USE OF RUBBER DAMS FOR FLOOD MITIGATION IN HONG KONG[a]

Discussion by Hubert Chanson[2]

The discusser congratulates the author for his interesting paper on rubber dams. For completeness the discusser wishes to add further information on the Australian experience with rubber dams and possible causes of rubber dam damage.

AUSTRALIAN EXPERIENCE WITH RUBBER DAMS

Rubber dams (i.e., inflatable flexible membrane dams) have been in use for over 30 years in Australia (Table 3). After an initial interest in rubber dams in the late 1960s, these structures went out of favor following failures [e.g., Koombooloomba Dam, Sheperd et al. (1969)]. Recently, the interest in rubber dams has again increased as these structures become more reliable.

The hydraulic design of overflow above rubber dams is presently under investigation in Brisbane (University of Queensland, Department of Natural Resources). It is hoped that results will be available in the near future.

It is worth noting that the list of rubber dam manufacturers (in use in Australia) includes a local manufacturer: Queensland Rubber Co. (Brisbane, Australia).

DAMAGE TO RUBBER MEMBRANES

The author listed some potential causes for damage, including vandalism. For completeness, the discusser would like to describe other causes of damage, i.e., hydrodynamic instabilities and debris passage. During the overflow of deflated rubber dams, the flexible membrane must lie flat on the floor to minimize flow disturbances and head losses. Anchors and casing must be streamlined with the floor, using a recess in the concrete floor. These dispositions minimize the floor discontinuity (protuberance or gap) caused by the rubber bag and reduce the vortex shedding effects.

For inflated rubber dams, the overflowing nappe adheres to the downstream rubber wall and the adherence of the nappe might lead to flow instability at the base of the nappe (i.e., next to the separation position), pressure fluctuations on the downstream face of the dam, and vibrations of the flexible membrane. In laboratory tests, Ogihara and Maramatsu (1985) recorded accelerations of the membrane (in a direction normal to the skin) of up to 0.12*g for H/D less than 1.8, where g = gravity acceleration; D = rubber dam height; and H = upstream total head.

Nappe adherence vibrations can be eliminated by ventilating the underside of the nappe and by deflecting the nappe off the rubber dam wall (Fig. 10). In practice, the later method is nowadays commonly used. The deflector is designed to project the nappe away from the membrane and to prevent the nappe reattachment on the membrane. The optimum characteristics of the deflector were investigated by the discusser (Chanson 1996).

During a small overflow event above an inflated rubber dam equipped with a deflector, an air cavity forms between the membrane and the thin nappe of water. Free-surface undulations and fluttering instabilities might occur if the air cavity is not ventilated or is poorly ventilated (i.e., Kelvin-Helmholtz instability). Kelvin-Helmholtz instabilities can be controlled or prevented by two means: (1) nappe ventilation; and (2) splitters (also called spoilers, longitudinal fins, dividing walls, cutwaters). Usually splitters are installed along the deflector at regular intervals to divide the nappe into several narrower nappes, creating numerous gaps in the nappe to allow for the passage of air.

Another form of hydrodynamic instability is the presence of near-critical flows (i.e., undular flows) in the vicinity of both inflated and deflated membrane dams. Undular flows are characterized by fluctuating bottom pressures and shear stresses. In some particular cases, separation and regions of very low pressure might take place and this could lead to uplift effort on the membrane. Such fluctuating loads are not acceptable on a flexible membrane. Chervet (1984) described one prototype failure case caused by undular flow. Chanson (1995, 1996) provided several criteria for undular flow situations.

Damage to rubber dams may be also caused by debris, i.e., recurrent abrasion and debris impacts. Abrasion may be caused

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TABLE 3. Examples of Rubber Dams in Australia

Year (1)	Site (2)	Characteristics (3)	Manufacturer (4)	Remarks (5)
1965	Koombooloomba Dam, Queensland	$L = 1 \times 60$ m D = 1.22 and 1.5 m H_{infl} = 0.91 m Water filled	Fabridam–Firestone	Rubber membrane without deflector. Placed on an ogee crest. Automatic deflation system (mechanical). Design overflow: 142 m^3/s (inflated), 2,120 m^3/s (deflated).
1967	Proston weir, Queensland	$L = 1 \times 51$ m D = 1.5 m H_{infl} = 1.4 m Water filled	Fabridam–Firestone	Rubber membrane without deflector. Automatic deflation system (mechanical).
1983	Val Bird weir, North Queensland	$L = 2 \times 82$ m D = 1.9 m H_{infl} = 0.5 m Water filled	Fabridam–Firestone	Automatic deflation system (mechanical: siphon).
1996	Lyell Dam, New South Wales	$L = 2 \times 40$ m D = 3.5 m H_{infl} = 1.4 m Air filled	Bridgestone	Rubber membrane equipped with deflector. Automatic deflation systems.
1997	Dumbleton weir, Central Queensland	$L = 2 \times 75$ m D = 2 m H_{infl} = 0.7 m Air filled	Queensland Rubber Co.	Rubber membrane equipped with deflector. Automatic deflation systems (electrical and mechanical).

Note: D = rubber dam height (fully inflated); H_{infl} = maximum head above inflated rubber dam crest; L = length of membrane.

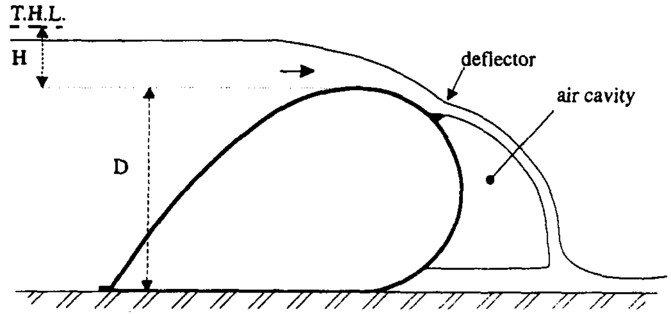

FIG. 10. Sketch of Overflow above a Rubber Dam Equipped with Deflector (i.e., Fin)

by the overflow of quartz sediment, ice, and branches. A protective casing or steel gate can be considered to reduce or prevent membrane abrasion (e.g., Omata weir, Japan). Debris impact is often not taken into account and the impact process is still poorly understood. In one case (Ngalimbiu bridge, Solomon Islands), substantial damage to concrete bridge piers was reported with plastic hinges in the pier portals. The equivalent static force at headstock level was estimated in excess of 3,000 kN, and it is believed that debris impacts contributed to the bridge failure (Boyce 1987)! Altogether the impact of debris (branch, tree, log, ice) must be avoided at any cost because of the risk of puncture. A hard cover (e.g., steel gate) might be required in case of potential debris impacts. Alternatively, rigid dams or gates must be selected in place of rubber dams.

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APPENDIX II. NOTATION

The following symbols are used in this paper:

D = rubber dam height (m);
H = head above dam crest (m);
H_{infl} = maximum head (m) above inflated rubber dam crest (m); and
L = rubber dam length (m).

Closure by Paul Wing Ming Tam[3]

The writer is grateful to the discusser for his encouragement and comments. The discusser raised some good points, which are not covered in the paper and he also provided experience of application from an Australian perspective. The writer finds it appropriate to respond to the discusser in a form of closure.

INFLATABLE DAM MANUFACTURERS

The discusser mentions the name of a local Australian rubber dam manufacturer. It is known that a number of small inflatable dam manufacturers exist in different parts of the world. The most well-known manufacturers of rubber dams are Bridgestone Corporation (Bridgestone) and Sumitomo Electric Industries, Ltd. (Sumitomo). Bridgestone has produced more than 600 dams since 1978 (Bridgestone 1997), whereas Sumitomo has produced more than 1,500 dams since 1966 (Sumitomo 1997). The writer has compiled a list of other less well-known manufacturers. The limited market shares of some of the manufacturers can be an impediment for them to conduct on-going research and development and to sustain their competitiveness in the market. Both Bridgestone and Sumitomo are seen to have pursued continued research in the manufacture of rubber dams to make them more dependable and to permit the dams to be installed in different climatic and operating conditions.

DURABILITY

The quality of the rubber dam is a major factor determining the applicability of rubber dams. The first inflatable dam installed in California suffered problems related to the elastomers used (Takahashi and Ellis 1992). The discusser has correctly remarked that due to the improved reliability of the rubber, interest in rubber dams is growing.

OVERFLOW

The writer would be pleased to see what hydraulic design of overflow is being investigated by the discusser and what results will be available. Interesting research results have previously been reported by some authors. Anwar (1967) investigated the coefficient of discharge of inflatable dams and Sumitomo (1985) reported their experimental results. An experimental investigation of inflatable dams is reported by Economides (1993). Moorthy et al. (1995) presented a discussion on the effects of three-dimensional vibrations of inflatable dams.

FLOOD-BORNE DEBRIS

The discusser has rightly pointed out that the damaging effects of flood-borne debris can cause severe damage to an inflatable dam. Tai Po Tau Dam, Hong Kong, was damaged in 1993 by flood-borne debris and was subsequently repaired. It is suspected that Tau Pass Fabridam also suffered similar damage (Fig. 11). Both dams were of the earlier type.

Sumitomo reported that the main cause of damage to their dams (Sumigates) is from dam body punctures by large rocks and stones while the dam is deflated (during flooding). In 1976, Sumitomo adopted a "shock-absorbing" procedure by the inclusion of resilient cushions inside the dam bodies for the absorption of impacts from rolling rocks and stones (Sumitomo 1985).

In addition to damage by flood-borne debris, sharp objects deposited immediately downstream of a dam can also cause damage during dam deflation. On the other hand, sharp objects deposited immediately upstream of a dam can also damage the dam body during dam inflation. Fig. 12 shows Dam No. YLN 65 damaged by a piece of glass. It is believed that it is a fragment of a broken glass bottle. Glass bottles are commonly found in streamcourses in Hong Kong. Fig. 13 shows glass bottles collected behind Dam No. BR 16.

Cut-resistant fabric has been developed that should be of

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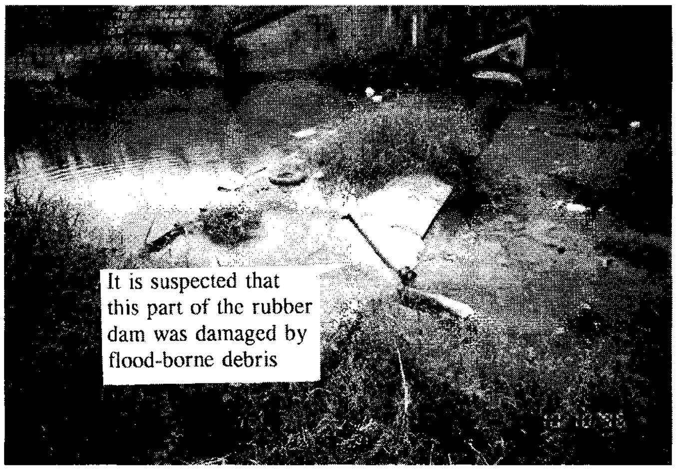

FIG. 11. Tau Pass Fabridam

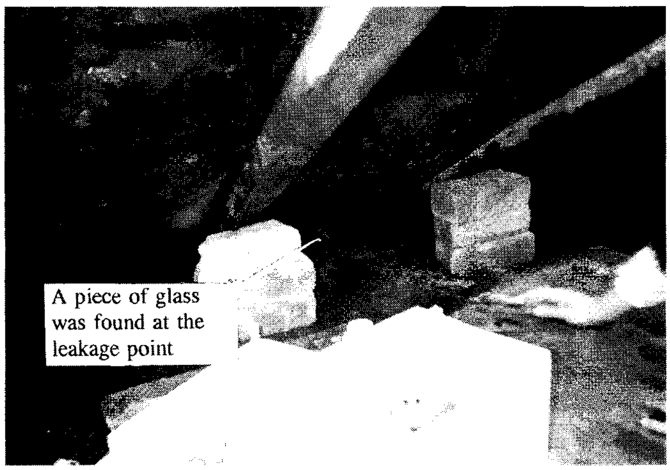

FIG. 12. Dam No. YLN 65

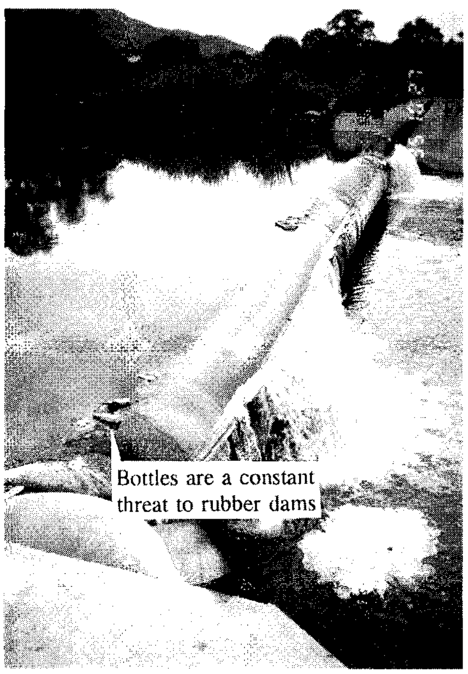

FIG. 13. Dam No. BR 16

help against damage by flood-borne debris and vandalism. A ceramic coating has been mentioned by the writer. Recently, a stainless steel reinforced fabric has become available. Fig. 14 shows a close-up photograph of a stainless steel reinforced fabric.

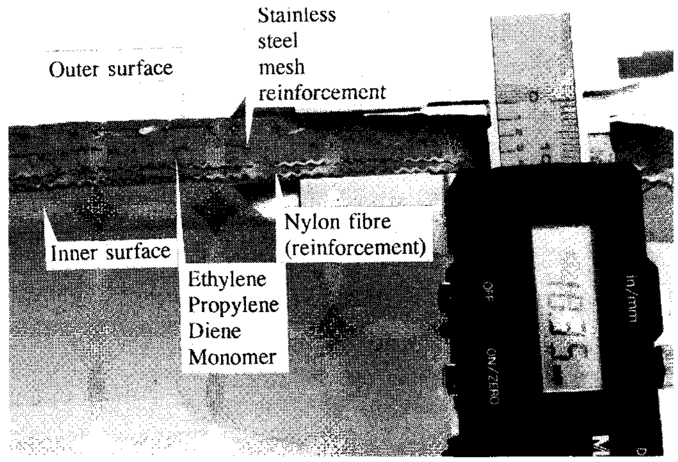

FIG. 14. Close-Up View of Cut-Resistant Fabric

The writer understands that the hydraulic characteristics of inflatable rubber bladders, with or without a steel flap gate, are being investigated by the Water Resources Research laboratory, Bureau of Reclamation, U.S. Department of Interior, in project-specific model tests (Bureau 1997). The idea is to provide reliable options to traditional hydraulic gate structures. The steel flap gate with an inflatable bladder may solve the problem caused by floating debris mentioned by the discusser.

HYDRODYNAMIC INSTABILITY

Bridgestone uses a fin for improving the stability of their dams. Sumitomo uses the following approaches (Sumitomo 1985, 1997):

- Double-line anchorage instead of single-line anchorage (i.e., two lines of fixtures, one on the upstream side and the other on the downstream side)
- Semi-circular dam cross section
- Higher inflation pressure

In a "double-line" anchorage system, it is reported that the greater the spacing between the upstream and downstream rows of anchors the lesser the effects of the vibration (Sumitomo 1985).

Most rubber dams constructed in the world are supplied by Sumitomo and most of the dams are located in Japan. Sumitomo does not use a fin for reduction of vibration.

The provision of a fin is important for the formation of an air chamber. It should be noted that during serious flooding, when floodwater covers the entire weir and adjoining areas, the formation of an air chamber for the avoidance of negative pressure on the downstream side of the dam may not be achieveable. In addition to providing a fin structure, the side slopes of the Omata Dam were made at 1.5 times the maximum height of the dam. This prevents floodwater from overflowing the side slope, ensuring that an air gap is always achieved by the fin structure (Takasaki 1989).

ACCESS TO DAMS FOR INSPECTION AND REPAIR

The discusser may be interested to know that access into the inflatable dam body is now possible. It is possible to inspect damage and to measure the abrasion of a dam by electronic devices from inside the dam body while it is inflated. The Naruse Dam has such an access system (Bridgestone 1992).

NEW DAM TYPES

New concepts of inflatable dams are being developed (Sumitomo 1997). New dam types are also being investigated by the Bureau of Reclamation (1997). The writer believes that more versatile and more dependable dams will be available in the near future. The investigation on the use of higher dams has been ongoing. The highest dam in the world so far is the 6-m-high, 34.5-m-wide Kurotani Dam constructed on Kurotani River in Japan. The dam was commissioned in 1994 (Sumitomo 1994).

SUMMARY AND CONCLUSION

The writer is encouraged that more and more inflatable dams are being built in the world for a wider variety of purposes. Both Vietnam and Bangladesh recently saw their first inflatable dams. In addition, higher dams are also possible.

The writer wishes to point out that apart from the dam's capability for flood mitigation there are other notable advantages. Inflatable dams may be installed in extremely cold climates. Steel gates may be "frozen" (gate jamming) under such temperatures, whereas inflatable dams are still operable. Another problem associated with "frozen" steel gates is the flooding upstream caused by ice formation at the steel gates. Broadwater Dam, Missouri River, Montana (Bridgestone 1982, 1997) is an example of such an application in a cold climate.

ACKNOWLEDGMENTS

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RESPONSE OF UNCONFINED AQUIFER TO SUDDEN CHANGE IN BOUNDARY HEAD[a]

Discussion by D. E. Smiles[2] and J. H. Knight[3]

Absorption of water by an initially uniform dry soil column has been used for many years to illustrate nonsteady flow in soils and to extend that understanding to more complicated systems. Solutions of the strongly nonlinear diffusion equation often used to describe these experiments have also been well studied in soil physics (see e.g., Philip 1969). If both the specific yield, S, and hydraulic conductivity, K, are constant, the Boussinesq equation can be treated as a weakly nonlinear diffusion equation and solved in the same way. The author develops a perturbation approach of a form discussed, for example, by Polubarinova-Kochina (1962) to solve this equation. This discussion illustrates a rapidly converging iterative solution to the Boussinesq equation (1) subject to (2), (3), and (4), which may offer flexibility denied a perturbation method.

This method groups K/S with h in (1) rather than with t and introduces the substitution $\phi = x/\sqrt{t}$ (5). Eqs. (1)–(5) then become

$$\frac{d}{d\phi}\left(\frac{K}{S}h\frac{dh}{d\phi}\right) + \frac{\phi}{2}\frac{dh}{d\phi} = 0 \quad (37)$$

subject to

$$h = h_1, \ \phi = 0 \quad (38)$$

$$h = h_0, \ \phi \to \infty \quad (39)$$

and integration of (37) using (39), which implies that at $h = h_0$, $dh/d\phi = 0$, yields

$$\left(Kh\frac{dh}{d\phi}\right)_h = -(S/2)\int_{h_0}^{h} \phi \, dh \quad (40)$$

In (37)–(40), h = elevation of the water table above an impermeable aquifer floor; x and t = horizontal distance and time, respectively; and the left-hand side of (40) represents the "reduced" flux of water (in terms of the variable, ϕ) at $\phi(h)$. Furthermore, the reduced flux at the inflow or outflow surface, where $\phi = 0$ and $h = h_1$, is

$$\left(Kh\frac{dh}{d\phi}\right)_{h_1} = -(S/2)\int_{h_0}^{h_1} \phi \, dh = -\beta(h_0, h_1) \quad (41)$$

with $\beta(h_0, h_1)$ a constant for a particular set of initial and boundary conditions. The ratio of the flux at $\phi(h)$ to that at the inflow surface, $\phi(h_1) = 0$, defined by

$$\left(\int_{h_0}^{h} \phi \, dh\right) \Big/ \left(\int_{h_0}^{h_1} \phi \, dh\right) = F\left(\frac{h - h_0}{h_1 - h_0}\right) \quad (42)$$

is monotonic and unique with $F(h, h_0, h_1) = 1$, when $h = h_1$ and $F(h, h_0, h_1) = 0$, when $h = h_0$. If $F(h, h_0, h_1)$ is known, then substitution for $\int_{h_0}^{h} \phi \, dh$ in (40) from (42) and integration gives the identity

$$\phi(h)/\beta(h_0, h_1) = (2K/S)\int_{h_1}^{h} [h/F(h, h_0, h_1)] \, dh \quad (43)$$

[a]January/February 1997, Vol. 123, No. 1, by D. A. Lockington (Paper 11214).

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