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The 1786 earthquake-triggered landslide dam and subsequent dam-break flood on the Dadu river, southwestern China ☆

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Abstract

Forensic studies of past hydraulic structure failures are rare despite their critical relevance to modern hydraulic design, and the writers (Dai et al., 2005) must be congratulated for their outstanding study. Herein the discussion is focused on two aspects of the conclusion. It is believed that dam overtopping was the primary cause of the Dadu river landslide dam failure, although aftershocks may have further weakened the embankment. Using physically based equations supported by recent physical model data, the maximum outflow may be estimated to be about 6000 m^3/s.

Keywords: Landslide dam; Breach; Flood; Discharge

Forensic studies of past hydraulic structure failures are rare despite their critical relevance to modern hydraulic design, and the writers must be congratulated for their outstanding study. Herein the discussion is focused on two aspects of the conclusion.

First it is argued that the mechanism of dam failure was overtopping. Embankment dam overtopping is the most common cause of earth dam failures, include landslide dam failures (Schnitter, 1994). For example, a 217-m high natural dam in the Tzao-Ling valley (Taiwan) was overtopped and failed in May 1951, killing 154 people in the subsequent floods (Hwang, 1999). In New Zealand, a 70-m high landslide dam was overtopped 11 months after formation and subsequently failed (Coleman et al., 2002). The overtopping of an embankment is a relatively slow process. It is not comparable to a sudden dam failure. For example, the South-Fork dam (USA) was overtopped at 11:30 am and the reservoir rose more than 0.5 m above the dam crest before the wall failed at 3:00 pm on 31 May 1889 (Wegmann, 1911). During the failure of the Glashütte dam (Germany) in August 2002, the dam was overtopped at 12:45 pm and the embankment failed completely within 30 min between 4:10 and 4:40 pm (Bornschein and Pohl, 2003). Basically the complete failure of an embankment may occur several hours

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after the start of overtopping. In June 1786, the Dadu river landslide dam started to be overtopped on 9 June and failed rapidly between 9 and 10 June. The timing was consistent with the rapid development of the dam breach resulting from the landslide dam overtopping, while it is likely that aftershocks on 10 June 1786 may have weakened the embankment.

Second, recent studies demonstrated that embankment dam failure by overtopping evolved from an initial phase, followed by a rapid breach development by vertical erosion, then breach width enlargement by lateral erosion, and reservoir drawdown (Andrews, 1998; Coleman et al., 2002; Rozov, 2003). During breach development, there is some basic analogy between the breach shape and the inlet designs of Minimum Energy Loss culvert and weirs (Coleman et al., 2002; Chanson, 2004a,b,c). The re-analysis of detailed experimental data (Andrews, 1998; Coleman et al., 2002) demonstrated that the flow in the breach is trans-critical (i.e. $0.5 < Fr < 1.8$) and that the total head remains constant throughout the breach inlet up to the throat (Chanson, 2004a). Head losses occur downstream of the throat when the flow expands and separation takes place at the lateral boundaries (Fig. 1). Separation is associated with form drag and head losses. Basically the movable boundary flow tends to an equilibrium that is associated with minimum energy conditions and maximum discharge per unit width for the available specific energy.

Using the analogy with minimum energy loss structures, the outflow rate during breach development must satisfy the continuity equation and Bernoulli principle. That is:

$$Q = C_D * \frac{2}{3} * \sqrt{\frac{2}{3} * g * E_1^3} * B_{max} \tag{1}$$

where E_1 is the upstream specific energy above centreline dam breach elevation, B_{max} is the free-surface width at the upper lip of the breach, and g is the gravity acceleration. The coefficient C_D accounts for

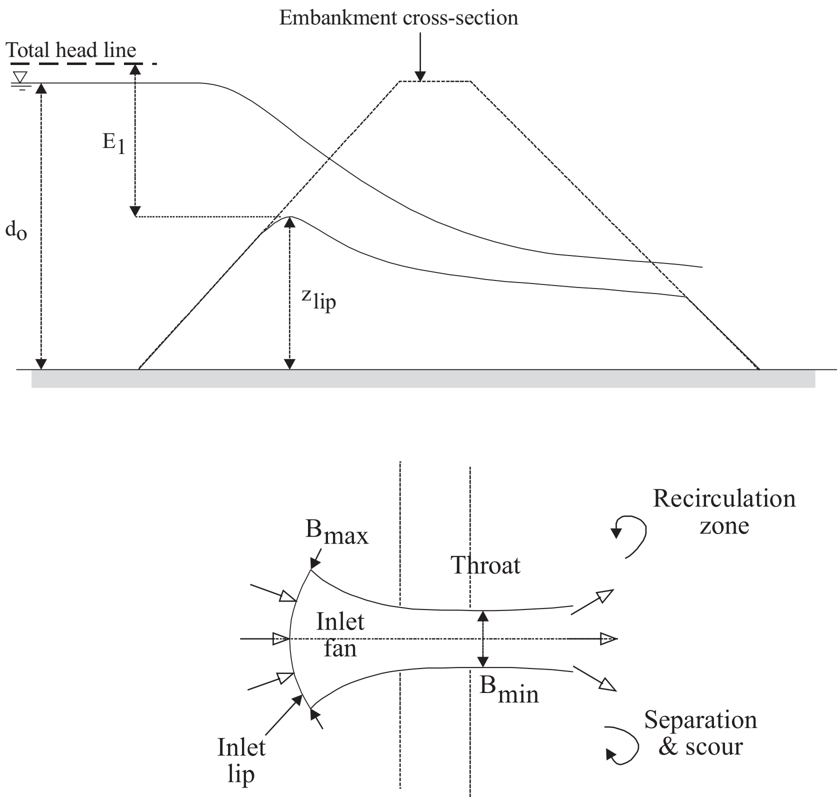

Fig. 1. Sketch of embankment dam breach development: cross-section through the breach centreline and detail of the breach flow (below).

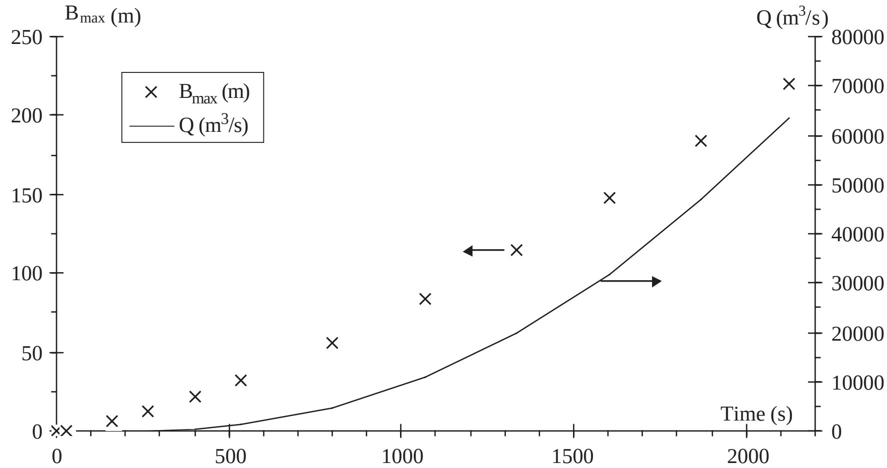

Fig. 2. Calculations of breach outflow rate and breach inlet width during breach development.

the non-rectangular flow cross-sectional shape and some energy loss. For the data of Coleman et al. (2002), C_D~0.6 $m^{1/2}$/s. During an overtopping event, the breach size increases with time resulting in the hydrograph of the breach. In Eq. (1), the breach free-surface width and specific energy are both functions of time, embankment properties and reservoir size. For an infinitely long reservoir, the re-analysis of embankment breach data suggests that:

$$\frac{z_{\text{lip}}}{d_o} = 1.08*\exp\left(-0.0013*t*\sqrt{\frac{g}{d_o}}\right)$$

$$\text{for } 60 < t*\sqrt{\frac{g}{d_o}} < 1750 \qquad (2)$$

$$\frac{B_{\max}}{d_o} = 2.73E-4*\left(t*\sqrt{\frac{g}{d_o}}\right)^{1.4}$$

$$\text{for } t*\sqrt{\frac{g}{d_o}} < 1000 \qquad (3)$$

where z_{lip} is the inlet lip elevation on the breach centreline, d_o is the reservoir height and $B_{\min}$ is the free-surface width at the breach throat (Fig. 1). For completeness, the breach width at the throat is best correlated by:

$$\frac{B_{\min}}{d_o} = 4.01E-7*\left(t*\sqrt{\frac{g}{d_o}}\right)^{2.28}$$

$$\text{for } t*\sqrt{\frac{g}{d_o}} < 1000 \qquad (4)$$

Eqs. (1) (2) and (3) were applied to the Dadu river landslide dam breach development. Typical results are shown in Fig. 2 where t is the time from the start of rapid breach development. They show that the breach upper lip width reached the dam length (~220 m) about 35 min after breach start and that the maximum outflow rate was about 6000 m^3/s corresponding to a breach throat velocity in excess of 17 m/s. For larger times, the underlying assumptions of an infinitely long and wide reservoir are not appropriate, and the above equations should not be used.

In summary, it is believed that dam overtopping was the primary cause of the Dadu river landslide dam failure, although aftershocks may have further weakened the embankment. Using physically based equations supported by recent physical model data, the maximum outflow may be estimated to be about 6000 m^3/s.

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