New Performance-Based Seismic Design Guidelines for High Consequence Dikes in South Western British Columbia, Canada

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ABSTRACT: This paper presents an overview of the basis and methodologies proposed for seismic design of High Consequence Dikes in Southwestern British Columbia, Canada. The guidelines adopt a combination of traditional and performance-based design criteria for the seismic design of dikes. Dike performance is specified in terms of measureable criteria such as crest displacements of the dike structure. The methodologies and criteria were established following a review of practices currently followed in other regions of the world that are also prone to high seismic hazards.

1 INTRODUCTION

Densely populated urban communities and regional infrastructure in British Columbia are protected from flooding by close to 500 km of river and sea dikes. These dikes comprise earthen embankments of varying height and dimension, constructed over varying foundation soils using different construction practices and materials. The stability of the dike systems and their performance under the loads imposed by natural hazards such as floods, storms, and earthquakes is of paramount importance in protecting both rural and urban communities and regional infrastructure. The protection offered by the dike system is dependent on the performance of the weakest areas of the specific dike system under consideration. The extent of damage to the existing urban communities and regional infrastructure due to large scale flooding resulting from breaches in the different diking systems has been estimated to reach upwards of C$50 Billon (in 2013 dollars).

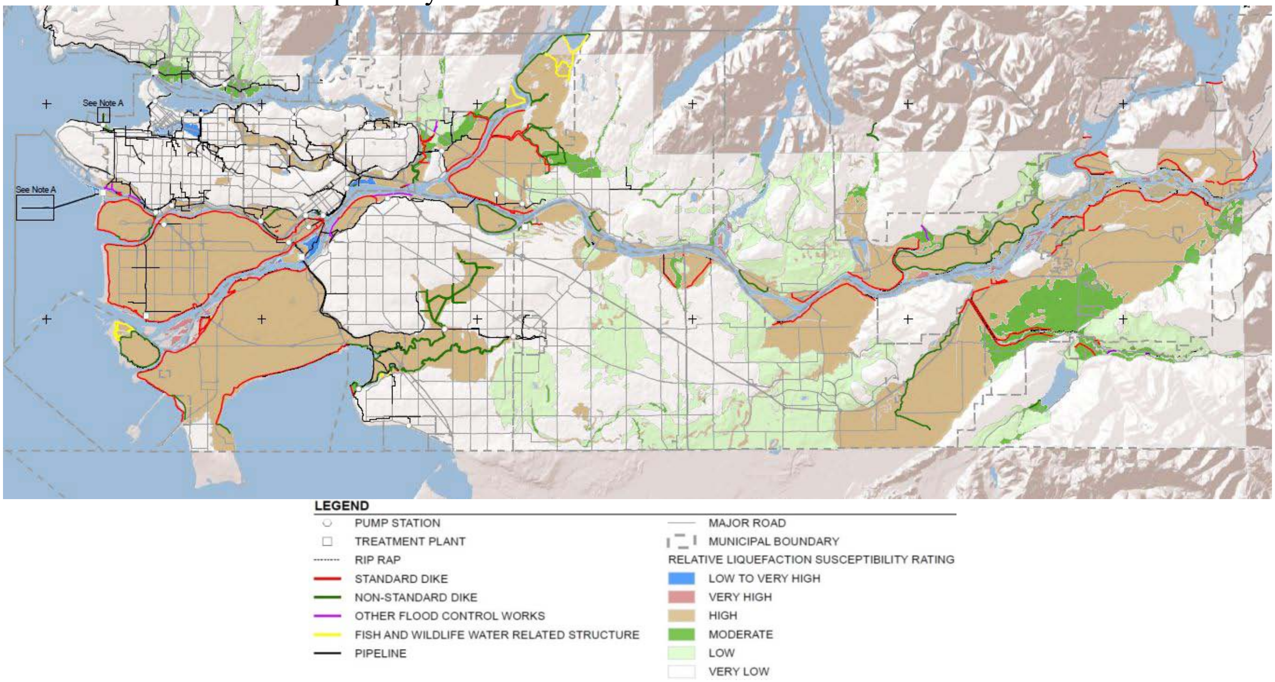

Fig. 1 The System of Dikes in Southwestern British Columbia

Dike design in British Columbia has historically been based on hydraulic criteria to prevent failure by static instability, overtopping and/or piping and has not considered other failure modes such as seismic activity, generally due to economic drivers and limited knowledge of seismic performance and appreciation. Significant portions of British Columbia are situated in a seismically active zone where there is significant potential for extensive damage to dike systems from seismic events.

To address this risk, the Flood Safety Section undertook the development of seismic design guidelines for dikes, which are a condition of the Dike Maintenance Act (DMA) approval process.

The guidelines are applicable for High Consequence dikes where the consequences of dike failure are very high, and include design and construction of new dikes or upgrading of existing dikes. The different dike systems under consideration are shown on Fig. 1.

2 APPLICATION OF GUIDELINES TO HIGHLY VULNERABLE SITES

Some of the dikes are located in sites that are highly vulnerable to damage from strong shaking during and/or following an earthquake. Seismic strengthening and remediation of these dikes using ground improvement techniques are costly and may only be practical for short sections of dikes and appurtenant structures. For dike segments where the performance criteria cannot be met, provisions can be made to:

- Re-aligning the dike;
- 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; and
- Documenting the expected damage, developing a remediation plan, restricting land use and regulating floodplain development in the protected area to justify removal of the High Consequence Dike classification.

As seismic design requirements may impact dike alignment and land acquisition requirements, it is a general recommendation that pre-feasibility geotechnical studies, including the seismic assessment be completed prior to detailed civil design of the dike.

3 SEISMIC DESIGN OBJECTIVES FOR DIKES

The seismic design objectives for dikes are as follows:

- Dikes subjected to seismic ground motions with a <u>short return period</u> or a <u>high annual exceedance</u> probability event during the design life should perform with <u>insignificant damage</u> to the dike body, without compromising the post-earthquake flood protection ability;
- Dikes subjected to seismic ground motions with an <u>intermediate return period</u> or an <u>intermediate annual exceedance</u> probability event during the design life may experience some <u>repairable damage</u> to the dike body, without compromising the post-earthquake flood protection ability; and
- Dikes subjected to seismic ground motions with a <u>long return period</u> or a <u>rare/low annual exceedance</u> probability event during the design life may undergo <u>significant damage</u> to the dike body potentially requiring more complex subsurface repairs, with the short-term post-earthquake flood protection ability possibly compromised.

Typical return periods considered are summarized in Table 1:

Table 1. Typical Return Periods and Event Classifications Considered

Return Period Classification	**Event Classification**	**Return Period (Years)**
Short	Frequent	100 to 200
Intermediate	Intermediate	475 to 975
Long	Rare	2,475 to 10,000

4 SEISMIC HAZARDS CONSIDERED

Potential seismic hazards affecting the dikes located in Southwestern British Columbia include the following:

- Ground shaking;
- Slope movements caused by ground shaking;
- Bearing capacity and sliding failure;
- Soil liquefaction and flow slide failure;
- Vertical and horizontal total and differential ground displacements;
- Loss of free board due to ground subsidence and slope failure; and
- Piping failure through fissures induced by ground movements.

The seismic hazard to Southwestern British Columbia results from the offshore subducting of the Juan de Fuca Plate beneath the Continental Plate. The tectonic environment gives rise to three different types of earthquakes, each with its own specific characteristics; i.e.: shallow crustal earthquakes (up to M_w7.5, with epicenter as close as a few km from a site of interest), deep intra-plate earthquakes (up to M_w7.5, with epicenters as close as 40 km from the site of interest), and inter-plate or subduction earthquakes (up to M_w9, with the epicenter as close as about 140 km from the site of interest).

In order to avoid unrealistically low combined probabilities, "mean annual river water" and "mean annual sea water" levels are considered in the seismic assessments of dikes. However, in some instances (e.g. for sea dikes), the sensitivity to varying water levels should be considered. In addition, future dike upgrades will need to consider projected future sea levels.

5 GEOTECHNICAL INVESTIGATIONS FOR DIKE DESIGN AND ANALYSIS

Flood protection dikes are almost always located along river banks and shorelines. Historically, river banks and shorelines have experienced considerable damage following earthquakes due to soil liquefaction, slope failure, settlement, and permanent lateral movement. As a result, dikes have a high geo-hazard exposure and need to be investigated in detail to allow identification and assessment of soil conditions and strata that are vulnerable to liquefaction, loss of shear strength, and movement.

The main objective of a geotechnical investigation is to identify soil strata that are susceptible to liquefaction and/or cyclic softening as a result of strong ground shaking, to determine their in-situ state and engineering properties. A suitable investigation should include, but may not be limited to, the following:

- Continuous or near-continuous profiles of the soil strata;
- Measurement of depth to ground water levels on either side of and within the dike;
- In-situ testing of soil strata susceptible to liquefaction or cyclic mobility in the form of penetration resistance, strength, and shear wave velocity;
- Sampling of soil strata susceptible to liquefaction or cyclic mobility;
- Gradation of soils susceptible to liquefaction or cyclic mobility;
- Index testing of soils susceptible to liquefaction or cyclic mobility; and
- Cyclic simple shear testing of fine-grained soils to investigate liquefaction susceptibility or cyclic mobility.

Dikes comprise hundreds of kilometers of earth fill embankments constructed over varying ground conditions that may include reclaimed areas, buried channels, previous failures, river meander and bar deposits, and marshy/swampy areas. The flood protection offered by the dike system is dependent on the performance of the weakest areas of the specific dike system, and this aspect should be taken into consideration when planning field investigations.

Several different field investigation methods are commonly used by the practitioners to obtain engineering properties of soils. These include the Standard Penetration Test (SPT), the Cone Penetration Test (CPT), Becker Penetration Test (BPT), and Shear Wave Velocity Test (SWVT) methods.

Other field exploration and in-situ testing methods for assessment of soil liquefaction may be used provided that site-specific correlations have been developed with one of the methods described above.

The soil liquefaction susceptibility of soils over the region is also shown on Fig. 1 and it has been prepared to assist with initial screening level evaluations.

A minimum of three borings should be drilled for each section of the dike; one on the water side of the dike, one through the center of the dike, and one on the land side of the dike. The horizontal spacing of data sections along the dike should not be greater than 300 m. Closer spacing of data sections may be required where significant variations in subsurface conditions are anticipated. Drilling boreholes over water is costly, but establishing reliable soil stratigraphy and parameters is important in the dike stability analyses.

For dike segments where the initially available subsurface data is limited, the analyses and investigations may be carried out in stages, starting with screening level analyses/investigations. However, the final design and analysis of the dike segment need to incorporate subsurface investigations as identified above.

6 PERFORMANCE-BASED DESIGN CRITERIA

A performance-based seismic design is accomplished by defining appropriate levels of design earthquake ground motions and corresponding acceptable levels of damage (Sugita & Tamura, 2007). The design earthquake motions include those from frequent events that are likely to occur within the life of the structure as well as infrequent or rare events that typically involve very strong ground shaking. The acceptable level of damage is specified in terms of displacements to be experienced by the structure. Damage is categorized in terms of "Performance Categories", which are related to the effort required to restore the full functionality of the structure.

The performance of the dike system should be checked for all three Design Earthquake Ground Motion Levels defined below:

1. Design Earthquake Ground Motions
   Ground motions that correspond to three different return periods described below are to be considered in seismic design.
   - Earthquake Shaking Level 1 (EQL-1)
     1:100-year return period ground motions
   - Earthquake Shaking Level 2 (EQL-2)
     1:475-year return period ground motions
   - Earthquake Shaking Level 3 (EQL-3)
     1:2475-year return period ground motions
2. Performance Categories and Permissible Displacements

   Performance Category A: No significant damage to the dike body, post-seismic flood protection ability is not compromised.

   Performance Category B: Some repairable damage to the dike body, post-seismic flood protection ability is not compromised.

   Performance Category C: Significant damage to the dike body, post-seismic flood protection ability is possibly compromised.

The maximum allowable dike displacements are provided in Table 2.

Table 2. Summary of Maximum Dike Crest Displacements Corresponding to Performance Categories

Performance Category	**EQ Shaking Level**	**Max. Vertical Displ.**	**Max. Horizontal Displ.**
A	EQL-1	<0.03 m	<0.03 m
B	EQL-2	0.15 m	0.3 m
C	EQL-3	0.5 m	0.9 m

The maximum allowable displacements given in Table 2 have been established with the intent of preserving the structural integrity of the dike body. They represent total displacements. It is implied that for earthen dikes, satisfying the maximum allowable dike crest displacements at sections that are located with a maximum horizontal distance of 300 m along the dike would reduce the hazards associated with a dike breach as a result of differential or relative displacements.

The design of structural elements such as floodwalls may need to satisfy alternate (less tolerant) displacement criteria in order to achieve the performance expectations described herein.

The designer has to independently confirm that the displaced configuration of the diking system would provide at least 0.3 m of post-earthquake freeboard above 1:10-yr return period water level to meet performance expectations. Individual communities may impose more stringent minimum post-earthquake freeboard than specified herein.

7 CONCLUSIONS

Performance-based seismic design guidelines have been developed for High consequence Dikes in South Western British Columbia and Vancouver Island. Three levels of ground shaking and associated performance criteria have been developed. The performance criteria are in terms of measureable quantities such as dike crest displacements and settlements. The design has to be carried out for all three levels of shaking.

Limits on dike crest displacements and settlements are provided for each level of shaking. The intent is that if these criteria are satisfied (i.e. calculated movements are less than the criteria for a given shaking level) for dike sections taken at a horizontal spacing of 300 m or less, the differential movements and settlements that could cause dike distortions leading to a dike breach are unlikely to occur.

The alternatives on reconfiguration of dikes to satisfy the guidelines were briefly discussed in this paper. Always there will be some cost, land, and environmental concerns associated with the design and the subsequent implementation strategy. However considering the loss of life and damages, it will be worth to consider improving the dike system.

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