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Use of fusegates for improving dam safety

Sébastien Lacroix

(HYDROPLUS, 5 cours Ferdinand-de-Lesseps, 92851 Rueil-Malmaison Cedex, France)

Abstract: This paper discusses the advantages of auxiliary spillways and the benefits of the use of fusegates. It also includes, with the three projects: Jindadyne dam, Canton dam and Otter Brook dam, a glimpse of the selection process and a description of the prominent features of the fusegate system.

Key words: fuseplug; fusegate; dam safety; auxiliary spillway; gate

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Biography: Sébastien Lacroix (1971－), male. He graduated as a hydraulic engineer in 1995 from “Ecole Nationale Supérieure d’Hydraulique et de Mécanique” of Grenoble, France. He started his career at VINCI Group (GTM) as a project engineer for HYDROPLUS in South Africa, and then supervised refurbishment works for ENTREPOSE. In HYDROPLUS, he is now regional manager in charge of North and South American, as well as the Australian market. His responsibilities include project studies, engineering and design, work supervision and contract management. He has been involved in more than 100 dam projects.

利用自倾门提高大坝安全性能

摘　要：探讨了辅助溢洪道及采用自倾门泄洪的优点，并通过 Jindabyne 大坝、Otter Brook 大坝和 Canto 大坝三个工程，介绍了自倾门系统的显著特点以及选择流程。

关键词：非常溢洪道；自倾门；大坝安全；辅助溢洪道；门

0 Introduction

When modern standards are applied to existing dams using better flood hydrology and methods, the studies often seem to indicate that the spillways suffer from an inadequate discharge capability. It is perhaps worth noting that the general consensus is that between one-quarter and one-third of all dam failures are due to overtopping.

If the dams under consideration pose a high hazard or an unacceptable level of risk, the spillway discharge potential will often require upgrading. Common remediation methods include raising the dam crest, installing overtopping protection or widening / deepening the existing spillway sill. Constructing an auxiliary spillway can also offer a economic and effective solution in the case of severe spillway discharge inadequacies especially since the downstream chute can often be allowed to erode somewhat under extreme flood events as long as such action does not jeopardise the safety of the dam. The challenge of providing a fixed overflow auxiliary sill in the latter case however is the crest requires location at a reasonable level above the main service spillway in order to provide sufficient hydraulic head on the main spillway so that the auxiliary spillway does not operate too frequently. However the closer the fixed auxiliary sill is to the dam crest, the wider it is required to be in order to be able to pass a given peak discharge. The cost and the spatial constraints may well prohibit such a design approach and in such cases the use of a “breaching section” such as an earthen fuseplug will be considered in order to provide a more effective and economical design. Increasingly however, the reliability of such fuseplugs has been called into question. Concerns are that the original design assumptions may not be replicated when the fuseplug is required to operate some time after construction. A reliable and cost effective alternative to the fuseplug approach has been available for over fifteen years now (the Fusegate System) and the potential for this system is highlighted herein using three recent applications at

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Jindabyne dam (Australia) and at Canton and Otter Brook dams (USA).

1 Fusegates concept

1.1 General comments

Fusegates are an innovative and reliable spillway system patented by Hydroplus. They represent a genuine alternative to conventional systems, such as gates, flaps or inflatable tubes. Fusegates have successfully been implemented on 40 dams throughout the world, providing solid evidence of their value and effectiveness.

Fusegates are modular freestanding units that can be installed side by side on a spillway's modified sill (the sill must be levelled to provide the necessary flat structure to accommodate the Fusegate modules). The modules consist of a vertical facing connected to a horizontal slab atop the sill. Watertight seals around the upstream perimeter of each Fusegate make it complete waterproof. Each unit rests on abutment blocks on top of the sill and is weighted with ballast to resist hydrostatic pressure (see Fig. 1 and 2).

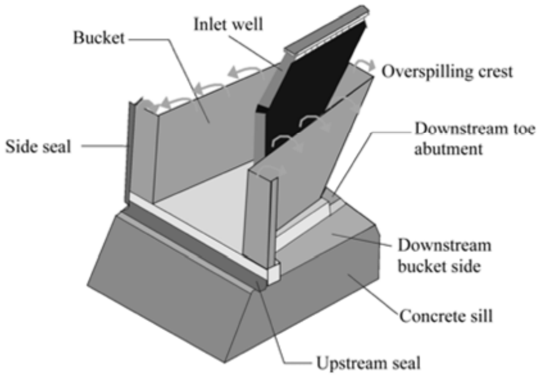

Fig.1 3D view of a fusegate

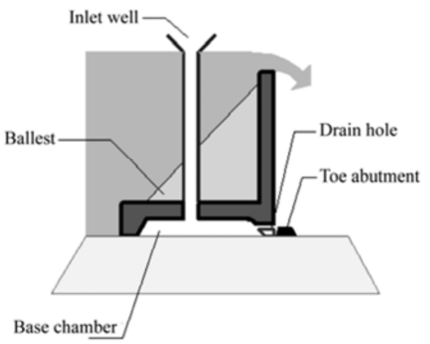

Fig. 2 Moderate overspill

Fusegates come in two models according to the shape of their vertical facing: straight crested and labyrinth crested. Each is associated with a particular benefit: ① straight crested Fusegates provide resistance to significant spill-over (up to three times their own height); and ② labyrinth crested Fusegates can discharge greater flows for a given water depth.

The operating principle results from the shape of the fusegate base. The central part of the horizontal slab underneath is hollow, forming a chamber equipped with drain holes. The chamber is connected to the reservoir via an inlet well that admits water to the underface when the headwater reaches the top of the funnel.

Low-height modules (less than 1.0 m in height), applied on rustic projects, might be designed without an inlet well. In such cases, this patented system of self-stabilizing blocks works in a very simple fashion, using the equilibrium between gravity and hydrostatic forces. However, they are not as reliable and accurate as the fusegates described above.

1.2 Normal functioning

Thanks to their watertight system, fusegates allow water storage up to their crest. Ordinary and average floods are discharged over the fusegates crest, as in the case of free overflow weirs (see Fig. 2). The chamber is drained to discharge all accidental flows (due, for example, to a problem with the seals) to ensure no uplift pressure develops in the base chamber.

Before the inlet well is fed, fusegates offer a high stability margin such that they withstand significant external loading without premature tipping. Specific research in reputable hydraulic laboratories around the world has been undertaken to assess the possible effect of ice, impact from floating debris, and waves on the fusegates and they have demonstrated their minimal incidence on the system.

1.3 Safety in case of major flood

Fusegates are designed to tip over in case of exceptional floods, which, otherwise, would be strong enough to jeopardize the whole dam safety. The successive tip-offs gradually increase the spillway's discharge capacity and protect the dam from failure.

The fusegate starts to tip when the reservoir level exceeds the crest of the funnel. The water entering the inlet well cannot be evacuated by the drain holes without creating significant uplift pressure in the chamber (see Fig. 3).

The uplift pressure, combined with the hydrostatic pressure is sufficient to overcome the restraining forces and the imbalance causes rotation of the unit off the spillway. The fusegate is then washed away clear of the spillway by the flood (see Fig. 4).

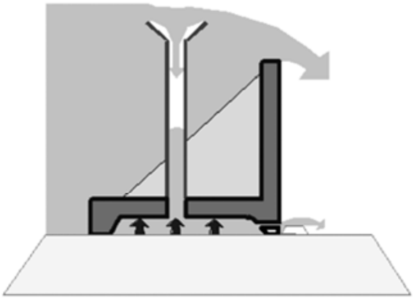

Fig. 3 Inlet well being fed

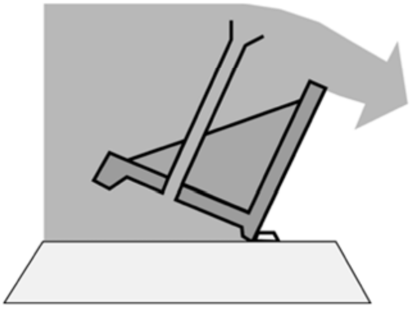

Fig. 4 Fusegate tipping

Each inlet well is set at a different height to ensure that the fusegates tip in sequence, thus ensuring progressive discharges and preventing sudden flash floods in the river that may pose a threat to downstream populations and property.

The tipping recurrence of a fusegate tipping is selected so that the loss does not adversely impact the project economy. The associated direct and indirect costs are actually amortized over the long period between two tipping events. Concerns arise about the impact on the reservoir firm yield especially in the case of pluriannual dams located in dry areas. Pitmann and Watson (1998) have studied thirty river catchments in South Africa in order to assess the possible reduction in reservoir firm yield caused by a tip-off. It was found that the risk becomes nearly negligible in case the first fusegate is designed to rotate for floods in excess of the 100 years event and prompt actions are taken to reinstate the storage. No regional trends emerged from the study and there was no correlation with the coefficient of variability of the historical streamflow. It can be concluded that the results can be applied to any catchment area in South Africa and other areas as well.

1.4 Cases of application

Fusegates are often used to increase reservoir storage capacity for free-sill spillways without modifying the high-water line, thereby providing two important benefits: it limits the social and environmental impact of the upgrade; and it does not alter the ultimate loading condition applied to the dam embankment and its appurtenants.

Fusegates also constitute a cost-effective way to upgrade undersized spillways providing a safety profile comparable to that of free-overflow spillway crests. Two upgrade types are typically envisaged:

(1) For all types of spillways: an auxiliary spillway is created to provide additional discharge capacity, which, when combined with the existing spillway, enables the dam to cope with the flood design discharge safely and effectively. This is a highly reliable alternative in comparison to fuseplug spillways (see the Jindabyne and Canton projects).

(2) For free-overflow spillways: the existing sill is planed to a level where the design flood can be discharged safely. The storage capacity lost by lowering the sill is restored (and, in some cases, augmented) by integrating a system of fusegates to the modified sill (see the Otter Brook project).

2 Auxiliary spillways

2.1 General

Auxiliary spillways complement the capacity of the service spillway in order to safely discharge the maximum design flood. They can often offer attractive solutions to severe spillway discharge inadequacy problems especially in the case where a suitable location is available (such as a topographic saddle sufficiently remote from the main dam). The effectiveness of such an alternative can be enhanced by the use of a fusible spillway control system as mentioned above. Among fusible spillway control systems, the fuseplug has been the most widely used around the world, but there are few documented cases of fuseplug spillways actually operating during the extreme flood events for which they are designed. The fusegate concept has, however, over the last decade or so gained significant recognition as a more reliable, accurate and versatile system.

2.2 Fuseplug

Fuseplug spillways are normally fairly low embankment sections constructed within a relatively non-erodible channel. The fuseplugs are designed to be overtopped during exceptional flood events, resulting in erosion of the section and allowing reservoir outflow through the breach.

The embankment should be stable under normal flow conditions and only overtopped when required to safeguard the dam structures. Central to the design philosophy of the fuseplug is its failure mechanism. This is dependent on many factors, and the results of analytical models based on hydraulic and erosion theories could be of limited value since the outcomes cannot be calibrated against reliable physical modeling due to the inherent complexities of replicating scale factors on soil structures. The selection of an appropriate material is vital to the predictability of the rate and extent of embankment failure during overtopping as is the long term soil characteristics.

Typical design features generally include an impervious core, sand and gravel forming the major part of the embankment and slope protection (see Fig. 5). The downstream channel is usually sloped in order to ensure that the downstream water level and embankment does not impair the rate of erosion. The fuseplug foundation should resist erosion so that the minimum level reached during a flood is predictable.

Despite the fact that normal operation of fuseplug spillways has been reasonably dependable, there are concerns regarding the possibility that the failure section will not erode as intended. Reasons for which fuseplug operation can be jeopardized include freezing of the erodible zone, compaction over a long period and vegetation on the embankment slopes.

Another difficulty with fuseplug spillways is the uncontrolled nature of the discharge. As the section fails, a dam-breach outflow is created which can increase downstream flood hazards beyond those normally expected for a given flood magnitude. Dividing walls are often used to section the fuseplug and to get a more progressive release of the flood water.

2.3 Advantages of the fusegates over fuseplug

Fusegates have successfully been implemented on 50 dams throughout the world, providing solid evidence of their value and effectiveness. Over a fuseplug, a Fusegate system would offer the following benefits: ① fusegates can withstand significant discharge over their crest before they tip-off, ② fusegates are inherently more predictable and reliable during operation, ③ fusegates require less maintenance, ④ the material characteristics of fusegates is dependable and not subject to change with time, ⑤ fusegates offer a more controlled release of water during extreme flood events, ⑥ there have been no cases where fusegates have behaved contrary to design, ⑦ fusegates often have a smaller environmental "footprint", and ⑧ fusegates can be model tested to ensure reliable and reproducible calibration against theoretical structural and hydraulic models and their actual likely performance in the scope of a project.

3 Jindabyne dam

3.1 Project background

Jindabyne dam consists of a 65 m high rockfill embankment constructed across the Snowy River near Cooma in New South Wales, Australia. It is owned and operated by Snowy Hydro Ltd primarily for power generation, but also for sustaining an environmental flow in the snowy River (see Fig. 6).

The spillway was originally designed to pass the Probable Maximum Flood, with a freeboard of 1.20 m, as calculated using methodology and data current at the time of construction. At that time, the PMF flood was estimated to have a peak inflow of 6100 m^3/s and a peak outflow of 3000 m^3/s. In the mid 1990's Jindabyne dam

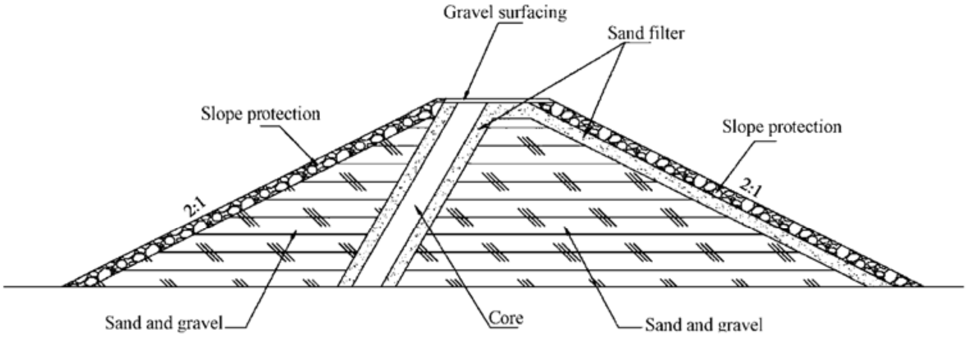

Fig. 5 Cross section through typical erodible fuseplug

was assessed as having a "High B Consequence Category" (major severity of damage and loss with population at risk between 10 and 100). In order to meet the Dam Safety Requirements and ANCOLD guidelines, it was necessary for the dam to pass either the 1：1000000 joint AEP flood or the Probable Maximum Precipitation Design Flood, whichever gave the lowest water level.

Fig. 6 Artistic impression with location of service and auxiliary spillways

3.2　Evaluation of alternatives

Numerous options were studied including overtopping protection of the dam embankment, raising the dam crest and creating a new spillway equipped with various spillway control systems (mechanical gates, fusegates, drop inlet, labyrinth spillway, inflatable rubber dam and fuseplug).

A preliminary selection was made to provide additional spillway capacity by maintaining the existing radial gated service spillway and constructing a new auxiliary spillway on the right bank. In order to ensure that the unlined auxiliary spillway would not operate until extreme flooding occurred, it was decided that a control structure would be required.

After various spillway control systems were evaluated and shortlisted into final options (see Table 1) in terms of capital and whole of life costs, construction issues, maintenance, reliability and environmental aspects, it was decided to adopt the fusegate system.

The fusegate system was considered to be practically maintenance free due to the lack of moving parts and the fact that concrete cast in-situ fusegates with stainless steel inlet wells and seal Fixing arrangement were proposed. The other systems have mechanical items such as guard valves, cone valves and trash racks, bearings, etc. which required maintenance and operational costs to be accounted for. The mechanical gates would have required painting for the mild steel components as part of a maintenance program.

Table 1 Summary of cost factors for short listed options

Description of the alternative	Cost ratio to lowest cost
New auxiliary spillway controlled by conventional balanced automatic radial gates	1.15
New auxiliary spillway controlled by buoyancy gates	1.21
New auxiliary spillway controlled by fusegates	1.00
New service spillway controlled by conventional radial gates	1.17
New service spillway controlled by buoyancy gates	1.35

3.3　Fusegates design

Flood routing based on model tests findings indicated that the spillway discharge requirements are met with an auxiliary spillway having an effective length of 90.5 m and a sill set at El.905.90 m. The spillway was equipped with eight fusegates with a crest set at El.913.50 m, which is 3.15 m above the normal reservoir level. In such configuration, the fusegate units are 7.6 m high setting a world record for the tallest ever constructed (see Fig. 7).

Fig. 7 Auxiliary spillway from upstream

The auxiliary spillway has been located on the right embankment of the dam. The excavation volume for the approach channel and chute was calculated to be 60000 m^3 of mainly rock material (most of which could be used in construction of the 130000 m^3 coffer dam).

The fusegates tip-off individually for predetermined reservoir levels ranging between El.914.60 m and El.916.35 m. In such a configuration, of the PMF peak discharge, approximately 3200 m^3/s is discharged through the service spillway radial gates and 5600 m^3/s through the newly constructed auxiliary spillway with all Fusegates having tipped.

It was targeted that the flood which would cause the fusegates to be overtopped would be the 1 in 1000 years event and the flood causing the first fusegate to tip the 1 in 5000 years event. For replacement of the unit after tipping and repair of erosion damage, should there be any, the risk costs were considered to be acceptably low. Fig. 8 is a typical cross section of Jindadyne dam.

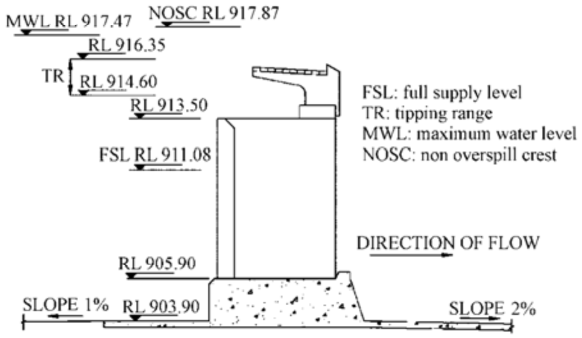

Fig. 8 Jindabyne dam typical cross section through the spillway with key elevation

4 Canton dam

4.1 Project background

Canton Dam is located in western Oklahoma in the United States of America. It is owned and operated by the US Army Corps of Engineers, Tulsa District, for protecting Oklahoma City against the flooding of the North Canadian River, and it is also a pleasant area for recreational activities.

The dam consists of a 4600 m long earth-fill embankment with a maximum height of 20.0 m above streambed. It has got a 233 m wide service spillway controlled by 16 Tainter gates located at the right abutment with a capacity of 9600 m^3/s at maximum pool (see Fig. 9).

Fig. 9 Service spillway from downstream

According to Engineer Regulation (ER) 1110-2-1155, the project shall meet the Base Safety Condition (BSC) as determined by comparing loss of life for various floods, expressed as percentages of the PMF, beginning with the threshold flood (defined as the flood fully utilizing the existing spillway). The threshold flood for Canton dam is equivalent to 59.5% of the PMF. The dam safety studies have demonstrated that incremental loss of life occurs in all floods from the threshold flood to 100% of the PMF, establishing the BSC at 100% of the PMF.

4.2 Evaluation of alternatives

Eight options have been studied to remedy to the hydrologic deficiency (see Table 2). It was found that constructing an auxiliary spillway would offer the most feasible option.

Table 2 List of the options

NO.	Description
1	Raise the dam by 2.10 m (maintain the freeboard)
2	Raise the dam by 0.4 (eliminate freeboard)
3	Add an uncontrolled spillway
4	Additional fuse plug spillway
5	Additional fusegated spillway
6	Additional gated spillway
7	Reduction of flood control storage

Although less expensive, the fuseplug option was discarded because of serious safety and operational concerns inherent to the system. The recommendation was then to evaluate in depth alternatives consisting of various design widths utilizing fusegates or tainter gates. The adopted solution involves excavating a new auxiliary spillway to bring the extra 7800 m^3/s of discharge capacity which is required to ensure a safe evacuation of the PMF. Use of fusegates was preferred since they are 50% less expensive than the tainter gates and offer valuable benefits from a dam safety point of view.

4.3 Fusegates design

The proposed configuration consists of excavating a 975 m long and 146 m wide channel bypassing the service spillway at the right bank (see Fig. 10). The excavation volume for the approach channel and chute was calculated to be 4300000 m^3. An elevated concrete sill will accommodate nine 9.14 m high and 16.25 m wide fusegates, each of them being made in reinforced concrete cast in-situ and weighing 530 tons. The first unit would tip-off for 58 percent of the PMF, which is in excess of the floods usually serving as a design flood for numerous small to medium dams across the USA.

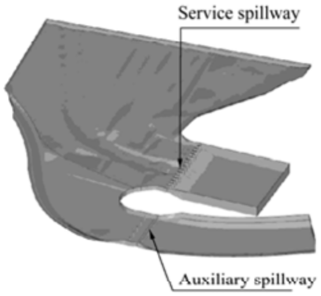

Fig. 10 Geometry of the auxiliary and service spillways

Due to wave action and to the relatively long approach channel, the inlet wells will be gathered in a protective enclosure open to the reservoir. A network of pipes will be embedded in the concrete sill to connect the inlet wells to the base chambers of the fusegates. Such arrangement has been successfully implemented at Terminus dam in the United States of America among other projects.

The first stage of the project includes the optimization of the emergency spillway channel configuration in order to minimize the overall project cost whilst meeting the hydraulic performances requirements. Because of the complex flow pattern resulting from the proximity between the intakes of the two spillway channels it was determined that a physical model study was required. Model tests are expected to be completed in October 2008 and excavation works for the spillway channel will start shortly after. Fig. 11 is a typical cross section of Canton dam.

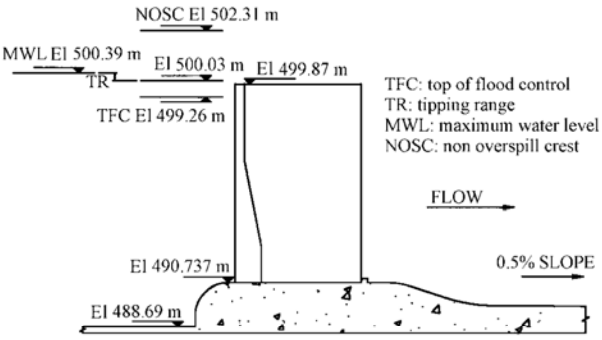

Fig. 11 Canton dam: typical cross section through the spillway with key elevation

5 Otter Brook

5.1 Project background

Otter Brook dam consists on a 40 m high embankment completed in 1958 as a component of a network of flood control dams built on the tributaries of the Connecticut River located in New Hampshire in the United States of America. It is owned and operated by the US Army Corps of Engineers, New England District.

After the original construction, the dam constituted a flow restriction, with resultant outlet conduit capacity of 37 m^3/s at the spillway crest. It was also equipped with a 48 m long free overflow spillway for large floods discharge.

The spillway design criterion at the time of design and construction stages was for a storm of 0.6 m of precipitation over 72 hours, which would involve a flood with a peak inflow of 1076 m^3/s. This design criterion was reassessed using up to date guidance documents. The design flood should be based on a 0.75 m precipitation event, giving a peak inflow of 1834 m^3/s. The occurrence of the updated storm would involve an overtopping of the dam crest by 0.30 m and, therefore, would possibly cause the failure of the dam.

5.2 Review of options

It was noted during preliminary design stage that the spillway channel, with its sill at El.238.0 m removed, and with excavation to El.235.3 m, would be able to pass the design flood. This design satisfies needs for low cost, but increase costs for damages in the more routine smaller flood events, since it would result in a loss of 17% of the reservoir storage capacity.

Following the initial assessment of the economical benefits, a comprehensive review of remediation options was undertaken, including conventional methods and spillway control systems. Following this review, it was concluded the most feasible alternative was to excavate the sill to El.235.3 m and to rectify the permanent loss of storage space with the installation of Fusegates designed to spill only when the pool reaches El.238.0 m.

5.3 Fusegates design

A total of six fusegates, each 2.75 m high and 8.00 m wide, were installed during the second half of 2005 (see Fig. 12). The first fusegate is designed to tip-off when the head of water reaches 1.82 m above its crest. Such flood has a very low probability of occurrence; for instance, the first and only spillway discharge at Otter Brook Dam involved only a 0.35 m head of water above the sill. Once all fusegates have tipped, the discharge capacity is 1650 m^3/s; thus meeting the project requirements.

This project takes advantage of the ability of fusegates to withstand large amount of water over their crest before they open. The operation mode of the new spillway duplicates what would be obtained with a free overflow service spillway supplemented with an auxiliary fuseplug spillway for extreme floods discharge.

Fig. 12 Otter Brook fusegates from upstream

6 Conclusions

The fusegate system constitutes a strong and reliable alternative to fuseplug, whose use is more and more coming into question. Fusegates alleviate the main concerns of engineers with regard to accuracy and reliability of operation associated to fuseplugs and offer a wider range of application, with for instance the possibility of enabling significant discharge over their crest before their tip-off if required.

Three recent projects also confirm that fusegates are a cost-effective alternative to any kind of mechanical gates. In term of dam safety, fusegates if used on an auxiliary spillway are very complementary to gates equipping the service spillway; the fusegates are actually ideal for dealing with extreme flood events whereas gates are ideal for daily operation and upstream water levels control.

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