply when lives could be in danger. For instance, the Institution of Civil Engineers (UK) code states that engineers must: "Ensure that reasonable steps are taken to minimise the risk of loss of life, injury or suffering which may result from your engineering activities, either directly or indirectly."

Dam safety rules also apply and may even impose greater obligations than the health and safety regulations. Unfortunately, in many countries dam safety rules consist of a set of regulations that must be complied with and if this is done, the engineer is automatically absolved from any responsibility for a subsequent failure. In many cases, these regulations will not be appropriate to the situation – regulations that say that there must be a spare gate without giving any consideration to the possibility of all gates failing are a good example. In many countries effective dam safety regulations do not exist.

## 7. Conclusions

The failure of spillway gates to open is a significant factor in dam failures worldwide. Many existing gate installations can suffer from total failure from a single cause. At a significant number of dams spillway gates can be opened only if operators are in attendance in spite of the fact that it is impossible to guarantee that they will always be available and always be able to travel to the dam during the worst storm is experienced. Risk analysis shows that some gates failing during a moderate flood is a significant risk factor.

In many new installations, the risks can be minimised by avoiding gates that need an external power supply to open or by providing an emergency spillway.

On both new and existing installations where power is needed to open the gates, a major improvement in reliability can be achieved by installing two independent lifting systems one of which will operate without an external power supply and without the intervention of operators. If the system proposed in this paper is adopted it is likely to be only slightly more expensive than conventional systems without independent backup.

A substantial improvement in safety will be achieved if all engineers adopt the safety principles required by modern health and safety regulations and codes of ethics of the professional engineering institutions.

Banks and other financial institutions often require the appointment of an independent Dam Safety Panel to keep the safety of the dam under constant review during design, construction and initial operation. They reasonably assume that such panels will carry out a rigourous review of dam safety that covers everything that could possibly cause safety problems. The experience with the Dam Safety Panel in West Africa described above demonstrates that this does not always happen. It is recommended that the requirements for dam safety panels also include a requirement that the panel carries out a formal safety assessment in line with modern risk analysis practice.

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