THE BEHAVIOR OF FUSEGATES IN ICE AFFECTED ENVIRONMENTS

Hasan T. Kocahan, *Business Development Manager, Hydroplus, Inc.*
PO Box 1731
Falls Church, VA 22041, USA
Phone : 703-575-9075, Fax: 703-575-9193

V. B. Rodionov, *Director, Center for Hydraulic Research Institute of Energy Structures, Moscow, RUSSIA*

ABSTRACT:

Since the Fusegate System was invented in 1989, the study of its reliability of operation in extreme conditions has been the basis of various theoretical studies and model tests. Fusegate operation in ice-affected environments is one the main subjects that has been studied.

After an extensive theoretical investigation, two complementary model testing programs were carried out, in collaboration with renowned laboratories, to analyze:

- Ice action on Fusegates during the winter in very cold regions, in cases where reservoirs remain full during cold period; and,
- The impact, during the spring, of floating ice floes combined with exceptional floods.

It was concluded from these studies and model tests that in very cold regions, during the winter, when the reservoir is completely frozen, thermal expansion or a change in reservoir level can either lead to no movement of the Fusegates or in extreme conditions may cause a very small rotation without any influence on the stability of the Fusegates.

It was possible to observe the remarkable behavior of the Fusegates at Khorobrovskaya Dam, an hydro power project located 75 miles North of Moscow, Russia, which has been serving as a testing facility of Fusegates in ice affected environments.

Spillway monitoring was performed during the 2001-2002 winter at this project. Despite severe operating conditions (2 ft thick ice layers upstream, freezing of the Fusegates and floating ice), no displacement or noticeable deformation of Fusegate elements was recorded.

1. INTRODUCTION:

The Fusegate System is an innovative and cost effective spillway technology to increase the reservoir storage capacity and/or to increase spillway discharge capacity. Fusegates are free standing gravity blocks placed side by side on a spillway sill to form a watertight barrier. Each gate consists of three components; a bucket made of metal or reinforced concrete, a base, and an intake well that is connected to a chamber in the base. Accumulation of seepage water in the bottom chamber is prevented by providing each chamber with two drains. The joint between adjacent fusegates is sealed with a flat rubber gasket. Fusegates can increase both spillway capacity and reservoir storage. For a retrofit on an existing spillway, a portion of the ogee crest is removed and provided with a flat surface. If the goal of the retrofit is only to increase spillway capacity, the crest of the fusegates is set near the original ogee crest elevation. If the purpose is to increase storage, then the crest of the fusegates is set above the original ogee crest elevation. For discharges up to the design flood, the fusegate functions like an aerated labyrinth weir. Typically, the design flow is chosen to be the discharge with a return period of about 100 years. (Figure 1a).

For discharges greater than the design flow, water begins to flow through the well and into the chamber located in the base of the gate (Figure 1b).

When the inflow into the well exceeds the flow out of the drain holes, the water level in the well increases. This causes the pressure in the bottom chamber to increase. The increased pressure in the bottom chamber exerts an uplift force on the gate and decreases its stability. For a specific depth of water in the well, the gate becomes unstable and tilts by rotating about its downstream edge. (Figure 1c)

The crest of the well in each fusegate is set at a different elevation so the gates do not tilt in unison. In this manner, the increase in discharge over the spillway, as a function of reservoir elevation, can be precisely controlled.

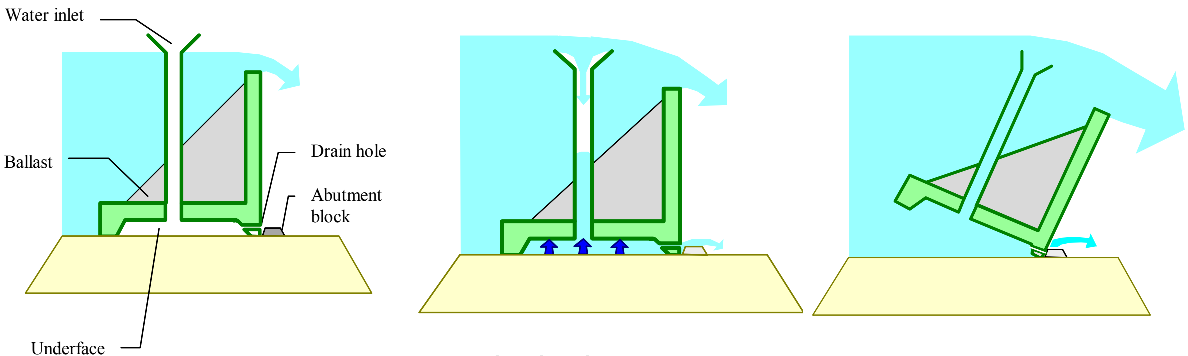


Fig. 1a, 1b, 1c : Description of a fusegate system

Invented in 1989, the “Fusegate System” has been implemented in more than 40 dams in 13 different countries across five continents. Since then, the study of its reliability of operation in ice affected environments has been the basis of various theoretical studies and model tests.

Fusegates are generally labyrinth crested shaped in order to offer a good hydraulic efficiency in terms of discharge for a determined head. The concerns related to the behavior of traditional labyrinth shaped fusegates in ice affected environments led to the development of a different kind of Fusegate dedicated to this kind of situation. Ice Fusegates have a round shaped upstream face and they are coated with a low-friction chemical paint. The round-shaped upstream face contributes to the stability of the Fusegate when submitted to ice thrust.

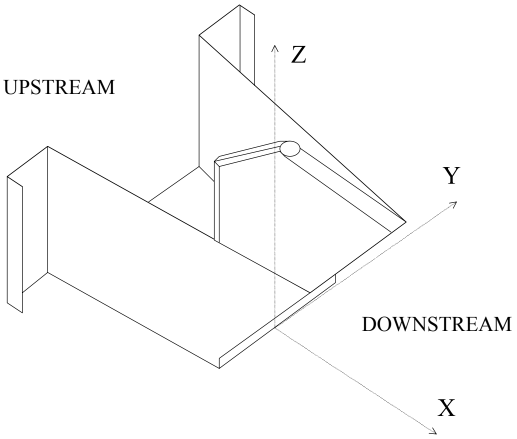


Fig. 2 : Labyrinth Fusegate

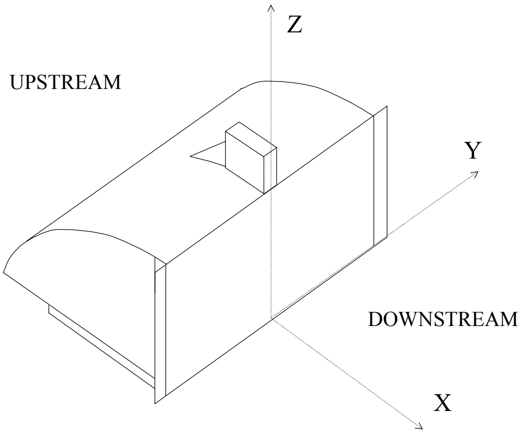


Fig. 3 : Ice Fusegate

2. ICY CONDITIONS; GENERAL BACKGROUND:

Formation of an ice cover appears in reservoirs mostly during winter months. Depending on the way it is formed, various kinds of ice can develop. Primary ice is formed on the top layer; secondary ice is formed below the primary ice layer; whereas stacked-up ice is formed on the top of the existing ice slab. Each kind of ice have a specific structure and thus different mechanical characteristics. A detailed study regarding ice effects and calculation of its mechanical effects on hydraulic structures should also specify the ice structure which is considered.

Three main impacts of ice on hydraulic structures can be identified as :

- Thermal expansion affect
- Vertical affect due to variation in the upstream water level in the lake,
- Impact of moving ice blocks

3. THERMAL EXPANSION:

3.1 General

The main factors, which can influence thermal expansion of ice are :

- *Surface effect*, caused by the difference between air and ice slab surface temperature.
- *Snow cover, which* acts as an insulating material (snow conductivity is 10 to 30 times lower than ice conductivity).
- *Solar energy absorption*, which affects temperature distribution inside the ice cover.
- *Cracks,* which can appear when temperature drops, and which makes the ice fragile.
- *Ice thickness*, which tends to reduce the effect of air temperature.

The number of parameters is such that it complicates drastically any theoretical approach. Generally, thermal thrust is taken into account by applying an additional force, which the figure varies depending on the country:

- In Canada, this figure is between 150 to 220 kN/lm for stiff structures and 70 kN/lm for more flexible structures
- In the USA, 150 kN/lm are used for 25 inch thick ice, and 220 kN/lm for 35 inch thick ice.
- In Russia, Siberia, Saint-Petersburg and Caucasus are considered to have thrusts of 150, 200 and 300 kN/lm.
- In Norway, the typical value is 100 kN/lm, or 150-200 kN/lm for more severe conditions.

Thermal thrust against Fusegates should be lower since they are not rigid structures and can slightly rotate around their downstream lugs.

3.2 Experimental Approach

Tests were performed for thermal expansion effect in the Institute for Marine Dynamics (IMD) of the National Research Council of Canada on 1.65 ft. high Fusegates. Two ice sheets, each 245 ft long, were cultivated for this test program, one for each type of Fusegates (labyrinth and round shaped). Each sheet took five days to grow to a thickness of 5.9 inches and involved continuous testing over that period to achieve different ice thicknesses. Freshwater was used throughout the whole test, to obtain a good ad freeze bond.

The Fusegates were placed on an instrumental sill box and were attached to the carriage of the ice tank. The Fusegates were then slowly pushed into the ice sheet by the main carriage to simulate the infinite thermal expansion of an ice sheet. Observation during these tests showed that soon after the test had started, the Fusegates began to rotate, causing a large bending moment in the ice sheet which opposed further rotation of the Fusegate, and caused a flexural failure of the ice sheet near the mouth of the Fusegates.

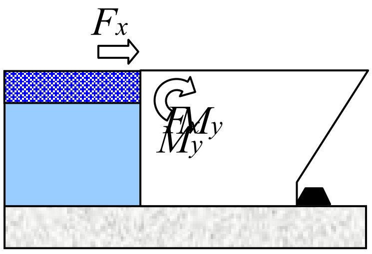


Fig. 4(a) Ice is pushing against the Fusegate without overturning it.

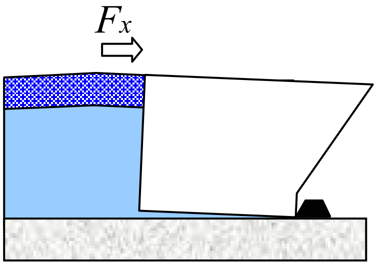


Fig. 4(b) If the force is strong enough, the Fusegate rotates around the lugs and the ice slab is bent.

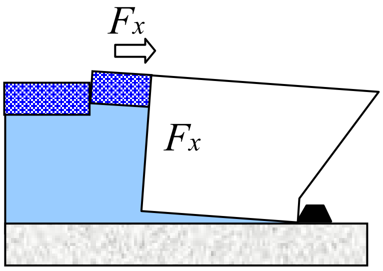
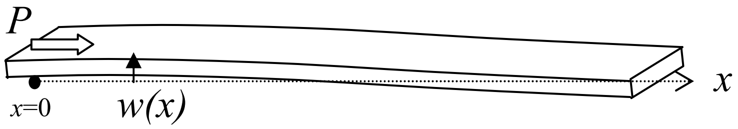


Fig. 4(c) For a certain rotation angle (typically 0.5° to 1°), ice breaks.

In practice, the reservoir shore and the dam itself will shield the Fusegate from any such free expansion. Thus, displacement of the Fusegates will depend on local conditions, and each reservoir will have to be modeled individually.

3.3 Theoretical Approach

This problem could be analyzed by simulating the ice sheet as a buckling semi-infinite beam.



The equation of a buckled beam with a *t* thickness is as follows :

$$\mathbf{EI}\ \frac{d^4w}{dx^4} + P\,\frac{d^2w}{dx^2} + kw = 0$$

Where E is the Young module, I is the beam inertia, k is the reaction module of water and *P* is the horizontal thrust against the beam.

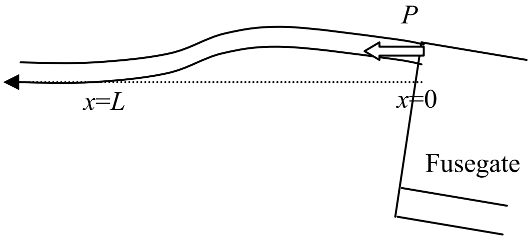
The above formula is solved considering the following border conditions:

w''(x=0) = 0 no bending moment : Fusegate uplifted

w'''(x=0) = 0 force P pushing against ice has no vertical component

w(x=L) = 0 no movement

w'(x=L) = 0 no breaking



4. VARIATION IN RESERVOIR LEVEL:

4.1 General

The behavior of ice for rising and falling reservoir is very similar. The ice beam becomes cantilevered with its root at the fusegates. The far ice sheet floats on the water but is fixed horizontally (x-direction). Since the ice sheet is fixed at both ends it must elongate during either rising or falling water levels inducing an axial tensile stress in the ice sheet. The resulting tensile force induces a stabilizing moment in the fusegate. The ice will finally crack during rising/falling water level due to the bending stress at the root (fusegates). Since ice has a higher compressive strength then tensile strength, it is expected that the failure will start on the tensile surface. This is the bottom surface for rising water level and top surface for the falling level.

4.2 Experimental approach

The effect of variation of the reservoir level was tested in the Institute for Marine Dynamics (IMD) of the National Research Council during the testing campaign undertaken to assess the effect of thermal expansion of ice. The 1.65 ft high Fusegates were placed on the instrumental sill box, which could be raised or lowered to simulate the fall and rise of the water level.

Two scenarios were planned for varying the reservoir water level, corresponding to a rising level and a falling level, and each of them was studied at a low rate (5.5 inches/h) and a high rate (155 inches/h). The temperature of the tests was also varied, because the low rate corresponds to changes which is typically in the winter when it is cold (5°F), while the fast rate occurs in the thawing phase in spring, when the temperature is higher (23°F).

Observation during these tests showed that an initial bending crack is formed close to the Fusegate-ice interface before any substantial movement of the Fusegates occurred.

- *drop in reservoir water level*

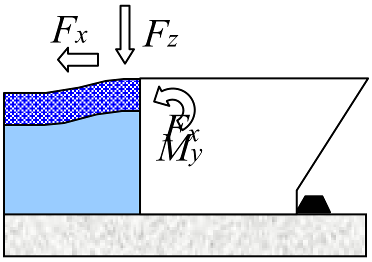


Fig. 5(a) Reservoir level is lowered. The ice sheet is put under a horizontal tensile stress, which tends to elongate the ice sheet.

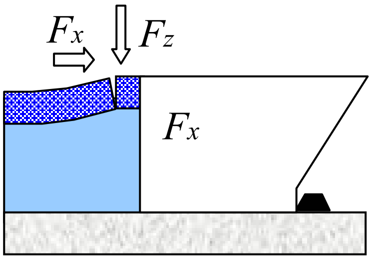


Fig. 5(b) If the bending moment exceeds the flexural strength of the ice, a crack is formed just upstream of Fusegate, which is pushed back against the lugs.

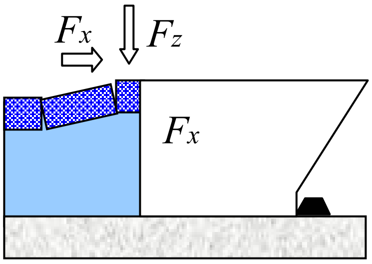


Fig. 5(c) If the bending effort particularly high, a second crack could be formed upstream of first crack.

- *raise in reservoir water level*

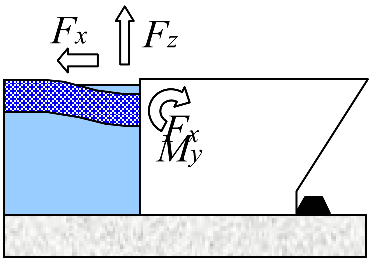


Fig. 6(a) Reservoir level is raised. Ice slab is bent.

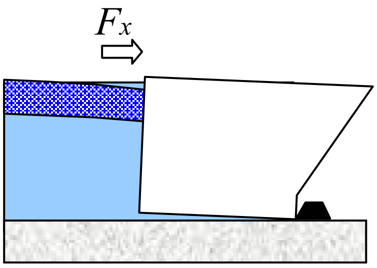


Fig. 6(b) If the bending effort is strong enough, the Fusegate slightly rotates around the lugs.

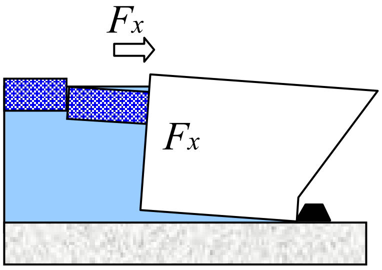
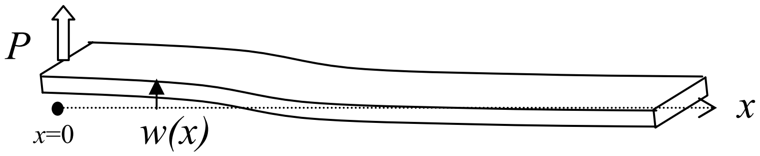


Fig. 6(c) If the bending exceeds the flexural strength of the ice, a crack occurs upstream of the Fusegate.

The breaking processes, represented here for labyrinth Fusegates, are the same for ice Fusegates.

4.3 Theoritical approach

The change in reservoir level could be analyzed by simulating the ice sheet as a deformed semi-infinite beam.



The equation of a deformed beam with the *t* thickness is as follows :

$$\mathrm{EI}\,\frac{d^4 w}{dx^4} + k\,w = 0$$

Where E is the Young module, I is the beam inertia and k is the reaction module of water.

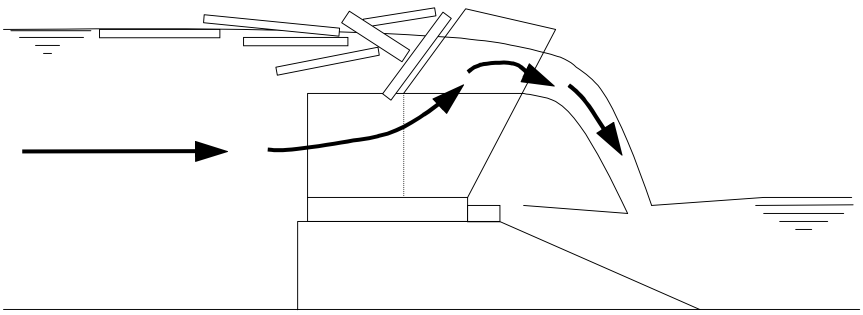
The border conditions depend on the scenario considered as to whether the Fusegate is uplifted or not. It appears that the vertical ice breaking force is in proportion with the ice thickness to the power of 5/4.

5. EFFECT OF FLOE OVERSPILLING OVER FUSEGATES:

5.1 Testing background

More model tests were performed at the Research Institute for Energy Structures (Russia), which was established some 50 years ago and is responsible for research and development in the field of engineering. The purpose of the model tests on the Fusegates was to test its reliability in the northern regions of Russia, and in particular, to study the interaction of Fusegates with flow containing floating ice. Spring floods in the rivers of northern regions of Russia (which run from south to north) are caused by melting snow and ice. The ice cover break-up begins simultaneously with the increasing flood, which leads to the necessity to pass ice over spillways at times of very high discharge.

Fig. 7 Ice accumulation in front of fusegates during high overspilling



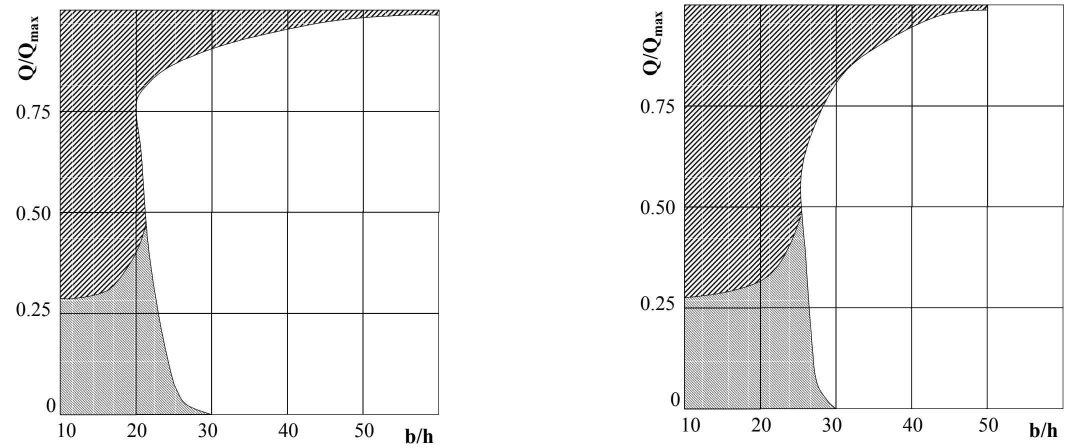
5.2 Testing conditions

The Fusegates were installed in sets of three at the test sill in an experimental canal. Three types of Fusegates were tested, each of them 8 inches high : labyrinth with moderate overspilling, labyrinth with high overspilling and ice Fusegates. For each type of Fusegate, the level in the headrace canal H_{max} and the discharge Q_{max} of the flow free of ice, corresponding to normal overturning, were measured.

Distance between wells of two adjacent Fusegates was denoted as b. Ice thickness h was used as a characteristic of the flow with floating ice, the plane size of the ice floes was d and ice movement density P, which was determined as the upper ice floe surface area ratio to the surface area of the flow.

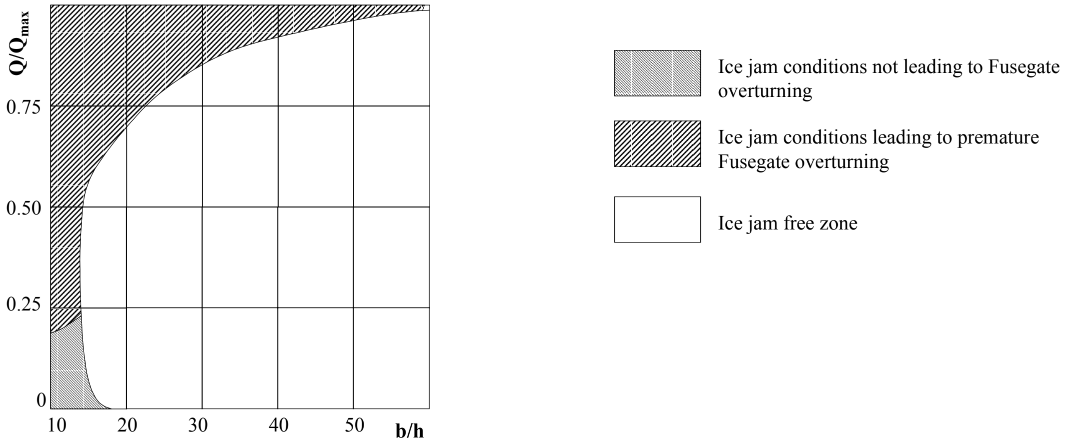
Model ice floes were made containing paraffin, with a specific weight of 0.87 to 0.91, which is equal to the specific weight of ice at a temperature close to 0°C (32°F). In accordance with the typical floe of European Russia, ice floes were fragmented to a relative size verifying $d / h > 15$ and the density of the ice movement was $P = 0.7$ to 0.9.

As soon as the approximate dimensions of the Fusegates are known, and the form of the ice flows are determined, the h/b parameter becomes universal, and both geometry of ice floes and the geometry of the Fusegates can be determined. Effect of both geometries on discharge capacity is described in Fig. 8 below :



(a) labyrinth Fusegates with moderate overspilling

(b) labyrinth Fusegates with high overspilling



(c) ice Fusegates

Fig. 8 : Universal operation characteristic for different ice conditions

Fig. 8 shows that for discharges less than 25 per cent of the normal overturning discharge Q$_{max}$, the ice accumulation does not cause any premature overturning of the Fusegates, even without special arrangements. Fields observation and special studies have shown that, practically everywhere, the maximum ice depths at the moment of its break-up during the spring flood period amount to 14-31 inches.

6. KHOROBROVSKAYA SCHEME:

6.1 General

Khorobrovskaya HPP is located on the Nerl-Volzhskaya River, in one of the most picturesque areas of the Russian Golden Ring: Pereslavl-Zalessky Rayon of Yaroslavskaya oblast.

The concrete embankment is 360 feet long, including the power house located on the left bank. The spillway consists of a free labyrinth concrete spillway, which the design has been done similar to the Snare Cascade Hydro Project (Northern territories - Canada).

On each bank of the spillway, experimental 20 feet wide spans are equipped with a set of two steel high head labyrinth Fusegates of 5.75 ft high and 10.4 ft wide.

The reservoir of channel basin type is 33.5 miles long, with an average depth of 6.5 ft, without flooding of the Nerl river lowlands.

Fig. 9 Dowstream View

6.2 Ice consideration

The spillway design took into consideration the dam operation in typical Russian winter and the spring ice-affected conditions. Russian standards for hydraulic steel structures have been used for Fusegate structural calculation.

Extra load of 12.6 psi was taken into consideration as ice expansion effect inside the bucket, which led to a slightly oversized belt stiffener. It should be noted that the fusegates can withstand plastic deflection of several mm, without its functioning being jeopardized.

The Fusegate crest is set 3.9 inches below the crest of the fixed labyrinth. Moderate flows, which are permanent in winter, are spilling on the concrete labyrinth only, delaying ice-building risks on these structures.

Fusegate front side is set 5.9 ft back from upstream concrete face, inside the experimental spans, which the width has been chosen to transfer ice pressure expansion effect to the concrete structure (arch effect).

6.3 Winter monitoring

The spillway monitoring was performed during 2001/2002 winter on a weekly basis .

The period with negative temperatures began in mid November. In the second week of December the temperature fell down to -4°F. Then, between mid December and beginning of January it fluctuated within a range of 14 to -10°F without approaching the freezing point.

During this period ice thickness at the surface of the reservoir reached 20 inches, and 24 inches – upstream of Fusegates. The Fusegate bucket, wells and drainage holes were frozen thoroughly. The concrete sill of the gates on the tail-water side was covered with solid ice up to 4 inches thick; resulting in icing formed on the vertical faces of the Fusegates on the tail-water side and on the walls of the concrete labyrinth.

Fig. 10 Downstream view of fusegates in Winter

At the end of the first week and throughout the second week of January, there were temperature swings from -6°F to 28°F (during three days), then during 2-3 days there was a sharp fall of temperature down to -9.5°F and then a rise in the temperature up to +35.5°F. Then up to mid February the temperature fluctuated around 32°F with amplitude of 25°F to 39°F. The average air temperature in February amounted to +35.5 to 39°F.

Despite severe operating conditions of the Fusegates (sharp temperature fluctuations passing through the freezing-point) no displacement or noticeable deformation of Fusegate elements was observed. There were also no disturbances in the operation of the concrete labyrinth.

When duration of thaws (periods of positive temperature) exceeded one week, all the icings from the tail-water side melted and the Fusegate drainage system began operating again. A gap filled with free water is formed on the inner side along the perimeter of the bucket (due to high heat conductivity of the metal faces). This led to the movement of water along the Fusegate face and to fast release from the ice of the whole fusegate structure.

After floods in 2002 and drying of the fusegates, no leakage was noticed through the visible sections of the fusegate seals.

The monitoring of fusegates was continued during winter period of 2002-2003 and after two severe winter conditions, the fusegates are in great shape and responded all conditions with a high degree of accuracy.

Fig. 11 Fusegate during snowmelt

7. CONCLUSION :

In very cold regions, during the winter, when the reservoir is completely frozen, thermal expansion or a change in reservoir level can either lead to no movement of the fusegates or in extreme conditions may cause a very small rotation without any influence on the stability of the fusegates.

In the case of rivers in very cold regions, and running from south to north, one of the following protective measures should be implemented to make provision for dealing with large ice floes:

- The use of ice-breaking structures, which are used for all types of gates on spillways in the northern regions of Russia;
- The use of multi-element fusegates, to widen the distance between adjacent inlet wells; and,
- The installation of inlet wells in the spillway abutments.

The two series of model tests were found to be very useful in demonstrating the necessary steps to be taken to deal with extreme ice conditions.

References :

Michel, B. 1978 ; "Ice Mechanics", Les Presses de l'Université Laval, Québec

Michel, B. & M. Drouin 1971 « Les poussées d'origine thermique exercées par les couverts de glace sur les structures hydrauliques", Université Laval, Québec.

Bureau of Reclamation : "Design of Small Dams", third edition, Water Resources Technical Publication, Denver, Colorado, (860 pages) 1987.

Carstens T. : "Maintaining an ice-free Harbour by pumping of warm water", the River and Harbour laboratory, Trondheim, Norway, (page 357 to 353) September 1990.

Cammaert, A.B., Muggeridge, D.B., 1988, "Ice interaction with Offshore Structure"

Cammaert, A.B. : "Thermal Expansion Effects of Ice on HYDROPLUS Fusegate" Final report of Cold Oceans Design Associates Limited (CODA), Canada, Saint John's, September 1993.

Croasdale, K. R. : "Ice forces on marine structures", International Symposium on Ice Problems, New Hampshire, USA, 1976

Croasdale, K.R. : "Ice forces on fixed, rigid structures" Report for the Working Group on Ice Interaction on Hydraulic Structures, A State-of-the-Art Report, CRREL Special Report 80-26, Hanover, N.H.

Derycke R.J. : "Sea ice motions off Antartica in the Vicinity of the Eastern Ross Sea as observed by satellite", Journal of Geophysical Research (7 pages), December 1973.

Frederking, R., 1980. "Dynamic Ice Forces on an Inclined Structure*". In Physics and Mec. Of Ice.*

Londe, P., Expert engineer, Chairman of the International Committee on Large Dams, between 1979 and 1982 : "HYDROPLUS – Poussée des glaces", August 1991.

Pounder, E.P. : "The physics of ice", Pergamon Press, New York (151 pages) January 1964.

Prost, J. : "Durabilité des bétons durcis soumis au gel, en présence ou non de sels de déverglaçage", annales de l'Institut Technique du Batiment et des Travaux Publics, Série : Technique générale de la construction, n° 508 (139 pages), November 1992.

Rae, P.J. ANDERSON, J.E. COTRONEO, G.V. : "Ice Engineering for Better Hydro Generation", Hydro Review, October 1988.

Timco, G.W., 1984. "Model tests of Ice Forces on a Wide Inclined Structure". Proc. IAHR Ice Symposium, Vol. 2, Hamburg, pages 87 to 97.

Xian-zhi, S. : "Study on Ice Static Pressure on Ice Cover in Reservoir", IAHR Ice Symposium 1988.

Zhydkykh, M.I. : "Calculation of flow velocity in the operative zone of pneumatic installations used for ice-fighting", Ice Symposium 1970 (6 pages), Reykjavik.

BIOGRAPHY OF HASAN T. KOCAHAN, SPEAKER

Hasan T. Kocahan received a bachelor's degree in Civil Engineering from Middle East Technical University in Turkey and is currently a Business Development Manager at Hydroplus, Inc., a firm that promotes the patented "Fusegate System" for spillway rehabilitation. He began his career in Turkey as a design engineer for State Hydraulic Works (DSI). He has 12 years experience in large dam & HEPP projects in a variety of engineering fields, such as Structural Design and Analysis, Quality Control, Contract Administration, Procurement, Supervision and Commissioning.

He can be reached at:
Hydroplus, Inc. PO Box 1731 Falls Church, VA 22041
Phone: 703-575-9075 Fax: 703-575-9193 E-mail: HydroplusUSA@aol.com