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Seismic Vulnerability Assessment of High-Consequence Dikes in Vancouver's Lower Mainland

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ABSTRACT

The Lower Mainland is a seismically active region and the dikes located along the Fraser River (and sea dikes) are vulnerable to earthquake damage. The seismic vulnerability of these dikes is due to their proximity to riverbanks, where soils are susceptible to liquefaction. Development in the Lower Mainland has increasingly relied on dikes as primary flood protection structures, but insufficient effort has been spent on understanding the seismic vulnerability and implications for ground improvement requirements.

This paper presents a seismic vulnerability assessment of the High-Consequence diking system in the Lower Mainland. The seismic vulnerability was evaluated using prediction models to estimate likely damage levels considering various probability exceedance levels of damaging earthquakes occurring within a 50-year period. Damage was categorized in terms of settlement ranges, as one of the objectives of this study was to provide estimates of vertical displacements as input to the probabilistic analysis of seismic-induced flooding.

The system of dikes was divided into a series of vulnerability classes using factors that differentiate the expected performance of the dikes subjected to same earthquake hazard. The evaluation of dike vulnerability (fragility) for a given vulnerability class is a function several variables describing dike geometry, soil conditions and as well as the earthquake return period.

The results of a comprehensive geotechnical investigation program have been used to conduct detailed stress-deformation Finite Element (FE) analyses to assess the seismic stability and expected deformations of selected dike segments under various levels of seismic shaking. The results of the FE simulations were processed using an artificial neural network (ANN) approach that allowed the development of predictive relationships for estimating earthquake-induced deformations at a regional level.

Keywords: high-consequence dikes, seismic vulnerability, liquefaction, dike stability, seismic-induced settlements.

INTRODUCTION

The Lower Mainland is a seismically active region and the dikes located along the Fraser River and the coastline are vulnerable to earthquake damage. The seismic vulnerability of these dikes is due to their proximity to riverbanks, where soils are susceptible to liquefaction. Development in the Lower Mainland has increasingly relied on dikes as primary flood protection structures, but insufficient effort has been spent on understanding the seismic vulnerability and implications for ground improvement requirements.

Flood-induced dike failures leading to land inundations have occurred since the last century. The Fraser River flood of 1894 is the largest of written record. Accounts of this flood are limited, but some insights can be found in newspaper articles and in photos collected by the railway companies. At its peak, the water level was estimated at 7.92 meters (nearly 26 feet) at Mission. Dikes and other river structures were overtopped or breached along the river. More recently in the early morning hours of Nov. 16 2021, the Sumas River dike in Abbotsford, B.C., overflowed and later failed, causing swelling rivers to flood agricultural lands in the province. The floods destroyed homes and farms, triggering an estimated $1 billion in damage (Gomez, M., 2021).

There is no evidence to indicate that seismic shaking has ever induced significant damage to Lower Mainland Dikes. This lack of historic damage in the diking system due to seismic events is a result of the fact that no significant seismic events have occurred in the Lower Mainland which could potentially cause damage. Historic records (the last 70 years) however, provide numerous examples of dike damage in other regions cause by earthquakes (Imperial Valley, 1940; Loma Prieta, 1989; Kobe, 1995; New Zealand, 2010 - 2011 Canterbury Earthquake Sequence) when shaking was significantly strong. One challenge that local governments face in building seismic resiliency into their dike upgrade programs is the inadequate information available on geotechnical information and an understanding of the seismic vulnerability under existing conditions.

This paper presents the results of a seismic vulnerability study of the high-consequence-diking-system in the Lower Mainland. The seismic vulnerability was evaluated using prediction models to estimate likely damage levels considering various probability exceedance levels of damaging earthquakes occurring within a 50-year period.

The results of the geotechnical investigations have been used to conduct detailed stress-deformation finite element (FE) analyses to assess the seismic stability and expected deformations of selected dike segments under various levels of seismic shaking.

In order to estimate earthquake-induced deformations at a regional level, the results of the FE simulations were processed to develop a seismic-induced dike-crest-settlement predictive relationship using an artificial neural network (ANN) algorithm. ANNs are well suited to modeling the complex behavior of most geotechnical engineering materials which, by their very nature, exhibit extreme variability. The results of the ANN allowed estimating the sensitivity of dike-crest settlement to various input variables, which included various measures of dike geometry, the fundamental period of vibration of the foundation soils, the depth to firm-ground, earthquake intensity measures, among others.

The system of dikes was divided into a series of vulnerability classes using factors that differentiate the expected performance of the dikes subjected to same earthquake hazard. The evaluation of dike vulnerability (fragility) for a given vulnerability class is a function of several variables describing dike geometry, soil conditions and as well as the earthquake return period.

Damage has been categorized in terms of settlement ranges, as one of the objectives of this study is to provide estimates of vertical displacements as input to the probabilistic analysis of seismic-induced flooding; horizontal displacements can also be estimated using the results of this study.

GEOTECHNICAL INVESTIGATIONS

Background

The study was initiated by collecting and reviewing available geotechnical data from past studies and investigations undertaken or commissioned by local municipalities. One of the objectives of the data review was to identify data gaps and propose a geotechnical investigation program to collect additional information that can be used in this assessment as well as future studies.

The information available consisted of several geotechnical reports, which included borehole and auger hole (AH) logs, cone penetration tests (CPT), seismic cone penetration tests (SCPT), dynamic cone penetration tests (DCPTs), and standard penetration tests (SPTs). The existing information was used to establish the locations and types of the field investigations to be undertaken as part of this study, which consisted of the following field investigation program:

A field investigation program comprising twenty-six (26) SCPT's, fourteen (14) CPT's and nine (9) sampling AH's was carried out as part of the study. The test hole locations and depths are summarized in Table 1.

Locations where more than 1 CPT was pushed are identified with DA (for Detailed Analyses). Other locations with only one CPT will be referred to as screening analysis locations throughout the paper.

Ambient Vibration Tests

The field Investigations included Ambient Vibration Tests (AVTs) at eighteen (18) locations distributed throughout the high consequence diking system. The objective of these vibration tests was to determine the H/V spectral ratio curves and natural frequency of the soil deposit. This information was used to help categorize seismic site classes, estimate the natural frequency of the soil column, and confirm dynamic soil properties and depth to firm ground.

Laboratory Tests

A limited number of laboratory tests were conducted on disturbed samples recovered from the AH's. Laboratory tests included twenty two natural water contents, ten Atterberg limits, and thirty three sieve analyses were carried out for soil classification purposes.

Table 1. Summary of Geotechnical Site Investigation Program.

Test Hole	Municipality	Depth	Test Hole	Municipality	Depth
CPT/AH19-DA1A	Richmond	CPT to 30m AH to 10.7m	CPT19-08B	Pitt Meadows	CPT to 18.3m
SCPT/AH19-DA1B	Richmond	SCPT to 30m AH to 12.1m	SCPT19-09	Township of Langley	SCPT to 30m
CPT/AH19-DA1C	Richmond	CPT to 40m AH to 10.7m	SCPT19-10	Nicomen Island Improvement District	SCPT to 7.8m
CPT/AH19-DA2A	Delta	CPT to 40m AH to 10.7m	CPT19-10B	Nicomen Island Improvement District	CPT to 7.3m
SCPT/AH19-DA2B	Delta	SCPT to 50m AH to 10.7m	SCPT19-11	Pitt Meadows	SCPT to 20.3m
CPT/AH19-DA2C	Delta	CPT to 45m AH to 10.7m	SCPT19-12	Dewdney Area Improvement District	SCPT to 34m
CPT19-DA2D to CPT19-DA2G	Delta	CPT to 15m	SCPT19-13	Nicomen Island Improvement District	SCPT to 32.8m
SCPT/AH19-DA3A	Chilliwack	SCPT to 7.475m AH to 10.7m	SCPT19-14C	Kent/Agassiz	SCPT to 1.4m
SCPT/AH19-DA3B	Chilliwack	SCPT to 7.6m AH to 10.7m	SCPT19-15	Dewdney Area Improvement District	SCPT to 12.8m
SCPT19-DA3B(B)	Chilliwack	SCPT to 7.5m	CPT19-15B	Dewdney Area Improvement District	CPT to 12.4m
SCPT/AH19-DA3C	Chilliwack	SCPT to 7.3m AH to 10.7m	SCPT19-17	Chilliwack	SCPT to 6.0m
SCPT19-01	Richmond	SCPT to 30.1m	CPT19-17B	Chilliwack	CPT to 5.4m
SCPT19-02	Delta	SCPT to 30m	SCPT19-18	Surrey	SCPT to 50m
SCPT19-03	New Westminster	SCPT to 40.1m	SCPT19-20	Chilliwack	SCPT to 3.9m
SCPT19-04	Delta	SCPT to 30m	CPT19-20B	Chilliwack	CPT to 3.7m
SCPT19-05	Coquitlam	SCPT to 40m	SCPT19-21	Kent/Agassiz	SCPT to 6.3m
SCPT19-06	Port Coquitlam	SCPT to 35.1m	CPT19-21B	Kent/Agassiz	CPT to 5.5m
SCPT19-07	Pitt Meadows	SCPT to 30m	SCPT19-22	Harrison Hot Springs	SCPT to 31m
SCPT19-08	Pitt Meadows	SCPT to 18.1m			

REGIONAL SEISMICITY

The seismic site response FE models require the development of earthquake time histories representative of the regional seismic hazard as input. Existing time histories from past earthquakes are commonly modified so that the response spectra approximate a uniform hazard response spectrum (UHRS), obtained from a probabilistic seismic hazard analysis (PSHA). When developing a UHRS, the PSHA calculates the hazard for a specific location by considering the aggregated hazard contribution from individual seismic sources identified in the region.

The seismic design provisions for this study were based on the 5th generation seismic hazard model developed for the National Building Code of Canada of 2015 (NBC 2015) for the three tectonic regimes governing the hazard, i.e., crustal, inslab, and interface.

Time histories were developed for three hazard levels A2475 (2%/50yrs), A475(10%/50yrs) and A100(40%/50yrs) corresponding to outcropping firm-ground with an average shear wave velocity in the top 30 m of soil (V_{s30}) of 450m/s. Representative seed acceleration time histories were selected, then spectrally matched to the UHS of each source. The seed acceleration time histories were obtained from the Pacific Earthquake Engineering Research Center (PEER), Consortium of Organizations for Strong-Motion Observations Systems (COSMOS), University of Chile and S2GM tool databases.

Given the large number of simulations involved, a limited set of seven time histories was used to assess the seismic response at each dike location (Table 2). The motions were selected based on the bracketed duration and Arias intensity.

Table 2. Characteristics of Time Histories Used for this Study.

Return Period (years)	Poe in 50 Years (%)	Seismic Source Type	Bracketed Duration (s)	Motion ID
100	40	Crustal	27.6	RSN3756_LANDERS_MVP_090
100	40	Inslab	9.1	Miyagi_MYG006_EW
475	10	Crustal	38.8	RSN3756_LANDERS_MVP_090
475	10	Inslab	26.2	Miyagi_MYG006_EW
2,475	2	Crustal	50.0	RSN3756_LANDERS_MVP_090
2,475	2	Inslab	44.3	Miyagi_MYG006_EW
2,475	2	Interface	56.8	Tokachioki_HKD181_NS

Depth to Firm-Ground

Determining the depth to firm ground is an input variable required for seismic site response analysis. The seismic hazard spectral accelerations provided in Natural Resources Canada (NRCan) website are representative of Class C outcropping ground conditions with a time-averaged shear wave velocity (V_s) between 360 m/s to 760 m/s in the top 30 m ($V_{s\text{-}30}$) and an assumed average of 450 m/s (NBC 2015). The time histories were linearly scaled to the reference V_{s30} at each dike location, which was found to generally consists of V_{s30} generally varying between 360 m/s and 760 m/s.

The depth to firm ground at those locations where soils within the top 120 m were judged to comprise of Postglacial sediments (i.e., Delta and Richmond), was established using the mean shear wave velocity data presented by Hunter et al. [1]. The V_s database compiled by Hunter et al. indicate that postglacial sediments in the Lower Mainland within the area of study have been found to have a V_s, on average, of about 360 m/s at a depth of about 120 m below ground surface. At those locations where Pleistocene soils (or older deposits) with $V_{s\text{-}30}$ greater than about 450 m/s are located within the top 120 m, Class C conditions were stablished using various sources of information:

- Results of horizontal-to-vertical (H/V) spectral ratios recorded as part of this project complimented with additional measurements provided by Western University as part of their seismic microzonation study (https://metrovanmicromap.ca/).
- Historical borehole information in Golder Associate's archives
- Borehole information available in the BC Groundwater Wells and Aquifers Database (https://apps.nrs.gov.bc.ca/gwells/).
- Geology maps.
- Effective refusal depths during SCPT pushing.
- Interpolation between data points.

At dike locations where the depth to firm ground was deeper than about 30 to 50 m, seismic motions were propagated to the base of the 2D dynamic models (PLAXIS) developed to simulate the seismic response of dikes using 1D site response analyses in the time domain using non-linear models. In this case, the motions were input at the base of the PLAXIS model (located about 30 m below ground surface) as "within" motions.

In those instances where the depth to firm ground was relatively shallow (less than 30 m), the motions were directly applied at the base of the 2D dynamic PLAXIS models using a compliant base boundary condition.

NUMERICAL SIMULATIONS

Background

The response of the selected dike locations under dynamic shaking were evaluated using the program PLAXIS 2D. PLAXIS 2D is a computer program that performs finite element (FE) analyses for geotechnical engineering applications, including static and dynamic deformations coupled with water flow. The program can model 2D plane strain and axisymmetric soil-structure systems.

PLAXIS offers the advantage of allowing calculation phases simultaneously using parallel processing when these phases are independent. The program's calculation kernel can do the matrix decomposition over multiple CPU cores, making calculations with advanced soil models faster, particularly for calculation phases that required many steps (e.g., dynamics). The PLAXIS software further provides a hypertext transfer protocol (HTTP) based Application Programming Interface (API), for which a special Python wrapper was developed for an easy-to-use scripting API. Both PLAXIS Input and PLAXIS Output support this usage of a remote scripting server. The ability to use of multiple CPU cores and the flexibility to use remote scripting with Python are the two main reasons why this software was adopted over other commercially available FE or finite difference (FD) programs, as it lends itself for batch processing under multiple time history inputs.

Design Soil Properties

One of the principal objectives of the seismic site response analyses was to evaluate the cyclic response of soils when subjected to seismic shaking and to identify the potential for large displacements to develop as the soil liquefies and/or softens. The geotechnical characterization focused on differentiating between those soils that could be prone to liquefaction and exhibiting a sand-like behavior from soils expected to exhibit a clay-like behavior.

Previous studies (Idriss and Boulanger [2]; Sancio and Bray [3]; Seed et al. [4]) found that the transition between sand-like and clay-like soils may be established using the soil's Plasticity Index (PI). Currently available CPT semi-empirical methods exhibit a significant variability in the estimation of soil type. The probabilistic CPT-based soil characterization methodology presented by Cetin and Ozan [5] was used to obtain estimates of PI, which were later used to differentiate soils with sand-like from clay-like behavior. The method of Cetin et al. was favored as it addresses uncertainty and was found to correlate favorably with measurements of PI obtained at the detailed locations.

Constitutive Models

PLAXIS 2D includes the PM4Sand model (Boulanger & Ziotopoulou [6]) as a User Defined Soil Model for simulating soil liquefaction. Materials characterized as exhibiting a sand-like behaviour were modelled using PM4Sand.Another model included in PLAXIS is HS Small (Benz, 2007 [7]) which accounts for the increased stiffness of soils at small strains. The HS Small model was used to simulate the cyclic behaviour of soils characterized as exhibiting a clay-like behaviour with no strength reduction during earthquake shaking due to development of excess pore water pressure.

A model validation exercise was carried out to assess the performance of chosen constitutive models (PM4Sand and HS Small) and their calibration. One-dimensional site-response analysis were conducted in PLAXIS using data from the Treasure Island case history where surface motions were recorded during the 1989 Loma Prieta earthquake, in California.

Design Water Levels

Establishing a groundwater flow regime through the dike is important in seismic site response analyses, particularly if loose granular soils become saturated as they could be prone to liquefaction. Dike embankments and foundations primarily composed of low hydraulic conductivity materials (e.g., clay and clayey soil) or recently constructed dikes with engineered fill and low permeability dike core materials that are subjected to periodic high water events could constantly be experiencing transient groundwater flow conditions. Nevertheless, a common assumption in ground response analyses is to assume a steady-state flow regime.

Two-Dimensional Finite Element Models

A total of seven (7) ground motions were considered for the numerical model at each dike location (Table 1) and water levels corresponding to the mean annual and 1-in-200-year flood elevations were applied (Toable 2) to the model. A total of 322 numerical simulations were performed to evaluate the seismic dike performance in terms of the permanent dike crest displacement for detailed and screening locations. An additional 400 simulations that evaluated specific model variables, and don't necessarily represent a physical dike location, were carried as part of an effort for developing a predictive model for performing a regional assessment. Figure 1 shows the typical PLAXIS model, soil layering, constitutive model assignment, applied water level, and meshing for one of the studied dike locations.

The displacements vary considerably across the dike, and each grid node within the FE model would provide a distinctive displacement vector with corresponding horizontal and vertical components. To select one single value for use in the predictive relationship, a representative total dike crest settlement and horizontal displacement was obtained by considering the maximum displacement vector within a rectangular zone bounded laterally by the limits of the deformed dike crest, and horizontally by the top and bottom boundaries of the deformed dike body. There could be other zones outside this area where larger displacements are predicted to occur, but the purpose of the study was to evaluate the loss of freeboard, which will increase the likelihood of flooding due to overtopping (or flooding due to dike crest erosion if deformations are large and assessed to result in development of cracks within the dike leading to eventual breaching).

Figure 2 shows the variation in total horizontal and vertical displacements in the longitudinal direction of the dike at one of the analyzed dike locations for all seven earthquake ground motions for the mean annual water level. Lateral displacements are generally greatest within the waterside slope, whereas vertical settlements are greater near the toe of the dike crest, or top of the failure mechanism. As illustrated, a representative total dike crest settlements and horizontal displacement is obtained by taking the maximum displacement components within a limited extent of the dike crest.

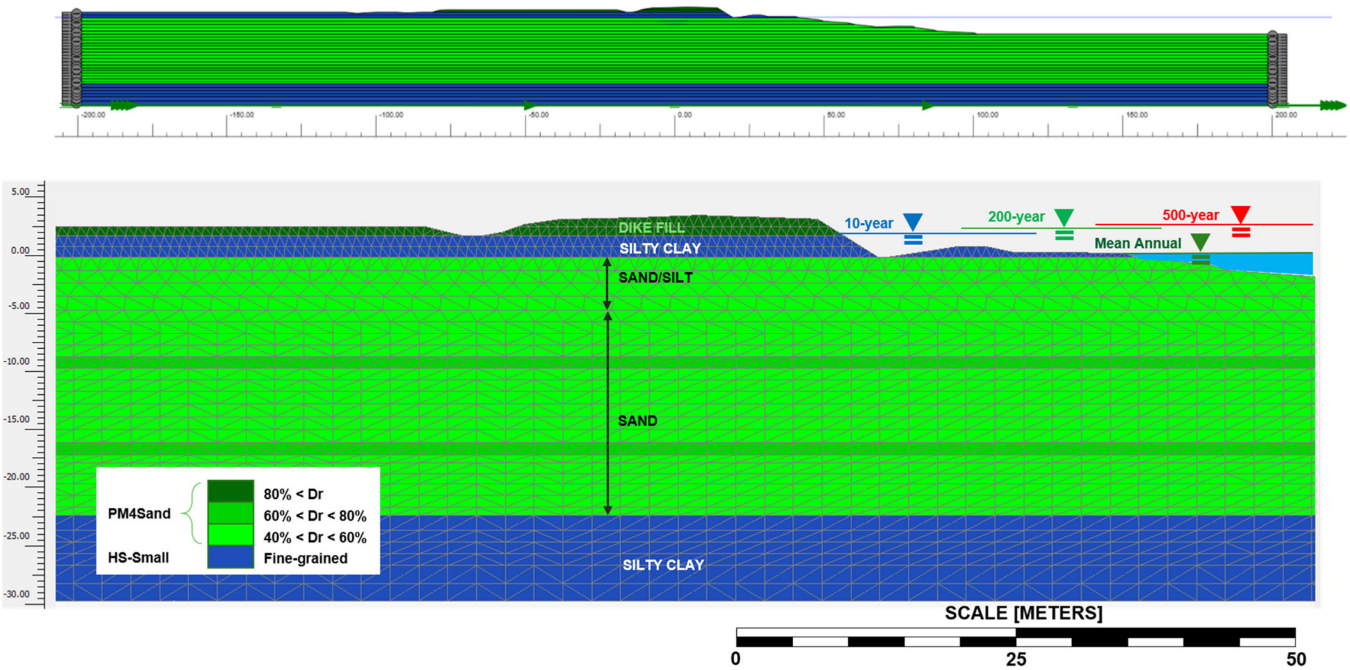


Figure 1. Example of typical PLAXIS cross section and distribution of constitutive models.

The collective analyses performed for this dike location for different water levels, return periods, and seismic sources are summarized in Figure 3 with respect to maximum total and post-liquefaction settlements as measured at the dike crest. Although various Intensity Measures were considered to correlate to dike crest settlement, PGV was selected based on the observation by Kwak et al. (2016) that dike damage, as expressed in terms of dike subsidence, presents a modestly lower dispersion when compared to PGA.

DEVELOPMENT OF A RESPONSE PREDICTION MODEL

One of the main objectives of this study was to develop predictive relationships between dike crest displacements (response) conditioned on various parameters assessed to influence the response. To achieve this objective, three categorical types of models were considered: a simple linear statistical procedure using a Response Surface (RS) approach, a second simple approach based on multilinear regression, and a third more sophisticated model based on artificial neural networks (ANNs) as part of a broader family of machine learning methods. Only the results obtained using the ANN are presented herein.

While peak acceleration and Arias intensity have historically been used to characterize the response of engineering systems, other ground motion parameters could, in concept, be used to characterize a system's response for seismic hazard evaluations. Intuitively, parameters affecting the response include earthquake IMs, the geometry of the dike section (i.e., steeper slopes are expected to experience higher displacements all else remaining equal), water elevation, and soil properties (i.e., liquefied versus non-liquefied soils). In practice, however, finding the optimum variables can be a difficult task requiring an iterative trial and error screening procedure. With such procedure, the predictive capabilities of the model would have to be assessed under different assumptions, and the variables observed to result in the least amount of dispersion in the predicted response then ranked and selected.

Selection of variables are also guided by notions of 'efficiency' and 'sufficiency' (Kramer et al., 2006). 'Efficiency' of a given unbiased estimator can be evaluated based on the dispersion of residuals about a 1:1 correlation between the predicted and measured responses (i.e., standard deviation or R^2 value). For example, a small standard deviation or high R^2 is an 'efficient' variable. A 'sufficient' variable generally refers to one that is independent of other quantities (e.g., earthquake magnitude and dike geometry, etc.). This section summarizes the procedure used to select the model variables.

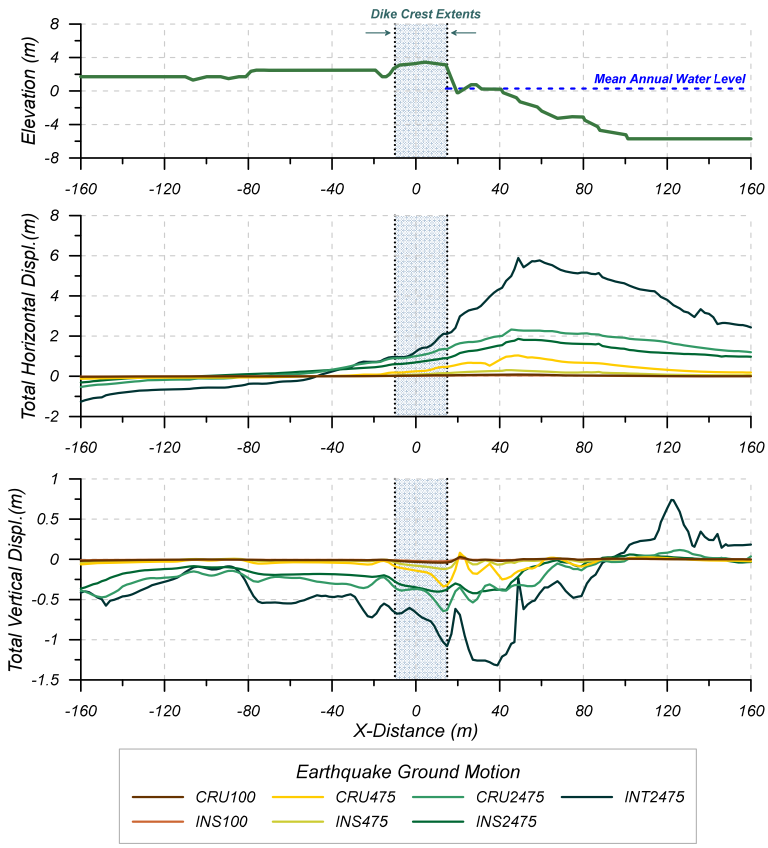


Figure 2. Total horizontal and vertical displacement with model distance for different earthquake ground motions at one of the analyzed dike locations, for mean annual water level.

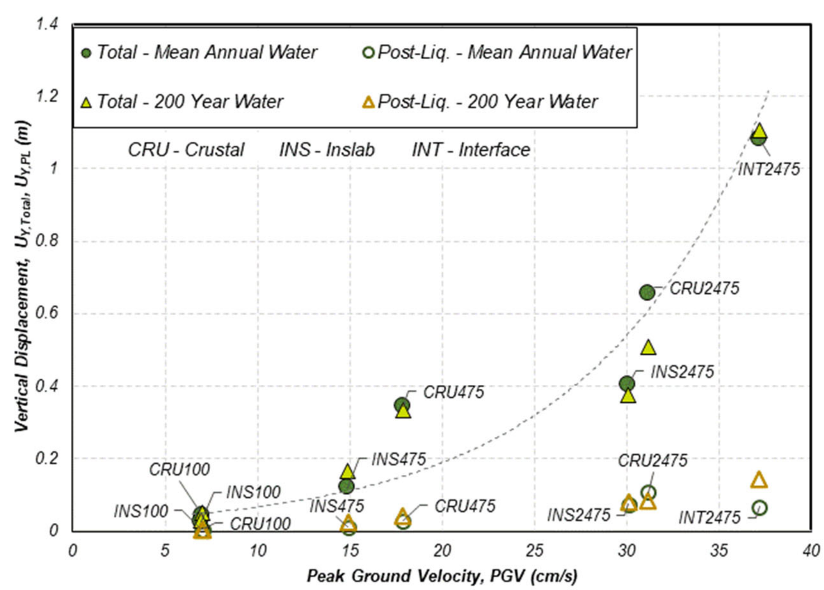


Figure 3. Summary of total and post-liquefaction settlement at one of the analyzed dike locations.

Response Model Variables

The main variables expected to affect the seismic response leading to settlement of the dike crest and loss of freeboard are postulated to be:

- Earthquake shaking intensity level represented by an Intensity Measure (IM), which could be any one of a number of ground motion parameters (e.g., peak ground acceleration PGA, peak ground velocity PGV, Arias intensity, etc.) that describe the motion applied to a give dike
- Water elevation on the waterside of the dike
- Local soil conditions
- Dike geometry

Identification of optimal variables was accomplished by examining the efficiency between the model predictions for different candidate variables. Before initializing this trial-and-error modelling process however, prior models presented in the technical literature for predicting lateral spreading and slope displacements were reviewed, and input variables to those existing models examined.

Screening of Model Variables

As mentioned previously, the selected response parameter for dike seismic performance is the total dike crest settlement ($U_{y,Total}$), which includes the contributions from dynamic and post-reconsolidation components. In order to identify optimal variables for the evaluation of $U_{y,Total}$, more than 30 candidate variables were investigated. These included ground motion parameters such as PGA, Arias intensity, bracketed duration, CAV_5, and PGV, the ratio of the soil's fundamental frequency to the frequency content of the input motion, duration of earthquake ground motions, which are used directly as input to the PLAXIS models, other parameters that reflect various aspects soil properties including fundamental period, cumulative thickness of liquefied layers, lateral displacement index (LDI, Idriss and Boulanger, 2006), the cumulative summation of post-liquefaction vertical strains over several depth intervals (S_{v-1D}, Idriss and Boulanger, 2006) and various dike geometry parameters.

Earthquake Intensity Measures

Initial sensitivity analyses were carried out to identify suitable IMs representing seismic demand. A preliminary purview considered different IM metrics, including 5% damped elastic spectral accelerations (S_a(T)), peak ground acceleration (PGA), Arias intensity (I_a), bracketed duration (T_d), significant duration (D_{5-95}), peak ground velocity (PGV), peak ground displacement (PGD), cumulative absolute velocity (CAV), and cumulative absolute velocity after application of a 5 cm/sec2 acceleration threshold (CAV_5), and earthquake magnitude (M) amongst others. These metrics were evaluated for firm ground or Class-C conditions (actual input into the process model), as well as corresponding to level free-field (FF) conditions at the surface (as obtained through intermediate calculations with 1D DeepSoil models).

Figure 4 illustrates the efficiency of various IMs as evaluated by R^2 scores for two flood levels at three locations, as well as for the median of R^2 scores across all sites. In the figure, 'FF' denotes IM metrics computed relative to free-field conditions (for level ground surface), whereas 'Class-C' indicate IM metrics computed relative to firm ground conditions (at the base of the model). A higher R^2 means that a particular IM is generally more efficient in capturing the variability about the mean regression for the dataset.

The results illustrate the correlation of $U_{y,Total}$ and the various intensity measures from which an optimal IM can be selected. Notably, the DA3 (refer to Borehole ID in Table 1)) location which is characterized by a short period or 'stiff' response has higher R^2 with PGA and short period S_a(T). In contrast, at DA1 and DA2 sites which are characterized by a long period or 'soft' response, PGV and long period S_a(T) tend to have higher R^2 values. It is noted that the majority of IM metrics shown in Figure 4 are statistically significant for a significance level of 0.05 (i.e., $p < 0.05$). Exceptions exist for select locations and IM combinations, however in such cases, R^2 tend also to be low scoring (e.g., PGD and D_{5-95} for DA3).

Ultimately, PGV was selected as the primary intensity measure based on consideration of performance-based case histories, internal evaluations, and concepts of efficiency and sufficiency and superior predictability. In addition, a key consideration for the selection of PGV was the ability to spatially forecast their values for different exposure levels throughout the Lower Mainland using the Canadian 5th Generation Seismic Hazard Model.

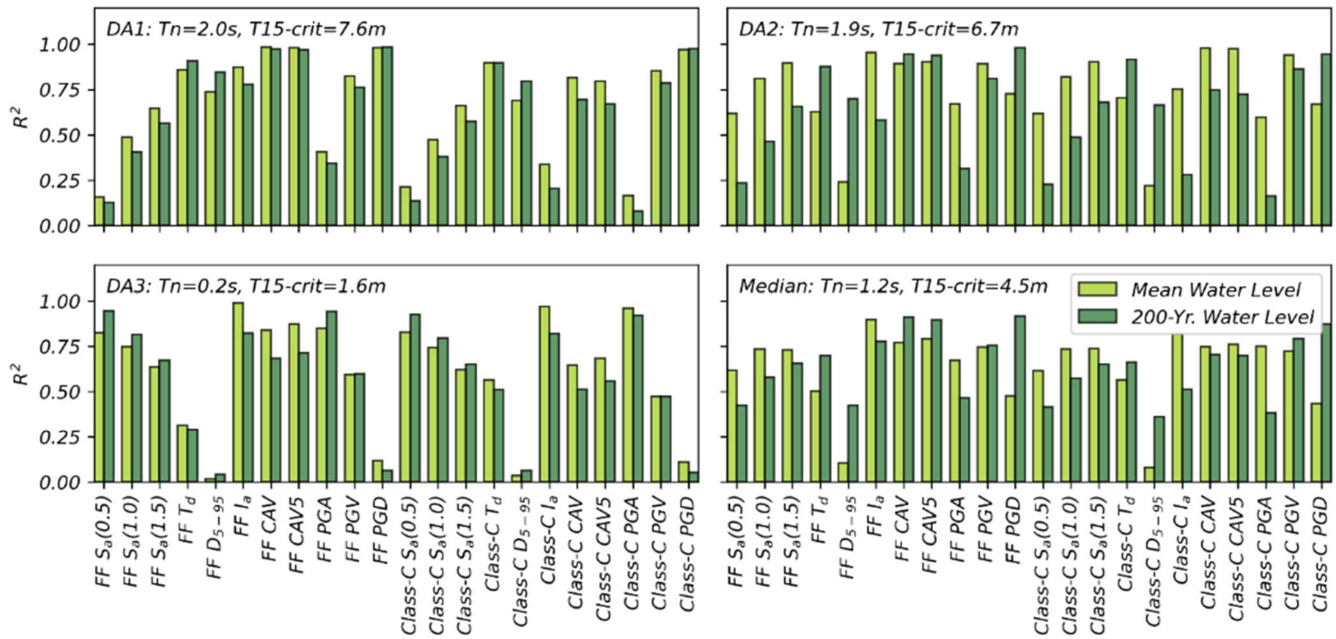


Figure 4. Efficiency of select IM metrics for mean and 200-year flood levels at three site locations (DA1, DA2 and DA3 in Table 1), and for the median of scores from individual sites as assessed by R^2. FF denotes free field, as in earthquake IMs correspond to level ground surface conditions. Class-C indicates that earthquake IMs correspond to the input base reference condition.

Dike Geometry

The selected dike geometry parameters (summarized in Figure 5) were found to be adequate for providing a reasonable approximation to the majority of site geometries obtained from the Lower Fraser River digital elevation model (DEM). The DEM was derived from a combination of underwater bathymetric surveys and topographic LiDAR data. The selection of geometry parameters was limited to actual descriptive inputs as used in analyses to preserve fidelity, consistency, and improve correlation with the overall process model used for generating data points.

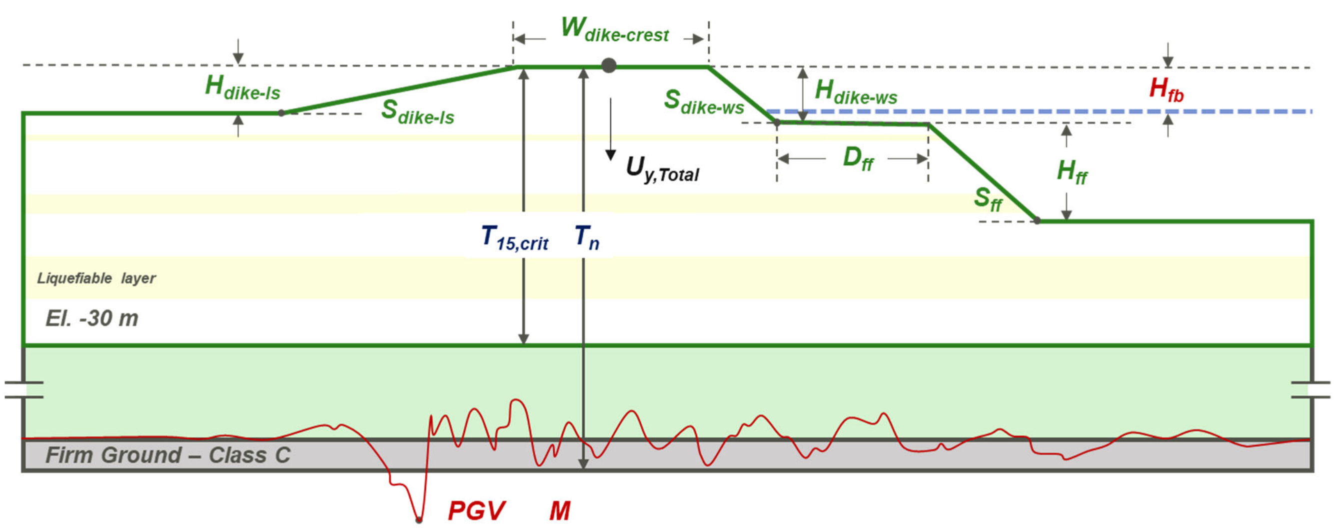


Figure 5. Schematic of response model input parameters.

Summary of Selected Model Variables

As previously explained, the ANN input parameters were selected through an iterative trial and error process. The primary aim was to develop a set of independent and sufficient variables, that are comprehensive enough for generalizing/parameterizing a wide variety of dike scenarios representative of the Lower Mainland. A further objective was to avoid parameter complexity or coupling (i.e., parameters conditioned on intermediate calculations or collinear variables) to maximize utility and ease of applying an ANN in forward predictions. Lastly, selection of parameters was limited to actual descriptive inputs as used in analyses to preserve fidelity, consistency, and improve correlation with the overall process model used for generating data points. The explicit loading parameters are peak ground velocity (PGV) of the earthquake associated with firm ground at the base of the model (as defined previously), earthquake magnitude (M), and freeboard (H_{fb}) associated with a given flood level. The soil parameters consist of a set of proxy parameters for strength against liquefaction and stiffness as captured by a cumulative critical liquefaction thickness parameter ($T_{15,crit}$), and the period of the soil column (T_n) associated with firm ground conditions (i.e., at the base of the model). The dike geometry parameters include descriptors for shape of the main body of the dike, including the dike crest width ($W_{dike-crest}$), the landside height ($H_{dike-ls}$) and slope ($S_{dike-ls}$), and waterside height ($H_{dike-ws}$) and slope ($S_{dike-ws}$). In addition, the geometry parameters include descriptors for a free face if present, as characterized by a distance from free face to dike body base (D_{ff}), height of free face (H_{ff}), and slope of free face (S_{ff}).

PREDICTIONS FROM RESPONSE MODEL

Supervised machine learning techniques based on ANN algorithms were used for developing a response model to relate total dike crest settlement $U_{Y,Total}$ to the various response parameters previously introduced. The results of the response-model are presented in Figure 6. Lines for 2:1/1:2 envelopes are also drawn for reference. Most data (approximately 70%) fall within the 1:2/2:1 with about 90% of the data residing below the 1H:2V line. This would indicate that predicted displacements are generally valid within a factor of 2 and that doubling the predicted displacement provides an estimate with approximately a 10 percent exceedance probability (i.e., 10% of the predicted displacements when doubled would still fall below the actual values from PLAXIS simulations).

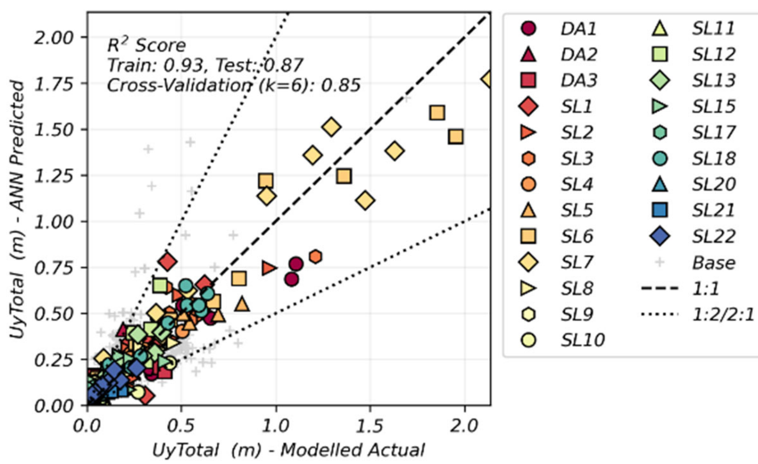


Figure 6. Comparison of predicted vs. actual total dike crest settlements using the ANN model. Grey symbols represent additional dike geometries that evaluated the effects of individual input variables on the response.

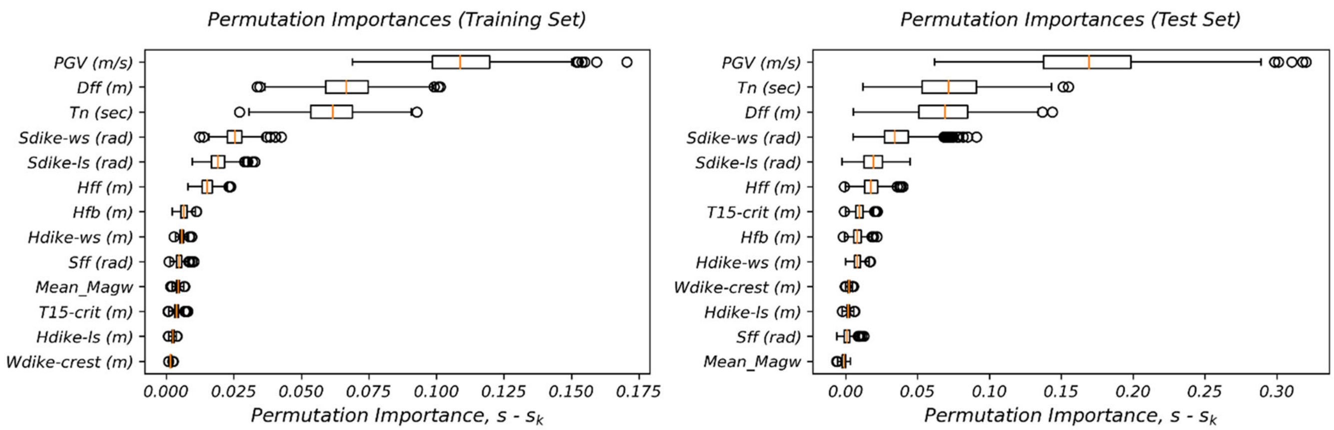
The scatter observed in the ANN model predictions is not uncommon in ground displacement models (e.g., see Youd et al. 2002) and reflect the complexity involved in predicting the seismic behaviour of geotechnical systems.

Permutation Feature of Importance

The permutation feature importance is evaluated for the ANN model to examine how important a specific input variable or feature is to make correct predictions. The permutation feature importance is calculated by measuring the increase in prediction error of a model when the values of a given feature (e.g., ground motion IM, site condition, dike geometry, etc.) is shuffled, i.e., permuted independently before making the prediction. If a feature (or variable) is 'important', then the model error will increase when the values are permuted because the model relies on this feature for making correct predictions. In contrast, a feature which is unimportant or insignificant should result in no or relatively small prediction errors from shuffling its values. By repeating this calculation for each feature, they can be ranked in terms of their relative importance.

Figure 7 presents the feature importance's as computed with the ANN model for the training and test sets. The total datapoints were split into a training set and a testing set. 80% for training, and 20% for testing. The ANN model was trained using the training set, while the accuracy of the model to predicted actual calculated displacements is verified using the testing set. The x-axis shows the permutation importance (i.e., error of model with permutated feature – error of original model with unpermuted feature) with respect to the negative mean squared error. The y-axis shows the features, ranked in terms of increasing error. The higher the rank, the larger the permutation importance, and the worse the predictions would be should that feature were to be removed from the model.

The salient observations to be made from Figure 7 are that PGV, T_n, in addition to some dike geometry parameters as being amongst the most important factors for correctly predicting dike crest settlement $U_{Y,Total}$. In addition, the similarity in rankings of feature importance between training and test sets indicate reasonable generalization behavior. Some differences are to be expected by virtue of differences between the size of training and test sets (i.e., 80/20 train/test split). Nonetheless, the four most significant features identified from the data analysis are identical between the training and test sets.



(a) *(b)*

Figure 7. Permutation feature importance: (a) training set, (b) test set. Error bars show median and standard deviation. Circles indicate outliers.

PREDICTIONS OF DAMAGE FOR DIKE SEISMIC VULNERABILITY ASSESSMENT

The results of the ANN model presented in the previous sections may be used to predict seismic-induced dike settlement as a function of a selected set of input variables. The seismic vulnerability of a dike is a measure associated with its "weakness" against earthquake shaking, so that assigning a quantitative descriptor would allow evaluating the expected damage severity from future earthquakes. Establishing the vulnerability of a given dike requires criteria relating expected post-earthquake performance, i.e., dike settlements, and damage level caused by such deformations.

Kwak et al. (2016), classified damage severity in five levels for 50 m (in length) dike segments using a dike field-performance case-history database from past earthquake along the Shinano River in Japan. These damage criteria were selected by Kwak et al. in consideration of data documented by the Shinano River Work Office (SWO, 2007 and 2008) following the 2004 M6.6 Niigata-ken Chuetsu and 2007 M6.6 Niigata-ken Chuetsu-oki earthquakes in Japan. As reported by Kwak et al. (2016), the damage levels they proposed also involved expert judgment regarding likely impact on post-event dike functionality.

Table 3. Damage States Assigned to Dike Segments (Modified from Kwak et al. 2016).

Damage State Index	Description	Dike Crest Subsidence ΔH (cm)
0	No damage reported	0 – 2.5
1	Slight damage, small cracks	2.5 – 5
2	Moderate damage, cracks, or small lateral spreading	5 – 15
3	Severe damage, lateral spreading	15 – 50
4	Levee collapse	>50

Damage state indices presented by Kwak, were developed for a certain range of dike heights, which are not necessarily the same heights of dikes present in the Lower Mainland. Since damage is expected to be a function of the initial dike height (e.g., Swaisgood 1998), the criteria presented by Kwak et al., was modified so that subsidence for a given damage state index corresponds, on average, to approximately the same $\Delta H/H_o$ ratio where ΔH is the subsidence, and H_o is the initial waterside dike height. Average Shinano River dike heights range from 4.5 m to 5.7 m in upstream and downstream areas, respectively, so the subsidence associated with damage level 4 (i.e., >100 cm) corresponds to about 17% to 22%? of the dike height.

The different dike geometry variables were calculated for this project using available topographic and LiDAR data at 168 sections using intervals of 2 km or less. The dike height in the upstream ($H_{dike-ws}$) and downstream ($H_{dike-ls}$) were processed and it was found that about 50% of the data ranges from 1.2 to 3.2 m downstream and from 1.5 to 4.0 m upstream. Perhaps coincidentally, the data indicates that on average, Shinano River Dikes are about twice as high as the High Consequence Dikes consider in this study. Therefore, half the total dike subsidence presented by Kwak, was considered to cause the same level of damaged when applied to the Lower Mainland High-Consequence Dikes. The damage criteria adjusted from Kwak is presented in Table 3.

It is emphasized that this study focused on the seismic vulnerability (i.e., vulnerability of a diking system to earthquake induced damage and associated displacements), but not the vulnerability to flooding. The effect of seismic displacements would contribute to a formal risk assessment of flooding following earthquake-induced deformations. The deformations would increase the vulnerability to flooding by reducing the effective dike height or by introducing other associated damage mechanisms that would weaken the flood protection ability of the diking system, which must be considered with respect to the design river/storm water level.

SEISMIC VULNERABILITY MAPS

Seismic vulnerability calculations were performed for select dike segments throughout the network of High-Consequence Dikes in the Lower Mainland for four seismic probabilities of exceedance of 40%, 10%, 5%, and 2% in 50 years, which correspond to return periods of 100, 475, and 1000, and 2,475 years. Due to space limitations the maps are not presented in the paper but have been included in [14].

Based on damage categories obtained for a seismic hazard with an exceedance probability of 2% in 50-years (2,475-year return period), 66% of the dike segments (constituting the majority of the dikes) fall in the extreme damage category (Category 4), 23% are in the severe damage category (Category 3 with 15 cm ≤ ΔH ≤ 50 cm) and the remaining 11% are in the moderate to no damage categories (ΔH ≤ 15 cm). Using the deformation criteria presented in the Ministry Guidelines (MFLNRO, 2014), the maximum allowable vertical displacement for a 2,475-year return period (Earthquake Shaking Level 3 (EQL-3) shaking level in the Ministry Guidelines) is 0.5 m. In total, 66% of the dike segments would not comply with the Ministry Guidelines deformation criteria corresponding to EQL-3 shaking level.

A similar assessment may be made for the damage categories corresponding to a seismic hazard with a probability of exceedance of 10% in 50-years (475-year return period), where 27% of the dike segments fall in the extreme damage category (Category 4), 21% are in the severe damage category (Category 3 with 15 cm ≤ ΔH ≤ 50 cm) and the remaining 52% are in the moderate to no damage categories (ΔH ≤ 15 cm). Using the deformation criteria presented in the Ministry Guidelines, the maximum allowable vertical displacement for a 475-year return period (EQL-2 shaking level in the Ministry Guidelines) is 0.15 m. In total, 48% of the dike segments would not comply with the Ministry Guidelines deformation criteria corresponding to EQL-2 level of shaking.

It should be emphasized that a given damage state will not necessarily indicate whether a dike has failed or not. In general, failure condition does not necessarily imply complete collapse, as it may also refer to the failure of the system to meet its intended function. In the context of flood-protection dikes, failure will be considered as any condition which compromises the flood-protection ability of the dike. This may occur due to a complete collapse of the dike body, or in less severe cases, due to the development of small or moderate cracks within the near surface areas of the dike body combined with a loss of the minimum required freeboard. Calculating this probability of failure would involve considering the water levels on the upstream side of the dikes and the probability that such levels will exceed the effective damaged dike height (i.e., available freeboard against flooding following a damage earthquake) during a given recovery time. The recovery time is the time, following strong shaking, that would take to repair the dike to its initial condition before the earthquake occurred or also to an enhanced condition with respect to the pre-earthquake state.

CONCLUSIONS

The present study represents the first quantitative regional assessment of dike vulnerability to seismic displacements, and a significant progress in the understanding of the seismic vulnerability of the system of high-consequence dikes in the Lower Mainland. The estimates of probable seismic-induced dike crest settlements allow the vulnerability maps to be used for damage estimation, emergency planning and preliminary screening and engineering design.

The results of this study, specifically at locations where no FE analyses or data were collected and displacements estimated with the ANN model, largely represent a screening-level assessment, and are not intended to override more comprehensive and detailed site-specific analyses, which should comply with Ministry guidelines. However, the FE analyses performed at detailed and screening locations in this study (DA and SL as locations indicated in Table 1), and where site data was also collected may be considered as comprehensive.

The complexity of the analyses undertaken evolved over time as the author's understanding of the seismic behaviour of dikes was progressing and different hypotheses were being tested. The development of an ANN algorithm to predict seismic-induced settlements constitutes an important tool that could be used to develop system-response curves (fragility curves), which combined with water elevations and their return periods can be used to perform formal risk-based assessments considering the consequence flooding over a given exposure period.

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