

HYDRAULICS AND DESIGN OF FUSEGATES

Hasan T. Kocahan, *Business Development Manager, Hydroplus, Inc.*

PO Box 1731

Falls Church, VA 22041, USA

Phone : 703-575-9075, Fax: 703-575-9193

INTRODUCTION:

The Fusegates were invented in 1989 as a simple, robust, and safe system to increase dam safety or increase live storage. The system has been patented by Hydroplus in the United States, Europe, and most other countries. It is implemented in more than 40 dams in 14 different countries across 5 continents.

Due to its inherent flexibility, the system can be used at many existing dams for:

- Increasing live storage capacity of dams with ungated spillways without raising the Maximum Water level,
- Improving spillway discharge capacity without sacrificing existing storage, by lowering the spillway crest before installing the Fusegates,
- It is possible to combine these two benefits and also to improve flood control dam performance by significantly reducing outflow during the more frequent floods whilst at the same time increasing spillway capacity (by 50 to 100 per cent in some cases), and sometimes the storage capacity as well.

The concept can be used at all new dams, large or small, and the design can be optimized by reducing the capital costs of construction and increasing the safety of operations. In particular, the Fusegate System can be used to reduce spillway sill length and dam height.

1. PRINCIPLE OF THE SYSTEM

1.1 DESCRIPTION

The Fusegate System is based on the following concept:

- Fusegates are free-standing units installed side-by-side on a spillway sill to form a watertight barrier.
- They bear against small abutment blocks set in the sill to prevent them from sliding before they are required to rotate (under extreme flood conditions).
- There is a chamber in the base of each Fusegate, with drain holes to discharge incidental inflow (due to leaking seals for example).
- An inlet well on the upstream side of the Fusegate crest discharges water into the chamber when the headwater reaches a predetermined level (see figure 3).

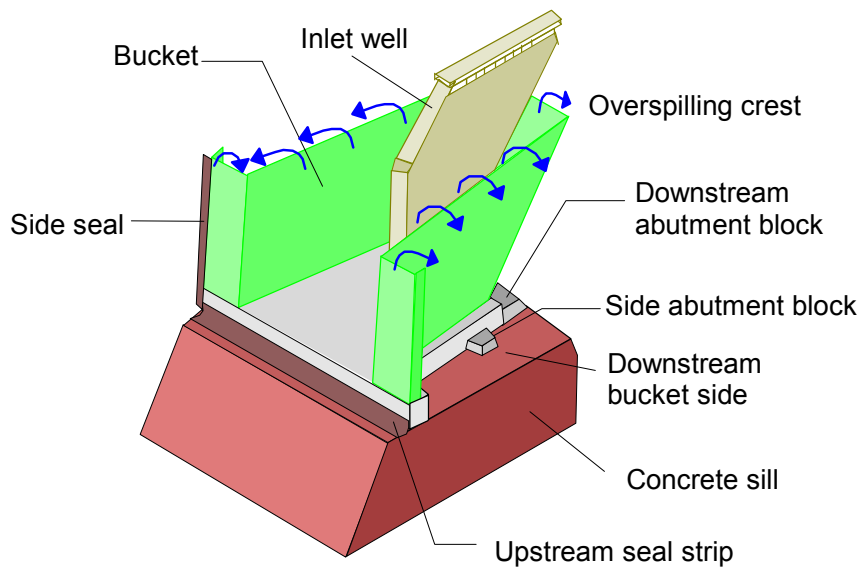


Figure 1: Typical 3D view of a Fusegate

1.2 NORMAL OPERATING CONDITION

In normal operating conditions, the Fusegates act as a watertight barrier. Medium to moderate floods are simply discharged above the Fusegate crest as they would do over a free weir (see figure 2).

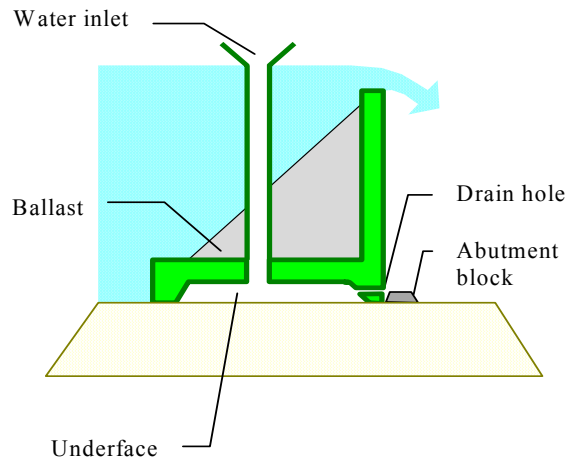


Figure 2: water spills over the Fusegate

1.3 EXCEPTIONAL FLOOD EVENT

If the reservoir level exceeds a predetermined value, water will flow into the inlet well and cause an uplift pressure to develop in the chamber (see figure 3).

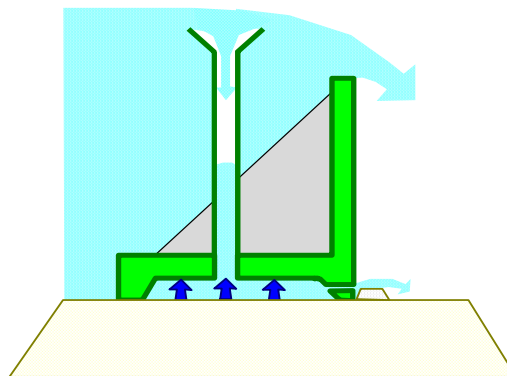


Figure 3: well being fed

The uplift pressure, combined with the hydrostatic pressure (acting from left to right on the adjacent diagram) 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 figure 4).

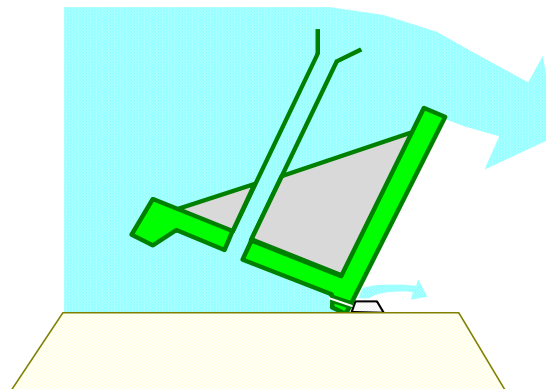


Figure 4: Fusegate tipping

Each Fusegate has a different overturning level, precisely determined by the height of the water inlet and its own unique stability.

If the water level continues to rise after the first breach more Fusegates can rotate, all according to pre-determined upstream water levels, until eventually there are no more units remaining and the spillway is free to pass the original maximum design flood.

The economic impact of the Fusegates rotation is to be regarded considering the low probability of the corresponding flood event, which can be adjusted accordingly (generally between 1 in 200 year and 1 in 1000 year flood). For instance, the first Fusegate to rotate at Kaweah Lake, California tips for floods in excess of the 1 in 1000 year flood. Until rotation of the first Fusegate, the user has the benefit of the additional storage and the system operates as any other ungated dam.

Fusegate could be considered as the mechanical equivalent of a Fuseplug. However, when the Fuseplug begins to operate, the entire plug fails. In contrast, with Fusegates, only the number of units required to pass a flood are operational. In addition, reservoir elevations at which each Fusegate tilts can be more precisely controlled.

2. DESIGN OF A FUSEGATE

2.1. LABYRINTH FUSEGATES

When installed, labyrinth crested Fusegates reproduce the shape of a labyrinth weir in which each Fusegate represents one cycle of the labyrinth (see figure 1).

The height of a labyrinth crested Fusegates can be customized to meet any project requirements. Review of the projects implemented so far shows that the Fusegate height ranges between 4' and 22'.

Labyrinth crested Fusegates are available in three standard configurations which are designated by the width of the Fusegate to its height as being wide (W) or narrow (N) and by the tilting range as being low head (LH) or high head (HH). The features of each of the configuration are given on figure 5.

	Tilting range (in % of the Fusegate height)	Ratio of width to height
Narrow Low Head (NLH)	Between 30% H and 70% H	1,0 (+/-5%)
Large Low Head (LLH)	Between 30% H and 70% H	1,5 (+/-5%)
Large High head (LHH)	Between 70% H and 140% H	1,8 (+/-5%)

Figure 5: main features of labyrinth crested Fusegates

Detailed hydraulic investigation of the Fusegate discharge characteristics were conducted at the Tennessee Valley Authority in Norris, Tennessee and in other reputable laboratories around the world. It was found that the discharge characteristics can be closely analyzed by the following formula :

$$\text{If } h > h_c \quad Q = A\sqrt{H}h + BH^{2/3}$$

where Q is the discharge per linear feet, H the Fusegate height, A and B discharge coefficients (dependant on the Fusegate geometry) and h the difference in the reservoir and the crest elevation. The discharge parameters are given in figure 6.

It will be noted that the above formula differs from the relation generally applied to free weir (where the discharge depends on h at the power 3/2). This is explained by the submergence of the labyrinth, which reduces the hydraulic efficiency as the flow depth over the Fusegate increases.

	A	B	h_c
Narrow Low Head (NLH)	4.836	-0.145	0.262
Large Low Head (LLH)	4.523	-0.093	0.591
Large High head (LHH)	5.606	-0.281	0.427

Figure 6: discharge parameters

The labyrinth shape of the Fusegates enables the system to discharge 1.5 to 2.5 times more water than a conventional ogee crest.

Fusegates are designed to operate with an aerated nappe. The tests at TVA showed that the discharge coefficient was constant up to the point where tailwater was equal to the crest elevation. The effects of submergence and nappe interaction on the discharge coefficients observed on fixed labyrinth weirs are not significant with Fusegates.

2.2. STRAIGHT FUSEGATES

The functioning principle of straight crested Fusegates is similar. Straight and labyrinth types of Fusegates differ only by the shape of the overspilling crest.



Figure 7: straight crested Fusegates

Straight crested Fusegates are generally considered when the conditions of applications do not allow for using labyrinth crested Fusegates or when a high discharge efficiency is not required. The latter case is typically when Fusegates are installed on an emergency or secondary spillway.

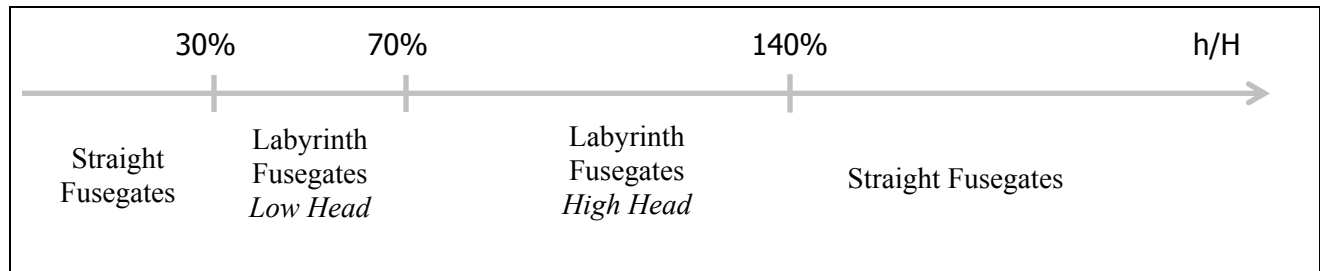


Figure 8: Typical field of application of straight crested Fusegates versus labyrinth crested Fusegates

Straight crested Fusegates can be engineered to withstand an overspilling in excess of 350% of their crest height.

Straight crested Fusegates can be fully customized, since no particular ratio of width to height is required. The only recommendation is to keep the Fusegate width larger than its height.

The discharge characteristics are expressed using the discharge coefficient C_d for weirs defined by Rouse (1960) as:

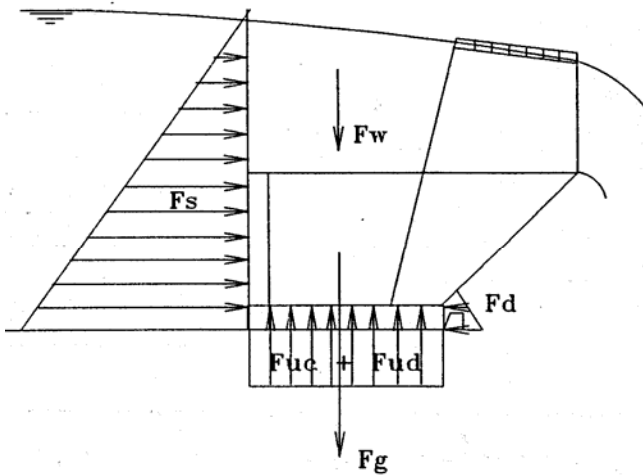
$$Q = \frac{2}{3} C_d \sqrt{2g} h^{3/2}$$

where Q is the discharge per linear feet, g the acceleration of gravity and h the difference in the reservoir and the crest elevation.

Model tests undertaken show that the value of C_d ranges between 0.61 and 0.64 depending on the Fusegate shape and spillway configuration.

3. STABILITY ANALYSIS

3.1. LOADS



Loads causing overturning moment

- F_s upstream hydrostatic force
- F_{uc} uplift force within the chamber
- F_{ud} uplift forces under the beams

Loads causing resisting moment

- F_g dead load of the Fusegate
- F_w water load above the Fusegate
- F_d downstream hydrostatic force

3.2. UPLIFT IN CHAMBER AND ON UNDERSIDE OF BASE

Theoretical analysis and model tests have been conducted to determine the uplift distribution in the chamber under normal conditions and in all conceivable critical situations.

Under normal conditions, the upstream seal prevents water from entering the chamber. When the Fusegate is spilling, leakage between the underside of the base and the sill will be discharged through the drain holes at the downstream edge.

These drain holes are large enough so that normal leakage into the chamber from downstream will be discharged with a near-zero depth of water in the chamber. The pressure in the chamber in such circumstances is called the “natural uplift pressure”.

Model tests considering the scenario of a Fusegate with its upstream edge slightly lifted off the sill were performed. They allowed for determining the magnitude of the maximum uplift pressure which can be

generated in the chamber. The pressure in the chamber in such theoretical circumstance is called the “lift-off uplift pressure”.

The Fusegates are engineered to tip-off when the uplift reaches a predetermined value ranging between the natural and lift-off uplift pressures.

3.3. TYPICAL STABILITY CURVE

The stability curve (see figure 9) shows the stabilizing moments and overturning moments as a function of the reservoir level (measured with reference to the Fusegate base). The Fusegate overturns when these two moments are equal.

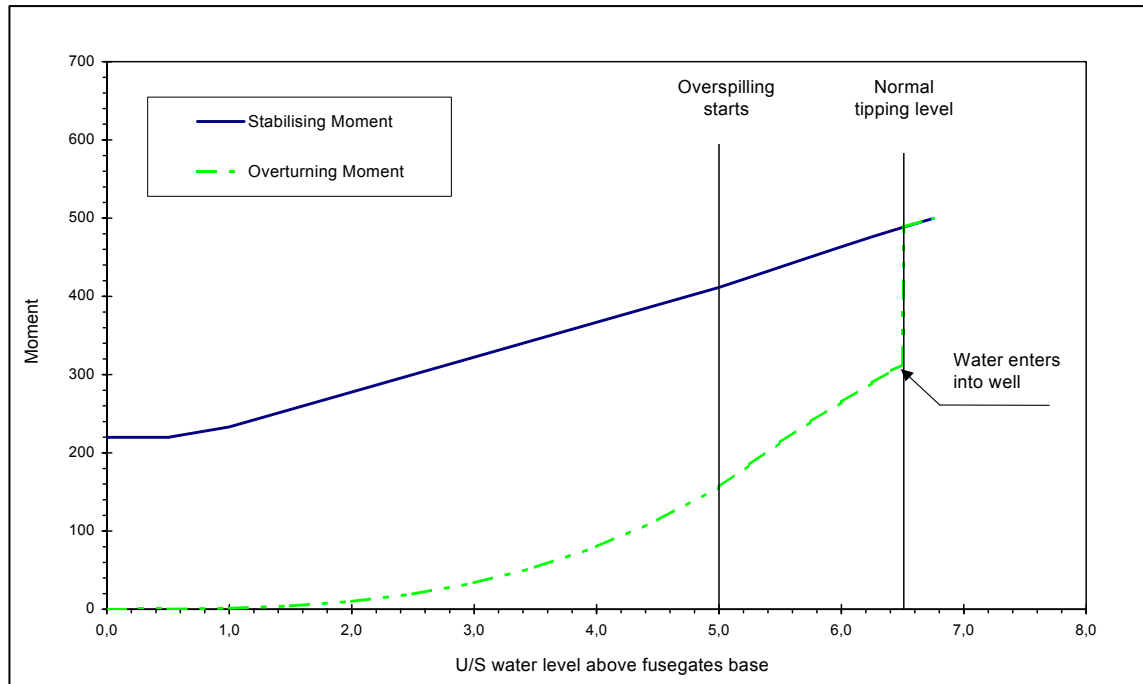


Figure 9: Stability curves, normal conditions.

The stability margin of a Fusegate is defined as the difference between the stability and the overturning moment for any assumed upstream water level. It will be noted from figure 9 that high stability margins are achieved until the well is fed. It reduces the possible effect of abnormal load cases such as impacts of floating debris as well as for withstanding quite large earthquakes as discussed in paragraph 4.

3.4. SAFETY LEVELS

The stability curve of a Fusegate can also be computed under two theoretical scenarios, namely with lift-off uplift pressure in the chamber and with the wells being completely inefficient.

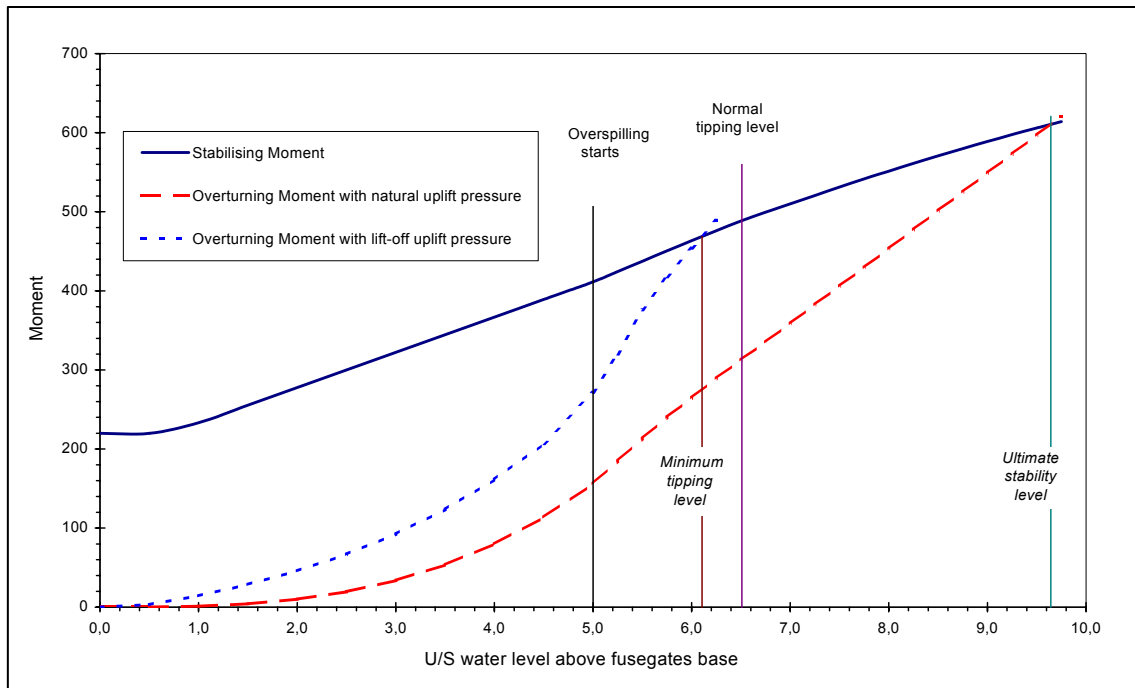


Figure 10: Stability curve with uplift pressure limit value

The case with lift-off uplift pressure in the chamber determines the **minimum tipping level** below which the Fusegate will return to its normal position even if the chamber is full (due to the impact by a very large floating debris, or water entered intentionally through the well)

The case with the well being completely inefficient (as a result of sabotage for instance) is called the **ultimate stability level** at which the Fusegate overturns even without water entering the well. In this case, the Fusegate rotate under the effect of the upstream pressure only.

4. OPERATIONAL RELIABILITY

4.1. SAFETY OF DOWNSTREAM POPULATION

The minimum tipping level defines the head below which the Fusegate can not rotate regardless of the scenario envisaged.

The minimum tipping level can be fixed at a given elevation by adjusting the amount of ballast (and thus the uplift pressure triggering the tip-off). The dam owner can specify his minimum tipping level and the magnitude of the corresponding flood.

This engineered safeguard is of vital importance for the people living downstream since it removes the risk of a sudden artificial flood in the absence of a natural river flood.

4.2. DAM SAFETY

The ultimate stability level is the reservoir level for which the Fusegate overturns even in the unlikely case of the well being completely blocked.

Since the individual Fusegates are independent from each other, the probability of this situation occurring on the whole set is practically nil.

Depending on the dam operator goals, the design of the Fusegates will be such that floods of very low probability of occurrence can be discharged without endangering the dam, even with many of the wells being blocked.

4.3. CRITICAL SITUATIONS

Besides the blocked well situation, the safety analyses conducted also takes into account the cases of the upstream seal being completely destroyed and the drain holes being blocked. These are entirely theoretical situations, which could occur only through willful damage or complete dereliction of the dam inspection.

Destruction of the upstream seal may lead to an increase in the chamber pressure because of leakage from the reservoir, although again, this cannot cause the Fusegate to tip-off before water is admitted through the well.

Drain holes blockage causes the pressure in the chamber to approximate the back-pressure downstream. However, the Fusegate will not rotate before the well is fed.

4.4. SPECIFIC DAM CONDITIONS

The design of a Fusegate System for any specific project should also include the effect of waves, floating debris and impacts of earthquake as well as of ice conditions. Mathematical models were developed to properly assess those effects depending on the particular project constraints.

- *Waves, floating debris and impacts*

The effect of waves and impacts have been the subject of specific research in reputable hydraulic laboratories (such as Utah State University, Tennessee Valley Authority), which have demonstrated their minimal incidence on the system. Floating debris are simply discharged over the Fusegates' crest when sufficient spillage occurs, and do not have any significant impact on the Fusegate stability.

Example of impact of large floating debris (Tennessee Valley Authority)



- *Earthquake*

Seismic effects can be examined in each individual project using a pseudo-static approach or a finite element analysis, if required. However, the stability of the Fusegates is usually sufficient to prevent problems induced by earthquakes.

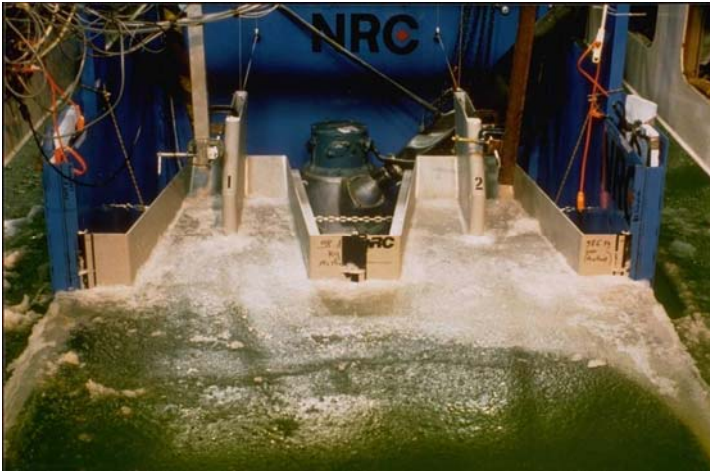
The behavior of the Fusegates during a major seism has been observed in Gujarat State in India that was hit early 2001 by a 7,6 magnitude (on the Richter scale) seism. None of the Fusegates installed on the four dams located within a 50 miles radius from the epicenter have been affected.

- *Ice-affected environments*

The effect of ice is examined with reference to tests undertaken in the hydraulic laboratories of the National Research Council (NRC) in Newfoundland, Canada and of the Institute of Energy Structures in Moscow, Russia. Generally speaking, thermal expansion of ice and ice run off generally have very little influence on the Fusegates stability.

The behavior of the Fusegates in ice-affected environments has been observed on Khorobrovskaya scheme (located in Russia). The 4 off 6.6-foot high Fusegate units have successfully withstood the pressure of the 2-foot thick ice coat and to the subsequent ice run-off.

Model tests at the NRC



Khorobrovskaya in winter



4.5. INHERENT SAFETY FEATURES

The Fusegate System has valuable safety features inherent to the concept and not shared by any other spillway control systems

- Fusegates are entirely self-operating and do not require any source of power to operate.
- Only minimal maintenance is required compared to other mechanical gates.
- Fusegates overturn automatically, responding to those physical forces acting upon them.

The Fusegate massive structure offers little vulnerability to vandalism and, considering their high stability margin, to terrorist threat.

5. CONCLUSION

Fusegates are a simple, safe and robust method in increasing live storage or spillway capacity. The goal of the fusegate design rules is to maximize safety for the dam and the downstream population. Abnormal operating conditions may affect the precision of the system but not the reliability expected by the dam Owner.

Fusegates cannot overturn when headwater is below the minimum tipping level. There is no risk of creating an artificial flood in the absence of a river flood upstream, which is a primordial safety consideration for the inhabitants living downstream of a dam. Even if the water is prevented from flowing into the inlet well, fusegates will always overturn when headwater reaches the ultimate stability level. This level is below the level which would be dangerous for the dam.

These safety features are very significant advantages over all other existing spillway control systems.

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