Pavement Evaluation to Detect Potential Voids Under the Surface After the Historic Flood of June 2013 in the City of Calgary

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ABSTRACT

On June 20, 2013, The City of Calgary (The City) witnessed one of the worst floods in its known history. The flood was so devastating that about 100,000 people were evacuated from their residences. Public and private infrastructure suffered hundreds and hundreds of millions of dollars in damages. A state of local emergency (SOLE) was declared for 15 days.

Many roadways were washed out or had developed multiple sinkholes. The affected pavement network indicated about 250 sinkholes during only the time of SOLE. Some of the roadways were showing multiple sinkholes and it was believed that the flood water was flowing in channels under the pavement surface. This channelling may have created voids that collapsed with insufficient support for the material above. To demonstrate due diligence, The City decided to investigate the roads indicating multiple sinkholes for potential voids or other conditions that may not have surfaced yet.

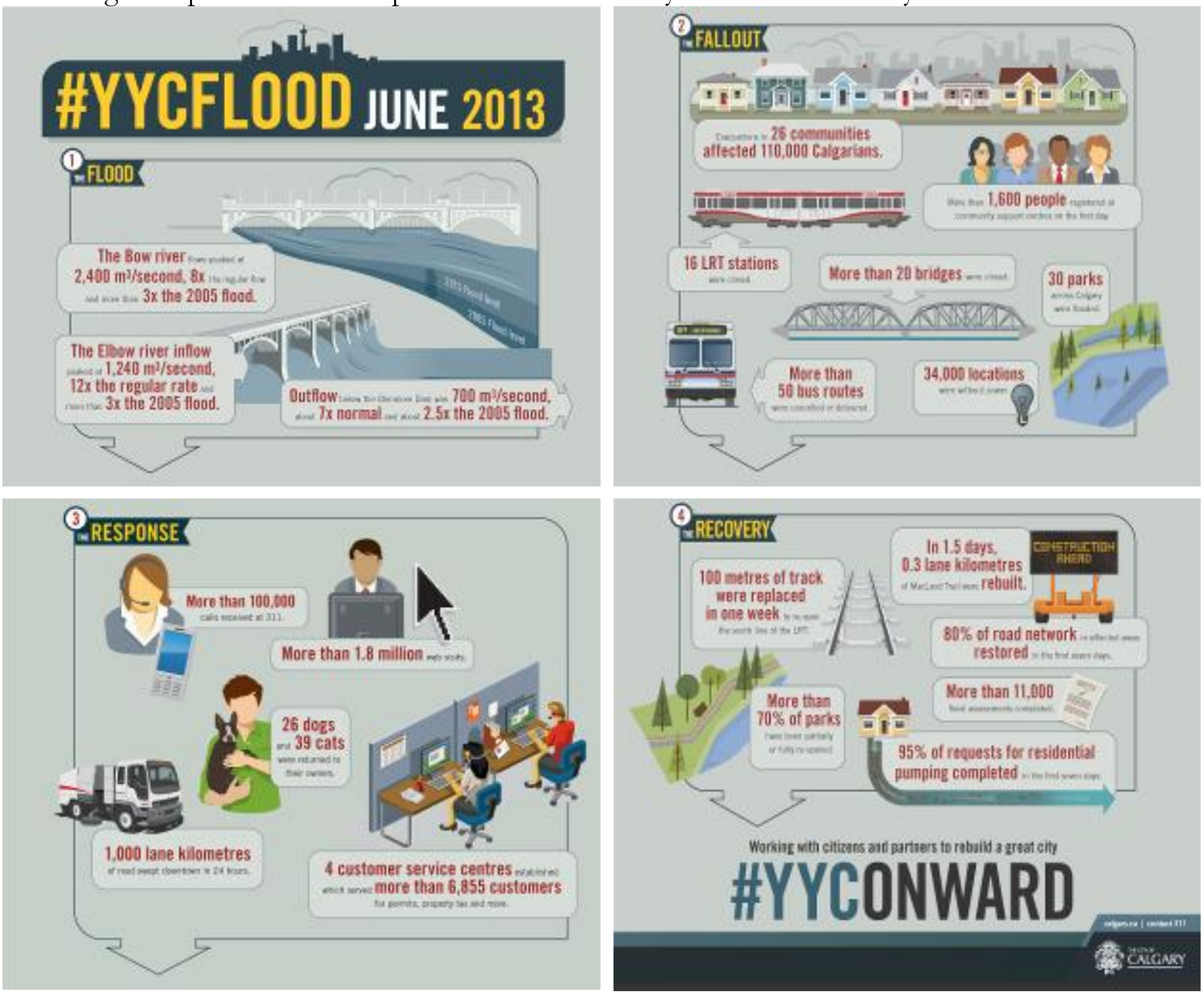
A pavement evaluation was conducted on affected portions of five roadways (MacLeod Trail, 1st Street SE,11 Avenue SE, 25 Avenue SW, and 38 Avenue SW) for the detection of potential voids under the pavements. A forensic non-destructive testing program utilizing Road Radar™ and Falling Weight Deflectometer (FWD) testing was developed. Two survey passes per lane, one in each wheelpath, was carried out. Anomalies underneath the pavement structure were identified with the Road Radar™ system.

The locations identified with anomalies were tested with FWD for further analysis. The spacing and location of the FWD tests were determined based on the severity, size, distribution and location of anomalies. Benchmarking criteria for the evaluation of the FWD deflections were established. All data was compiled into GIS that was used to reference all components of the data and aid analysis. This paper discusses the process of survey, Road Radar™ , FWD testing and analyses, a brief literature search, and developing deflection criteria and benchmarking. Conclusions and recommendations are presented at the end.

INTRODUCTION

On June 20, 2013, The City of Calgary (The City) witnessed one of the worst floods in its known history. The flood was so devastating that about 100,000 people were evacuated from their residences. Power, heating, gas-lines, internet and every other type of utility was out of order. Bridges, pavements, pathways, parks, zoo, Light Rail Transit (LRT), Transit Busses, buildings and houses suffered hundreds and hundreds of millions of dollars in damages. LRT tunnels, roadways, and underground parkades were filled with water. Fifty five million litres of water, equivalent to 22 Olympic sized pools, was pumped out of only one parkade [1]. A state of local emergency (SOLE) was declared for 15 days. A synopsis of the damages is given in info-graphs on the next page. A few photos of the damages are also presented.

Many roadways were washed out or showing multiple sinkholes. The affected pavement network indicated about 250 sinkholes during only the time of SOLE. Some of the roadways were showing multiple sinkholes and it was believed that the flood water was flowing in channels under the pavement surface. This channelling may have created voids that collapsed with insufficient support for the material above. To demonstrate due diligence, The City decided to investigate the roads indicating multiple sinkholes for potential voids that may not have surfaced yet.



Washed out portion of Macleod Tr. at Victoria Bridge

Undermined Sidewalk at 1st St. SE and 15 Ave. intersection

BACKGROUND

The week of June 17th, 2013 began like any other week for the population of Southern Alberta. But by Friday June 21st, a day we usually associate with the beginning of summer, what happened with the weather became a footnote of provincial history. Both the Bow and Elbow Rivers spilled so much water that it converted into a historic flood. Seventy-three communities were affected that flooded about 33,600,000 m^2 area and forced close to 100,000 people leave their homes. Figure 1 presents some communities flooded in 2013.

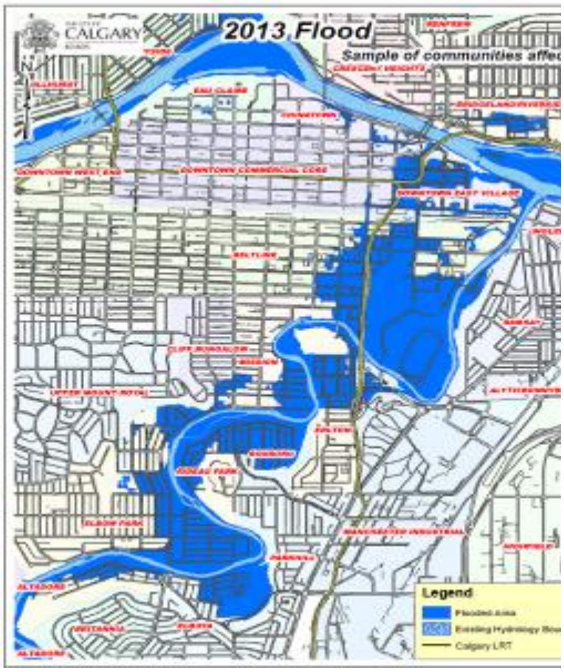


Figure 1: Sample of Flooded communities

Figure 2: Hourly Increase in Water Level Through Bow River During Flood

Figure 2 indicates the hourly increase in flow of water through the Bow River at Calgary. At its peak, The Bow River, according to Alberta Environment [3], was estimated to be flowing at 1,740m^3/sec . That's about 100 million liters of water rushing past every minute; more than twice as much water as the 2005 floods. The City has reported 2,400 m^3/sec flow through the Bow River, which is 2.5 times more than the 2005 flood.

This has left many living in the city's floodplains wondering: Could this happen again? And how often do floods of this magnitude happen in the area? Could it have been worse?

To answer those questions, we need to look at the past. Continuous water flow records of the Bow River in Calgary began in 1911. Before the 2013 flood, the highest recorded instantaneous flow level was 1,520 m^3/sec, set in 1932. In other words, the 2013 flood's peak water flow of 1,740 m^3/sec was the highest in the City's recorded history.

Although continuous records began in 1911, Calgary's earlier history unearths some of the City's worst floods. Three major floods occurred in the decades prior to 1911. And in fact, until this year, Calgary's eight worst floods in history had all occurred before 1932. Figure 3 summarizes the history of floods for the Bow River in Calgary. It is clear that the 2013 flood was the worst in the known history. One hundred and sixteen years ago an approximately similar magnitude of this event had occurred. No living person has ever seen the flood of this magnitude in his or her life ever.

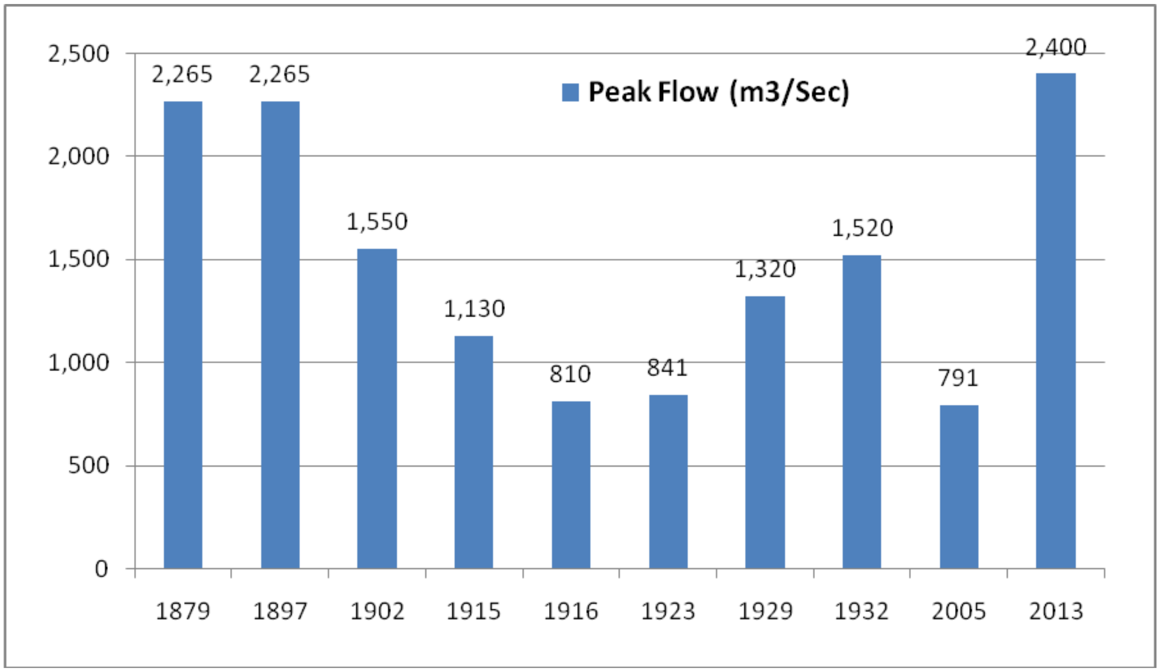


Figure 3: Peak Flow through the Bow River in Calgary during the Historic Floods.

Two floods in particular, the 1879 and 1897 were unprecedented, with river flows 50 percent higher than the 1932 flood event. Best estimates put each of those two floods at about 6 per cent lower than the 2013's devastating flood.

EVALUATION OF PAVEMENTS AFFECTED BY FLOOD

As noted previously, many roadways were washed out or were showing multiple sinkholes after the flood (Note that "sinkholes" as referred to in this paper are areas of loss of underlying support of the pavement surface resulting in significant settlement or failure of the pavement surface). The affected pavement network indicated about 250 sinkholes during only the time of State of Emergency. Figure 4 shows a zoomed in view of some of the areas where sinkholes had developed. Some of the roadways were showing multiple sinkholes and it was believed that the flood water was flowing in channels under the pavement surface. This channelling may have created voids that collapsed with insufficient support for the material above.

To demonstrate due diligence, The City decided to investigate the roads exhibiting multiple sinkholes for potential voids that may not have surfaced. Tetra Tech EBA Inc. (Tetra Tech) was retained to investigate the following roadway segments:

- Macleod Trail SE (Northbound) – 25 Avenue SE to 9 Avenue SE;
- 1 Street SE (Southbound) – 9 Avenue SE to 25 Avenue SE;
- 11 Avenue SE – 4 Street SE to 6 Street SE;
- 25 Avenue SW – Macleod Trail S to 5 Street SW; and
- 38 Avenue SW – 8A Street to Edison Crescent.

These roadway segments are shown in Figure 5.

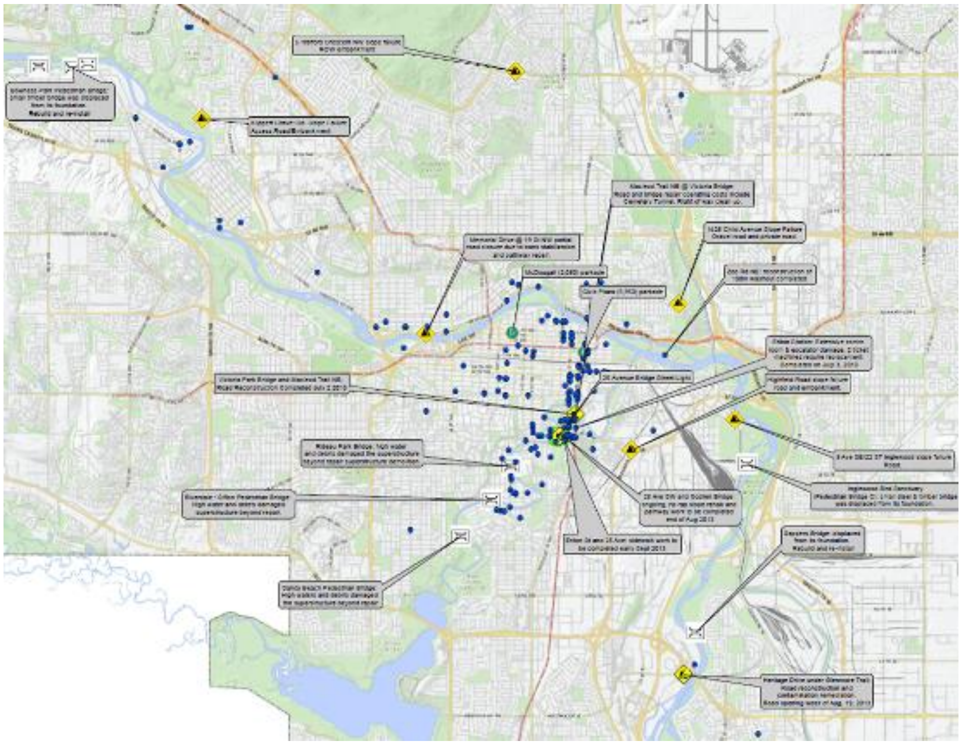


Figure 4: Majority of the Sinkhole Locations Developed During the 2013 Flood in the City of Calgary

Figure 5: Roadway Segments Included in the Evaluation

For the purposes of this evaluation, a void was defined as an opening, filled with air or water, that exists below and is bridged by the asphalt concrete layer, and was caused by a recent flood event, and which has resulted in one of the two conditions:

- Moving water has eroded and removed granular materials in the pavement structure; or
- Moving water has eroded and removed near surface (within 1.5 m of the pavement surface) subgrade material beneath the pavement structure.

METHODOLOGY

The following methodology was developed to complete this evaluation:

- Review of background information;
- Visual condition survey to observe the post flood conditions of the pavements and sidewalks;
- Comparison of the pre-flood Google Earth (trademark) images;
- Evaluation of the roadway segments to identify potential locations of anomalies / shallow voids underneath the pavement surface utilizing Road Radar™ technology;
- Pavement strength testing at select locations to determine pavement weaknesses at locations with apparent anomalies underneath the pavement surface (as indicated by the Road Radar™ survey) utilizing a Falling Weight Deflectometer (FWD);
- Analysis of the collected data to determine the impact of flooding on the pavement structure;
- Review of the collected and analysed data to determine the potential impact of the flooding event on the expected service life of the pavement structures; and
- Recommendations regarding pavement rehabilitation strategies where warranted.

All relevant data was compiled into a project Geographic Information System (GIS) that was used to geographically locate and spatially reference all components of the data collection for each roadway section. The GIS provided an environment to warehouse, visualize, analyze, interpret, and understand data to reveal patterns, relationships, and trends.

1. REVIEW OF BACKGROUND INFORMATION

1.1 Literature Search

A limited literature search was carried out to identify any recent publications or research related to void detection under pavements using GPR or FWD technologies. All of the information available/reviewed related only to void detection under Portland Cement Concrete slabs due to temperature effects and nothing was available for void detection under asphalt concrete pavements.

1.2 Sinkhole Location Map

A review of the sinkhole location map shown in Figure 4 indicates that although the sinkholes developed throughout the City's road network, they were concentrated within the road segments identified for detailed investigations.

1.3 Preliminary Site Reconnaissance and Post Flood Photographs

A post flood site reconnaissance was carried out in September 2013 to observe the existing condition of the pavement surface and predominant distresses exhibited by the roadway infrastructure. The existing condition of the roadway infrastructure was compared with the condition of the infrastructure prior to the flooding event utilizing Google Earth images. A few photographs comparing the pre flooding and post flooding condition of the roadway infrastructure at a few select locations are presented below.

Cracked sidewalk along 25th Ave. SE, West of 1st St SW (Post Flooding)

Pre flooding image acquired from Google Earth Pro dated May 2012 with no signs of any cracking

Distressed pavement along 25th Ave S, East of 1st St SW, South side of the road.

Imagery acquired from Google Earth Pro. Image dated May 2012. Distress free pavement surface.

The photos above clearly indicate the damage caused to the roadway infrastructure by the flooding event.

1.4 Review of Pavement Condition Data

Most of the roadway segments included in the investigations were either paved just before the flood or in the past few years. Table 1 summarizes the condition of the roadway segments.

Table1: Pavement Condition Data

Street	Roadway Classification	From	To	Year Last Paved	Pre Flood		Post Flood	
					IRI (mm/m)	PQI[1]	IRI (mm/m)	PQI[1]
Macleod Tr. SE	Arterial	25 Ave. SE	9 Ave. SE	2013	1.50[2]	9.00[2]	4.06	6.91
1st St. SE	Arterial	9 Ave. SE	25 Ave. SE	2013	1.50[2]	9.00[2]	3.90	6.53
11 Ave. SE	Industrial / Collector	4 St. SE	6 ST. SE	2012	1.70[2]	9.50[2]	4.43	7.45
25 Ave. SW	Industrial / Collector	Macleod Tr.	5 St. SW	2011	1.80[2]	9.00[2]	-	-
38 Ave. SW	Local	8A St. SW	Edison Cr.	1992	6.27	5.31	-	-

[1]PQI or Pavement Quality Index is a composite index that takes into consideration the ride quality, structural adequacy as well as visual condition of the pavement. It ranges at a scale of 0 for a completely failed pavement to 10 for a pavement in perfect condition.
[2] Assumed value based on the age of the pavement and local experience.

Review of the information summarized in Table 1 indicates that all of the roadway segments included in this study had recent surfacing (2 years old or less) with the exception of 38 Ave. SW, which is a local residential road and was last paved in 1992.

Review of the City's Construction Specifications indicates that the average Lot or Partial Lot MIRI (Mean International Roughness Index) shall not exceed 2.50 mm/m and 2.90 mm/m for 'A' and 'B' Major Roads respectively. Although the smoothness data for the roadway segments at the completion of paving was not available, the post flood smoothness data collected by the City indicate very high IRI values (representing a rough road with poor ride quality).

Review of the post flood average PQI for the segments of Macleod Trail, 1st St. SE and 11 Ave. SE indicate relatively significant deterioration in the condition of the pavement surface than would be normally expected of a pavement surface that is less than a year old.

2. Road Radar™ DATA COLLECTION

Road Radar™ System is a hybrid ground penetrating radar system optimized for non-destructive substructure investigations. The system attains both non-destructive accuracy and high resolution by incorporating a dual radar configuration. A high-resolution air-launch radar system (2.5 GHz) provides thin layer resolution, typically allowing unambiguous resolution of structural layers as thin as 40 mm. A second surface-coupled array radar system (1.1 GHz), maintained in contact with the road surface, provides signal velocity (dielectric) measurements for each radar sample, as well as the ability to typically resolve structural layers up to 1.5 m below surface.

The Road Radar™ surveys were conducted on September 26 and 27, 2013 between 9 P.M and 6 A.M. owing to the high traffic volumes on these road sections during the day.
All distances were measured using a commercial distance-measuring device connected to the vehicle transmission. Each project was linearly referenced with Station 0 established at the western project limit for 11 Ave SE, 25 Ave SE and 38 Ave SE. Similarly Station 0 was established at the southern project limit for MacLeod Trail SE (intersection with 25 Ave SE) and at northern project limit for 1 St SE (intersection with 9 Ave SE). The radar surveys were completed with the radar system

programmed to acquire data at a longitudinal sampling interval of 0.09 m. This sampling interval resulted in over 1,000 samples collected per 100 m surveyed.

The radar information collected allowed the non-destructive identification of anomalous areas below the surface of the roadway. For this project, structural layer measurements from the radar information were not required.

The surveys were conducted in each wheelpath of each travel lane of the roadway segments under review.

2.1 Road Radar™ Signatures Overview

Radar signatures constitute those identifiable characteristic features of radar reflections, which allow the classification of subsurface relevant conditions and anomalies when presented with graphical radar data. An overview is given here to address those signatures that may be considered common:

When examining radar information, the boundary between dissimilar materials produce horizontal multi-coloured bands as indicated in Figure 6. For the Road Radar™ system, these signatures consist of three bands of opposite colour (black, copper black or copper black copper). The intensity of the band colours is indicative of the signal strength, which reflects a relative measure of the adjacent layer material dielectric contrast (very dissimilar materials produce strong contrasts).

High intensity locations within the radar data were identified as anomalous events. Based on the measured signal strength, the high signal strength arises from a strong dissimilarity between the materials at the boundary. Based on the intensity measured at the ACP/Base boundary, five anomaly severity levels were established:

- Unclassified (i.e. no indication of "abnormality")
- Wet
- Low severity anomaly
- Medium severity anomaly
- High severity anomaly

Wet areas were locations along the ACP / base boundary with high signal intensity. The Low, Medium, and High severity anomalies had increased levels of signal intensity respectively along with abnormal radar characteristics that may be indicative of a distressed ACP / base boundary. These locations in the radar data may be associated with air or water filled voids where the fine base materials have washed away due to the flooding.

Figure 6 shows, for a localized area of Macleod Trail SE , wet areas identified in light blue, and a low severity anomaly approximately at 945 m in light green. Figure 7 identifies the same section of data in the anomaly plan map. Anomaly Plan Maps for all five roadway segments surveyed were prepared.

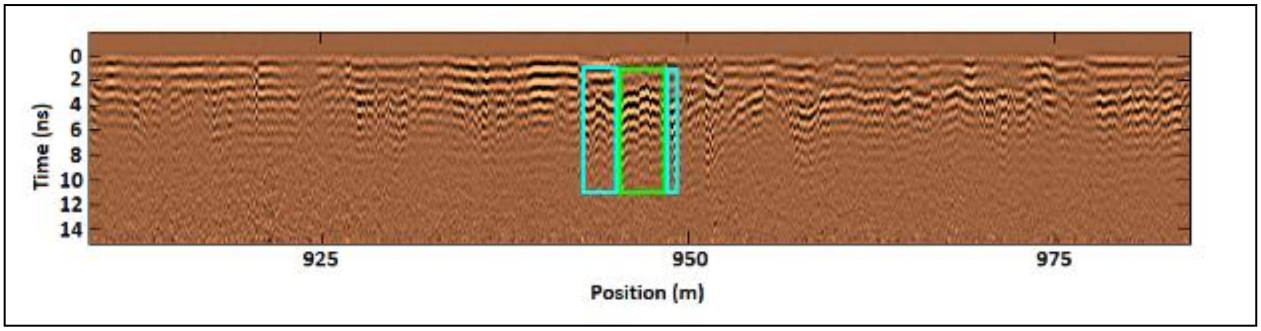


Figure 6: Radar Samples Annotated with Anomalies – Wet and Low Severity

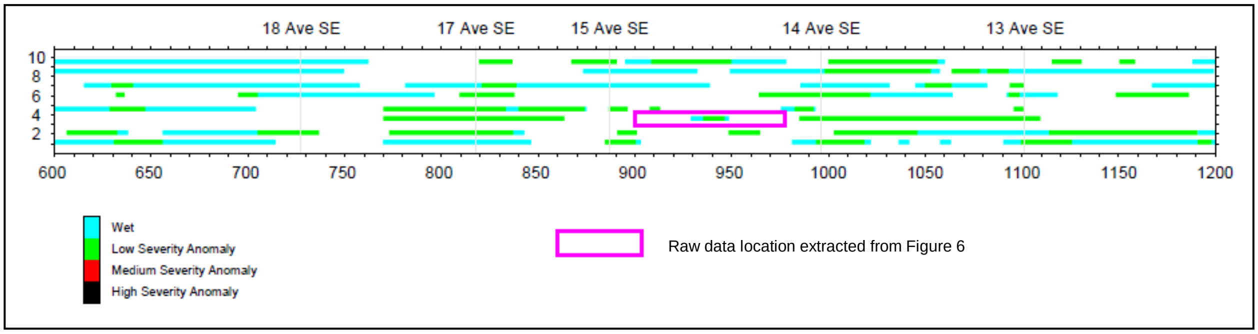


Figure 7: Plan Map View of Macleod Trail SE with Highlighted Section from Figure 6 Identified

3. FALLING WEIGHT DEFLECTOMETER (FWD) DATA COLLECTION

Select areas from the Road Radar™ analysis were identified for deflection testing by FWD. FWD test locations were selected based on the reported severity and density of subsurface anomalies. Test location spacing was determined as to provide a high resolution surface deflection profile for each of the areas selected. In most cases, FWD testing was completed in 10 or 20 m intervals in both wheel paths of each lane evaluated. It was the intent of the FWD testing program to collect pavement surface deflection for all classifications of sub-surface anomalies for each roadway section.

It should be noted that there are no specific industry recognized procedures correlating FWD deflection data with shallow void detection under flexible pavement structures. However, it is possible to identify localized areas of uncharacteristically large surface deflections which could be associated with a weakening pavement structure, possibly attributed to by the presence of subsurface voids. It was the objective of this assignment to correlate any such test locations with the anomalous areas reported from the Road Radar™ data collection and analysis. It would be expected that areas reported as potential void candidates that exhibited relatively large surface deflections would be classified as possible areas with some level of sub-surface shallow voids. Conversely, if surface deflections were found to be "typical" for a subject road segment, then it would be considered unlikely that significant sub-surface voids were present.
Based on a detailed review of the locations and distribution of the various anomalous events identified through the analysis of the Road Radar™ surveys, specific sites within each project roadway segment were identified for more intensive FWD testing and analysis:

Site 1–1, Macleod Trail SE, Station 770 to 920, Lanes 1 and 2.
Site 1–2, Macleod Trail SE, Station 960 to 1130, Lanes 3 and 4.
Site 1–3, Macleod Trail SE, Station 990 to 1200, Lane 1.
Site 1–4, Macleod Trail SE, Station 1300 to 1420, Lanes 1 and 4.
Site 2–1, 1 St. SE, Station 240 to 280, Lanes 1 and 4.
Site 2–2, 1 St. SE, Station 470 to 560, Lanes 1 and 2.
Site 2–3, 1 St. SE, Station 600 to 850, Lane 4.
Site 3–1, 11 Ave SE, Station 60 to 150, EB and WB.
Site 4–1, 25 Ave SE, Station 300 to 400, EB and WB.
Site 4–2, 25 Ave SE, Station 700 to 860, EB.
Site 5–1, 38 Ave SE, Station 300 to 560, EB and WB.

The locations of all the above sites are shown in Figure 8.

The FWD testing was conducted over two nights: October 30/31 and October 31/November 1, 2013. Tests were completed in both wheel paths (right wheel path and left wheel path facing the direction of traffic) of each lane at 10 or 20 m spacing at all the selected sites.

4. SUMMARY OF ANALYSIS AND DISCUSSION OF THE Road Radar™ AND FWD DATA

The general procedure followed for summarizing and reviewing the FWD deflection results for each roadway segment was as follows:

i. Normalized the 3-drop (targeting 40kN) central load deflection to 40kN – the standard load applied under the tire of one Equivalent Single Axle Load (ESAL).
ii. Temperature corrected each normalized deflection from reported ambient temperature to standard temperature of 20°C.
iii. For each project roadway segment:
    a. Reviewed each test location for "outliers", or test locations with "atypical" reported deflections.
    b. Visually examined all individual deflection bowls for uncharacteristic shapes.
iv. For each site:
    a. Summarized and reviewed FWD deflection results for each lane and line (wheel path) tested.
    b. Summarized and reviewed FWD deflection results for each reported severity classification.
    c. Determined the statistical minimum, maximum, average, standard deviation, and 95% confidence interval upper endpoint (average plus two standard deviations) of normalized deflection for each lane and line (wheel path) tested.
    d. Reviewed deflection data for possible correlations to reported anomaly type (i.e. did higher severity anomalies correspond to areas of higher deflection?).
    e. Reviewed deflection data for possible differences between reported anomaly types and control (i.e. unclassified) sections.

Examples of the analysis for Site 2-2 1st St SE and Site 5-1 38th Ave SE are shown on Figure 7.

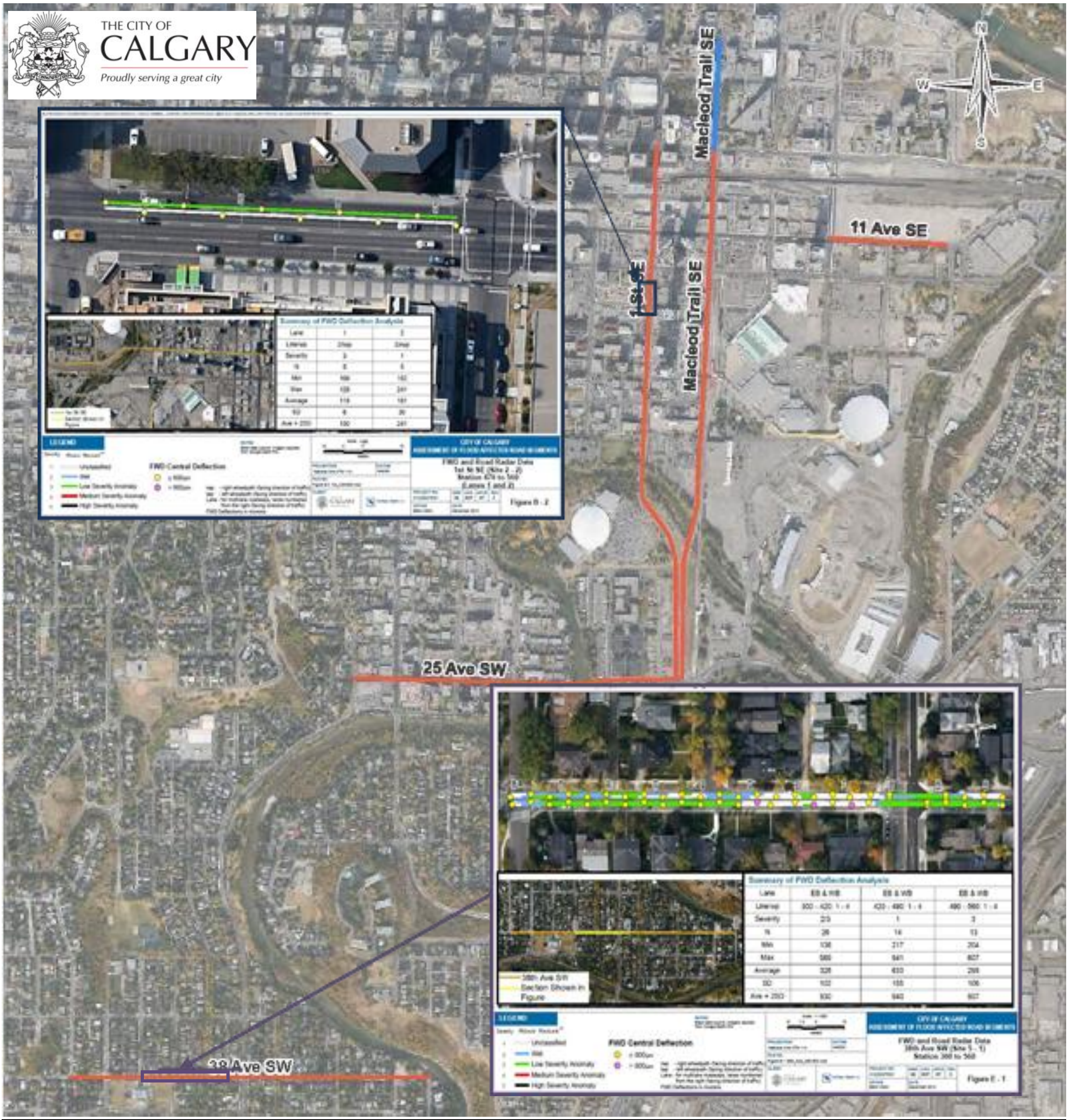


Figure 8: Location of FWD and Road Radar™ Test Sites (with Site 2-2 nd Site 5-1 shown as examples)

The reported normalized deflections and corresponding statistics were evaluated on the following benchmark:

- Reported normalized deflections <500 μm – insignificant.
- Reported normalized deflections between 500-800 μm – typical for roadways of the classification and serviceability of the 5 roads segments evaluated exhibiting a structural deficiency <50 mm for 5 – 10 million Design ESALs.

- Reported normalized deflections between 800-1000 μm – typical for roadways of the classification and serviceability of the 5 roads segments evaluated (requiring structural overlay of 50 mm for design traffic of 5 to 10 million ESALs).
- Reported normalized deflections>1000 μm – representative of a weakened pavement structure for roadways of the classification and serviceability of the 5 roads segments evaluated (requiring structural overlays > 50 mm for 5 to 10 million ESALs).
- This analysis of the central deflection is representative of the overall pavement/subgrade stiffness.

All the eleven sites identified for detailed FWD testing were analyzed closely. A summary of the analysis results from FWD and Road Radar™ data was prepared and is presented in Table 2. A review of this Table indicates that all but one site had only three categories of anomalies, i.e., wet, unclassified or low severity. Only one site (11th Ave SE) had one location of a medium severity anomaly. None of the sites indicated any high severity anomalies. Conclusions from all eleven sites were similar and are summarized in the following bullets:

- No discernable pattern or correlation of the reported anomalies and FWD
- The reported deflections were considered reasonable
- No conclusive evidence of the presence of shallow sub-surface voids

5. SUMMARY OF FINDINGS

i. Review of the observations made during the site reconnaissance was indicative of significant damage caused to the pavement infrastructure by the flooding event. Comparison of the photographs taken after the flooding event with the Google Earth Images from before the flooding event (as included in Section 1.3) clearly indicate that a number of distresses developed after the floods.

ii. Review of the photographs taken during the flood event showed the extent of the damage caused by the flood to the roadway infrastructure. The majority of the damage captured in the photographs was repaired prior to the site reconnaissance completed in September 2013.

iii. Observations made during the visual condition survey completed on March 12th and 13th, 2014 (after first winter season following the floods) indicated that the ride quality was very rough along the project road segments. Some of the pavement sections along 38 Street SW, 11 Avenue SE and 25 Avenue SW were exhibiting a pavement condition which had significantly deteriorated since the site reconnaissance completed in September 2013 and some newer distresses that weren't witnessed previously. These included new cracks, settlement of patches, separation of the asphalt concrete pavement from concrete gutter etc.

iv. The Road Radar™ was used to provide a continuous survey of both wheel paths of each lane for each of the five project roadway segments. This allowed for use of non destructive testing (NDT) to identify potential anomalies in the pavement structure and subgrade to about 1.5m below the pavement surface.

   Based on the review of the analyzed data from the Road Radar™, the majority of the areas were categorized as unclassified (no indication of "abnormality"), wet or with low severity anomalies. Only a couple of locations along 11 Avenue SE were identified as having medium severity anomalies and no areas were identified with high severity anomalies along the project roadway segments.

Table 2: Road Radar™ and FWD Data Analysis and Summary of the Areas Showing Anomalies

Roadway	From	To	Lane*	Length	Anomalies by Severity from Road Radar™	No of FWD tests	Deflection Range	Ave + 2SD	Summary
MacLeod Tr.	S. of 17 Ave	N of 15 Ave	1 & 2	150 m	Unclassified, wet, low severity	32	90-500 µm	346 µm	• no discernable pattern or correlation of the reported anomalies and FWD • the reported deflections are considered reasonable • no conclusive evidence of the presence of shallow sub-surface voids
MacLeod Tr.	S. of 14 Ave	N of 13 Ave	3 & 4	170 m	Unclassified, wet, low severity	36	156-809 µm	546 µm	• no discernable pattern of correlation of the reported anomalies and FWD • the reported deflections are considered reasonable • no conclusive evidence of the presence of shallow sub-surface voids
MacLeod Tr.	S. of 14 Ave	N of 12 Ave	1	210 m	Unclassified, wet, low severity	22	73-876 µm	722 µm	• no discernable pattern of correlation of the reported anomalies and FWD • the reported deflections are considered reasonable • no conclusive evidence of the presence of shallow sub-surface voids
MacLeod Tr.	11 Ave	10 Ave	All 4	120 m	Unclassified, wet, low severity	46	90-500 µm	673 µm	• no discernable pattern of correlation of the reported anomalies and FWD • the reported deflections are considered reasonable • no conclusive evidence of the presence of shallow sub-surface voids
1 Street SE	N of 11 Ave	S of 11 Ave	All 4	40 m	Unclassified, wet, low severity	39	82-489 µm	409 µm	• no discernable pattern of correlation of the reported anomalies and FWD • the reported deflections are considered reasonable • no conclusive evidence of the presence of shallow sub-surface voids
1 Street SE	14 Ave	13 Ave	1 & 2	90 m	Unclassified, low severity	10	108-241 µm	181 µm	• no discernable pattern of correlation of the reported anomalies and FWD • the reported deflections are considered reasonable • no conclusive evidence of the presence of shallow sub-surface voids
1 Street SE	N of 13 Ave	S of 18 Ave	4	250 m	Unclassified, wet, low severity	25	109-462 µm	432 µm	• no discernable pattern of correlation of the reported anomalies and FWD • the reported deflections are considered reasonable • no conclusive evidence of the presence of shallow sub-surface voids
11 Ave SE	E of 5 St	W of 5 St	both	90 m	Unclassified, wet, low severity, and medium severity	38	103-523 µm	326 µm	• no discernable pattern of correlation of the reported anomalies and FWD • the reported deflections are considered reasonable • no conclusive evidence of the presence of shallow sub-surface voids
25 Ave SW	2 St	E of 2 St	both	100 m	Unclassified, wet, low severity	43	191-792 µm	607 µm	• no discernable pattern of correlation of the reported anomalies and FWD • the reported deflections are considered reasonable • no conclusive evidence of the presence of shallow sub-surface voids
25 Ave SW	Bridge	Erlton Road	EB	160 m	Unclassified, wet, low severity	30	127-263 µm	260 µm	• no discernable pattern of correlation of the reported anomalies and FWD • the reported deflections are considered reasonable • no conclusive evidence of the presence of shallow sub-surface voids
38 Ave SW	7 St	E of Elbow Dr	both	260 m	Unclassified, wet, low severity	53	138-941 µm	633 µm	• no discernable pattern of correlation of the reported anomalies and FWD • the reported deflections are considered reasonable • no conclusive evidence of the presence of shallow sub-surface voids

*Lane number starting from left to right in the travel direction

v. FWD testing was completed on selected sites with the expectation that a shallow void in the pavement structure or subgrade below the asphalt concrete layer and bridged by the asphalt concrete layer, would have resulted in a significant measured surface deflection when tested with the FWD.
Observed deflections for all project roadways were generally low. Based on experience, measured deflections of less than 500 μm are considered insignificant and measured deflections between 500 and 800 μm are considered low. Individual deflections around 800 – 1000 μm would typically suggest a 50 mm strengthening deficiency for design ESALs ranging from 5-10 million.
vi. There was no discernable correlation between Road Radar™ reported anomaly severity levels and surface deflection as measured by the FWD. However, with the exception of a few isolated locations, the measured deflections were considered to be negligible or very low.
vii. Based on the comparison of the re-processed 2005 Road Radar™ data from Site 6 (Macleod Trail SE, 9 Ave to 6 Ave), the wet severity levels identified for the five project roadway segments in the 2013 study may be indicative of roadways that were subjected to flooding.

6. CONCLUSIONS

i. **Extensive Damage to Roadway Infrastructure:** Based on the observations made during the site visit, visual condition survey, review of the photographs and comparison of the pre-flood and post-flood photographs, it is evident that significant damage was caused to the roadway infrastructure (pavements, curb and gutters and sidewalks) along the project roadway segments.

ii. **Deterioration in Ride Quality:** Review of the post flood smoothness data indicated that the roads just paved the same year or during the last one or two years had significant deterioration in the ride quality. The measured post flood IRI's are significantly higher than the maximum allowable mean IRI of 2.50 and 2.90 mm/m for 'A' and 'B' Major Roads as per Section 307.00 of City's Road Construction [4]. Even if it is assumed that the pavements were paved meeting the maximum allowed smoothness requirements, it is evident that the pavement condition has significantly deteriorated within a short duration and it is expected that the City will need to complete rehabilitation intervention treatments within the next few years.

iii. **Need for Premature Rehabilitation Intervention:** The City utilizes Pavement Quality Index (PQI) as a trigger value to determine the rehabilitation needs of the pavement surface. The trigger values used by the City are 6.0, 5.0 and 4.0 for Arterial, Industrial/Collector and Residential streets respectively. PQI values of 6.91 and 6.53 were calculated for the project segments of Macleod Tr. SE and 1 St. SE respectively, which is very close to the trigger value of 6.0 for Arterial streets. Considering that the roadway segments were last rehabilitated in 2013, rehabilitation intervention will be needed earlier than expected (within a few years).

iv. **Presence of Moisture in Pavement Structure:** Review of the Road Radar™ data collected for the project roadway segments indicated large areas as wet. Review of the re-processed 2005 data collected along Macleod Tr. SE didn't provide any evidence of wet areas. This confirms the presence of moisture in the pavement structure, which in combination with freeze-thaw cycles, will result in the reduced service life and need for rehabilitation treatment earlier than typically warranted.

v. **City's Roads Construction Standard Specifications (2012):** In accordance with the Section 304.07.00 of the City's 2012 Standard Specifications, any road which is paved during the last two years, or has a Visual Condition Index (VCI) of 7.0 or more and is excavated for some repair, is subject to a surface restoration fee in the form of minimum 50 mm mill and inlay. Based on the above, the project roadway segments of Macleod Tr. SE (paved in 2013), 1 St. SE (paved in 2013), 11 Ave SE (paved in 2012) and 25 Ave. SW (paved in 2011) would need surface restoration based on the repairs taken place in response to flood related pavement distress.

vi. **Damage to Non-Pavement Surface Infrastructure:** Observations made during the site reconnaissance and review of the photographs indicated extensive damage to the concrete curb and gutter and sidewalks. The settlement of the curb and gutter will result in ponding of water on the pavement surface which will not only pose a safety risk (owing to the potential of the water freezing and forming ice), but will result in the premature failure of the pavement surface caused by the ingress of the water into the pavement structure. The cracked/heaved sidewalks could likely pose safety issues as they may result in people tripping over them or cause challenges to the wheel chair users. Similarly, undermined sidewalks have the potential of caving in at any time and result in potential health hazard to the users.

vii. **Reduced Service Life:** It is concluded that the flooding event adversely affected the integrity and the condition of the roadway infrastructure along the project roadway segments. This will result in the significant reduction of the service life of these components and will need rehabilitation / reconstruction of these components earlier than typically expected.

viii. **Potential Deep Voids:** There is still a concern of the existence of any potential voids that may exist deeper in or under the pavement structure and could surface later during the pavement service life.

7. RECOMMENDATIONS

Based on the review of the collected and analyzed data, the following recommendations were provided:

i. **Additional Testing:** Considering that the Road Radar™ data identified a number of locations as wet and having low severity anomalies in the pavement structure, which when tested with a FWD didn't indicate any pavement strength testing, it is recommended that further testing be conducted to rule out the presence of anomalies underneath the pavement structure. The additional testing can be in the form of boreholes drilled at select locations and FWD testing at the locations where the FWD testing was completed initially. It is suggested that a few boreholes be drilled at select locations to check for the presence of the voids and test the underlying pavement layers and subgrade soils for excessive moisture.

The FWD testing was completed late in the year (Oct.30 to Nov. 1), which may have resulted in somewhat lower deflections. It is recommended that the FWD testing be conducted in summer months to rule out the possibility of the impact of cold weather on the pavement strength test results.

ii. **Monitor the Condition of the Pavement Infrastructure:** It is further recommended that the City continue to monitor the condition of the roadway infrastructure at least in the short term as there is a potential for the quick deterioration in the condition of the infrastructure as the additional moisture in the pavement structure recedes or freezes during the winter months. There is also a potential for the undermined infrastructures such as sidewalks or pavement structures (where the asphalt concrete pavement is bridging over any voids) to give in, which will pose a potential safety risk to the public.

iii. **Program for Surface Works Restoration:** It would be prudent to plan for rehabilitation of these roadways in the coming years to address the significant distress caused by the flood event. This rehabilitation would likely entail partial or full depth repair of significantly distressed areas, followed by mill and inlay paving to restore surface condition and ride quality. It may be appropriate to defer to some extent these efforts to assist in identifying any further distress manifestation prior to resurfacing. Sidewalk replacement of select areas will also be required in a timely manner.

REFERENCES

[1] http://www.theweathernetwork.com/news/articles/calgary-floods-it-could-happen-again/8295/

[2] Alberta Transportation, Transportation and Civil Engineering Division, Civil Projects Branch, Report on Six Case Studies of Flood Frequency Analysis, April 2001.

[3] http://www.environment.alberta.ca

[4] City of Calgary, 2012 Roads Construction Standard Specifications.