FIELD INVESTIGATIONS OF A HANGING ICE DAM

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ABSTRACT

A hanging ice dam that forms annually in the lower Smoky River, Alberta, has been the object of continued investigation during the period 1975-1979. The study aims at documenting physical dimensions and material properties of the dam; elucidating the mechanisms of its formation and removal; and assessing its effects on the progress of breakup in the river. This paper presents a summary of the results obtained to date.

INTRODUCTION

A hanging ice dam is a downward projection of river ice, produced by deposition of frazil slush under an existing ice cover [15]. Typically, a hanging dam forms at a low speed section of a stream, located immediately downstream of a high speed section. During freeze up, the latter remains open while an ice cover forms at the former section. Frazil ice produced in the rapid flow section agglomerates into slush and pans that are transported under the cover of the tranquil section and deposit where the flow speed is sufficiently low. Deposition continues until either the upstream supply is discontinued or the flow velocity under the accumulation increases to a value capable of transporting the entire amount of incoming ice. The limiting velocity varies between 1 m/s and 1.5 m/s depending on the composition and dimensions of the transported material [14, 16].

Hanging dams are often mentioned in ice engineering literature [3, 5, 11, 16, 17] but there exists little documentation of their behaviour and effects. Gold and Williams [11] described a 90 m deep and 1200 m long hanging dam in the Ottawa River. Such massive accumulations of ice can obstruct the spring ice run and initiate major ice jams as well as being capable of interfering with river structures.

The possibility of a hanging dam occurring in the Smoky River, about 40 km above its confluence with Peace River (see Figure 1) was first detected in 1974 by British Columbia Hydro staff; the existence of the dam was confirmed by soundings in early 1975. Because of possible effects of this hanging dam on breakup near the town of Peace River (Figure 1), a long-term investigation was initiated by Alberta Research Council. The main objectives of this study are to document the formation of the dam, assess its effect on the breakup process in the Smoky and Peace Rivers and examine whether impact forces by moving fragments of such dams need be considered in the design of river structures. This paper presents a summary of the results obtained during the period 1975-79.

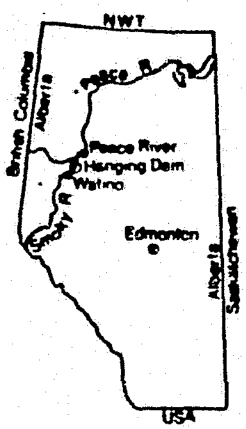


Fig. 1 Location map.

Fig. 2 Oblique air photo of hanging dam site (looking upstream, Dec. 2, 1975; note hummocked ice surface and open water lead in rapids upstream).

SMOKY RIVER HANGING DAM

The stream configuration in the vicinity of the hanging dam site consists of a deep and wide section preceded by a section of rapids upstream; this sequence exhibits features conducive to hanging dam formation and, to a degree, is illustrated in Figure 2. Also shown in Figure 2 is the hummocked and perceptibly elevated surface of the hanging dam. A longitudinal profile of the dam, obtained in March 1975, is shown in Figure 3. The frazil accumulation is roughly triangular with a base of 300 m and a maximum depth of 13 m below the water suface. These dimensions vary from year to year. In January 1976, the length and maximum depth of the dam were 300 m and 16.3 m while corresponding values for February 1977 were 700 m and 11.0 m. River cross sections, located as indicated in Figure 3, are shown in Figure 4 where the deepening and widening of the river near section 0-0 (deepest section) are well illustrated.

Open-water flow conditions at the dam site were documented in July 1975. It was found that, due to channel expansion, two large eddies were present near the river banks, as sketched in Figure 5; there was no evidence of the channel bed depression having been filled in by sediment

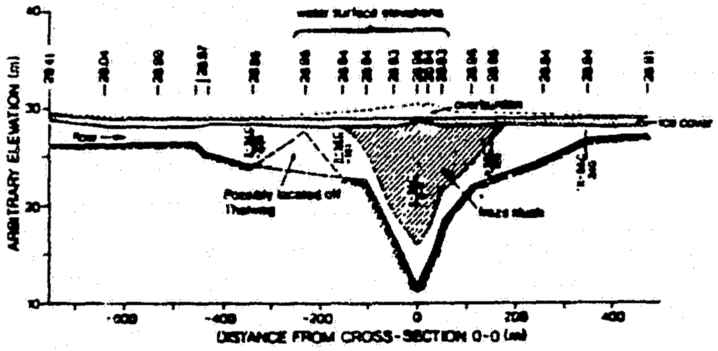


Fig. 3 Longitudinal profile of hanging dam (March 25 and 26, 1975)

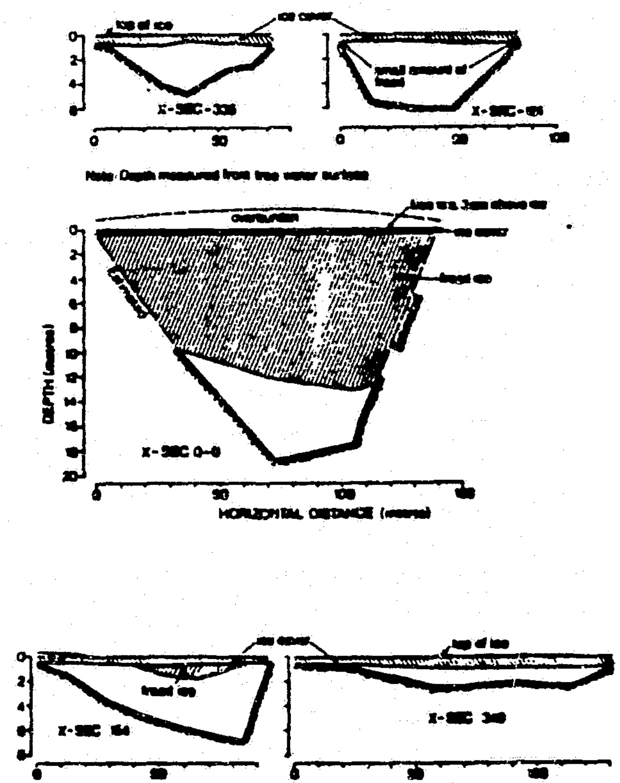


Fig. 4 River cross sections at hanging dam site (March 25 and 26, 1975)

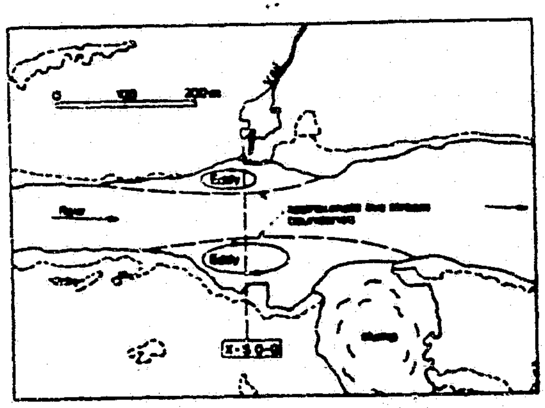


Fig. 5 Sketch of flow pattern at hanging dam site (July 30, 1975)

The same was reported for the Ottawa River dam [11]. A vertical velocity profile, taken in the live stream at section 0-0, indicated an average velocity of 1.2 m/s which is comparable to values measured in the rapids section upstream of the dam site. This explains why the river bed depression is not filled with sediment in the summer: as flow velocities and, hence, transport rates are comparable upstream of and at the dam site, deposition is not likely to occur.

FORMATION

Formation of the hanging dam was documented in November 1978 by means of an 8 mm movie camera, programmed to expose one frame per minute during daylight hours and installed near the top of the west valley wall. The resulting film shows freeze up events for a period of six days and provides a fair description of the dam formation mechanism. At the dam site, the ice cover is initiated at the eddy areas where frazil floes and pans recirculate and eventually become shore fast. Gradually, the firm ice cover extends outward from the banks toward the midstream and somewhat upstream. As this occurs, the eddies also move upstream which enables continued build up of the cover. Eventually, only a narrow strip of open water is left at midstream, corresponding roughly to the live stream under open-water conditions (see Figure 5). This strip is finally bridged by an arching mechanism similar to that studied by Calkins and Ashton [6]. For the 1978 freeze up, surface flux of ice pans began during the night of November 8 to 9 and a complete ice bridge across the river formed by the morning of November 14 Temperature records at Watino [1] indicate that November 8 was the first day of sustained frost while the average air temperature during the formation period was about -13.5°C.

It was mentioned earlier that the limiting frazil slush deposition velocity is in the range 1.0 to 1.5 m/s [14, 16]. Neglecting seepage through the dam and using the flow areas from Figure 4, average velocities under the dam are about 0.12 m/s for March 1975 (discharge=33 m^3/s). Allowing for a freeze up discharge of about 100 m^3/s (November 1974), the corresponding freeze up velocity is estimated as 0.20 m/s. This is much less than the limiting deposition value which suggests that vertical growth of the dam is limited by a discontinuation of ice supply due to freezing over of the rapids usptream. Vertical velocity profiles under the dam were measured in 1977 and 1978 using a magnetic flow meter. With the exception of one profile, the measured values [4] are well below 1.0 m/s which reinforces the above suggestion.

The measured velocity profiles showed further that the absolute roughness of the dam undersurface is highly variable, being sometimes less and sometimes more than that of the river bed. From semi-logarithmic plots of the velocity data, the average friction factor and equivalent sand roughness were estimated as 0.08 and 0.8 m respectively.

MATERIAL PROPERTIES

At the time this study was initiated, no information could be found on material properties of frazil accumulations. Such information was thought important in engineering applications, such as assessing effects on ice breakup, forces on river structures and flow through accumulations. The following is a summary of pertinent findings to date.

Composition

The non-submerged portion of the hanging dam ("overburden") consists of a hummocky accumulation of snow and weak granular ice with a maximum thickness of 2 m; the latter can be classified as S5 ice "drained congealed frazil slush", using the terminology of Michel [15]. A 6 cm thick layer of solid ice topped the overburden near the river banks, extending to approximately the live stream boundaries under open-water conditions. These findings are qualitatively similar to those concerning the Ottawa River dam [11].

Near the free water surface, there is a 0.3 to 0.9 m thick layer of solid ice, underlain by the main (submerged) accumulation of frazil. The latter is fairly dense frazil slush, similar in composition to the overburden material; its pores are saturated and its cohesion is much less than that of the overburden. The overburden originates from saturated frazil that rises above the water surface and drains as the accumulation grows in depth. The solid ice layer near the water surface forms from the slush as its crystals have random orientation and sizes comparable to those of the submerged frazil. The conductivity of this layer was found to vary in the vertical direction (1976), being 7.3 and 13.7 μmho/cm at respective depths of 0.1 and 0.3 m which suggests impurity migration (total sample depth=0.37 m; see also [4]). The thin top layer of ice near the banks is ordinary ice that forms at the eddy areas prior to significant frazil deposition underneath and consequent emergence above the surface. That no such layer has been found in midstream suggests that frazil accumulation in the live stream area is much faster than in the eddy areas.

The ice particles in the saturated slush are between spheroid and discoid in shape with a major diameter of 1-6 mm. The size distribution by weight is approximately: 60 percent in the range 1.1 to 2.4 mm; 35 percent in the range 2.4 to 4.8 mm; and 5 percent in the range 4.8 to 6 mm.

Shear Strength and Bearing Capacity

The shear strength of the slush was measured by means of shear vanes attached to a series of 1.5 m long extensions. Torque was applied and measured with a commercially available torque wrench. Figure 6 shows shear strength values (τ_f) measured in 1976, plotted versus depth at three locations; two vane sizes were used for comparison (two holes spaced 1 m apart were drilled at each location). The scatter in Figure 6 is typical and illustrates both the crudeness of the measurement technique and the natural variability of the strength. No consistent variation of τ_f is evident in Figure 6 but later data have shown that τ_f increases generally with height above the bottom of the accumulation (see, for example, 1979 data in Figure 7); this trend is sometimes obscured by scatter. Figure 8 gives a summary of shear strength measurements, plotted in the form of depth-averaged τ_f versus accumulation thickness. The shear strength is seen to vary from year to year.

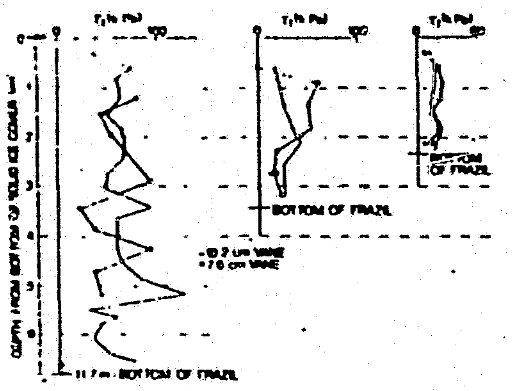


Fig. 6 Vertical profiles of shear strength (March 10 and 11, 1976)

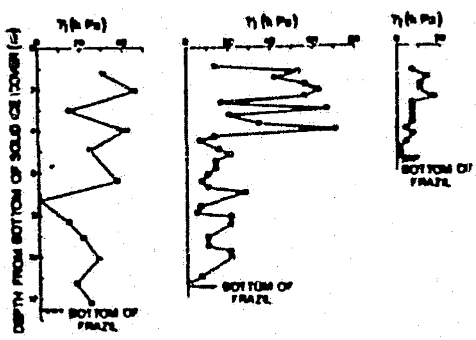


Fig. 7 Vertical profiles of shear strength (March 14, 1979; 10.2 cm vane)

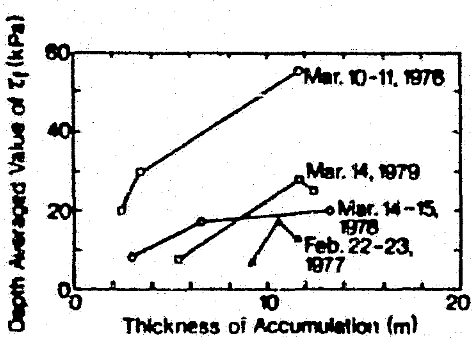


Fig. 8 Depth-averaged shear strength versus accumulation thickness

The results of plate bearing tests exhibited large scatter, but average values increased with height of observation from the bottom of the accumulation (h_f), being 300, 150 and 90 kPa at values of h_f equal to 11.2, 5.3 and 2.3 m respectively.

Density and Porosity

The dry density of the slush (ρ_f) obtained from the drained weights of known volumes, increased with h_f as shown in Figure 9. The porosity of the accumulation (ϵ_f) is given by:

$$\epsilon_f = 1 - (\rho_f/\rho_i) \qquad (1)$$

in which ρ_i=density of ice. From Figure 9, ϵ_f is calculated as 0.51 and 0.33 at h_f=2m and 12m respectively.

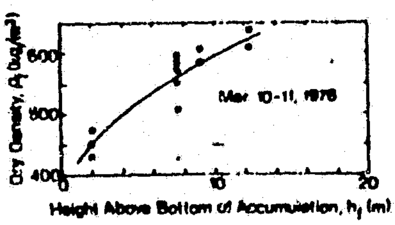


Fig. 9 Dry density versus height above bottom of accumulation.

Using average values of 1976 data on ρ_f (Figure 9) and τ_f (Figure 6) at corresponding heights h_f, an empirical correlation was obtained, as follows:

$$\tau_f = 0.25\,\rho_f - 85 \qquad (2)$$

in which τ_f is in kPa and ρ_f is in Kg/m^3. Equation 2 applies in the ranges τ_f=30-75 kPa and ρ_f=450-620 Kg/m^3.

Figure 9 may be used further to determine the stress-density relationship for the accumulation. The vertical stress gradient due to buoyancy is:

$$dp/dh_f = g\left[(1-\epsilon_f)\,\rho_w - \rho_f\right] \qquad (3)$$

in which p=vertical stress; g=acceleration of gravity; and ρ_w=density of water. Using Equation 1 and integrating gives:

$$p = g\left[(\rho_w/\rho_i) - 1\right]\int_0^{h_f} \rho_f\,dh_f \qquad (4)$$

An approximate calculation using graphical integration (see Figure 9) resulted in the stress-density relationship depicted in Figure 10 along with relevant findings for snow [13]. For the same stress level, frazil densification is about 1.5 times that of the lower bound of Mellor's [13] data. This is primarily caused by differences in temperature and water content and, to a lesser degree, by particle geometry effects. The mechanics of densification change significantly near 0°C in a saturated media where pressure melting and regelation [7] strongly affect the deformation of frazil ice and allow densification at a lower stress level than would be found in dry, colder media. Colbeck et al [8] discussed this difference and reported test results that compare saturated with dry snow at -2°C. If the same densification is considered linear and applied to the present results, the transformed data fall much closer to Mellor's (Figure 10).

Intrinsic Permeability

Permeability was calculated based on flow rate of a 10W motor oil through a cylindrical sample under a fixed head [10]. The equation used is (2):

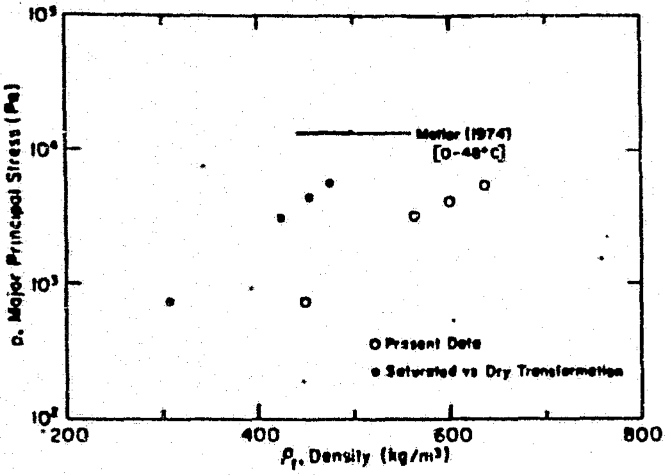


Fig. 10 Comparison of stress-density relationship for the frazil accumulation with Mellor's data for snow.

$$Q = k_f \rho g Ah'/\mu L' \qquad (5)$$

in which Q=flow rate; k_f=intrinsic permeability; A=cross-sectional area of test cylinder; μ=fluid viscosity at test temperature; ρ=fluid density at test temperature; h'=head=distance from top of input reservoir to tip of drain tube; and L'=length of test cylinder. Measured k_f values were 16.3×10^{-6}, 15.6×10^{-6} and 15.0×10^{-6} cm^2 at h_f values of 2 m, 7.6 m and 12.2 m. The hanging dam permeability is between those of coarse sand and fine gravel [12] which appears reasonable since the frazil particle size is consistently between 1 and 6 mm. Snow with 1 to 2 mm particles has a k_f value of 2×10^{-6} cm^2 [9].

BREAKUP

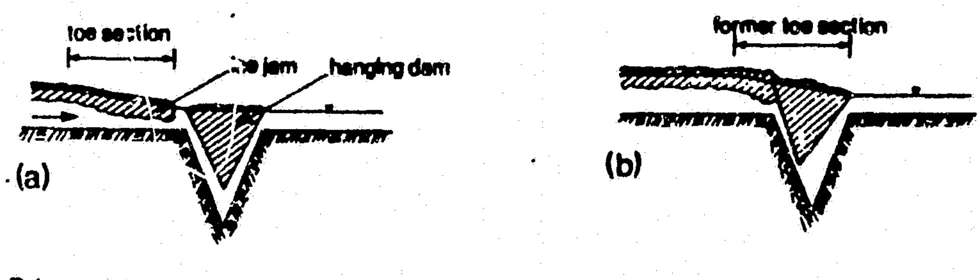
Breakup observations have been carried out annually during the period 1975-79. Detailed information may be found in [4]; only a brief summary will be given here.

The hanging dam obstructs the progress of the spring breakup and initiates ice jams, most of which are major. Removal of the dam is usually forced, that is, it shears off at the sides (roughly at the live stream boundaries) and is subsequently broken into small pieces upon the final release of the jam upstream. There was one instance, however, when the upstream ice passed under the dam; the latter remained in place for several days and was removed gradually by water erosion (1977). Twice (1976, 1979), removal of the dam was followed by surging ice runs that were only arrested 2 km upstream of the Smoky River mouth (about 38 km downstream of the dam site); on both occasions, major jams formed there and gradually broke through into Peace River. The effect of the dam on breakup near the town of Peace River (Figure 1) can be either beneficial or detrimental depending on prevailing ice conditions in the Peace River itself. Continued annual observations are deemed desirable so as to obtain a more complete record of, and assign frequencies to, various events of interest.

To develop a criterion for the removal of the dam, an approximate force analysis was carried out [4], as outlined briefly below. Upon release of the jam upstream, the main horizontal force on the dam is a net hydrostatic pressure caused by the advancing water wave (Figure 11); other forces, e.g. hydrodynamic force and pressure of advancing ice jams are relatively very small in this case. The dam shears off when the applied force exceeds its resistance on two vertical surfaces which separate the grounded portions of the accumulation near the banks from the floating portion in midstream. Analysis has shown that the dam will be removed when

$$S_T \gtrsim \bar{\tau} / \rho_w g W \qquad (6)$$

in which W=distance between the two shear surfaces; $\bar{\tau}$=average shear stress over the sheared area; and S_T=toe slope of the upstream jam just prior to release. Detailed breakup data taken in 1975 indicated that S_T was in the range 0.0043 to 0.007. Using W≃70 m (see Figure 4), Equation 6 gives $\bar{\tau}$=3 to 4.8 kPa which is generally lower than measured midwinter values shown in Figure 8. It is noted that a decrease in strength is likely during the spring breakup if the water temperature rises above 0°C. If $\bar{\tau}$ and W do not change appreciably from year to year, Equation 6 would suggest that there is a limiting value of S_T, between 0.004 and 0.007, that must be attained before the dam can be removed. This is consistent with the 1977 finding, i.e. that the dam did not "break" and the upstream ice passed under it: the available data for 1977 indicated that S_T could not have exceeded 0.0039.



Prior to jam release: negligible horizontal component of net hydrostatic pressure

Shortly after jam release: significant horizontal component of net hydrostatic pressure.

Fig. 11 Sketch of assumed mechanism of dam removal

SUMMARY AND CONCLUSIONS

A hanging ice dam that forms in the lower Smoky River has been the object of annual field observations and the results have been reported in the previous sections.

The hanging dam site is a depression of the river bed, preceded by a section of rapids. The mode of dam formation is essentially as has already been described by others; site-specific peculiarities have been identified, based on a visual record obtained by means of an automatic, time-lapse photography apparatus.

The streamwise profile of the dam is roughly triangular, with a base of 300 to 700 m and a depth of 11 to 16 m; the dam consists of porous frazil slush with ice particles 1 to 6 mm in size. The in situ shear strength of this material varies from year to year; in any one year, it increases with height above the bottom of the accumulation and generally does not exceed 80 kPa. A similar variation was found for the dry density of the material. The intrinsic permeability of the dam is about 15.5×10^{-6} cm^2 and decreases slightly with height above the bottom of the accumulation. Velocity measurements under the dam indicated average values of 0.08 and 0.8 m for the friction factor and equivalent sand roughness height of the dam underside respectively.

During spring breakup, the dam initiates an ice jam upstream. Usually, final release of this jam is followed by removal of the dam and occasional ice surges that are only arrested near the river mouth, 38 km downstream. On one occasion, jammed ice upstream released and was transported under the dam rather than dislodging it. To explain the mechanism of dam removal, a preliminary force analysis has been carried out and partly documented using available data. The effect of the dam on spring water levels near the town of Peace River can be either beneficial or detrimental depending on simultaneous ice conditions in Peace River itself. Continued observations are deemed desirable in order to develop an adequate statistical record.

ACKNOWLEDGEMENTS

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