Consequence of Failure Classification: A Guide for Initial Assessment

Audience: Dam Safety Officers (DSO)
Owners of small dams
Community emergency preparedness coordinators

Introduction

This document provides an overview of consequence classification for dams in British Columbia. It outlines a rough method for assessing consequence and some key concepts that require consideration in assessing consequence. If the method provides a clearly defined consequence classification then a consequence classification can be assigned. If the results are uncertain, use of the higher possible consequence classification is appropriate or a more detailed assessment method should be used. For larger structures or complicated downstream channel conditions more detailed procedures may be required.

These guidelines are only intended for consequence of failure classification. They are not adequate for the preparation of inundation mapping for Emergency Preparedness Planning (EPP), or for the assessment of hazards and risk analysis.

Consequence Classification Guide

The BC Dam Safety Regulation - Schedule 1 “Downstream Consequence Classification Guide” outlines a classification guide for all dams in British Columbia. The consequence classification (very high, high, low, or very low) identifies the potential for damage and loss in the unlikely event of a dam failure. The consequence classification is not a reflection on how safe the dam is; thus age and condition of the dam are not reflected in the Consequence classification.

The consequence classification is used to determine the design requirements for a particular dam, with dams of higher downstream consequence having higher design standards. Suggested design requirements for dams falling under the various consequence classifications are identified in the “Dam Safety Guidelines” published by the Canadian Dam Association.

Dam Breach Flood Determination

The flood hydrograph resulting from a dam breach is dependent on many factors. The primary factors are the physical characteristics of the dam, the volume of the reservoir, and the mode of failure. The dam characteristics such as dam geometry, construction materials, and mode of failure; determine the dimensions and timing of breach formation. Breach formation, volume of reservoir storage, and reservoir inflow at the time of failure determine the peak discharge and the shape of the flood hydrograph.

The following sections provide a method for estimating dam breach parameters and peak flow discharges for earthfill dams. Earthfill dams are focused on because the great majority of small dams are earthfill. When estimating concrete gravity dam breach parameters, a complete failure of a discrete number of monoliths is considered. For concrete arch dams a complete dam failure is considered. Breach times for concrete gravity dams generally fall between 0.1 and 0.5 hours and for concrete arch dams they generally fall between instantaneous and 0.1 hours.

Estimation of Dam Breach Parameters

Work by MacDonald and Landridge-Monopolis (MacDonald, 1984) were successful in relating breaching characteristics of earthfill dams to measurable characteristics of the dam and reservoir. Specifically, a relationship exists between the volume of material eroded in the breach and the Breach Formation Factor (BFF):

$$BFF = V_w (H)$$

where:

V_w = Volume of water stored in the reservoir (acre-ft) at the water surface elevation under consideration
H = Height of water (feet) over the base elevation of the breach

Interpretation of data (MacDonald, 1984) suggests that the estimates of material eroded from earthfill dams may be taken to be:

$$V_m = 3.75\,(BFF)^{0.77} \quad \text{for Cohesionless Embankment Materials; and}$$

$$V_m = 2.50\,(BFF)^{0.77} \quad \text{for Erosion Resistant Embankment Materials}$$

where:

V_m = Volume of material in breach (yds^3) which is eroded

Using the geometry of the dam and assuming a trapezoidal breach with sideslopes of (Z_b:1) the base width of the breach can be computed (MacDonald, 1984) as a function of the eroded volume of material as:

$$W_b = [27V_m - H^2 (CZ_b + HZ_bZ_3/3)] / [H (C + HZ_3/2)]$$

where:

W_b = Width of breach (feet) at base elevation of breach
C = Crest Width of dam (feet)
$Z_3 = Z_1 + Z_2$
Z_1 = Slope (Z_1:1) of upstream face of dam
Z_2 = Slope (Z_2:1) of downstream face of dam

If the calculated breach width is negative then the reservoir volume is not large enough to fully breach the dam and a partial breach will result. In this case the head of water (H) needs to be adjusted to estimate the breach depth and peak discharge. Maximum breach widths have historically been limited to breach widths less than 3 times dam height (Fread, 1981). In addition site geometry often limits breach width.

The time of breach development (τ) in hours, has been related to the volume of eroded material (MacDonald, 1984). Interpretation of data suggests that the time for breach development can be estimated by:

$\tau = 0.028\ V_m^{0.36}$ for Cohesionless Embankment Materials; and

$\tau = 0.042\ V_m^{0.36}$ for Erosion Resistant Embankment Materials

There is a large uncertainty in the eyewitness accounts for many of these failures; thus these equations may tend to overestimate breach times. In addition, these equations appear to produce unrealistically short breach development times in the case of small dams. A lower limit for the breach development time of perhaps 10 minutes for dams constructed of cohesionless materials and 15 minutes for dams constructed of erosion resistant materials seems reasonable.

Due to the uncertainties in breach development parameters, a range of values should be used to assess the computed dam break flood peak discharges. There is a range of alternative procedures for estimating dam break parameters. An example is the computer program BREACH, developed by Fread (1987) which is used for larger complex dams.

Estimation of Dam Breach Peak Discharge

A number of computer programs, such as DAMBRK (Fread, 1988), have been developed for estimating dam break peak discharge. This computer model, and others, utilises unsteady flow conditions in combination with user selected breach parameters to compute the breach flood hydrograph.

Fread (1981) gives an alternative method suitable for many planning purposes. He developed an empirical equation based on numerous simulations with the DAMBRK model. Estimation of the peak discharge from a dam breach is computed as:

$$Q_p = 3.1\ W\ H^{1.5}\ [\ A\ /\ (A + \tau\ H^{0.5}]^3$$

where:

Q_p = Dam breach discharge (cfs)
W = Average breach width (feet) $W = W_b + Z_b H$
H = Initial height of water (feet) over the base elevation of the breach
τ = Elapsed time for breach development (hours)
A = $23.4\ S_a / W$
S_a = Surface area of reservoir (acres) at level corresponding to depth H

The following Tables 1 & 2 contain estimates of dam breach peak flows for overtopping induced failures of earthfill dams based on Fread’s equation. The values used in developing these estimates are presented after the Tables.

Table 1 – Earthfill Dam Peak Discharge Estimates (metric units)

Dam Breach Discharge Estimates
for Earthfill Dams Constructed of Cohesionless Materials

Dam Breach Peak Discharge (m3/s)

		Reservoir Surface Area (hectares)								
		1	2	3	4	5	10	15	20	40
Dam Height (meters)	1.2	6.9	12*							
	2	14	23	31	39			Breach Width > 5xDam Height		
	3	23	38	50	61	72				
	4		52	69	84	98	160			
	5		67	88	106	123	200	267	329	
	6			106	128	149	239	318	391	
	7				149	173	277	367	450	
	8				170	196	313	414	507	832
	9					219	347	459	561	918
	11						411	542	661	1077
	13	Partial Breach					467	616	752	1221
	15							682	832	1351

* This discharge value results from a breach width of 5.2 times the dam height

Dam Breach Discharge Estimates
for Earthfill Dams Constructed of Erosion Resistant Materials

Dam Breach Peak Discharge (m3/s)

		Reservoir Surface Area (hectares)								
		1	2	3	4	5	10	15	20	40
Dam Height (meters)	1.2	4.5	7.8	11						
	2	8.8	15	21	26	31		Breach Width > 5xDam Height		
	3	15	25	34	41	49	81			
	4	22	35	46	57	67	110	148	183	
	5		45	59	72	84	138	185	228	
	6		56	72	88	102	165	221	272	452
	7			85	103	119	192	256	315	521
	8			98	118	136	218	290	356	587
	9				132	153	244	323	396	651
	11					184	292	385	471	771
	13	Partial Breach					336	443	541	881
	15						376	496	605	983

Table 2 – Earthfill Dam Peak Discharge Estimates (imperial units)

Dam Breach Discharge Estimates
for Earthfill Dams Constructed of Cohesionless Materials

Dam Breach Peak Discharge (cfs)

		Reservoir Surface Area (acres)								
		2	4	7	10	15	20	35	50	100
Dam Height (feet)	4	212	362							
	6	362	612	942				Breach Width > 5xDam Height		
	8	532	888	1335	1723					
	10	722	1176	1722	2212	2956	3641			
	15		1883	2702	3433	4540	5557	8295		
	20			3669	4628	6072	7395	10946	14124	
	25				5767	7530	9138	13440	17279	28413
	30					8892	10771	15773	20223	33099
	35						12276	17939	22959	37442
	40							19932	25487	41464
	45	Partial Breach						21746	27808	45182
	50							23374	29919	48608

Dam Breach Discharge Estimates
for Earthfill Dams Constructed of Erosion Resistant Materials

Dam Breach Peak Discharge (cfs)

		Reservoir Surface Area (acres)								
		2	4	7	10	15	20	35	50	100
Dam Height (feet)	4	139	239	372						
	6	235	401	621	821	1129		Breach Width > 5xDam Height		
	8	342	578	889	1166	1571	1944			
	10	461	770	1162	1499	2012	2484	3759		
	15		1262	1829	2336	3105	3814	5722	7435	
	20			2499	3168	4178	5106	7602	9839	16348
	25			3159	3981	5219	6353	9396	12119	20029
	30				4764	6220	7549	11105	14280	23489
	35					7169	8685	12726	16325	26745
	40					8058	9755	14258	18257	29811
	45	Partial Breach					10750	15697	20076	32696
	50							17040	21781	35409

The tables were computed based on:

Failure by overtopping thus H, S_a, and V_w are for reservoir at crest of dam (they are not values for maximum reservoir level)
Storage volume was calculated as ($H S_a / 3$)
Upstream face of 3H: 1V
Downstream face of 2H: 1V
Crest width $C = 2 + 2 H^{0.5}$ (in feet)
Breach sideslopes (Z_b: 1) are 1.0 for cohesionless embankment material, and 0.5 for erosion resistant embankment material
Minimum breach development times of 10 minutes for cohesionless embankment material, and 15 minutes for erosion resistant embankment material was used.

Values were not entered into the Tables for cases in which the calculated breach did not develop to the full depth of the dam. In addition, values were not entered into the Tables when breach widths were calculated to be greater than 5 times the dam height.

It should be noted that actual peak discharges could vary greatly from the calculated peak discharges. Differences in site conditions, dam materials, and reservoir inflow could greatly influence the results. For example a dam increasing storage on an existing lake could result is greater peak breach flows due to a greater reservoir volume than modelled.

Selection of Reservoir Conditions for Breach Analysis

The selected reservoir storage is an important consideration in dam breach analysis. Normally a couple of reservoir conditions, normal pool and maximum storage elevation during floods are considered. For smaller unattended structures usually only the case of dam failure during overtopping needs to be considered. Overtopping could result from a debris blockage, or a beaver dam constructed, in overflow spillway channel.
In evaluating the overtopping dam breach it needs to be remembered that the reservoir storage and head on the dam are greater than for normal pool levels.

Downstream Routing of Dam Breach Flood

As the dam breach flood wave travels downstream there is a reduction in the peak flow. This effect is governed by factors such as:

the channel bedslope,
the cross-sectional area and geometry of the channel and overbank areas,
the roughness of the main channel and overbank,
the existage of storage for floodwaters in off-channel areas, and
the shape of the flood hydrograph.

Small attenuation is associated with:

large reservoir volume,
small confining channel,
steep channel slopes, and
little frictional resistance in channel and overbank areas.

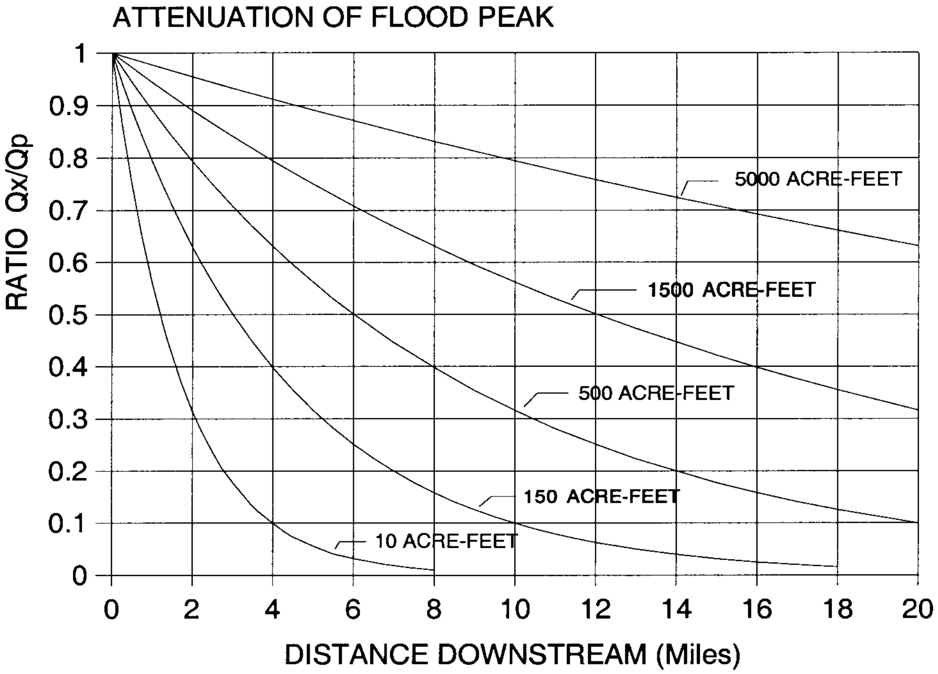
Large attenuation is associated with:

small reservoir volume,
broad floodplain and/or off-channel storage areas,
mild channel slopes, and
large frictional resistance in channel and overbank areas.

There are a number of methods for modelling the attenuation of peak flow as the breach flood wave travels downstream. For consequence classification a simplified procedure based on generalised flood attenuation curves developed by the USBR (1982) is often adequate. The curves presented in Figure 1 should be used conservatively as they utilize generalised solutions to approximate the reduction of flood peak discharge with distance downstream of the dam. For example the attenuation would be much smaller for a dam breach flow travelling down a steep narrow valley.

Figure 1 – Generalised Flood Attenuation Curves

Note: This figure is in imperial units



The curves in Figure 1 are arranged in terms of reservoir storage. They show flood attenuation in terms of peak dam breach discharge (Q_p) at the dam site and peak discharge (Q_x) at some distance downstream.

Downstream Inundation

For many planning purposes a reasonable approximation of the inundation at a given location can be made using peak dam breach discharge from the Figure 1 or 2, the attenuation curves in Figure 3, and site specific channel cross-section data and representative flow velocities from Table 3.

Table 3 - Representative Velocities for use in Estimating Inundation from Dam Break Floods

Note: This figure is in imperial units

TYPE 1 **MAIN CHANNEL - GRAVEL** **OVERBANKS - GRASS, PASTURE**		**TYPE 2** **MAIN CHANNEL - GRAVEL, COBBLES** **OVERBANKS - IRREGULAR, BRUSH,** **SCATTERED SHRUBS**		**TYPE 3** **MAIN CHANNEL GRAVEL** **COBBLES, BOULDERS** **OVERBANKS WOODED**	
BEDSLOPE (ft/mi)	VELOCITY (ft/sec)	BEDSLOPE (ft/mi)	VELOCITY (ft/sec)	BEDSLOPE (ft/ml)	VELOCITY (ft/sec)
5	2.4	5	1.7	5	1.4
10	3.4	10	2.4	10	1.9
15	4.1	15	3.0	15	2.4
20	4.8	20	3.5	20	2.7
30	5.8	30	4.2	30	3.3
40	6.7	40	4.9	40	3.8
60	8.2	60	6.0	60	4.7
80	9.5	80	6.9	80	5.4
100	10.6	100	7.7	100	6.1
200	12.0	200	10.9	200	8.6
300	12.0	300	12.0	300	10.5
400 or greater	12.0	400 or greater	12.0	400 or greater	12.0

The cross sectional channel area required to pass the flood would be:

$$A = Q_x / V$$

where:

A = Cross-sectional area of channel and overbank (feet)

Q_x = Peak flood discharge (cfs)

V = Representative average velocity (feet/sec) at the cross-section

The resulting inundation mapping should represent a conservative estimate of the consequences of a dam failure.

Downstream Hazard Classification

Once the dam breach flood inundation path has been determined, the resulting consequence of failure classification can be determined. For BC, the classification system is outlined in Schedule 1 “Downstream Consequence Classification Guide” of the British Columbia Dam Safety Regulation. Refer to the Regulation for Schedule 1. The highest consequence rating in one of the three categories; loss of life, economic and social loss, and environmental and cultural losses is the consequence rating for the dam.

In estimating loss of life in a dam breach one needs to consider:

Time of day of failure
Number of homes in inundation area
Flood depth and velocity
3 people per home (USBR, 1988)
Highways
Recreation
Warning time
Sources of uncertainty

For further information on this topic the “Downstream Hazard Classification Guidelines” produced by the US Bureau of Reclamation (USBR, 1988) are a good starting point.

Other Considerations

There are many other factors that can influence the consequence of failure classification. They include:

Debris build-up and sediment transport can increase floodwave size and its destructive power,
Channel avulsions especially on alluvial fans,
Multiple dams on a river system, and
Current and potential future downstream development,

Warning systems can be effective in reducing loss of life in the event of a dam failure. Thus they are effective risk management tools, however they do not change the consequence of failure classification.

Acknowledgement

This document in part follows the Washington State Department of Ecology publication “Dam Safety Guidelines, Technical Note 1: Dam Breach Inundation Analysis and Downstream Hazard Classification” (Schaefer, 1992). The Washington State Dam Safety Office site at http://www.ecy.wa.gov/programs/wr/dams/dss.html has a good site that includes excel spreadsheets for calculating peak dam break flood flows.

References

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