Effects of extreme rainfall on geotechnical hazards in the Canadian Rocky Mountains

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ABSTRACT
In June, 2013, southwestern Alberta, Canada experienced an up to 1 in 750 year rainfall. The flooding that resulted led to geotechnical and hydrologic hazards in the Front and Main Ranges of the Canadian Rocky Mountains and on the Bow River watershed. The Main Ranges are folded and faulted limestones, reaching above local tree lines at about 2,000 m. The Foothills to the east are sandstones, shales and coals. Glacial deposits fill the river valleys and have been modified by 10,000 years of stream erosion. Among the hazards observed in 2013 in the mountains were rock falls, earth slides, and debris flows, as well as riverbank erosion, avulsion and overland flow. These posed threats to infrastructure, and in more than 350 cases resulted in damage. This project characterized the damage that occurred to roads and railways, and assessed the qualitative risk of the hazard in each case. Analysis of site reports showed that the greatest concern for highway corridors was debris flows. Of the hazards observed, they were the most numerous and most damaging. We assessed the risks associated by applying a risk template with measures of probability and consequence to each damaged site. The probability measure relates to temporal frequency, and is determined from historic events and data. The consequence measure records the severity of the damage by the hazard. Where available, this information was supplemented with historical records. These ratings can be used to develop a weighted risk map of the area and a prioritized list of sites at risk. This paper provides insights into the geotechnical impacts of a high return period rainfall and flood in similar mountain ranges to the Canadian Rockies.

Keywords: Rainfall, hazard, debris flow, Rocky Mountains, Alberta

1 INTRODUCTION

The western border of the province of Alberta, Canada trends north-westwards from the USA border (49°N latitude), west of the 114° longitude. The border follows the continental divide and the strike of the folded and faulted Palaeozoic sedimentary rocks that form the Canadian Rocky Mountains. The Rockies are a barrier to the eastward flow of moist Pacific air. A low-pressure zone is often trapped east of the mountains by higher pressure air moving up from the south. As the pressure builds, upslope weather develops (Gadd, 1995) and the moist Pacific air, forced to rise against the west side of the mountains, produces intense rainfalls or snowfalls.

1.1 Alberta and the Rocky Mountains

The Rocky Mountains are home to dangerous geotechnical hazards. The Frank Slide, for example, was a landslide that initiated the movement of 30 million cubic metres of limestone on Turtle Mountain and buried the coal mining settlement of Frank (Cruden and Martin, 2007). The 1903 Frank Slide is widely known, but there are other events that have affected the mountains, not least of which is the flood of 2013.

Alberta has experienced several notable floods; in recent years some of the largest on record have been observed. The event in 2013 came on the heels of the floods of 2005 and 2010, which affected the south-west and south-east of the province, respectively. Until 2013, these were the largest floods in memory.

1.2 The 2013 Flood

In June 2013, southern Alberta experienced a three-day heavy rainfall event. The flood that resulted affected residents, damaged infrastructure and altered the region's landscape. It was the most costly natural disaster in Canadian history (The Canadian Press, 2013), costing the provincial and federal governments more than 5 billion dollars for flood mitigation. In total, 120,000 residents were evacuated from flooded areas, 14,500 homes were damaged, and 4 Albertans were killed (Shaw Media, 2013; the Canadian Press, 2013). Transportation infrastructure was severely damaged, with highways and rail lines being among the most heavily impacted.

The problems began earlier in 2013, with heavy snowfall in the winter and cold temperatures that delayed snow pack melting in the spring. In early June, many areas in the province received rain, which left the ground saturated. These conditions helped to set the stage for the flood that would occur. A low-pressure storm front rolled into Alberta and stalled over the foothills of the Rocky Mountains in the south of the province. When the storm began, the rain-on-snow caused snow melting and excess runoff (Pomeroy, 2014).

Leading up to the 2013 storm, mitigation work and preparations were made for an event similar in scale to the 2005 flood. During that event, there was steady rain with 250 mm falling over the course of a month. In 2013, however, 325 mm of rain fell in just 3 days. Heavy, persistent rain began on June 19th, which in some areas amounted to more than 100 mm per day (Alberta Environment, 2013). By June 21st, flooding was widespread and impacted much of the southern part of the province; several communities declared local states of emergency. In the Rocky Mountains, the damage was particularly severe due to the extremely high incidence of geotechnical hazards (Skirrow, 2015).

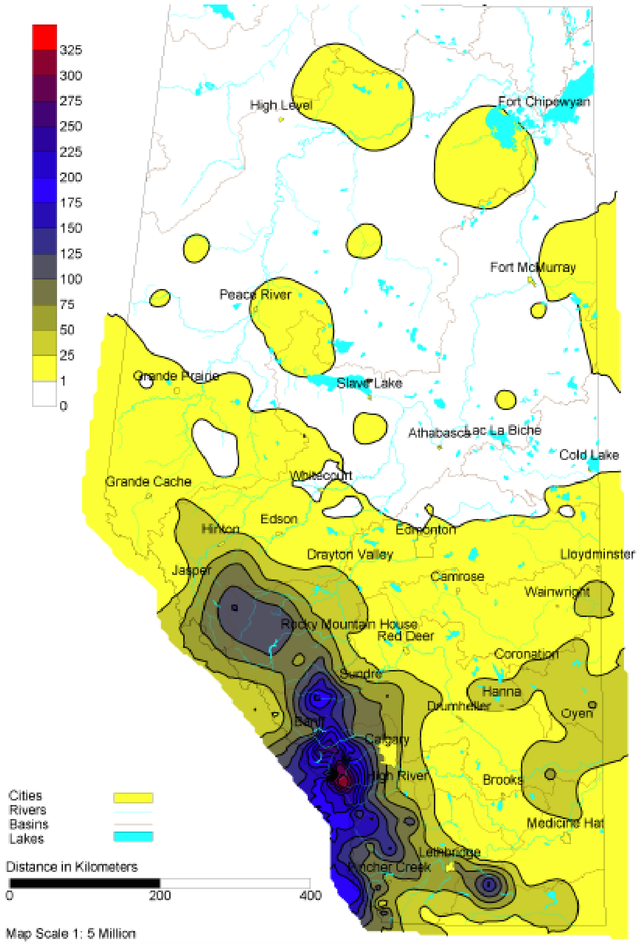

Figure 1 Alberta Precipitation Map for June 19 to 22, 2013 (Adapted from Alberta Environment, 2013)

Flooding was limited, for the most part, to the South Saskatchewan River Basin, which encompasses the Bow, Red Deer and Oldman Rivers, and their tributaries in the southern part of the province (Alberta Environment, 2013). Figure 1 shows the affected area, with the majority of the rain falling south of Red Deer (latitude 52.27°) to Pincher Creek (latitude 49.49°). The rainfall was centered in the mountains, which led to runoff and excess snowmelt into the streams that feed some of Alberta's major rivers. The surge from the mountains then travelled east and through many already waterlogged communities, causing extremely high flows and more damage. Among the most affected were the City of Calgary, and the towns of Canmore and High River.

The Bow River was flowing at 8 times its normal discharge by the time the surge reached the City of Calgary. The flows were approximately 3 times those experienced in 2005 (Government of Canada, 2015). Some areas, such as the community of High River, were particularly hard-hit, and experienced floods double their 100-year return period level (Government of Alberta, 2014). The government of Alberta has defined 100-year return period maps for most major watersheds. They are used for design and development approval purposes.

It is difficult to report on the historical magnitude of the flood. Reliable data extend over only 100 years, from the construction of the Canadian Pacific Railway. Flood frequency analysis and hazard studies have been completed for most watersheds in Alberta. These estimates, however, are based in almost all cases on less than 100 years of data. Many of the studies were completed in the 1980s, and do not include some of the more recent and largest floods on record. The current hazard assessment that defines the 100-year design threshold for the Bow River at the City of Calgary relies on data from 1879 to 1980. This period omits the floods of 2005 and 2013, 2 of the 11 major floods in Calgary's history (Calgary Public Library, 2014; Alberta Transportation, 2001).

It is possible that, due to climate change, the frequency of extreme rain events will increase in the coming years. In Alberta, significant development has taken place in flood-affected areas, and the province is vulnerable to damage from low magnitude floods as well. For this reason, defining design criteria on the basis of historical data may no longer be entirely reliable or practical. It may be necessary to evaluate whether the 100-year flood still provides a valid basis for design, and if so revisit standards to incorporate events as they occur (Skirrow, 2015). Many flood hazard assessments and maps are being revisited for Alberta's major waterways and communities, which will put the flood of 2013 into perspective.

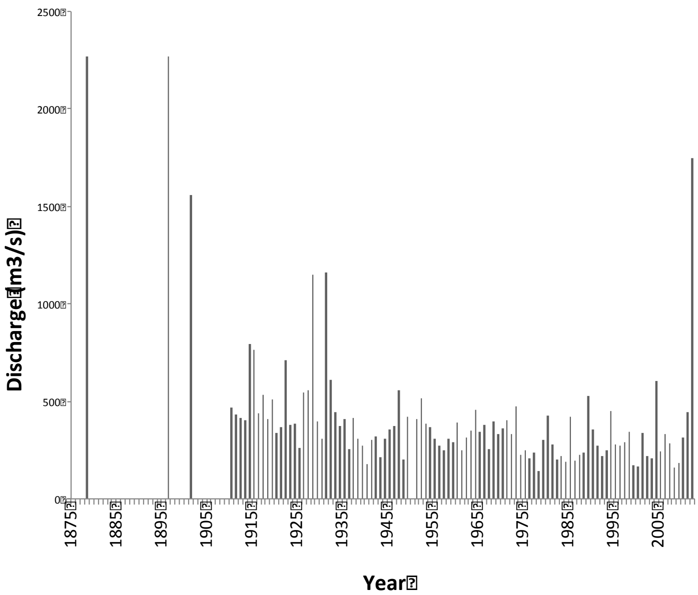

Figure 2 Compilation of historical hydrometric data for the Bow River at Calgary (Government of Canada 2015, Alberta Transportation 2001)

Based on the Calgary study currently in use (Alberta Environment, 1983), the flood was approximately a 70-year return period event. Historic data shows that three events of similar magnitude have been observed in the past 150 years, as can be seen in Figure 2. However, the severity of the event was not consistent throughout the affected area. While communities outside of the mountains may not have exceeded 100-year thresholds, in Canmore, the three-day rainfall had an estimated return period of up to 750 years (BGC, 2013; Alberta Environment, 2015).

2 ANALYSIS

In order to better understand the event, information was synthesized and compiled from available sources on the geotechnical and hydrological impacts to transportation infrastructure in the Rocky Mountains. For the purpose of the study, Alberta highway and rail corridors through the mountains were considered. Linear infrastructure of this type is inherently at risk of being impacted by hazards, and in the case of the 2013 flood both rail and highways suffered significant damage.

2.1 *Preliminary Analysis*

Information was compiled for rail and highway infrastructure from sources including the Alberta government's transportation department, independent geotechnical consultants, and Canadian Pacific (2015), a major railway operating in Canada and the United States. (Canadian Pacific, 2015; Government of Alberta, 2013; AMEC, 2013; BGC, 2013; Golder, 2013; KCB, 2013; Thurber, 2013).

2.1.1 *Alberta Transportation*

At the time of the floods in 2013, a large number of geotechnical hazards impacted the highways in the mountains. For disaster relief funding purposes, the Alberta government hired geotechnical consulting firms to document the damage. Five consulting firms were assigned highway corridors through the mountains, and all provided reports detailing the hazards and repairs that had taken place on their length of highway. Because the reports came from several sources, it was necessary to compile and normalize the information to quantify the event. We were interested in determining the types of events that had occurred, how many had taken place, and the damage and risk to each affected site.

Overall, there were 403 sites that had been affected by geotechnical and hydrological hazards on the 11 highway corridors considered. In going through the consultant reports (AMEC, 2013; BGC, 2013; Golder, 2013; KCB, 2013; Thurber, 2013), 8 categories of events were determined to have occurred. All of the affected sites could be assigned to one of the following categories:

- Bank erosion
- Culvert erosion
- Channel aggradation
- Debris flows
- Encroachment and avulsion
- Earth slides
- Overland flow erosion
- Rock falls

In addition to being categorized in this way, each site was rated on a scale from 1 to 4 based on its impact on the highway. Sites with a score of 1 would have eroded the asphalt or made the highway impassable, whereas a site with a score of 4 would not have resulted in damage or traffic disruption.

From this process, it was clear that debris flows were the most frequent hazard; 106 of the 403 reported sites were debris flows. In addition, 32 of 98 sites graded with a severity of 1, and 35 of 100 sites graded with a severity of 2 were debris flows, which indicated that they were also the most impactful hazard. It was decided that the focus of the analysis would be to examine the debris flows that affected highway corridors as a consequence of the 2013 floods.

Debris flows are landslides characterized by high ratios of debris to water. They occur most often in streambeds or channels, and are commonly initiated by shallow landslides in the source material. Debris floods are closely related to debris flows, differing in the water content accompanying the debris. (Jakob and Hungr, 2005). Until the floods of 2013, debris flows had been observed infrequently in the Front Ranges of the Rocky Mountains. Historically, Alberta highways have been affected by an average of one per year (Skirrow, 2015). Debris flows comparable in effects and magnitude to the 2013 hazards have been observed and studied, such as the event at Five Mile Creek in August, 1999 (Cullum-Kenyon et al., 2004). However, they were not common in the Front Ranges, and were not a major concern for the province until over 100 were triggered by this single rain event.

2.1.2 *Canadian Pacific*

Rail lines were also impacted by geotechnical hazards at the time of the floods. Emergency mitigation was undertaken by CP on their line to repair outages and re-establish service as quickly as possible. Detailed site records were not compiled. Information related to the damage sustained by the railway was gathered by conducting interviews with CP personnel. The damage was sustained for the most part through the mountains near Canmore, within the City of Calgary, and in the south of the province along the Sheep River (Canadian Pacific, 2015).

Several different hazard types affected the rail lines through Alberta and limited service. However, in contrast to highway infrastructure, it was not clear that one type in particular was the most damaging. One significant observed hazard was overland flow stemming from debris flows, which washed out tracks in several locations. In some cases, action was taken by CP to prevent damage to the track from hazards. Excavators were placed in channels that had become aggraded by debris flows to remove material and prevent the water from overtopping and washing out the tracks. Several bridge piers and abutments were damaged by scouring, and embankment failures left tracks hanging without support in some locations.

2.2 Secondary Analysis

Once the information was compiled from the various sources and evaluated, it was necessary to develop a format to concisely present the information for each site, and a method by which to determine the risk.

2.2.1 Alberta Transportation

A common condensed report format was developed for Alberta Transportation to present basic information about each site. The reports included risk scores by which the sites could be compared. The scores were based on a frequency-severity matrix for debris flows that was developed for the government of Alberta following the floods in 2005 (AMEC, 2006; Bidwell et al. 2010). This risk matrix is complementary to those used by Alberta Transportation to evaluate other types of geohazards. It is shown in Table 1.

Its application involves assigning a score to each site based on the consequence or damage caused by the event, and a score based on the probability of its occurrence. The product of these two factors is a risk score, which in this case can be used as a normalized measure across the reports completed by the consultants.

Table 1 Frequency-severity matrix for debris flows (AMEC 2006).

Probability Factor	
Weight	Description
1	Inactive, debris flow very improbable. No historical or current visual evidence of debris flow activity.
3	Inactive, debris flow improbable.
5	Inactive, remote probability of a debris flow based on channel morphology and presence of debris in the potential source zone.
7	Inactive, occasional debris flow; a debris flow has occurred in the historic past and/or debris buildup in the channel/source area is considered to be ongoing.
9	Debris accumulation normally present in the source area. Fan is considered to be active, with debris flows occurring after the melting of an exceptional snow accumulation or an exceptionally intense rainfall.
11	Active, one or two debris flows per year triggered by annually recurring weather conditions.
13	Active, several debris flows each year.
15	Active, frequent debris flows each year, the area producing debris flows is expanding.
20	Active, a large volume of debris is impounding a large and rising reservoir of water upstream. Overtopping and dam-break is expected.

Consequence Factor	
Weight	Description
1	Debris flow contained by the ditch or able to be conveyed past the road alignment via a sufficiently sized culvert or clear span bridge.
2	Debris flow onto roadway easily removable by maintenance crews. No damage to the road surface. Road closure not required and/or road still passable with reduced speed limit.
4	Partial closure of the road or significant detours would result from a debris flow. Debris flow onto roadway that requires partial closure of the road or significant detours while maintenance crew uses heavy equipment to clear debris and restore road surface. Damage to the road surface possible.
6	Complete closure of the road would result

	from debris flow while maintenance crew uses heavy equipment to clear the roadway and/or remove debris flow deposits lugging culvert or ditch. Geotechnical inspection required to assess post-debris flow stability of road fills. Damage to the road surface likely from debris flows.
8	Same as weighting of 6, along with damage to bridges, bridge accesses or other infrastructure facilities.
10	Sites where the safety of the public is threatened by debris flows, where there will be a loss of infrastructure facilities or privately owned structures if a debris flow occurs.

The risk scores allow the spatial frequency of high-risk sites to be evaluated. From this, highway corridors having overall elevated risk can be identified. The two highest risk sites affect Highway 1 (Trans-Canada Trail) and Highway 1A (Bow Valley Trail) within the Bow Valley corridor. The steep mountain creeks that pass through the communities of Exshaw and Canmore both experienced large and destructive debris flows that affected the nearby communities. This is shown in Figures 3 and 4. The towns are partially developed on alluvial fans, and debris flows and creek avulsion hazards in these locations pose risk to the communities.

The site that saw the most damage was the debris flow fan at Cougar Creek (Figure 4). The channel is active, and has experienced debris flows in the past. The banks of Cougar Creek are lined with homes, many of which were damaged by the flooding in 2013. Figure 5 shows the debris flow passing through Canmore. It blocked and overtopped a large box culvert at Highway 1, and impacted a rail embankment and the overpass at Highway 1A. The debris flow posed a risk to human safety, and damage was done to private homes in addition to other infrastructure. For these reasons, the site was classified as high risk, receiving an overall score of 90. This is the highest score assigned to any site in the 2013 floods. An equivalent score was also assigned to the debris flow at Exshaw Creek, and two instances of bridge collapses on the CP line. In all cases, the risk was classified as elevated because of the risk posed to human safety.

Numerous other potential and active debris flow channels exist through the Bow Valley corridor and adjacent Kananaskis area. The risk scores may provide insight for Alberta Transportation into which sites should be of highest concern. Identifying vulnerable areas that may experience debris flows in the future can guide preparation and mitigation. It may be possible to direct response to areas with sites that have the highest risk, and therefore are most likely to experience damaging hazards. To this end, Alberta Transportation is currently completing an engineering study to identify alluvial fans and river erosion issues along transportation corridors.

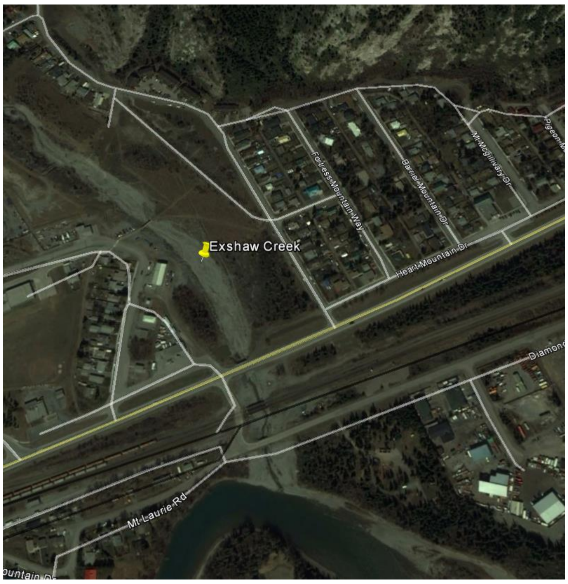

Figure 3 Exshaw Creek (Google, DigitalGlobe 2015)

Figure 4 Cougar Creek (Google, DigitalGlobe 2015)

Figure 5 Cougar Creek (Government of Alberta 2015)

2.2.2 Canadian Pacific

From the interviews conducted with CP personnel, information was collected about geohazards of all types that affected the rail lines. The study was not limited to debris flows. A separate reporting format was developed to compile information for the CP sites. It differs from the Alberta Transportation format by using information that is relevant to assess damage to rail. The effect of a hazard on a highway can be gathered by physical damage to the road surface, or presence of materials that make the highway impassable. The important measure for severity of railway impacts, however, is time out-of-service, which indicates the amount of time that trains were unable to move through a section of track due to a hazard.

The frequency-severity matrix was adapted to be applied to rail, taking into consideration the importance of time out-of-service. This matrix is shown in Table 2. It was used to establish consequence, probability, and thereby risk scores for each CP site. The rail risk scores are intended to be equivalent to those applied to highway sites, and should be comparable. However, the matrices rely on different assumptions and measures of what constitutes risk. The scores assigned to the CP sites were included in the reports, along with basic site information and accounts of the events obtained through the interviews.

Table 2 Frequency-severity matrix for geotechnical hazards affecting rail (AMEC 2006).

Probability Factor	
Weight	Description
1	Inactive, occurrence very improbable.
3	Inactive, occurrence or remobilization improbable.
5	Inactive, remote probability of remobilization, uncertainty level moderate, or active but very slow or indeterminate level of activity.
7	Inactive, high probability of remobilization or additional dangers, uncertainty level high, or… Active with perceptible movement rate and defined zones of movement/occurrence.
9	Active with moderate steady, or decreasing, rate of ongoing movement or occurrence.
11	Active with moderate but increasing rate of movement or occurrence.
13	Active with high rate of movement or occurrence, steady or increasing.
15	Active with high rate of movement or occurrence with additional hazards or dangers.
20	Catastrophic situation is occurring.

Consequence Factor	
Weight	Description
1	Hazard does not impact rail, no interruption to service, routine maintenance issue.
2	Hazard impacts rail, resulting in minor disruptions to service. Still able to run trains through at reduced speeds, or by using sidings.
4	Minor damage to rail resulting in disruption to service.
6	Major damage to rail resulting in disruption to service.
8	Major damage to rail and other infrastructure, e.g. bridge structures.
10	Issue presents potential consequences to public safety.

The cumulative time out-of-service for an area is an important consideration for the railway. Over a section of track, several outages may occur that all contribute to the service disruption. The individual effect that each hazard has may be difficult to isolate. A timeline was therefore developed to show when each site was out of service, and determine which hazard ultimately dictated the outage.

In general, hazards affecting track and slope stability were the most damaging. The sites that took the longest to repair and lead to prolonged service issues included washed out culverts, embankment failures, and severely scoured bridges.

All of the information for both rail and highway infrastructure was compiled into a single database, which maps all sites and information together to provide a complete picture of the flood's effects.

3 RECOMMENDATIONS AND FUTURE WORK

The government of Alberta intends to use a 300-year return period for design of debris flow mitigation projects, and 100-year return period for 'clearwater' flood projects. However, as previously mentioned, frequency analysis may be imprecise due to a lack of data, changes in climate, and other factors (Skirrow, 2015). It is possible that we are under-prepared and under-informed about extreme events. It is evident that a better understanding of Alberta's relationship with its changing climate and landscape is necessary in order to better prepare for the future.

To facilitate analysis of future events, a consistent reporting format could be developed for consultants evaluating geotechnical hazards. Including frequency-severity matrices, or a similar agreed upon risk measure, would allow sites to be accurately and consistently rated. In addition, developing agreed upon hazard classifications would make sites easily comparable and allow limited resources to be allocated to high-risk locations.

A challenge facing Alberta, as a relatively new province with little historical information, is that there are many unknowns related to mountain geotechnical hazards. In the interest of being able to prepare and respond to hazards in the future, it will be necessary to look further into the mechanisms, characteristics, and consequences of these events. Heavy rainfall and long, intense storms will likely become more frequent with climate change. Short of being able to predict events, examining the relationship between rainfall and geotechnical hazards can inform mitigation and response, and allow us to better understand the Rocky Mountains.

4 ACKNOWLEDGEMENTS

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5 REFERENCES

Alberta Environment (1983). City of Calgary Floodplain Study. Online at http://esrd.alberta.ca/water/programs-and-services/flood-hazard-identification-program/flood-hazard-studies/documents/Calgary-Bow.pdf [accessed January 2015].

Alberta Environment and Sustainable Resource Development (2015). Precipitation data June 19-23, 2013 [retrieved April 10, 2015]

Alberta Environment and Sustainable Ressource Development (2013). Precipitation map June 19-23, 2013 [retrieved January 2015].

Alberta Transportation (2001). Report on Six Case Studies of Flood Frequency Analyses. Online at http://www.transportation.alberta.ca/Content/doctype30/Production/ffasixcase.pdf [retrieved March 2015].

AMEC Earth and Environmental (2006). Geohazards review highway 40/highway 541 corridor southwestern Alberta.

AMEC Environment & Infrastructure (2013). Highway and geohazard assessments of June 2013 flood damage – Highways 940 (Forestry Trunk Road) and 532 (Kananaskis Country).

BGC Engineering (2013). Site inspection forms – Highways 1, 1A and Smith Dorrien/Spray Lakes Trail.

BGC Engineering (2013). Rainfall on June 19-21, 2013. Online at http://www.canmore.ca/About-Canmore/Flood/Mountain-Creek-Hazard-Mitigation.html [accessed January 2015].

Bidwell, A., Cruden, D.M., Skirrow, R., Dickson, R. (2010). Geohazard reviews of highway corridors through Mountainous and Foothills terrain, southwestern Alberta. Proceedings, 63rd Canadian Geotechnical Conference, Calgary, Alberta, 12-16 September 2010, pp. 855-861.

Canadian Pacific (2015). Personal Communication. May and June, 2015.

Calgary Public Library (2014). Calgary Flood Story. Online at http://floodstory.com/ [accessed February 2015].

Cruden, D.M., Martin, C.D. (2007). Before the Frank Slide, Canadian Geotechnical Journal, 44: 765-780

Cullum-Kenyon, S., Heinz, H.K., Sobkowicz, J.C. (2004). Assessment of debris flow hazard at Five Mile Creek. Proceedings, 57th Canadian Geotechnical Conference and 5th Joint CGS/IAH-CNC Conference, Quebec City, Quebec, 24-27 October 2004.

DigitalGlobe (2015). Google Earth captured images.

Gadd, B. (1995). Handbook of the Canadian Rockies, Corax Press, Jasper, Alberta, pp. 205-219, 831.

Golder Associates (2013). Geotechnical flood damage assessment – Highway 66, Highway 68, Powderface Trail and Bragg Creek Alberta.

Government of Alberta (2013). Alberta Transportation photographs of flood damage.

Government of Alberta (2014). Highwood River Basin – Diversion Project. Online at http://www.alberta.ca/highwood-river-basin.cfm [accessed April 2015].

Government of Canada (2015). Water Survey of Canada. Historical Hydrometric Data, City of Calgary [retrieved January 2015].

Klohn Crippen Berger (2013). Flood damage assessment – Highway 541. Summary of flood damage inspection notes.

M. Jakob and O. Hungr (2005). Debris-flow Hazards and Related Phenomena. Praxis. Springer Berlin pp. 9-21.

Pomeroy, J. (2014). Mountain hydrology related to the Alberta flood of 2013. CWRA Alberta Branch Annual Conference, March 2013.

Shaw Media (2013). By the numbers: 2013 Alberta floods. Online at http://globalnews.ca/news/673236/by-the-numbers-2013-alberta-floods/ [accessed January 2015].

Skirrow, R. (2015). Geotechnical considerations from the June 2013 southern Alberta flood. Proceedings, 2015 Conference of the Transportation Association of Canada, Charlottetown, P.E.I., 27-30 September 2015.

The Canadian Press (2013). Alberta floods costliest natural disaster in Canadian history. Online at http://www.cbc.ca/news/canada/calgary/alberta-floods-costliest-natural-disaster-in-canadian-history-1.1864599 [accessed January 2015].

The Canadian Press (2013). Alberta flooding statistics released, demonstrate severity of loss. Online at http://www.huffingtonpost.ca/2013/08/21/alberta-flooding-statistics_n_3787490.html [accessed January 2015].

Thurber Engineering Ltd (2013). Highway and geotechnical assessment of flood damage – highways 40:10/40:12 (Kananaskis Country).