Dams, siltation and low-level outlets

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1. Introduction

It is inevitable that, sooner or later, most dams will fill with sediment. It is simply a matter of time.

When the sediment reaches the power intakes of a hydro dam, there is a risk of the turbines being destroyed and the power station being abandoned. If this happens the spillway will need to operate continuously and this may lead to spillway failure possibly followed by failure of the dam.

Spillways are likely to fail because they are not designed for continuously discharging large amounts of sediment. The concrete and fixed parts will soon be damaged and need to be repaired. Repair is possible only if the spillway is segregated into two or more chutes so that one chute can be isolated and the flow passed down the other chute(s)

Reservoir sedimentation is a serious long-term problem that threatens the long-term viability of storage hydropower schemes. In 2010 global storage capacity was estimated at 6,000,000 km^3 but it is projected that 4,000,000 km^3 will be lost to sedimentation by 2050.[1] It occurs worldwide at a rate of about 0.8 percent per year, but the sedimentation rate in many regions such as Asia is much higher.

Many reservoirs will fill with sediment within the next 100 years or so but some will fill up in a much shorter timeframe. The sediment builds up at the head of the lake and a wall of sediment moves slowly down the lake until it reaches the dam and, eventually, the power intakes.

This paper is intended to draw attention to the problem and to emphasise the need to mitigate or solve the problem by providing a scour intake beneath the turbine intakes.

The major problem is designing the upstream gate to operate reliably when finally needed after, possibly, many years with little or no maintenance. A solution is suggested but it is recognised that better ones may be found: the objective of this paper is to encourage designers and developers to consider a wide range of solutions and to examine the potential of modern materials to help solve this very serious problem.

2. Background

For many years the writer has been concerned that not enough attention is paid to the fact that dams, spillway gates and the like should be designed for a life of hundreds of years.[2] All too often, it is assumed that designing for an economic life of 100 – 150 years is all that matters. The reality is that many of the dams now in service could still be there in 1000 years time – or even more. Six Roman dams are still in operation! Any dam that is not monitored and maintained all its life is likely to fail with possibly disastrous effects for the environment and the local population.

A few years ago the writer was working for a development bank on a Russian designed and built dam that was about 40 years old. The designers had provided for a low-level outlet located under the power intakes and, quite obviously, intended to keep them free of sediment after the lake had filled with silt. The Russian designers were showing commendable foresight.

Figure 1

Figure 1 shows picture of the dam with the scour outlet circled just to the right and below the spillway.

Figure 2 shows a cross section of the dam and the scour layout.

Figure 3 shows an upstream view of the power intakes, the scour intake and the expected final extent of sedimentation.

3. Intake

The ideal location for the intake is directly below the power intakes as indicated in Figure 4. However, this could easily cause considerable complications in the arrangement of the penstocks.

In some cases it might be possible to increase the length of the powerhouse by a few metres and locate the discharge above and between the two middle draft tubes. In other cases may be possible to arrange discharge over the roof of the powerhouse. In many cases, the solution adopted by the Russians will be quite satisfactory.

It is also possible to locate the intake near the bottom of the dam where it could be even more effective. This will not change the design considerations discussed in this paper.

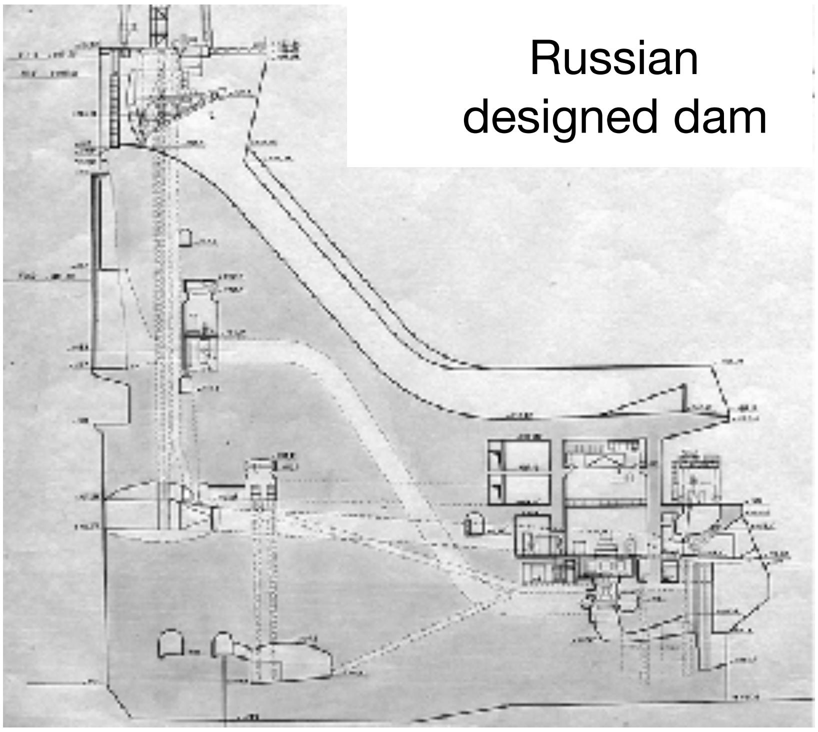

Figure 2

4. Intake gate

The intake gate is critical. It must be able to do its job after more than 100 years with little or no maintenance.

The key decision is whether or not it should close against flow in an emergency. The two options have quite different design outcomes.

There is a strong case for deciding that it does not need to close against flow and to accept that its only purpose is to seal off the downstream waterway and regulating gate. It can be strongly argued that if it does this reliably then there is no need for to close against flow because the downstream gate can be maintained and tested to show that it can open and close with the upstream closed. Its ability to open under full head can be tested safely by flooding the downstream waterway using the bypass valve and then testing to see if the downstream gate will open against full pressure.

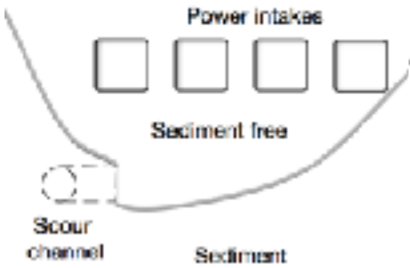

Figure 3

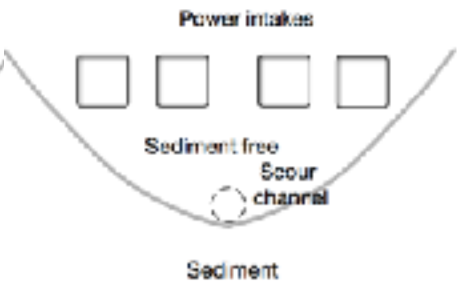

Figure 4

If the upstream gate does not need to close against flow it can be a simple gate sliding on low friction plastic runners and closing under gravity. A lost motion valve in the gate attached to the lifting gear would serve as a filling valve. It can be lifted and lowered by a winch using high density polyethylene rope that has many advantages over wire rope. The gate would be sealed on the downstream side and located on the face of the dam so that the gate and its lifting gear etc would be accessible by divers using saturation diving if necessary.

If we assume the gate is 5 m square and subject to a maximum pressure of 50 m, the loading on the gate would be about 1250 tons. If the gate was made of steel it would weigh about 130 tons. This would require massive lifting gear and gantry crane for handling it. It would also involve considerable problems in providing corrosion protection that would last for more than 100 years.

Fabricating the gate from carbon fibre composite is a very attractive alternative to steel. Its strength to weight ratio is about four times better than steel and a carbon fibre gate would be about 30% of the weight of the equivalent steel gate.

Carbon fibre is corrosion free and has a proven life of at least 50 years – as long as it has been a available. Experts in carbon fibre are confident that life underwater would be more than 200 years. Fabricated carbon fibre costs about $40/kg while fabricated and painted steelwork costs about $15/kg. Given the weight difference, the carbon fibre equivalent would cost much the same as a painted steel gate. When the savings in the lifting gear are also included is likely that the carbon fibre gate would be cheaper.

The risk of the gate getting stuck in the closed position could be reduced by designing the gate as a sealed box and providing for a supply of compressed air to the gate chamber. This could be done using a flexible pipe attached to the top of the gate or by embedding pipes in the concrete that could discharge air into the bottom of the gate. If the gate was 1 m thick the buoyancy effect would be in the vicinity of 25 tonnes – a very useful extra force in an emergency. If the gate became buried in silt it would be possible to blow air into the gate chamber and release it from a series of holes at the bottom and sides of the gate so that the air bubbles would agitate the sediment and allow the gate to lift. Another option would be to pump water into the waterway downstream of the gate chamber and create a differential pressure that pushed the gate away from the fixed parts.

The gate would need to be guided all the way to the surface and one way of doing this would be to provide U shaped carbon fibre inserts in the concrete to guide the gate. There would need to be clearance between the low friction plastic guides on the gate and the insert to allow the gate to seat when under pressure.

Erosion of the gate seals and fixed parts due to leakage water is a potential problem. This risk can be minimised by keeping the filler valve open under normal circumstances. If this was done erosion would be limited to the short periods when the downstream gate was open for maintenance or inspection.

The fixed parts associated with sealing the gate need to last for, possibly, hundreds of years and be resistant to erosion when scouring. It would seem that titanium is the ideal material. It currently costs about $30/kilogram – about six times the cost of stainless steel. Stainless steel will corrode in low oxygen environments so it is not ideal. Bronze is an alternative but probably less resistant to erosion. The gate slots will need to be carefully designed to minimise the risk of erosion from gravel and silt passing through the gate.

Erosion of the concrete by the gravel and silt will also be a problem. Polyurethane is widely used for this purpose in the mineral industry because it is highly resistant to gravel erosion. The waterways could be lined with polyurethane sheets to minimise erosion.[3] This would certainly need to be done immediately upstream and under the gate because it would be virtually impossible to do any repairs in this area. Downstream of the gate is less important because it can be isolated and any damage can be repaired in the dry.

It must be possible to remove the gate for maintenance so there is a good argument for mounting the lifting gear on top of the dam. One option is hydraulic lifting gear connected to the gate by a series of rods each as long as the gate and connected together. The lifting process consists of retracting the hydraulic cylinder, securing the shaft, dismantling the upper section of shaft and extending and reconnecting the cylinder. A major problem is that the rods need to be guided and this adds considerable complication. If the rods corrode the rod may stick in the guides or, in the extreme, may break.

A more attractive option is to use winch lifting gear using high-strength plastic rope such as Dyneema or Dynex. The winch would have two drums with a loop of rope starting at one drum, then looping around a generously sized semicircular fairlead on the gate and back to the other drum.

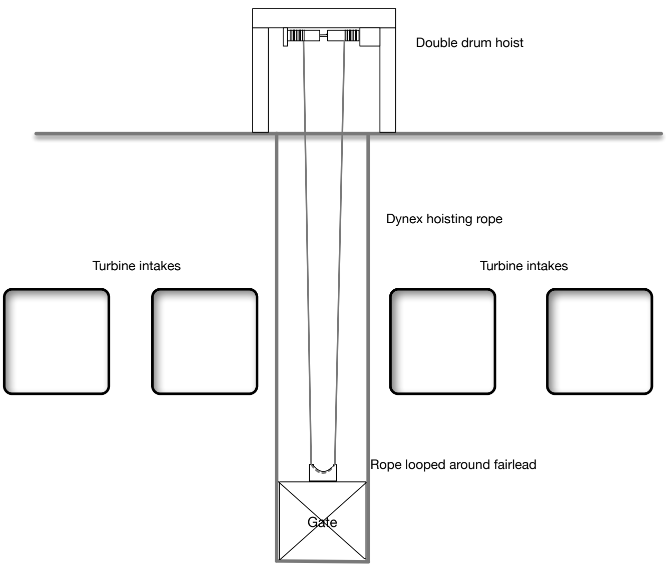

Figure 3

Figure 5 shows the suggested arrangement of the gate and lifting gear.

These plastic ropes are as strong as steel wire of the same diameter[4] and have a specific gravity of 0.97 so they float. They do not corrode and their life underwater is very long indeed – probably more than 100 years. They do suffer from ultraviolet radiation but, even then, their life when exposed to sunshine is well above 10 years.

With the suggested arrangement rope replacement is simple and easy because all that needs to be done is to attach a new rope to one end of the existing rope and pull it down and around the fairlead. If the rope breaks it will float and it will be easy to retrieve it and reeve a new rope. Divers will not be needed.

A gate or valve will be needed to flood the downstream chamber when it has been drained for maintenance. A good way of doing this is to arrange for a valve operated by lost motion of the lifting device. It would be closed when the hoisting rope is loose and it would be opened simply by winding the winch rope in by 100 mm or so. Under normal conditions, the lifting rope would be kept under sufficient tension to hold the flooding valve open and so reduce the risk of seal erosion.

If it is decided that the gate needs to close against flow, the complexity of the problem increases because wheels will probably be needed, vibration could be a major problem and lifting ropes may not be suitable because they could increase the risk of vibration.

A rational assessment may well conclude that the only time that the gate would need to close against flow would be if the regulating gate was opened without first testing it with the upstream gate closed and then it was discovered that the regulating gate failed to close. Whether or not the gate would close would be the prime concern of anyone needing to open the downstream gate for scouring. The best way of easing this concern is to open the gate with the upstream gate closed and the downstream chamber full of water. If a radial gate is used for regulating the flow it is reasonable to assume that if the gate can be opened it can also be closed because the forces on it are exactly the same. This may not be the case if the vertical lift gate used and this fact, combined with the problems associated with gate slots and seals, is a strong reason for not using a vertical lift gate.

It is hard to avoid the conclusion that having the isolating gate capable of closing against flow increases the complexity and cost and does little to reduce the risk of problems. It seems to be far better to have an intake gate that is low maintenance and largely problem free and a downstream regulating gate that is simple and easy to maintain.

5. Downstream regulating gate

A vertical lift gate or radial gate can be used for controlling the flow. The gate can be located just downstream from the isolating gate or further downstream. If it is inside the waterway it must have a generous air supply. Because of the very high water load it is almost certain to require wheels and these add complication and are a maintenance problem. Sealing is relatively difficult because the seals could easily be eroded by gravel passing through the gate. The gravel can also damage the fixed parts.

Radial gates have big advantages over slide gates because opening and closing forces are lower and more predictable and the seals can be clear of the water passage which eliminates the risk of damage to the seals and gate slots.

The gate bearing assembly can include eccentric trunnions that move the gate away from the seals before it is opened and against the seals after it is closed.[5] If they are used then the opening and closing forces are determined by the friction in the trunnion bearing and not by seal friction. This makes a significant reduction in the risk of the gate failing to open or close. It should be noted that an additional advantage of the eccentric arrangement is it allows the bearings to be exercised without actually opening the gate.

Figure 6 From reference 5 shows a typical arrangement of a gate with an eccentric trunnion. (e) indicates the eccentric and (d) is the small hydraulic ram that operates it.

Figure 7 is a picture of the Russian designed gate. The design appears to be good and would be even better if the trunnion had included an eccentric arrangement.

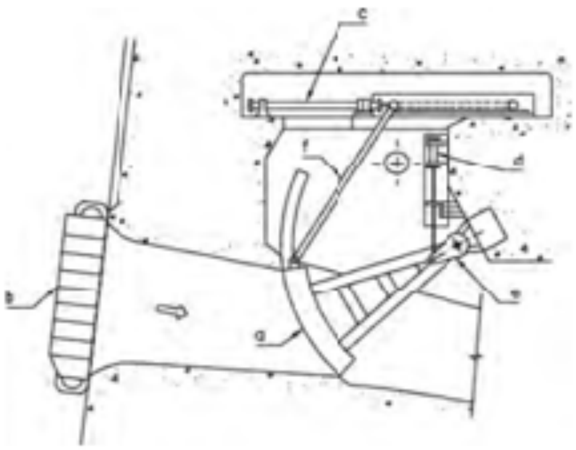

Figure 6

Figure 7

6. Conclusion

Locating a scour intake beneath the power intakes has the potential for keeping the power intakes clear of sediment once the lake has silted up. The big problem is providing an upstream scour gate that will last for, possibly, hundreds of years and still be serviceable when needed.

This paper shows how this could be done using modern materials that have a very long life and can survive the conditions peculiar to a scour outlet.

It is hoped that this paper will encourage those contemplating the construction of a hydro dam to contemplate ways of ensuring that the power intakes can be kept free of sediment if the lake is likely to fill up in the foreseeable future. If they do, generations of dam engineers will be very grateful!

Should ICOLD give this matter serious consideration and contemplate making a strong recommendation that all hydro dams that could fill with sediment within 300 years or so be equipped with a scour outlet designed for a very long life?

References

[1] Sedimentation and Sustainable Use of Reservoirs and River Systems ICOLD 2007

[2] "Large dams: implications of immortality" B Leyland, International Water Power and Dam Construction 1990. http://www.bryanleyland.co.nz/hydropower.html

[3] https://gallaghercorp.com/design-guide/polyurethane-abrasion-resistance/

[4] 48mm rope has a breaking strength of 170 tonnes (http://phillystran.com/product-catalog/12-Strand-Braids-Spectra-Dyneema)

5 "Design of Hydraulic Gates" 2nd ed by Paulo Erbisti p363