STRATEGIES FOR IMPROVING THE SAFETY OF SPILLWAY GATES

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ABSTRACT

The failure of spillway gates is a significant contributor to dam failures worldwide. There is an urgent need to improve gate safety bearing in mind that the dam and its spillway gates must continue to operate safely for hundreds of years.

The paper classifies spillway gates according to their inherent reliability. The highest ranking is given to gates whose opening and closing is entirely dependent on water level. The lowest ranking is given to gates that need an external power supply and operator attendance to open or close.

The last section of the paper the paper suggests what can be done to improve the reliability of new and existing gates.

1. INTRODUCTION

It is well established that spillway gate failure is a significant cause of dam failures and, in many cases, some or all fail to open but without causing a disaster. (Micovic et al. 2015) estimates the following probabilities of gate failure based on the experience of BC Hydro.

Condition	Single gate failure	Multiple gates failure	
		2 gates	3 gates
Gate is unavailable for 12 hours	0.015	0.010	0.009
Gate remains unavailable	0.010	0.001	0.0009

This means that there is a one in 100 chance that a single gate will fail to open when needed and a one in 1000 chance that all gates will fail open when needed. It is important to remember that these probabilities apply to one of the best managed hydropower organisations in the world. Many other organisations would have a much greater risk of failure.

It is interesting – and relevant – to compare the failure rate of gates with the failure rate of aeroplanes and nuclear power stations. Both are examples of failures that can cause a major loss of life or have significant public impact.

There are approximately 100,000 airline flights each day around the world. According to Boeing, the fatal accident rate is 0.28 per million flights.

There are 437 operational nuclear reactors in the world with about 16,000 reactor years of commercial operation. There have been three major accidents to nuclear power plants. Chernobyl alone caused any deaths and, according to UNSCEAR, between 50 and 60 died of acute radiation sickness. There is no credible evidence of increased risk of cancer among the survivors. Fukushima has not, and will not, cause any deaths from radiation.

1.1. Risks and failures

According to ICOLD, there are about 60,000 dams worldwide. It is probable that somewhere between 10 and 30% have spillway gates. According to Wikipedia, dam failures since 1960 have resulted in more than 150,000 deaths. Two major failures were at Banquio in China that failed because the spillway was seriously undersized and at Machhu 2 Dam in India where the spillway was undersized and three of the 18 gates could not be opened.

A close examination of a set of 14 - 6m x 6m radial gates designed for a dam in Africa revealed that any one of five incidents could disable all the gates. (Loss of backup power supply, failure of electrical equipment and/or cabling, failure of the control system, failure of control system power supply and terrorist action that resulted in the operators being killed or fleeing.) Every one of these risks would have been eliminated if the pivoting gates described below had been recommended.

When the author visited the Kentucky Dam on the Tennessee River in 2014 he was told that a gantry crane with an experienced crane operator and four assistants was needed to lift the ~20 vertical lift gates. There are two gates leaves in each slot and attaching the lifting gear to the lower leaf when floodwater is passing over it can be seriously difficult. It would probably take 24 hours to raise all the spillway gates. There are eight dams above the Kentucky dam in a continuous cascade. If one of them failed there is little or no chance that the gates could be opened in time to pass the flood safely.

At the Sayano-Shusenskaya dam near Lake Baikal the powerhouse was flooded when one of the turbines was destroyed. It transpired that the spillway gates could not be opened open because the power supply to the single gantry crane provided to open the 11 gates came from the powerhouse. Fortunately, the lake level was quite low so they had time to find an emergency diesel generator, bring it to site and connect it to the gantry crane before the 200 m high arch dam overtopped. If the lake had been full it is possible that the dam would have been overtopped and this could have resulted in the catastrophic failure of the dam that would have put something like 1 million people at risk of drowning Leyland B (2010).

According to Hinks JL & Charles JA (2004) during the 1987 floods in Norway, 50% of the dam owners experienced problems with power failures, 23% had communication problems, 19% had failure of spillways to open and 17% had damage to the access road. This is in a country where It is reasonable to assume that the dam safety standards are very high.

A reliability assessment of three 50 year-old spillway gate installations (Lewin J et al. 2006) identified the following significant contributors to potential failure:

- Failure of the gate electric motor or associated equipment ~30%
- Failure to raise a gate because motors are overloaded due to seized rollers (bearings or debris) ~20%
- Failure of electric power supply to the gate ~15%
- Failure of gate mechanical drive ~15%
- Failure of gate control equipment ~10%

According to Bowles DS (2007) the risk of dam failure from any one incident should be in the region of 1:10,000. In many circumstances, failure of all the gates will result in dam failure. At a recent conference Micovic Z (2014) 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.

The conclusion is that the risk of spillway gate failure is much greater than the risk of a fatal accident while flying or the risk of a serious radiation release from a nuclear power station. Is this reasonable or acceptable.

2. SPILLWAY OPTIONS

During the design stage all the available options for the spillway should be considered. (Lempiere F et al. 2012) describes a number of overspill options such as labyrinth spillways and tipping blocks that significantly reduce the rise in lake level during a major flood. The paper also points out that if gates are used in combination with overflow and/or emergency spillways when higher discharges are needed, the risk of the dam over topping if the gates fail is much reduced.

If it is concluded that gates are needed the first preference should be given to gates that do not require an external power supply to open. In order of reliability, these include:

- Tipping gates such as Hydroplus fuse gates and concrete blocks that overturn;
- Pivoting gates such as the TOPS gate from S Africa;
- Float operated radial gates as, for instance, used by Snowy Mountains;
- Flap gates raised by hydraulic cylinders or by air bags.

Only if the above gates do not provide sufficient spillway flow should radial gates be considered. Gates with hydraulic lifting gear have proven to be more reliable than gates with mechanical lifting gear using wire ropes or chains. If mechanical lifting gear is needed for some reason, modern, ultraviolet resistant, plastic ropes that do not corrode underwater and are stronger than wire ropes and more reliable than chains should be used.

For the reasons set out below, vertical lift gates should be avoided if at all possible.

Tipping gates have been covered comprehensively by Lemperiere (2010) so they are not discussed further.

2.1. Pivoting gates

A simple, ingenious and extremely reliable, gate has been developed by Amanziflow Projects (Pty) Ltd in South Africa. The gate consists of a large tank suspended from two pivot arms and ballasted with water so that it closes off the spillway for upstream levels below top of the tank. If the upstream level rises, the water pressure overcomes the ballast and the gate opens. The rotation of the gate causes water to drain from the tank so that the further the upstream level rises, the lighter the tank becomes. When it is full open, the tank floats on the top of the flow over the spillway. When the upstream level decreases, the tank rotates, fills, and eventually closes off the flow. The operating principle is shown in Figure 1 below.

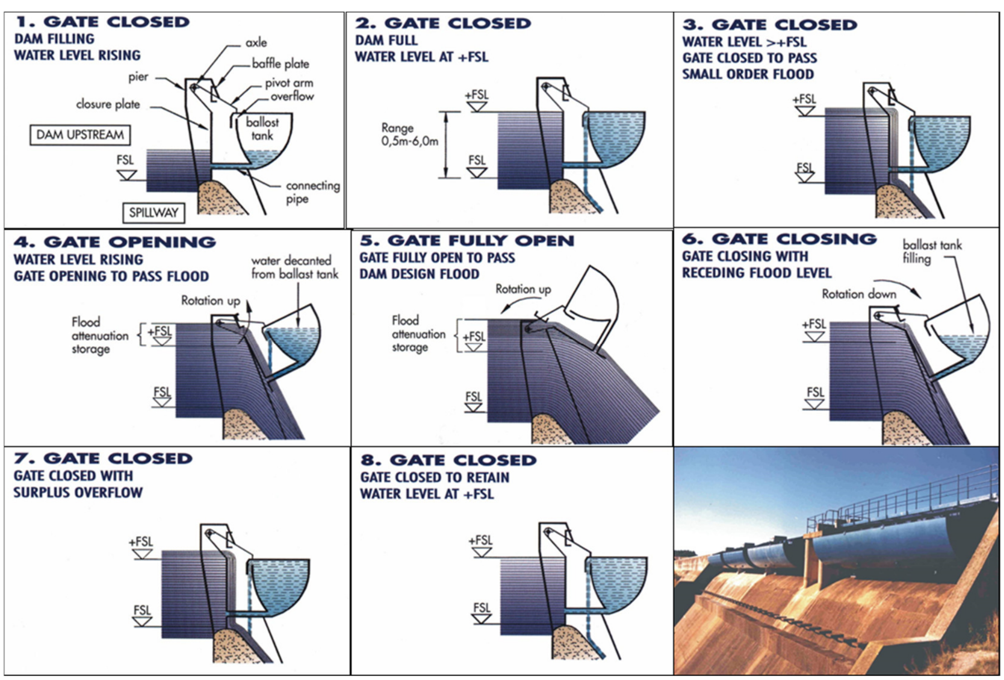

Figure 1. Pivoting gate

A drain valve is provided so that the tank can be drained manually or remotely if needed. This will open the gate.

The gate operates in response to water level without any outside intervention or the need for any power supply.

Because of limitations on the loading of the pivot bearings the maximum dimensions of the gate are in the region of 12 m high and 20 m long. Gates of this size would probably be made of fibre reinforced concrete and built on site (Townshend P, pers.comm).

As it has fewer moving parts than the float operated gates described later, it should be among the first to be considered where gates are needed and, in particular, at remote dam sites or in developing countries.

2.2. Float operated gates

There are many types of float operated gates but it seems that the most successful is a system where the gate is counterweighted to open and is held closed by another counterweight mounted in a well. The well has a water supply pipe with its intake at the level at which the gate should start to open and has an orifice controlled drain. When the flow into the pipe exceeds the capacity of the orifice the well commences to fill and steadily reduces the weight of the counterweight until it is no longer sufficient to hold the gate closed. As the gate opens it slowly raises the level of the intake of the water supply pipe to ensure stable operation.

Figure 2 below shows the principle of operation. The drawing is based on a gate Leyland Consultants Ltd designed in conjunction with Snowy Hydro of Australia. According to the owner, it has been in service for more than 35 years and it has never failed to open when needed. As it operates about 20 times each year, this corresponds to a failure rate better than 1:700. The only problem has been a tendency of the intake pipe to block with weed that was solved long ago by changing the intake arrangement.

The gate can be arranged to open in response to a remote control system by simply adding a second submerged intake controlled by an electrically actuated valve or by providing a small winch that lifts the counterweight.

Snowy Hydro has used this system on radial gates 21 m wide and 11.5 m high and it could be used on even larger gates. These gates have been in service for about 50 years and there is no record of any serious problems or failure to operate when needed. They have had minor problems with seal friction which probably indicates that the counterweight was undersized.

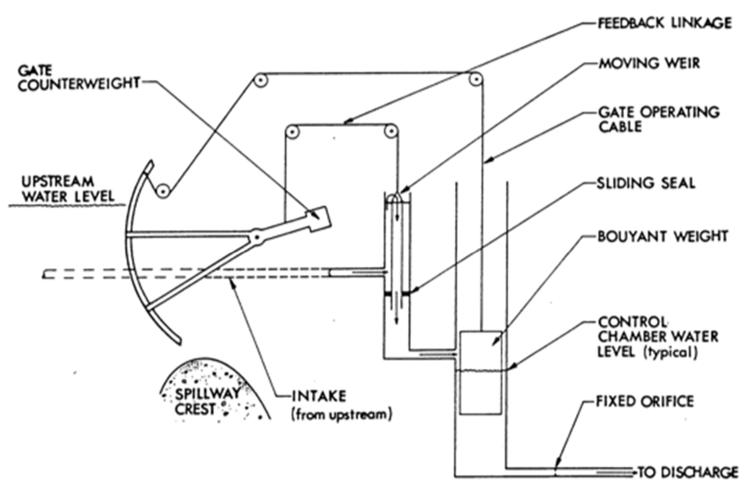

Figure 2. Float operated gate

If the water intake is adequately screened and the counterweight is adequately sized the major remaining risk is failure of the rope attached to the counterweight. This risk can be minimised by using modern plastic rope. If the rope breaks, the gate will open and prompt action can be expected. If the gate has remote controls there is always a possibility of someone hacking into the system and opening the gates. If it is properly designed hackers cannot stop it opening when needed.

2.3. Flap gates

Flap gates are hinged at the bottom and held up against water pressure by an hydraulic ram or by airbags. Some flap gates are 7 m high and 20 m or more long. It seems that structural problems increase quite rapidly with greater heights.

The advantage of flap gates is that they do not require an external power supply to open. This means that they can be relied upon to open in an emergency simply by arranging to have a water operated valve triggered by excess water level.

A claimed disadvantage of flap gates is that, for example, a saboteur could damage the hydraulic system or the airbags and lower them and thereby cause a major flood. This disadvantage applies to any power operated gate that can open if the control system malfunctions or if someone hacks into the remote control system.

Because the pivoting gate does not require a power supply to open or close and it is less vulnerable to sabotage and hacking, it can be argued that it has – or should have – superseded flap gates.

Figure 3 shows a flap gate supported by airbags.

Figure 3. Flap gate with air bags (Obermeyer)

2.4. Radial gates

Radial gates are most often needed when large flood flows must be passed. Most modern gates use hydraulic lifting gear but there are still some consultants and organisations who believe that wire rope or chain lifting gear is sufficiently safe.

To open a radial gate a substantial supply of electric power and a working control system are needed. Many designers and/or operators do not pay enough attention to ensuring that the power supply and control systems will always be available.

If the gate is operated by a mechanical hoisting system failure to operate can result from mechanical failure of any of the components – the motor, gearbox, shafting and lifting rope or chain. Failure can also result from the failure of a limit switch to switch off the motor if the gate is in the fully up or down position. For all these reasons, mechanical systems have proven to be less reliable than hydraulic systems.

2.5. Vertical lift gates

Vertical lift gates should be avoided if at all possible because they require much more power to open and they usually have a number of wheels that can cause problems with bearing friction and track fouling in the long-term.

Some vertical gates – and, perhaps, some radial gates – are lifted by one or more gantry cranes moving from gate to gate. This usually requires a crew of three or four people including an experienced crane driver and, of course, a reliable power supply. This type of gate should never be considered for a new installation.

3. DESIGN CONSIDERATIONS FOR RELIABILITY

Reliability and a high standard of maintenance are essential. Ensuring that this will be the case for as long as the dam lasts – which may be hundreds of years – poses a difficult problem for the designers and the operators. It must receive a very serious consideration.

Tipping and pivoting gates are inherently extremely reliable provided they are properly designed. As design will normally be carried out by specialised companies, this should not be difficult to achieve.

Float operated gates need to be designed carefully with due consideration given to ensuring that the intake screen will not get blocked, the counterweights on the gate and in the well are adequately sized and bearing and seal friction are minimised. On the float operated gates designed by Leyland Consultants the long shaft which was rotated by the counterweight in the well and controlled the position of the gate was carried on rollers rather than large bearings that would be difficult to maintain and prone to seizure. Any ropes that are used should be made from Dynex or similar high-strength ultraviolet resistant plastic rope because it does not suffer from corrosion or fatigue. Gate seals need to be designed for low friction and the sides of the gate should have 20 mm or so clearance from the concrete so that the gate will not jam in an earthquake or if the concrete moves for any other reason.

Radial gates present many problems because a substantial power supply is needed to open them. The design process needs to start with an analysis of the whole system and identification of everything that could cause the failure of one, several or all gates. Particular attention needs to be paid to the integrity of the power supply and the control system.

The probability that no power will be available to all gates must be in the region of 1:10,000. It should be assumed that the main power supply fed from the station and the outside system will be out of service in a natural disaster such as a major flood caused by local rainstorms. Major earthquakes are also likely to shut down the main power supply – a situation where the spillway gates may be needed to lower the lake level rapidly because of earthquake damage to the dam.

A minimum of two alternative power supplies is essential. If diesel engines are to be relied on, the implication is that, for as long as the station lasts – maybe hundreds of years – the engines will be kept in service with a serviceable starting battery, a supply of clean fuel, and cooling system capable of coping with the engine operating at full load for several hours.

According to one industry source the most frequent reasons for start failure are battery failure, followed by cooling system problems.

The reliability of standard emergency generators can be substantially increased by replacing the electric starter and battery with hydraulic starting gear that cranks the engine from stored energy in hydraulic accumulators. If the accumulator pressure is sufficient then it can be guaranteed that the starter will work. Hydraulic starters offer a very substantial improvement over a battery system because they eliminate the risk of the battery being stolen, discharged or having insufficient capacity from old age or lack of water.

The cooling problem arises from loss of coolant, a blocked radiator or the failure of a cooling fan. It can be virtually eliminated using air-cooled diesel engines that are available in sizes up to 150 kW (Cheetham J, pers. comm.).

It must be possible to synchronise the diesels with the main system so that they can be tested at full load at regular intervals. Simply testing that the engines start and the generators excite does not prove that they can run for hours at full output and, anyway, is not good for the engines.

All remote controlled gates should be designed to be proof against hacking. Hackers can either open gates when they are not needed thus causing a major flood and loss of water or they can stop gates opening when they are needed. One option is a hardwired control system that stops more than say, one or two gates opening by remote control if the water level is below maximum normal level and opens all the gates progressively if the water level is dangerously high.

3.1. Hydraulically operated radial gates

The power, hydraulic supply and controls to the gate lifting gear must also be secure. A possible way of doing this is shown in Figure 4 below. There is an emergency diesel at each end of the spillway that feed into two cables running on separate routes and each supplying one of two pumps on each pumping unit. The main power supply is not shown because, in an emergency, it is assumed to be absent.

Each pumping unit is the primary hydraulic supply to one gate and provides a backup supply to an adjacent gate. As hydraulic cylinders have an excellent reliability record high reliability is achieved by having two oil supplies to each set of cylinders with automatic valving that monitors pressure in the main supply and switches to the backup supply if the main hydraulic supply is not available. The control system is also duplicated with duplicated cables for control and DC supply run on a separate route.

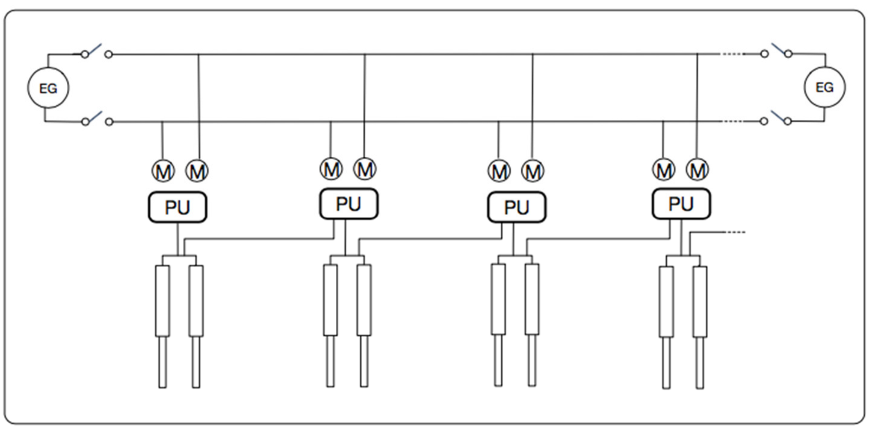

Figure 4. Arrangement of pumping units

The reliability of the control system can be increased by adding water actuated control valves sensitive to lake water level. If the water level is excessive they open one gate after another as the water level continues to rise.

If the whole system is tested regularly, the reliability should be very high indeed. The extra cost of the duplication is not likely to result in a substantial increase in the cost of the gate installation. The disadvantage of the system is that it is fairly complex and may not be understood by the operators.

The author developed an alternative system that has two completely independent operating systems. One of them is a conventional electrically powered system and the other uses a small water turbine driving an hydraulic pump that comes into operation if the water level is above normal. There are duplicate hydraulic cylinders that extend to open the gate thereby ensuring that the jamming of one cylinder will not stop the other cylinders opening the gate. The system is described in Leyland B (2008). It is much simpler and probably cheaper than the system described above. It is illustrated in Figure 5 below.

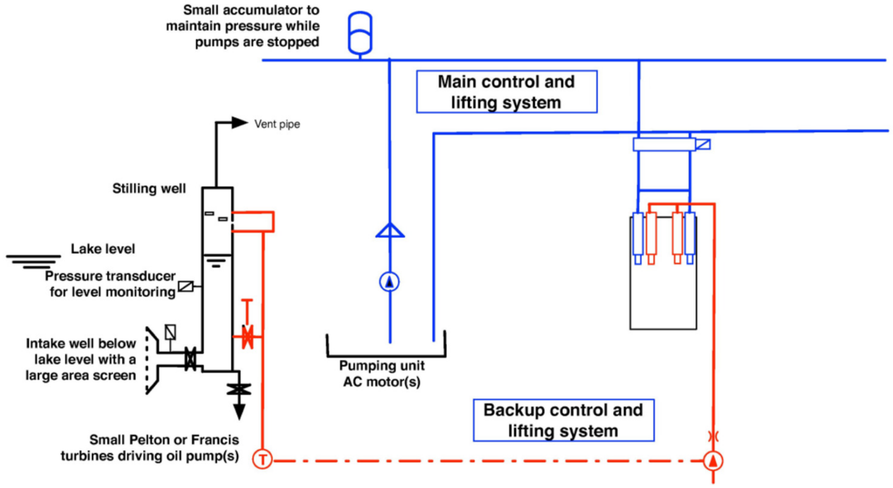

Figure 5. Duplicated lifting system

3.2. Mechanically operated radial gates

This seems to be little doubt that mechanically operated gates are less reliable than hydraulically operated gates. This is because of the extra complication of electric motors, gearboxes shafts, chain or winch lifting gear, slack rope detectors limit switches and are like that do the same job as main and backup electric pump, hydraulic piping and a hydraulic ram. There would have to be very special reasons to justify the selection of mechanical lifting gear on a new installation.

4. IMPROVING THE RELIABILITY OF EXISTING GATES

Improving the reliability of existing gates is a very important step in improving the safety of existing dams. Any gates relying on gantry cranes for operation should be upgraded by installing individual lifting gear that can open each gate without an operator being in attendance.

All systems relying on a distributed control system to control gate opening and closing should have a water pressure operated valve or an independent pressure switch that will open the gate if the lake level is entering the danger region.

4.1. Flap gates

The main safety improvement that can be made is ensuring that the gates lower automatically in the event of high water level. It is strongly recommended that there be a backup system relying on valves that are directly actuated by water pressure. This eliminates the possibility of a gate failing to open due to failure of the electrical control system.

4.2. Hydraulically operated radial gates

The main problems are loss of the electric power supply or failure of the control system.

It should be assumed that the main power supply will not be available during a disaster and therefore two other independent supplies are needed. The integrity of the power cables, the control cables and the water level detection system also needs to be examined.

It may also be worthwhile considering using the hydraulic supply from an adjacent gate as a backup supply to the existing hydraulic cylinders.

In many circumstances a new duplicated control system will be needed.

4.3. Mechanically operated radial gates

The option of converting to hydraulic operation should always be considered. Leyland (2008) shows how existing winch lifting gear can be replaced relatively easily by single or duplicate hydraulic rams that lift the gate from the same attachment points using modern high-strength slings or ropes. It also shows how push rams can be installed on the back of the gate to replace chain lifting gear.

The options suggested are illustrated in Figure 6 below.

If it is decided to retain the mechanical lifting gear consideration should be given to replacing wire ropes or chains with modern plastic rope.

Limit switches, slack rope detectors and the like should be duplicated. The gearbox, shafting and bearings need to be reviewed in the light of their maintenance history and current condition to identify steps that can be taken to increase their reliability.

Comments made regarding power and control systems for hydraulically operated gates also apply.

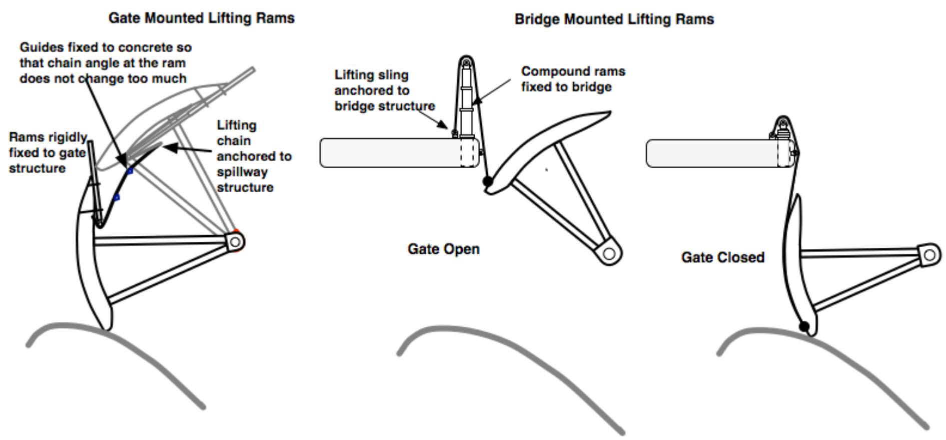

Figure 6. Lifting system options

4.4. Vertical lift gates

If the gates have mechanical lifting gear then consideration should be given to converting it to hydraulic operation. One possibility Is illustrated in Figure 6 above where compound rams are arranged like forklifts on each side of the gate pushing upwards and lifting the gate via a rope anchored at the top of the dam and passing over pulleys at the top of the ram.

If the gates are lifted by a travelling gantry crane then arranging for them to open automatically in the absence of a main power supply and operators is likely to be seriously difficult and expensive. Mounting rams on each side of the gate as suggested above could be a very attractive option.

5. CONCLUSIONS

Many spillway gate systems come nowhere near the reliability expected and achieved by aeroplanes, nuclear power stations and the like. Spillway gate installations are technologically much simpler and, in theory at least, it should be quite easy to make the massive improvements in reliability that are needed.

As the paper shows, there are many ways of improving gate safety and most of them are not very expensive when considered in the context of the cost of the dam. For many gate systems a significant increase in reliability will be achieved simply by purchasing emergency generators with hydraulic starting and air-cooled engines.

Gate safety must be evaluated in terms of system failure rather than relying on codes that, for instance, decree that the design flood must be passed with one gate unavailable. It should never be assumed that operators will be available and capable of taking action in what could be the worst weather conditions ever experienced. This is no different from relying entirely on operators to take all the actions needed in the event of a nuclear meltdown!

It is hoped that, by showing ways of improving gate reliability, this paper will help to reduce the risk of failure of spillway gate systems.

An outcome much to be desired.

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Air cooled engines can be obtained from, for instance,
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