DAM BREACH INUNDATION ANALYSIS USING HEC-RAS AND GIS
TWO CASE STUDIES IN BRITISH COLUMBIA, CANADA

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ABSTRACT:

Hypothetical dam breach scenarios of the Pinaus Lake Dam near Vernon, BC and Cold Spring Creek Dam in Fairmont, BC were analyzed using the HEC-RAS software in conjunction with a Geographic Information System (GIS). The overall objective was to estimate the dam-break outflow hydrograph, route the dam-break hydrograph through the downstream valley and floodplain, and estimate the inundation levels, resulting damages to downstream communities and structures, and potential loss of life in order to classify the dams. The dam breach simulations were challenging due to available topographic data resolution, accuracy of extreme flood estimates, channel slope, and the attenuation caused by water bodies downstream of the subject dams. This paper discusses some of the commonly used techniques, assumptions and important lessons learned during modelling exercise. A number of dam breach simulation results will be also presented in this paper.

RÉSUMÉ

Scénario de rupture de barrage de Pinaus Lake, BC, et Cold Spring Creek Dam en Fairmont, BC ont été analysés au moyen du modèle hydraulique HEC-RAS, conjonction avec le Système d'information géographique (SIG). L'objectif global était d'estimer d'hydrogramme de crue sortant des barrages en cas de rupture, laminage de crue dans la vallée en aval du barrage et le niveau d'eau causé par la rupture dans la rivière et plaine inondable. Finalement, l'article estime des dommages-intérêts pour les bâtiments et l'infrastructure des transports, par exemple, pour déterminer le niveau des conséquences de rupture dans la communauté en aval. Les simulations de rupture des barrages ont été difficiles en raison de résolution des données topographiques, l'exactitude des estimations des crues extrêmes, la pente moyenne du cours d'eau et l'atténuation provoquée par les masses d'eau en aval des barrages en question. Ce document traite ainsi certaines techniques couramment utilisées, les hypothèses et surtout les leçons apprises lors de la modélisation de l'exercice. Les résultats des simulations d'écoulement instables seront également présentés dans le présent.
1) GENERAL INTRODUCTION

In Canada incremental hazard analysis is used to classify existing dams and dams under construction or in the planning stage. As outlined in the Canadian Dam Safety Guidelines (2007), issued by the Canadian Dam Association (CDA), the consequences of various dam failure scenarios must be studied in order to assess the associated classification. Classification is then used to calculate robustness such as spillway discharge capacity, seismic parameters etc. and to set the frequency of activities for the management of dams.

Dam failures may occur due to a variety of causes such as a significant hydrologic event, seismic activity, operational error, and other deficiencies. If a dam breach occurs, an uncontrolled release of water impounded behind the structure will cause flooding in the downstream area. Over last five years two dams were breached in British Columbia (BC). On June 13, 2010, Testalinden Dam failed and caused a debris and mud torrent that demolished five downstream homes and farms, severed a main provincial highway and introduced significant quantities of sediment into fish bearing waters. Most recently, Mount Polley Mine tailing dam was breached and released five million cubic meters of water and tailing waste in local lakes and creeks. The estimated damage remains undetermined. There are many other significant dam failures across BC.

For this study, two dams, Pinaus Lake Dam and Cold Spring Creek Dam, were considered for dam breach simulations. The case study dams were located in BC and Kerr Wood Leidal Associates Ltd. (KWL) has conducted dam break modelling using HEC-GeoRAS, a Geographic Information System (GIS) tool combined with HEC-RAS. The model was fully geo-referenced, and developed using ArcGIS before simulating the dam failure scenarios in HEC-RAS.

Dam break models were established to estimate the consequences of a hypothetical breach of a dam during flood flow conditions and normal operation under sunny day weather. Flood condition analyses are intended to estimate the required discharge capacity to pass the Inflow Design Flood (IDF) without overtopping the dam. Sunny day condition analyses are used to design a dam and its appurtenant to withstand against earthquakes or unforeseen events.

While there is extensive literature and case histories regarding dam break modelling there is less information available for the challenges that modellers usually face. This paper provides useful and practical insight into the challenges and the lessons that were learned during the simulations exercise. Some of the simulation results will be also summarized in this paper.

The location of the Pinaus Lake dam from Vernon is approximately 45 km across forest service roads and travel time is approximately 1 hour (Latitude 50°25'18"N and Longitude 119°34'16"W). The dam was constructed in 1923 and significantly rebuilt in September 1951. It is a reinforced concrete counterfort (buttressed) retaining wall. The dimensions of the dam are 11.7 m (bank to bank), 2.4 m high and 0.46 m wide (upstream face); The wing (return) walls are non-structural but extend the width of the dam to the abutments.

The Cold Spring Creek Dam is located approximately 0.3 km upstream of the Fairmont village on the eastern slopes of the Columbia River valley, approximately two kilometres from the confluence with Columbia River (Latitude 50°20'15"N and Longitude 115°50'45"W). The creek is predominantly west facing with an average gradient of approximately 8%. The dam is relatively small since it covers a basin area of approximately 7.7 km² (Clarke, 2013) and provides a maximum storage volume of just over 1600 cubic metres. The dam is a concrete gravity structure 22 m long and 4.6 m high from the structure crest to the river bed of the creek at the downstream outside limit of the dam. The reservoir volume at full supply level (FSL) was estimated to be 1,600 m³ at an elevation of 943.4 m (Stepanek, 2013). Outflow through the dam is controlled by a free Ogee spillway and a gated 0.9 m diameter pipe outlet. The full flow capacity of the unblocked Ogee is approximately 4.4 m³/s at full supply level.
2 DAM BREACH MODELLING

All dams, regardless of their design or construction, have increased forces applied to them during extreme events which increases the potential risk of failure. Therefore, a dam breach analysis is usually conducted to determine the ultimate discharge from a hypothetical breach of a dam under such events. The outcome is a breach hydrograph from dam failure with a flood wave immediately downstream of the dam, which is routed throughout the river system to determine the flood arrival time, peak flow, and the depth of flow at downstream locations. Mapping of inundation areas (i.e. areas flooded by the flood wave) is used for:

- estimating the potential consequences of a dam breach;
- confirming the classification; and
- emergency planning purposes.

To simulate the dam-breach flood, a one-dimensional HecRAS model was used to simulate the dam breach process and determine breach outflow and water-surface profiles in downstream.

The downstream valley from dam to the study limit was represented as a series of cross sections into the dam break model. 68 cross section were used for Pinaus Lake Dam in the model to represent the downstream valleys. The cross sections were generated from available 1:20,000 TRIM topography maps for Pinaus Lake dam; the best available information. Conversely, Cold Spring Creek used detailed topographic information, 1 m contour map, for extracting cross sections. A total of 17 cross sections, located along the study reach, were extracted. Figure 1 shows HecRAS longitudinal profile of the Cold Spring Creek showing the dam location, cross sections and downstream river.

Figure 1: Longitudinal profile of the Cold spring Creek, showing the subject dams
2.1 Breach Scenarios

Two dam failure scenarios and two background no breach scenarios were examined in this study:

- **Sunny day failure**: This is a sudden dam failure that occurs during normal operations, with the water level at full supply and the water released causing the largest change in flows. It may be caused by foundation failure, earthquakes, or another such event. This scenario normally refers to internal erosion (piping) failure.
- **Flood induced failure**: This is a dam failure resulting from a natural flood of a magnitude that is greater than what the dam can safely pass. This scenario normally refers to overtopping failure.

2.2 Dam-Breach Parameters

The assumptions regarding dam breach parameters are critical for dam break modelling. Thus, reasonable values for the breach size and development time along with feasible breach geometry are needed to make a realistic estimate of the outflow hydrographs. Nonetheless, determining the size and growth rate for breaches is an inexact science while they are key parameters in dam break models. Therefore, the estimation of the breach parameters yield a significant source of uncertainty in the results and in turn downstream inundation extends. These uncertainties require conservative assumptions to be made as a larger flood may be expected to occur and is preferred by most authorities. For the subject dams, the 1986 BC Hydro and 1993 FERC Guidelines were used to assist in the assessment of the dam breach parameters. Table 1 summarizes the proposed breach parameters for the Cold Spring Creek Dam.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Sunny Day</th>
<th>Flood</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dam Crest Elevation (m)</td>
<td>944.2</td>
<td></td>
</tr>
<tr>
<td>Reservoir Level at time of breach (m)</td>
<td>943.5</td>
<td>944.5</td>
</tr>
<tr>
<td>Effective Height (m)</td>
<td>3.7</td>
<td>4.5</td>
</tr>
<tr>
<td>Breach top width (m)</td>
<td>11</td>
<td></td>
</tr>
<tr>
<td>Breach width at bottom (m)*</td>
<td>11</td>
<td></td>
</tr>
<tr>
<td>Time to failure (h)</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>Breach side slope (Z)</td>
<td>0:1 (vertical)</td>
<td></td>
</tr>
</tbody>
</table>

* Breach width limited to half structure width as suggested in most guidelines. In accordance with the FERC Engineering Guidelines, the loss of several complete monoliths with full height of the dam was considered.

2.3 Boundary Conditions

The assumptions regarding boundary conditions are also critical for dam break modelling as they could directly affect extend of downstream floodwaters. Initial flows and water level values, input hydrographs, and downstream boundary conditions, were specified to initialize and run the dam break model. These boundary conditions must be properly selected and they must best represent the site conditions. In this study the following conditions were considered:

- the inflow hydrographs for the upstream boundary; four extreme input hydrographs of Probable Maximum Flood (PMF), 2/3PMF, 1/3 PMF, and 1:1000 flood were considered for the flood simulations. The PMF for the study dams were determined based on the “PMF Estimator of BC”. The estimated PMF values were compared using the regional equations to corroborate the values, the moderate conservative values were adopted.
- initial flows and internal locations such as Little Pinaus Lake at the beginning of the simulation; and
- downstream boundary conditions were established at a large body of water relative to the impoundment water volume behind the study dam. For instance, approximately 2 km downstream of the Cold Spring Creek Dam, the Columbia River water level of 803 m was set for downstream boundary conditions.
• Elevation-volume tables were used to represent the storage upstream of the dams. HEC-RAS used level-pool routing during breach of the dam.

2.4 Breach Time and Trigger Water Levels

For the sunny-day failure, it was assumed that the reservoir would be at full supply level plus base flow approximately over the spillway or outlet works at the time of the breach. For the analysis of the flood scenarios, it was assumed that water levels marginally exceeded the structure crest. Failure of the dam was simulated when the reservoir levels overtop the structure, approximately 0.3 m of overtopping, and breach happened at the peak of the flood event. This is consistent with the CDA Dam Safety Guidelines.

For all simulations, channel roughness values (Manning “n”) of 0.03 to 0.05 and overbank roughness values ranging from 0.06 to 0.1 were used for the majority of the reach. These values were selected based on reviewing the site visit, photographs and aerial imagery of channel and flood plain areas.

It was found that higher Manning’s values not only produced marginal increases in the flood profile but also produced more stable model. For conservatism, the greater Manning’s “n” values were used in this study.

2.5 Sensitivity Analysis

The water levels in the downstream inundated areas are influenced by various factors which may be put into two groups, namely the breach parameters, and the physiographic feature of the upstream basin and the creek downstream of the dam. Though these factors are known, sensitivity tests are needed to quantify the magnitude of the effects on breach outflow and downstream water levels. Sensitivity analyses would also diminish the effect of data limitations and help to better understand the effect of the assumptions and input parameters on the extension of the inundated areas.

The sensitivity analysis of the breach parameters reveals that the outflow is very sensitive to breach size and breach development time, particularly in sunny-day scenarios. Manning’s “n” values are also key input parameters in dam breach analysis. Sensitivity tests were conducted to determine the effect of Manning’s “n” values on downstream flood profiles. It was found that increases in the Manning number decreased the flow but increased the water levels.

Sensitivity analysis demonstrates that the effect of the dam breach parameters, in particular the size of breach, is more noticeable than Manning’s “n” number effect. While Manning’s “n” number had little influence on the downstream maximum water level in this study, the resolution of data did not allow changes in the map to be seen.

3 DAM BREACH SIMULATION RESULTS

3.1 Small Reservoir Upstream of Dam

As mentioned above, the Cold Spring Creek Dam case study, has a small reservoir upstream of the dam. Figure 2 shows the computed breach outflow hydrograph at the dam site during normal operation. The red line shows a peak value of 15 m$^3$/s and a total duration of breach outflow of about 5 minutes. This short time flood wave is due to the small reservoir. Given a constant discharge rate of 15 m$^3$/s, it would take less than 2 minutes to drain 1,600 m$^3$ of water from the reservoir.
The simulation of a dam breach during various flood conditions was carried out with the purpose of selecting the appropriate IDF. Figure 3 shows the breach outflow during flood conditions. The dam breach model indicates a resulting insignificant spike in discharge at the dam location. The hydrograph in Figure 3 clearly shows this “spike”. The water level results showed that the “spike” in discharge would result in a minimal incremental depth of water at the downstream area.

3.2 Downstream Large Water Bodies Effects

In hydrodynamic modelling, flood routing accounts for changes in the time distribution of flood flows caused by storage and attenuation. The effect of storage and the geometry of the downstream valley can attenuate flood flows due to available water which can both slow the flood wave and dampen the peak as seen in Figure 4.
The dam breach outflows obtained in the Pinaus Lake Dam model are shown in Figure 4 for a location just upstream of the Little Pinaus Lake and for a location downstream of the Little Pinaus Lake. Figure 4 indicates that the peak flows attenuated through Little Pinaus Lake from 65 m$^3$/s to 50 m$^3$/s while this flow, 50 m$^3$/s, propagated all the way downstream with a minimal attenuation.

![Figure 4: Flood attenuation effect by downstream lake, Little Pinaus Lake,](image)

4 FLOOD INUNDATION MAPPING

Dam-breach flood-inundation maps indicate areas that may be flooded as a result of a dam failure. The maps are used by wide range of end-users for planning and as a response tool to determine the effects of dam failure in downstream areas. In addition, the incremental areas flooded as a consequence of dam failure were considered for a dam classification exercise. For this study, flood inundation maps were generated using HEC-GeoRAS and ArcGIS.

Due to the small volume of the Cold Spring Creek Dam reservoir, very small increases in flood levels were observed downstream of the dam. The background flood (no dam failure scenario) was superimposed with dam failure flood extents in the maps. Due to minor changes between with and without dam failure scenarios under flood conditions, it was deemed to produce maximum flood-inundation extent for downstream creek and floodplain areas. The maps were plotted using the worst-case scenario in order to show the largest area that could be inundated. Subsequently, incremental consequence analyses were conducted separately using spreadsheets to assess hazards and dam classifications.

5 CHALLENGES AND LESSONS LEARNED

As well as posing a number of challenges, the dam breach modelling assignment provided important lessons. Both challenges and lessons are summarized below:
The single greatest challenge facing modellers had to do with model instabilities, some of which were addressed in this paper. Both dam break models were sensitive to computational time steps. Smaller time steps made for a more stable model. The spacing between cross sections was another important factor in determining model stability. A coarse spacing resulted in greater instability and vice versa. It was discovered that the combination of cross section spacing and computation time steps was also important. Fread (1993) and Samuel (1989) proposed equations for selecting time steps and distances between cross sections. The literature advises keeping the Courant number close to one in order to maximize model stability.

In both case studies, topographic data resolution proved incapable of resolving elevation differences between a dam breach flood and natural flood scenarios. All the maps were produced on the basis of conservative assumptions.

Cutting cross sections from the coarse topographic data produced a horizontal line in the channel portion of the digital elevation model (DEM). For lower flows, before breach of the dam, the dry-bed or shallow water situations would happen and crash the model. A pilot channel was created in the cross sections to keep the channel “wet” and provide stability in the HEC-RAS model.

No site specific PMP-PMF study was available for the watershed upstream of the subject dams. Greater diligence is required to reduce hydrologic input uncertainties. At some point in the future, a site specific PMP-PMF study needs to be conducted for the dams.

It is recommended that the higher approximate values of the Manning roughness coefficient “n” be used in areas downstream of the dam and steep slopes. This would account for the high level of turbulence of the outflow from the dam breach and help to improve the model’s stability.

During dam breach simulations, it is essential for engineers to exercise judgement in selecting breach parameters and other input data. Several assumptions were also made with respect to representing existing conditions. Given these judgments and assumptions, sensitivity analysis is strongly recommended for the parameters, the purpose being to identify those that are critical in affecting the flood level in the downstream areas.

For the subject dams, the sensitivity analysis results showed that changes in the Manning “n” had little effect on inundation levels for the locations downstream of the dam. However, the breach parameters did influence peak flows for downstream locations, in particular those near the dam.

The effect of storage capacity downstream of the study dam needs to be carefully considered in dam break models. As shown in the Pinaus Lake Dam case study, the storage downstream of the dam reduced the dam breach peak outflow by attenuating the flood flows.

For small dams, such as Cold Spring Creek Dam, with little impounded water, the incremental effects of a dam breach during an extreme flood event were insignificant and could not be differentiated from a natural event. However, the sunny-day breach scenario provided the maximum differentiation.

During flood conditions, the dam break flow will likely carry significant sediment resulting from erosion, along with trees and debris, all of which will be transported downstream. However, this effect could not be differentiated from the natural event in order to account for the incremental downstream effects. Further research needs to be conducted to determine the influence of debris on the downstream water levels. It is recommended that to improve consistency, provincial guidelines include a set of criteria to account for debris effects.

The experience and lessons learned from the case studies will, it is hoped, contribute to improving dam beach modelling exercises.

6 REFERENCES