Geotechnical Design Challenges Associated with the Lower Fraser River Dikes

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ABSTRACT 500 kilometres of dikes (55 separate dikes) in the Lower Fraser River Valley and Delta protect roughly 70,000 hectares of floodplain lands, 500,000 British Columbians' homes and jobs, and tens of billions of dollars worth of buildings and critical infrastructure. While many of these dike systems were upgraded during the 1970's and 80's, others were not and the extent and sufficiency of geotechnical design is highly variable. For the past 50 years flood risks have been magnified by intensive floodplain development and aging flood protection works. These factors will continue to increase flood risk in the decades ahead, but will also be exacerbated by climate change - through both sea level rise and potentially higher river flows. Because flood mitigation alternatives other than diking have significant limitations, the increased flood risks must be addressed primarily through higher and safer dikes. Due to the variability of dike geometry, foundation soils and dike fill materials over many kilometres of a specific dike, achieving the required high standards of geotechnical reliability will be a major challenge. Two key problems are: preventing piping failures, particularly at structures through the dikes; and increasing the seismic resilience of diking systems. Examples of past piping failures and lessons learned are briefly described. The objectives and application of the ministry's "Seismic Design Guidelines for Dikes" are also discussed.

Introduction

The major economic and population base of British Columbia is located in the south west corner of the province near the mouth of one of the major rivers of North America, the Fraser River. The successful occupation of Fraser River floodplain and coastal delta lands is in part due to foreshore engineering knowledge and design of the existing flood protection works. The minimal impact of river floods on this area over the past 60 years is also, in part, due simply to our "good luck" that the Fraser River watershed has not generated a big flood since 1948.

Approximately 500 kilometres of dikes (55 separate dikes, including dikes on tributaries) in the Lower Fraser River Valley and Delta protect roughly 70,000 hectares (700 square kilometres) of floodplain lands, 500,000 British Columbians' homes and jobs, and more than 50 billion dollars worth of buildings and critical infrastructure. While detailed current damage estimates for the entire Fraser Valley are not available, a recurrence of the record 1894 flood could cause tens of billions of dollars economic damage, extensive disruption and trauma, and potential loss of life.

This paper provides some background on the Fraser River and Strait of Georgia flood hazards, the history of the Lower Fraser Diking system, and the increasing risks. Because flood mitigation alternatives other than diking have significant limitations, the increased flood risks must be addressed primarily through higher and safer dikes. While there are many aspects of dike design and potential modes of dike failure, good geotechnical design is fundamental to increasing system reliability.

Two key geotechnical challenges are preventing piping failures, particularly at structures through the dikes, and increasing the seismic resilience of diking systems. The piping issue is illustrated by two case examples. The ministry's "Seismic Design Guidelines for Dikes" were developed in an attempt to address seismic risks. The final section of the paper presents and discusses the objectives and application of these guidelines.

The Flood Hazard

Fraser River

The Fraser River is 1,375 km long, drains one quarter of the total area of BC and is one of the major rivers of western North America. The record 1894 flow at Hope is estimated to be 17,000 $m^{3/}s$, which is ten times the peak flow of the Bow River at Calgary during the June 2013 floods.

Fraser River floods are caused by rapid snow melt in spring during extended periods of warm weather, frequently in combination with two or three days of rain over a significant portion of the watershed.

For a large river, the Lower Fraser can rise very quickly. Flood levels can go from bank-full conditions with no flooding to extreme flood conditions and catastrophic flooding in only five to 7 days. The high water period can also persist for several weeks with near peak levels for many days. In 1948, at Mission BC, the flood level was within 0.15 m of the peak level for 14 days. This means that dikes must be designed for steady state seepage conditions.

The five largest floods on the Fraser River, from largest to smallest, occurred in 1894, 1948, 1972, 1950, and 2012. The current minimum provincial standard for new river dikes and dike upgrades is based on a hydraulic model flood profile of the 1894 flood flow at Hope, BC, which is estimated to have an Annual Exceedance Probability (AEP) of about 1:500, or a 10% chance of being equalled or exceeded in 50 years. At Mission the design flood level of 9.0 m geodetic datum, without freeboard, is 1.8 m higher than the observed 1972 flood peak and 2.6 m higher than the 2012 flood peak.

Strait of Georgia

There are approximately 125 km of existing sea dikes in the Fraser Delta. These include dikes exposed to ocean wind and waves, such as the Delta Boundary Bay dikes, plus the dikes in more sheltered areas of the Fraser Estuary, but where high tide and storm surge levels exceed spring freshet levels. Ocean design levels generally exceed spring freshet design flood levels downstream of the Alex Fraser Bridge.

The tidal cycle partially loads the diking system at least once daily and this can have significant implications for situations where there is inadequate provision of filters to prevent internal erosion. The storm surge component can add more than 1 m to the high tide level for several hours, which is a consideration for the design of seepage control measures.

History of Dike Construction

Early Dike Construction

The first Fraser Valley dikes were constructed on Lulu Island (Richmond) in 1864. From that beginning, and after the major 1894 event, a series of diking districts developed, extending upstream to Agassiz, near the eastern end of the Valley. By the time of the 1948 flood the total length of diking was over 350 km.

The dikes were generally founded on recent alluvial and floodplain deposits including sands, silts and organic deposits. The first valley wide geotechnical investigation and stability analyses of the dikes in 1963 (Jones, 1963) concluded that early dike construction involved limited stripping of organics and little or no compaction of the dike embankment materials. Native fine grained materials (predominantly sandy silts and silty sands) were typically excavated by dragline for the dikes, creating a drainage ditch on the land side.

Because dike upgrading has generally involved widening and raising existing structures, many of these early embankments are still present within the existing dike structures.

The 1948 flood caused multiple dike failures and resulted in flooding of about one third of the entire Lower Fraser floodplain. After the flood, the "Fraser Valley Dyking Board" was formed to reconstruct the dikes, and these withstood the high water of 1950, which was the fourth largest Fraser River flood.

Fraser River Flood Control Program 1968 to 1994

After the 1948 flood and rebuilding of the dikes, a number of federal-provincial studies were initiated with the objective of further reducing the potential for flood damage. These culminated in a 1968 agreement establishing the Fraser River Flood Control Program (FRFCP), which eventually was extended to 1994 and expended some $295 million in 1994 dollars on upgrading approximately 250 km of the diking system (Fraser Basin Management Board, 1994). This expenditure is equivalent to about a half billion of today's dollars.

The program developed both hydrotechnical and geotechnical design criteria. The 1894 peak discharge at Hope was adopted as the basis for hydraulic design. The dike design profile developed in 1969 incorporated a 0.6 m freeboard above the design flood level.

Many of the banks of the Fraser River are subject to significant erosion as part of natural river processes. The channel of the "gravel bed" reach upstream from Mission is laterally unstable and bank erosion is a major issue at several locations. The FRFCP addressed erosion through selection of setback dike alignments wherever possible, and through the construction of 84 km of bank protection works. These works typically consisted of large rock riprap placed at a 2H:1V slope with provision of an extra rock "toe" to allow for scour.

Geotechnical design included site specific stability and seepage investigations and analyses. Dike slopes of 3H:1V for the waterside slope and 2.5H:1V for the landside slope, or flatter, were generally specified. Seepage control measures included land side berms and pressure relief wells. Design measures to reduce seepage quantity (e.g. cutoff trenches, impervious blankets etc.) were less commonly used.

Early FRFCP studies concluded that many of the dikes would be vulnerable to earthquake damage due to liquefaction of saturated foundation soils. However, the decision was made to exclude seismic design, except for the major Barrowtown pump station in Abbotsford. The rationale for this decision is discussed later in the paper.

Recent Funding Programs

Following the completion of the last FRFCP project in the early 1990's, there have been a number of senior government funding programs to assist local diking authorities with flood protection projects. These funds have been used effectively to update pumping stations, repair erosion protection works and other important projects. However, funding has been allocated on an application basis and there has been no coordinated effort, or sufficient funds to upgrade dikes to current standards.

Higher and Safer Dikes

Risk is commonly defined as the product of the probability of hazard occurrence multiplied by the consequences of that event. Several risk factors that increase both the probability and consequences of flooding are shown in Fig. 1. While many factors are increasing the probability of flooding, intensified floodplain development and urbanization is the primary cause of increased risk, simply through increased exposure to the hazard. It is likely that this ongoing floodplain development will continue because of the large economic benefits generated by the use of flood hazard lands.

Possible means of reducing risk are also shown in Fig. 1. below the "Risk = Probability x Consequences" equation. In the absence of effective policies to minimize the "consequences" through control of floodplain development, the principal means of reducing risk, by default, is that the dikes be upgraded to a very high standard.

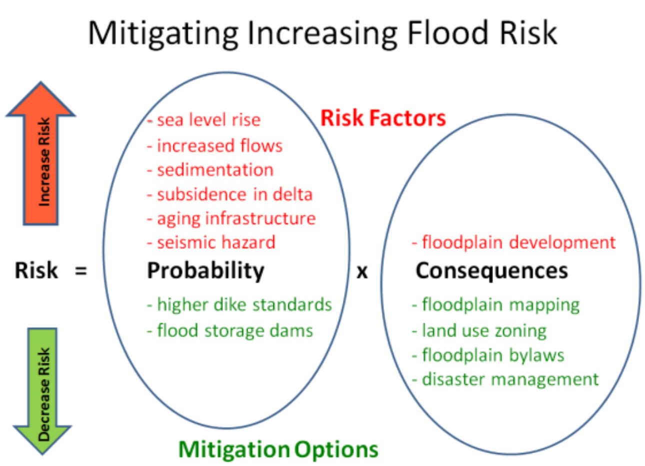

Figure 1. Mitigating Increasing Flood Risk

Higher Design Flood Levels

Higher design flood levels for the Fraser River dikes are necessary for a number of reasons:

- Improved river surveying and computer modelling have determined that much of the 1969 FRFCP dike design profile was approximately 1 m lower than would be expected with a recurrence of the 1894 design flood.
- A higher standard of protection is warranted, given the significant economic damage potential and use of a cost benefit analysis approach. For example, river and sea dikes protecting urban areas in the Netherlands, are typically designed for 1:4,000 and 1:10,000 Annual Exceedance Probability standards, respectively.
- A sea level rise of 1 m by the year 2100 would significantly affect the design level of Fraser River Dikes as far upstream as Mission, as well as the sea dikes.
- A preliminary watershed and hydraulic modelling study indicates that peak flood flows and design flood levels on the Fraser are likely to increase significantly (e.g. in excess of 1 m at Mission) over the next several decades (Ministry of Forests Lands and Natural Resource Operations 2014).

The Geotechnical Design Challenge

Because the dikes must be raised in the order of 1 to 2 metres to meet updated hydrotechnical criteria, the overall reliability of the system must also be increased commensurate with new standards. This requires that all potential modes of failure must be considered.

Increasing the standard of protection in the face of climate change and seismic risks presents a daunting challenge because of the following factors:

- Each dike ring is a "series system", where failure of one component results in catastrophic failure of the entire dike. Investigations and analyses must address the "weakest links".
- The relatively long length of each dike (a few kilometres to tens of kilometres) typically means that there is a wide variation in soil conditions, existing dike materials and site geometry along the dike. Soils investigations will need to be much more detailed than those completed by the FRFCP.
- The existing river dikes and foundation soils have not been hydraulically load tested. Flood levels near the design levels (e.g. within 1 m) have never been experienced. Even the 1948 and 1972 floods, which were the second and third largest floods on record were 1.4 m and 1.8 m below the current 1894 design level at Mission, respectively. Also, the 1972 event was much shorter than the anticipated design level duration of two to three weeks.
- Land availability for significantly wider dikes is a major constraint in many areas. Flatter side slopes, toe drains, berms and other design features will likely be required to address stability, seismic design and seepage control.
- Structures through the dikes are a special challenge. The Fraser Valley dikes contain approximately 300 major appurtenant structures (i.e. pump stations and floodboxes) and thousands of buried utility crossings.

Piping Case Histories

While overtopping and erosion and may be two of the more obvious causes of dike failures, approximately half of historical dike failures in BC have been related to uncontrolled seepage and piping (Ministry of Environment, Lands and Parks 2000). This type of failure may be associated with defects in appurtenant structures, animal burrows, or simply due to the geometry and characteristics of the foundation soils and dike embankment (e.g. slough crossings, highly permeable zones etc.). The failures may occur at levels well below design flood level.

For the lower Fraser River, potential problem areas can be very difficult to identify in advance. The progression of piping prior to failure may not exhibit physical signs and symptoms that can be easily recognized by routine visual inspections.

Therefore, it is instructive to consider two dike failure case histories, one just east of Mission on Nicomen Island that occurred in June 2002, and one near the Queensborough Bridge on Lulu Island that occurred in June 2003.

Nicomen Island Floodbox – June 2002

Nicomen Island is an agricultural area located in the floodplain of the Fraser River 15 km east of Mission and is the home of several hundred people. The Island includes a 10 km long section of the Lougheed Highway (Highway 7) and about 1700 hectares of farm land and several thousand dairy cattle. A 35 km long perimeter dike protects the island from Fraser River flooding. To provide internal drainage, the diking system has 5 pump stations and 10 gravity flow floodboxes.

The Nicomen Island dike was first developed in the early 1900's. After a breach during the 1948 flood, the dike was reconstructed and somewhat improved, however, the dike was not upgraded by the Fraser River Flood Control Program and the structural competency of the dike remains questionable. The dike is the responsibility of the Nicomen Island Improvement District.

On June 24, 2002 during the Fraser River high water period, a 1.5 m diameter sinkhole developed on the north (river) side of the dike crest adjacent to Nicomen Slough. At this location, the Highway 7 road embankment is contiguous with the dike. The sinkhole was located in close proximity to the Pennington Pump Station and Floodbox discharge lines. The head difference across the dike was approximately 4 m.

A drilling program by Golder Associates found large voids and zones of loose unstable material in the embankment above and adjacent to the floodbox. The dike was deemed to be at a point of incipient failure if river levels were to rise. Fortunately the river levels were well below the crest of the dike (approximately 2.5 m) and were dropping.

The geotechnical investigation determined that internal material from the dike embankment had migrated into joints in the 1 m diameter, 40 m long concrete floodbox pipe buried approximately 7 metres below the top of the dike. It was concluded that a few of the joints had opened up due to differential settlement over a 50 year period.

Remediation was initiated immediately but was complicated by the requirement to keep at least one lane of Highway 7 open at all times. The work included:

- Installation of coffer dams and dewatering of the concrete floodbox pipe;
- Installation and seal grouting of a slightly smaller HDPE liner pipe within the concrete pipe;
- Compaction grouting of the embankment to fill the voids and densify the zone around and over the floodbox; and
- Rapid Impact Compaction of the upper 2 m of embankment.

This dike failure provided the following lessons:

- Floodbox pipes, especially older installations, should be internally examined on a routine basis and replaced as needed.
- Designs must allow for long term differential settlement during the life of the structure.
- Visual signs of any potential problems should be investigated carefully. (Note: at this site, a slight depression in the highway surface on the top of dike had to be filled and repaved a few times prior to the development of the major sink hole. It was later recognized that this depression was being caused by the gradual internal erosion of the dike embankment.)

Stanley Street Pump Station – June 2003

The City of Richmond and the Queensborough area of the City of New Westminster are located on Lulu Island in the floodplain of the Fraser River. The island is surrounded by a 55 km long perimeter diking system that protects over 200,000 residents and tens of billions worth of buildings and infrastructure from Fraser River and coastal flooding.

To provide internal drainage, the diking system has approximately 40 pump stations and gravity flow floodboxes. There are also hundreds of utility crossings through the dike.

Early Sunday morning on June 15, 2003 at high tide, a sudden major failure occurred in the dike at the Stanley Street pump station near the north eastern end of the island, 1 km east of the Queensborough Bridge. A section of dike that abutted against the concrete pump station structure collapsed, and allowed river water to flow past the pump station into the canal and drainage ditch system.

Alerted by a resident, New Westminster City crews responded quickly and within a few hours had constructed an earthen containment dam across the drainage canal leading to the pump station. A marine construction company was then contracted to install a sheet pile cofferdam on the Fraser River to secure and isolate the failed section of dike.

The 6 m high dike failed when the river level was well below flood conditions, approximately two metres below the crest of the dike. The relatively low river level coupled with a falling tide and the City's rapid emergency response reduced the extent of flooding, which was confined to minor flooding of an adjacent lumber yard.

At the time of the failure, the drainage structure was only 5 years old, and had been constructed to replace an older pump station at this location. The integrated, reinforced concrete pump station and floodbox structure was designed by a reputable civil engineering company that used a specialist engineering company for the geotechnical design. An independent engineering firm, Klohn Crippen Ltd, was retained to investigate the causes of the failure and to design remediation measures.

The as-constructed drawings indicated that the dike had a central impervious core, upstream and downstream granular shells, filter zones and riprap on the river side face. Geotextile filter fabric was shown beneath the pump station foundation, and encapsulating the dike core. The foundation soils included varying thicknesses of silt and organic silt overlying clean, fine to medium grained sand.

As well as the observation of significant voids and disturbed soils under and adjacent to the structure, the forensic investigation revealed a number of construction anomalies including fill samples not meeting specified gradations, filter fabric absent in some areas, and voids in the mass concrete foundation walls.

The investigation confirmed that the dike failed by foundation underseepage piping. Klohn Crippen noted that the following design and construction deficiencies contributed to the failure:

- Inadequate provision of filters;
- Inadequate seepage control design measures to accommodate differential settlement of the rigid, massive, pump station foundation slab founded on natural compressible and erodible soils; and
- Poorly constructed mass concrete foundation walls and poor quality dike fill construction.

This case history raises a number of points of interest:

- The section of dike at the Stanley Street pump station was apparently in a state of imminent failure for a significant period prior to failure.
- There were no visible signs of the weakened dike condition prior to the actual failure. City staff were at the site only two days prior to the failure and dike inspections were up to date.
- The failure occurred at relatively low water level conditions. If the failure had occurred during a large Fraser River freshet, it would have been very difficult or impossible to repair the breach in the dike (there are minimal tidal fluctuations at this location when the Fraser River is in flood).
- A major dike breach at this location could flood almost all of Queensborough and Richmond to a depth of 1 to 2 metres within about 48 hours, which would have resulted in mass evacuations of up to 180,000 people, and tens of billions of dollars of flood damage.

This event highlights the ongoing vulnerability of even modern, well maintained dike systems. Careful quality control during construction as well as robust design - plus good inspection, operation and maintenance programs are all vital in minimizing the risk of such failures.

Seismic Design of Dikes

The following sections give a brief overview of the rationale, history and application of seismic design guidelines for dikes in BC. The design criteria and analytical methodologies are provided in the 2nd Edition of the "Seismic Design Guidelines for Dikes" (Golder Associates 2014).

Rationale for Seismic Design

The tectonic setting along the west coast of BC means that the Lower Mainland is a seismically active, earthquake prone region. The Fraser Valley dikes are vulnerable to earthquake damage because most of the dikes are located in close proximity to river banks on deltaic/fluvial soils that are generally susceptible to liquefaction. Earthquake damage can include slope failures, settlement and cracking due to differential displacement.

Given increased reliance on dikes over the past several decades as the primary flood management strategy, it is critical the diking system be resilient to seismic events. Immediate repairs may not be feasible after a major quake as there will be limited resources to repair/rebuild the dikes prior to the next potential flood period. Hence, the objective of seismic design is to reduce the total damage to the Lower Fraser dikes, considered as a whole system.

Dikes are major public safety infrastructure that require large capital expenditures to build. Implementation of seismic design standards also help to protect this investment and reduce the vulnerability of communities exposed to both earthquake and flood hazards.

Except for tidal sea dikes and a few river dikes where high water levels hydraulically load the dikes on a daily basis, or for extended periods every year, the probability of a damaging earthquake occurring during a flood is very low. Therefore, the objective of seismic design is not to prevent immediate flooding, but is to facilitate the rehabilitation of the diking system prior to the next potential flood period. The maximum allowable displacements have been established with the intent of preserving the structural integrity of the dike body.

History of Seismic Design of Dikes in BC

As noted earlier in this paper, the FRFCP reconstructed approximately 250 km of river and sea dikes. Except for the major Barrowtown Pump Station in Abbotsford, the FRFCP projects did not include seismic design.

This approach was rationalized on the basis of cost constraints and the rare chance of occurrence of a major flood simultaneously with a large earthquake. In the 1970's it was also anticipated that development of upstream storage reservoirs and/or diversions in the Fraser River watershed would significantly reduce the Fraser River flood threat and justify the relatively modest standard of protection provided by diking.

In November 2010, interim guidelines were issued that required the design of dikes to consider the effects of seismic activity on the integrity of the dike structure and required the owner to demonstrate that it would be possible to repair the dike within 6 months to retain a 1:10 year annual exceedance probability flood. This approach had the benefit of determining the scale of potential damage, however, the feasibility of repair and re-construction was difficult to evaluate.

The Ministry published new guidelines in August 2011 (the first edition, also prepared by Golder Associates) that specified a level of required dike performance in terms of vertical and lateral dike displacements in response to three different levels of earthquake shaking. The Guidelines were updated in May 2014, primarily to clarify acceptable analytical methodologies.

Seismic Guideline Application

Seismic upgrading of the existing diking system is generally a long term, incremental process, typically as sections of dike are being upgraded for higher design flood levels. Seismic assessments and designs must generally be consistent with the Guidelines to obtain *Dike Maintenance Act* approval from the Ministry prior to construction.

The Guidelines apply only to the design and construction of new and major upgrades to "High Consequence Dikes", defined as "...flood protection dikes where the economic and/or life safety consequences of failure during a major flood are very high. These dikes typically protect urban or urbanizing areas, and failure could result in large economic losses and/or significant loss of life. The majority of the dikes reconstructed under the 1968 to 1994 Fraser River Flood Control Program would be considered High Consequence Dikes."

In situations where the displacement criteria cannot be met, modification of the dike geometry and/or ground improvement should be considered. However, ground improvement methods are costly and may only be practical for short sections of dike and appurtenant structures. It may be necessary for the dike owner to consider the following alternatives:

- Re-aligning the dike to avoid the high cost of ground improvement where the dike is located in seismically vulnerable areas adjacent to steeply sloping river banks.

- Overbuilding the dike to the extent possible and practical to satisfy post-earthquake vertical displacement requirements provided that displacement analyses confirm that the dike core will retain hydraulic integrity and the landside face geometry remains intact.

- Incorporating the "dike" into massive fills required for adjacent land development (*i.e.* the "superdike" concept) again with sufficient analyses to confirm that the flood protection system would retain its hydraulic integrity.

- Documenting expected damage, developing a remediation plan, restricting land use and regulating floodplain development in the protected area (*e.g.*, flood proofing bylaws and other regulatory tools) to justify removal of the *High Consequence Dike* classification.

Because seismic design may impact dike alignment and land acquisition requirements, it is recommended that the seismic assessment and other pre-feasibility geotechnical studies be completed prior to detailed civil design of the dike.

Concluding Remarks

Both of the piping case history examples illustrate the design and maintenance challenges of improving the reliability of large, complex diking systems. This task is exacerbated by the age of many of the structures and incremental construction and development of these dikes over more than a one hundred year period.

If the goal is to improve the standard of protection, the seismic risk to dikes in south western BC can no longer be ignored – i.e. addressed by the response that we can repair the dikes after the earthquake. Wherever possible, seismic resilience must be built into the system as part of any upgrading program. Otherwise, the dikes will only create a false sense of security.

The newly recognized impacts of climate change calls for a new long term, coordinated and integrated program to assess risks, develop new standards, and prioritize upgrading projects. As the standard of reliability required for dikes moves closer to that of earth dams, it would seem appropriate to adopt many of approaches used by the dam safety community.

Flood risks are increasing because of increased floodplain development, the aging infrastructure, and climate change effects on both sea level and peak river flows. We know that "good luck" cannot continue forever and there is an urgent need to increase the level of protection and reliability of the flood protection system. Geotechnical design will be fundamental to this effort.

Meeting these challenges will take a major effort and cost billions of dollars. However, spread over many years, the expenditures are affordable. We must acknowledge that this is the least expensive option. Given the consequences of multiple dike failures, we simply cannot afford the price of inaction.

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