Options for improving the safety of spillway gates

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1. Introduction

Many – maybe most – major dams use power operated spillway gates. If these gates fail to open during a flood the dam will be at risk and may suffer catastrophic failure.

According to Hinks[1], during the 1987 floods in Norway, 50% of the dam owners experienced problems with this 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 can be considered to be 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[2], the risk of dam failure from any one incident should be in the region of 1:10,000. Very often, the failure of some or all of the gates will result in dam failure. At a recent conference Micovic[3] 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 existing gate installations.

It is very clear that there is an urgent need to improve the safety of existing gated spillways and to adopt much higher standards of safety and reliability for spillway gates at new dams.

This paper discusses modern options for spillway gates. It then discusses what can to be done to ensure that the spillway system at new dams will be able to pass the predicted floods safely and reliably and goes on to discuss this various options for improving the safety of gated spillways at existing dams. It also gives examples of gate failures and near failures.

If the hydropower industry takes no action and there is a major dam failure due to the failure of spillway gates that kills thousands of people, there is a high chance of a strong reaction against large dams by environmentalists combined with the imposition of stringent – and often inappropriate – safety standards.

2. 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
- Tipping gates such as the Hydroplus fusegates[4]
- Pivoted gates controlled by water level
- Float operated gates of various types
- Flapgates supported by hydraulic cylinders or air bags
- 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. Providing an emergency spillway should be given even higher priority if the spillway gates need an external power supply to open.

Spillways that can pass the maximum flood without human intervention and without any power supply are always the best option. In the past, overspill spillways were the only available option. They were mostly used on dams with relatively small flood flows because an overspill spillway needs to have a substantial rise in water level to pass a major flood so the dam needs to be higher than it would have been with a gated spillway. Recently labyrinth spillways such as the "piano keys" weir have been developed that will pass three or four times the flow of an ogee weir for the same water level rise.

The water level rise when passing a large flood can be further reduced by using tipping blocks or fuse gates that pass water over the top during a moderate flood and tip over sequentially during a major flood so allowing a much bigger flood flow to be passed without an increase in water level or putting the dam at risk. As they are normally arranged to tip in a 1:50 year 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 contemplated.

2.1. Water level controlled gates

Recently a firm in South Africa developed an innovative gate that, it can be argued, supersedes flap gates and radial gates less than 10 m high.[5] The gate and its principle of operation are shown in Figure 1.

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.

Because little or no work is needed along the dam crest, is easy to install these gates on an existing dam provided the piers are strong enough to stand the pivot load.

The gate can be opened and closed remotely by operating a drain valve on the tank. By virtue of the design, it is not possible to stop the gate opening when the water level is high. This is a very important safety feature.

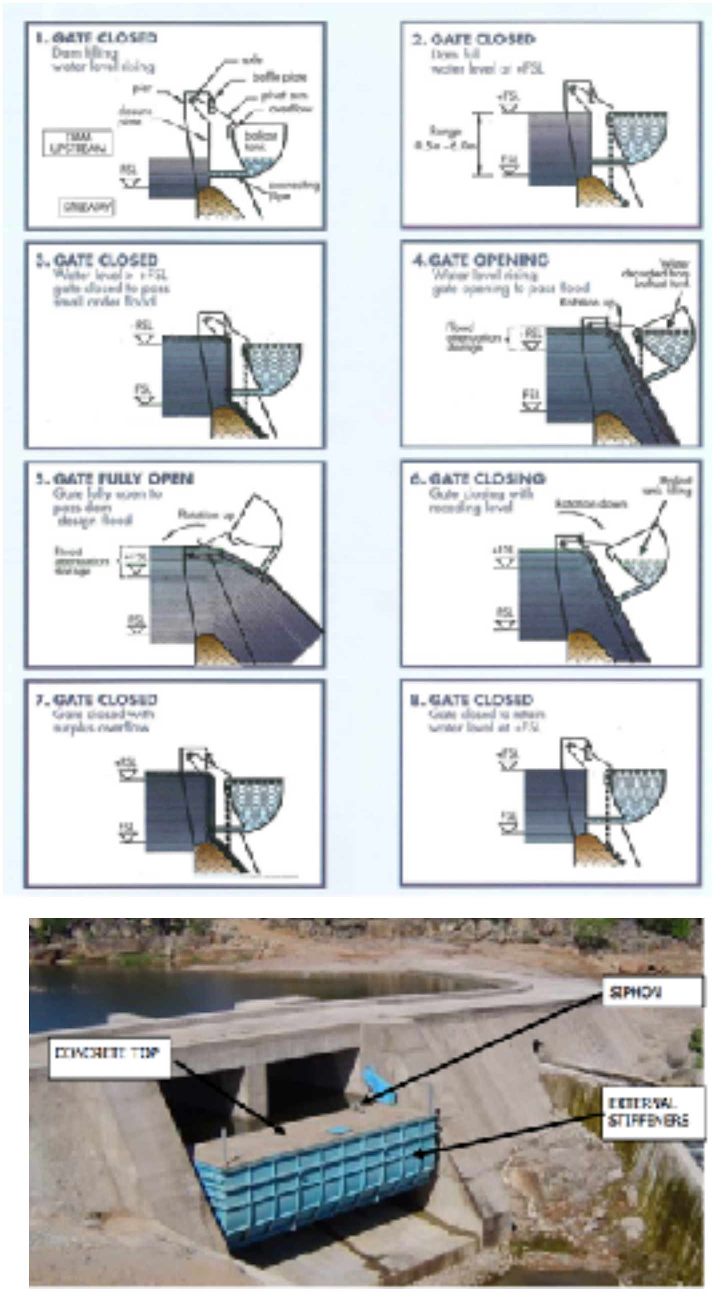

Figure 1

The major advantages of this gate are that it is water level controlled and operated for both closing and opening and it requires virtually no maintenance. It can be tested remotely simply by opening the drain valve and confirming that the gate has moved.

The largest gate that has been built so far is 20 m long and 5 m high. It passes 500 m3/s so several of these gates can pass quite large floods. According to the designer, a gate 30 m long and 10 m high passing 2000 m3/s is a feasible option. Estimates indicate that they are somewhat cheaper than radial gates that could pass the same discharge.

Wherever they are able to pass the required flood flow this gate should be considered as a prime option.

2.2. 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. It can be argued that they have now been superseded by the gate described in Section 2.1.

2.3. Rubber dams

Gates consisting of large rubber tubes filled with either air or water can also be used. They cannot maintain steady discharge while partially inflated so they cannot be used for regulating the water level. They have no advantages over the gates described in Section 2.1

2.4. Float operated gates

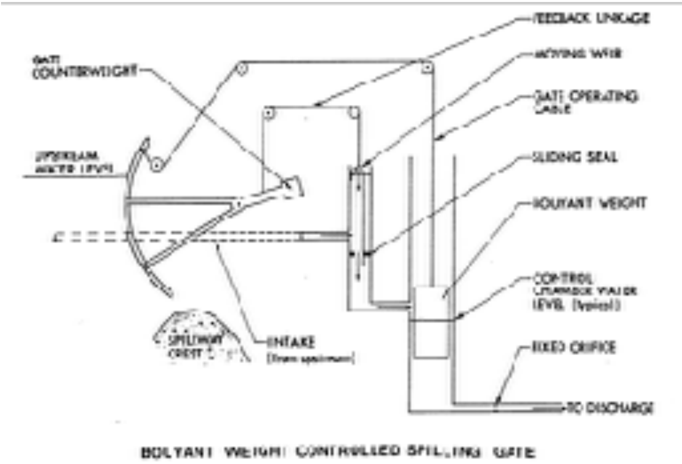

Figure 2

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 2. 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 even though it operates several times a year.

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.

2.5. Power operated gates

Many radial gates and virtually all vertical lift gates require an outside power supply to open and close them. Most 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.

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.

A few years ago the safety of three spillway gates for a dam in Australia was subject to a critical examination.[6] 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 might 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 each diesel will always have adequate clean fuel, a starting battery that is in good condition and fully charged and that it will be tested regularly. A much better solution is needed.

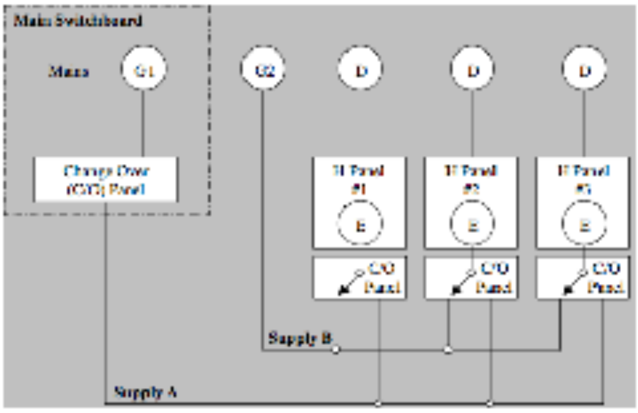

Figure 3

Power operated gates can also be disabled if the control system or cables fail, if the water level transmitters 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. Even so at many existing gate installations several individual failures would disable all the gates . 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.

Vertical lift spillway gates are even more risky than radial gates because of the higher risk that the gates will jam while they are being raised. 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. Many of them are raised using one or more gantry cranes moving from gate to gate.

3. Increasing the safety of gates that require power to open

In many cases, a relatively simple analysis will show that it is not difficult to make a substantial increase in the safety and reliability of spillway gates that require power to open.

3.1. Mechanical and electrical aspects

I believe that any gates that require a 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 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.[7] It was based on a system installed at a New Zealand hydropower station in the 1980s which, as far as I know, has never given any trouble.

The system relies on hydraulic rams that extend to open the gate rather than the conventional alternative of tension cylinders. Using rams that extend to lift the gate means that the failure of the ram 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 rams are cheaper than tension cylinders. Thousands of them are used in large forklifts and hydraulic cranes and, in many cases, a standard, low cost, 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[8].

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 more than 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.

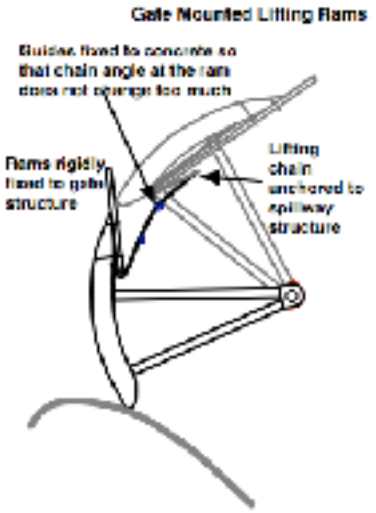

Figure 5

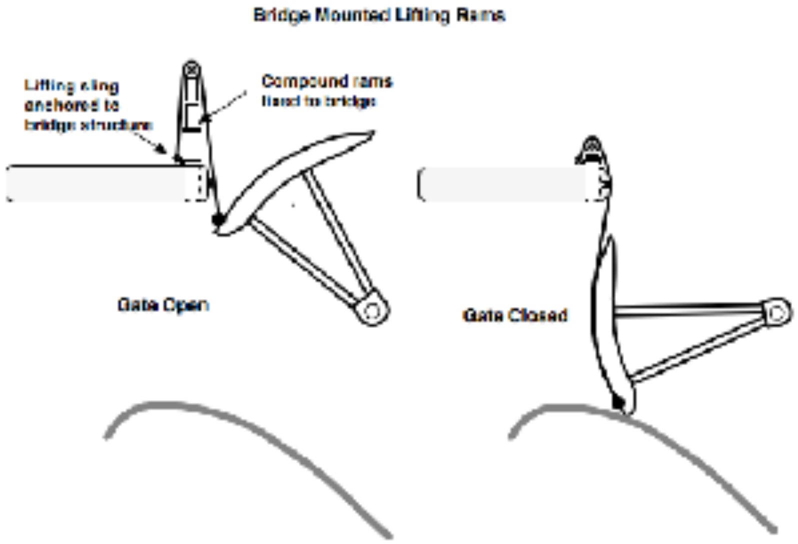

Figure 4

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.

The second pumping set is individual to each gate. A small oil pump is driven by a water turbine that is 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.

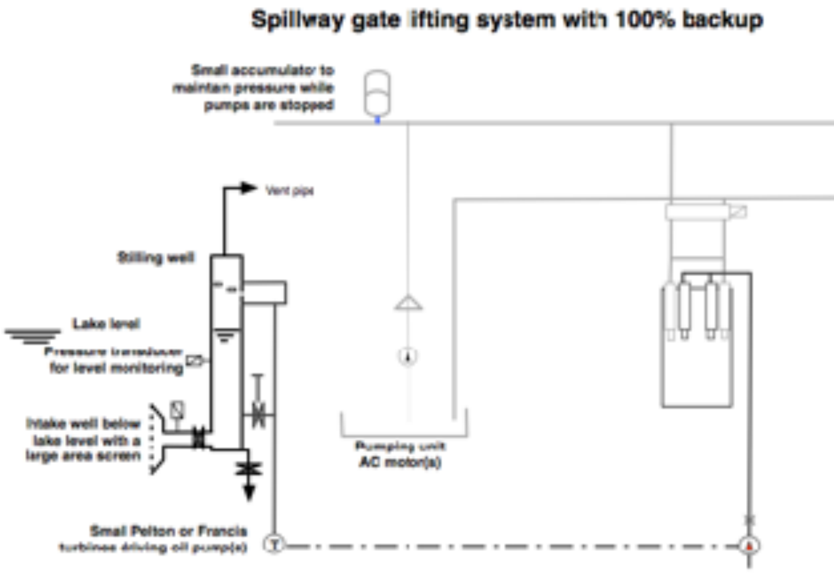

Figure 6

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.

If emergency diesel generators are needed they should be selected for maximum reliability. Major problems with diesel generators are failure to start because of faulty or flat or missing batteries and failure to maintain output due to cooling problems[9]. There is a simple, cheap and readily available solution to both problems. Start reliability can be improved enormously by using an hydraulic starting device fed from an accumulator that is kept pressurised by an engine driven pump and also has an emergency hand pump. All that is necessary is to monitor the accumulator pressure. If pressure is available, a start is virtually certain. Hydraulic starting is widely used in the marine industry and on oil rigs where reliability is very important.[10] Cooling system problems can be virtually eliminated by using air cooled diesel engines that are available in ratings up to 150 kW. A pair of air cooled diesel generators with hydraulic starting would provide high reliability without needing frequent maintenance and without the risk of the battery being stolen. There seems to be no reason to continue using electric starting radiator cooled diesel generators.

3.2. Control aspects

The control system is also a vital factor in gate safety. It must be very reliable, be provided with water level information from three independent sensors, and, if the gate position is controlled remotely, the remote control system must be proof against hacking. In addition, a separate hard wired control system should automatically regulate the gate position to maintain dam safety if the water level is dangerously high. The same system should not allow more than a few gates to open if the water level is normal to prevent generating a major flood because of a malfunction in the control system or hacking.

4. Maximising spillway gate safety at the design stage

Early on in the design process there should be a meeting is attended by civil, mechanical electrical and control engineers to have an open discussion on the options available and the risks associated with each option. The meeting should be conducted on a "value engineering" basis where the problem is carefully identified and all options considered before moving on to considering which option is best. The discussion should cover the risk to downstream populations and the risk of cascade failure if an upstream dam fails.

The objective of the meeting should be to choose the gate option that provides very high reliability without incurring an excessive cost. The discussion should include all the gate types identified above and any others that appeared to be attractive. It is highly likely that such an analysis will conclude that an emergency spillway should be provided if at all possible and, unless there is a requirement passing very large flood flows, water level operated gates should be used.

If large gates that need a power supply are selected the options of duplicated lifting gear with the normal lifting gear being provided by power from the station and backed up by an air cooled diesel and an emergency system using small water turbines should be seriously considered. If this cannot be done, then duplicated diesel generators should be a minimum requirement. It should never be assumed that, in the middle of the largest flood ever experienced, the station power supply will still be available.

In general, lifting gear should be hydraulic rather than using winches with plastic ropes or slings. Wire rope or chains that are more maintenance intensive and more failure prone than hydraulic systems should be avoided.

Once the design has been finalised, regular meetings should be held to review the designs and ensure that nothing is done during the design process that would compromise reliability.

5. Increasing the safety of existing spillway gates

A safety review of existing spillway gates should be held at regular intervals with the objective of ensuring that the gates are reliable be as they can be at a cost commiserate with the risk. The study should not simply look at what needs to be done to the existing gates to maintain the present level of reliability: it should consider what can be done to provide a substantial increase in reliability and cope with the possibility of future de-manning and a change to remote control. The risk to existing and future downstream populations and the possibility of a cascade failure resulting from the failure of an upstream dam must also be considered.

If the dam has flash boards or other devices that need to be removed manually, replacing them with pivoted gates or any other highly reliable water level controlled gate should be considered.

If the gates are lifted by one or two gantry cranes and a team of operators the installation of new individual lifting systems should be investigated. At the very least, the gantry cranes should have a very secure power supply and lifting the gates should not demand any special skills on the part of the crane operator and team.

On gates with winch lifting gear a substantial increase in reliability and reduction in maintenance can be achieved simply by replacing the wire ropes with modern plastic ropes such as Dyneema (Dynex)[11] that do not corrode, do not fatigue and are resistant to ultraviolet degradation. Alternatively, the winch lifting gear can be abandoned and replaced with hydraulic rams as illustrated in Figure 4 above.

If power is needed to open the gates, the provision of duplicate air cooled diesel generators with hydraulic starting must be considered.

On the control side, the installation of a system that automatically opens the gates in a controlled manner if the water level becomes dangerously high should be seriously considered. If the gates are remote-controlled, then precautions need to be taken to prevent a hacker stopping the gates opening when they are needed or opening them all when there is no flood risk.

When all these options have been considered and a new system has been decided upon then a thorough review is needed to ensure that no single failure can stop all the gates opening. This should be based on a thorough fault tree analysis.

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 the failure of spillways associated with 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 that eventually failed and flooded the power station.

The second thing that needs to be done is to ensure that spillway gates systems on every dam are subject to a rigorous 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.

The liability imposed on engineers responsible for design and operation of dams and spillway systems by modern health and safety regulations must also be considered. 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.

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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 operate when needed 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 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.

At 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. At the very least there should be two emergency diesels with hydraulic starting and air cooling..

References

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[6] **Vivian, Barker and Bowles** "Reliability assessment for a spillway Gate upgrade design in Queensland, Australia", *Vivian, Barker and Bowles, US Society on Dams, 2006*

[7] **B Leyland** "A new system for raising spillway gates", *Hydropower and Dams, 2008. Also at http://www.bryanleyland.co.nz/hydropower.html*

[8] *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.*

[9] *http://www.ecmweb.com/ops-amp-maintenance/top-nine-reasons-generators-fail-start*

[10] *http://www.ipu.co.uk/oil-gas/*

[11] *https://www.dsm.com/products/dyneema/en_AU/industries/heavy-lifting.html*

The Author

Bryan Leyland has been involved in the hydropower industry for nearly 50 years. He is an electrical and mechanical engineer and Fellow of three Institutions. He managed his own consulting business specialising in hydropower for 25 years and he has been responsible for the design, construction and commissioning of mechanical and electrical aspect of more than 30 power schemes. He and his wife are majority owners and operators of a 1 MW hydropower scheme.

Bryan has also acted as a specialist adviser on schemes all over the world. He has a special interest in the safety of dams, and, in particular, spillway gates and has always believed that the hydropower industry needs to adopt better and safer systems. He is a member of the ICOLD Committee V that deals with gate safety. It should not be assumed that this paper reflects the views of the Committee.

He has attended many overseas conferences and written papers on a wide variety of subjects on most aspects of hydropower. A few years ago he was named by "Waterpower and Dam Construction" as one of the 60 most influential people in the hydropower industry worldwide.

1. Appendix - 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 by the government 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.

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 the first 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 11 km earth fill dam is designed with limited freeboard and there is no allowance for a rise in lake level during a major flood. There is also a saddle dam with rock foundations. No consideration was given to using the saddle dam as an emergency spillway. The estimate 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 designers proposed 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. Six different single failures could disable all the gates.