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A method for calculating the time-dependent probability of failure of flood-protection dikes due to seismic loading and subsequent overtopping

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ABSTRACT

This paper presents a methodology to assess the time-dependent (e.g., annual) probability of dike breach and resultant flooding considering the effects of potential seismic-induced settlements and damage of a flood-protection dike, focusing on the Vancouver BC (Canada) region.

An example is presented where dike settlement resulting from particular seismic hazard at the site (using the fifth generation Probabilistic Seismic Hazard Model (PSHA) developed by Natural Resources Canada) was estimated using a custom-developed neural net algorithm that was previously developed from a large number of non-linear two-dimensional finite element ground response analyses for relevant ranges of select input parameters. The conditional probability distribution of crest vertical settlement for each of a comprehensive/non-overlapping discrete set of possible ground motions was then determined by Monte Carlo simulation of the settlement algorithm with assessed correlated probability distributions of the other dike/site/seismic input parameters. This conditional probability distribution of settlement for a particular ground motion was then combined with the time-dependent probability of that ground motion being the maximum (as determined by PSHA) to sequentially determine: 1) the time-dependent unconditional probability distribution of maximum crest vertical settlement; 2) combined with the time-dependent unconditional probability distribution of maximum water level, the time-dependent unconditional probability distribution of minimum dike freeboard; 3) combined with the seismically-degraded 'overtopping fragility curve' (including its uncertainty), the time-related unconditional probability of dike breach and subsequent flooding of the dike-protected area until the dike has been adequately repaired; and 4) combined with the recovery time (including its uncertainty), the average annual unconditional probability of dike breach and subsequent flooding of the dike-protected area, and its increase relative to the 'aseismic' case.

This information, combined with assessments of flood damages if flood-protection dike breach occurs, can then be used to defensibly identify, evaluate and recommend/approve dike improvements (if any) to cost-effectively manage dike seismic risk.

Keywords: Dike Assessment, Liquefaction, Seismic-Induced Settlements, Seismic Dike Vulnerability, Seismic Risk Assessment of Dikes

INTRODUCTION

Historically, significant development has occurred adjacent to water ways. Flood 'hazard' (i.e., the time-related probability of various magnitudes of flooding, especially in terms of depth) is a natural process in many these locations (although it may be changing with the climate over time). Such flooding can result in substantial consequences, including: casualties and damages to property, infrastructure and environment, with subsequent disruption of services and society until the damages have been repaired (all at some financial cost) and the affected area has adequately recovered. Flood 'risk' is the combination of: a) the probability of various potential flood magnitudes occurring during a particular time period; and b) the consequences if such flood magnitudes occur. Such flood risk is often at least partially 'mitigated' by protective dikes, among other actions (e.g., zoning, insurance, dredging, etc.), which reduce (relative to no dike) the probability of flooding the dike-protected areas (except for possibly very large infrequent floods) during a particular time period. Dikes therefore provide a specific level of flood protection and thus flood risk. That remaining flood risk can be quantified in terms of: a) the time-related probability of various specific dike-protected-area flood magnitudes occurring; and b) the consequences of each of those flood magnitudes occurring. If the flood risk of an existing unchanged dike is considered to be too high, the dike can potentially be improved (e.g., raised, made less erodible, etc.) to cost-effectively reduce that flood risk, i.e., each additional dollar spent on improvements should reduce the risk by at least another dollar (monetizing the various types of consequences). However, in seismically active areas, the existing dike could be damaged in the future by seismic events (among other potential dike-damaging events and processes). Such dike damage would increase (relative to the existing dike) the time-related probability of various dike-protected-area flood magnitudes and thus flood risk, until that dike damage has been adequately repaired/recovered. If the additional flood risk associated with seismicity is considered to be too high, the dike can potentially be improved (e.g., raised, ground-treated, etc.) to cost-effectively reduce that particular additional flood risk.

The time-dependent probability of dike breach and resultant flooding of the dike-protected area is a function of the time-dependent probability distribution of the minimum dike 'freeboard' (i.e., the minimum dike crest elevation minus the maximum water elevation at any time over the time period of interest). Once freeboard has reduced to zero, overtopping starts to occur at higher water levels (negative freeboard). It is often simplistically assumed that dike breach will occur if any overtopping occurs, and not occur if overtopping does not occur. However, dike breach can occur without overtopping and does not necessarily occur with some overtopping, generally depending on erodibility of the downstream slope and crest. The probability of dike breach as a function of freeboard is termed the 'overtopping fragility curve'. The time-dependent probability of dike breach is then simply the integration of the time-dependent probability distribution of minimum dike freeboard (typically a simple function of the time-dependent probability distribution of the maximum water level, where the dike crest is relatively static) and the overtopping fragility curve. However, the dike crest is not necessarily static and can settle and crack under seismic loading and/or become more erodible (increasing the overtopping fragility) for a time, until it has been adequately repaired and restored. Other processes, e.g., embankment instability possibly triggered by upstream slope erosion due to riverine flow and/or waves, can similarly cause dike crest lowering and damage, but are not considered here. Also, the conjunction of a significant seismic event and high water, which could cause an immediate dike breach, is extremely unlikely for most flood protection dikes (and thus typically ignored) and is also not considered further here.

This paper presents an analytical method for assessing the following: a) the time-related probability of dike 'breaching', leading to significant flooding of a dike-protected area for an existing (unchanged or changed by plan) dike without considering seismicity ('aseismic' case); b) the time-related probability of existing (or planned) dike breaching, explicitly considering seismicity and its repair; and c) the increase in time-related probability of existing (or planned) dike breaching, considering seismicity and its repair. These assessments can then be used, along with assessments of the dike-protected-area flood from a dike breach and its related consequences, to help make logical and defensible decisions on dike improvements in cost-effectively managing flood risk.

CONCEPTS

There are various ways of calculating the risk of flooding dike-protected areas caused by seismic shaking [1,2,3]; however, the methodology presented herein is meant to provide a suitable approach for a probabilistic-based design and to achieve consistency and uniformity in assessment of dike-protected-area flood probabilities resulting from seismic shaking. Other more rigorous calculation methods might be more suitable and could be used for more complex cases.

In the context of this methodology, failure of a dike is defined as any loading condition that significantly compromises the flood-protection capability of such dike; failure would lead to dike breach and large-scale flooding of a protected area, whereas simple overtopping without breach would lead to much smaller scale flooding of a protected area and is not considered a failure. Such failure could occur after seismic shaking due to major instability or complete collapse of the dike body, or in less severe cases, due to settlement of the dike crest that could lead to overtopping and/or the development of cracks and preferential flow paths that could result in internal erosion. Dike failure can also occur when the water levels simply exceed the available freeboard causing surficial erosion, or due to dike instability or internal erosion during high water (as well as prior to high water, also resulting in decreased flood protection until recovered), which can develop in the absence of earthquake loading[1].

[1] Other failure modes include: erosion of the water-side slope of a dike due to strong river currents or wave loading, or possibly excavation; open desiccation cracking in clayey soils (e.g., 1997 flood of record in Grand Forks, North Dakota [2]); "internal erosion", which describes erosion of soil particles by water passing through a body of soil (i.e., the dike, foundation, embankment-foundation interface, dike-embedded structures such as conduits or pump stations, and other preferential flow channels besides cracks in the crest, e.g., from animal burrows); and embankment instability, e.g., slip on foundation/embankment or abutment/embankment interface, foundation (soft-soil) bearing failure, or embankment slope failure.

Although the contributions of all the potential failure modes to the overall probability of dike breaching and dike-protected area flooding, when they exist, should be accounted for in the overall analyses [2], this paper focuses on the probability of dike breach due to overtopping, considering seismicity.

The logic of assessing dike-protected-area flood damage specifically for overtopping, including seismic impacts, is presented in Figure 1:

- *Consequences* (green boxes) - The dike-protected flood damage is calculated as a function of: a) the dike-protected flood scenario that occurs, which in turn is a function of the dike breach scenario (the focus of this paper), including the water elevation at breach and breach geometry, and the hydraulics of the dike-protected area; and b) the 'vulnerability' of that area to such flood scenarios, which in turn is a function of the population, property, infrastructure, services and environment in that area and their flood 'damage-functions' (e.g., mortality curves, including consideration of warning and response).
- *Dike breach* (blue boxes) – The dike breach scenario, specifically for overtopping, is calculated as a function of: a) the minimum dike 'freeboard', which in turn is the difference between the maximum water elevation scenario and the minimum dike crest elevation scenario, either existing or planned, with or without seismic impacts; and b) the 'fragility' of the dike at that minimum dike freeboard scenario location, which in turn is a function of the dike 'integrity' scenario (with respect to erosion related to water through or over the crest), either existing or planned, with or without seismic impacts, and the ability to stop the dike breach process (considering emergency action plans).
- *Seismic Impacts* (red boxes) – The seismic impact scenario consists of two components: a) a seismic loading event that shakes the dike, which in turn causes the dike crest to settle (thereby decreasing freeboard) and reduce its integrity (thereby increasing its fragility); and b) subsequent dike repair scenario, which in turn takes time after which the dike crest elevation and integrity/fragility 'recover'.

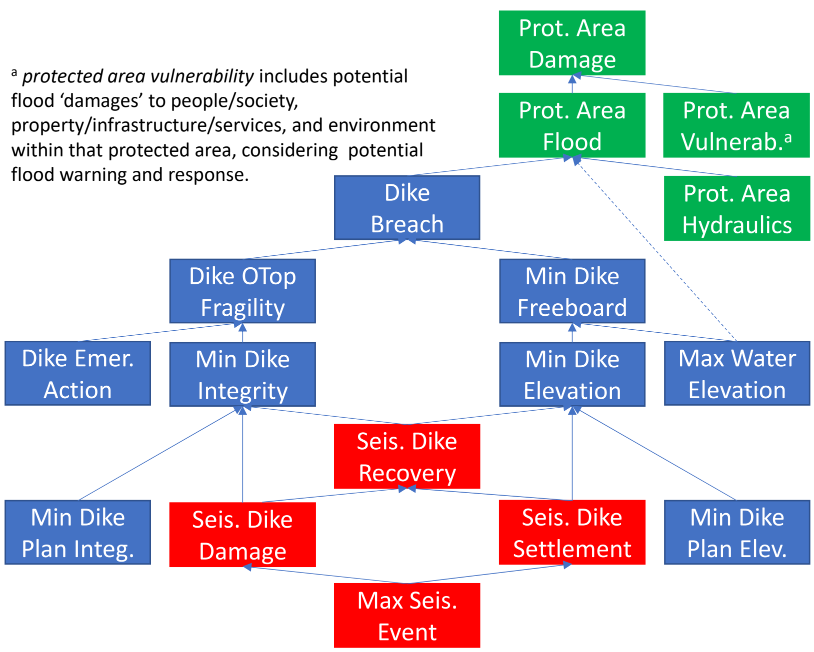


Figure 1. Flood risk due to overtopping assessment logic (considering seismicity)

PROBABILITY OF DIKE BREACHING DUE TO OVERTOPPING IN THE ABSENCE OF SEISMIC SHAKING

Dike breach failure (F) is generally assumed to occur at a location (x) when the maximum nominal water elevation (W_{max}) exceeds the minimum nominal dike crest elevation (D) at a given time (t), as shown in Figure 2, resulting in overtopping and possibly surficial erosion leading to a breach (Figure 1).

Water surface (river, lake or ocean) elevation and its associated time-related (analysis exposure time, e.g., annual) probability of exceedance are obviously a primary input parameter in calculating the probability of overtopping. This W_{max} is typically expressed in terms of exceedance return periods (see Figure 3a). In the example of Figure 3a, the water elevation should exceed 3.0 m about once every 200 years (on average). Such exceedance curves are typically derived from statistical analyses of historical records (e.g., direct measurements), but if such data is not available, or large changes in local hydrology have occurred, then these should be developed at a particular dike location based on hydrologic analyses as a function of upstream storm and snowmelt frequency magnitudes, basin topography, etc., any of which might change in the future (e.g., due to climate change or construction alterations).

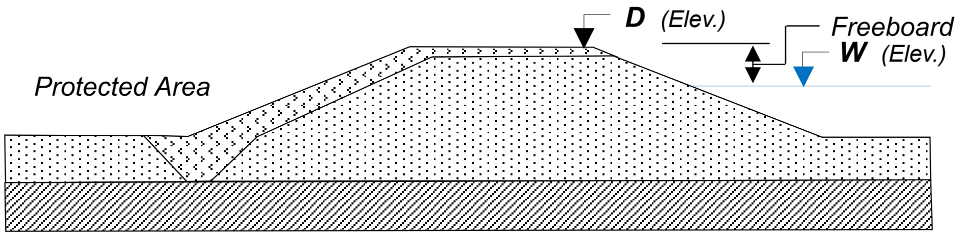
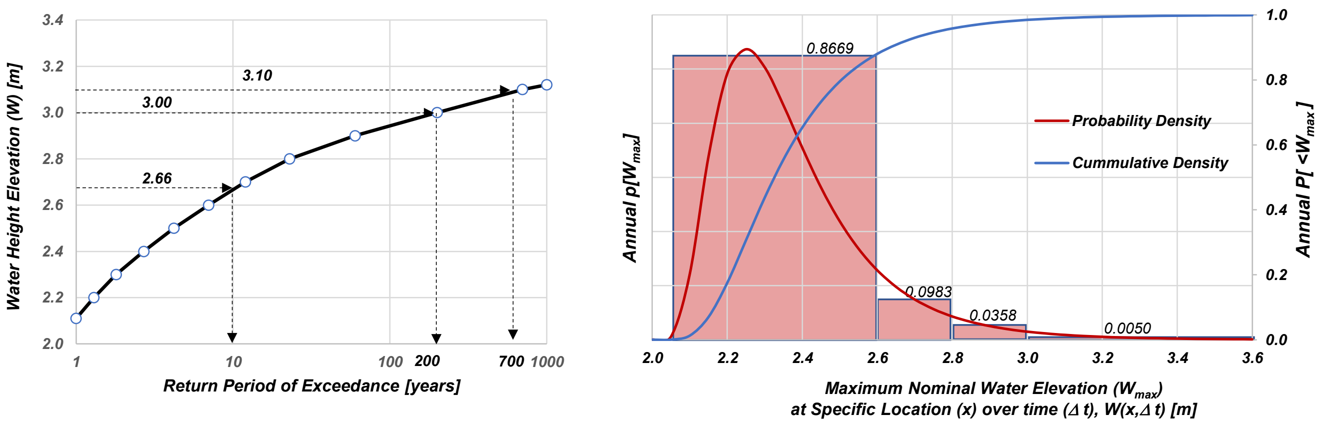


Figure 2. Definitions of dike crest (D) and water surface elevations (W), and 'freeboard' (D-W), at a particular location (x) at a given time (t).

From its frequency-magnitude relationship, the probability distribution (p[]) for the future <u>maximum</u> nominal water elevation (W_{max}) at a particular location (x) over any time period (Δt) (e.g., annual or other exposure time) $\mathrm{p}\left[W_{max,x,\Delta t}\right]$ can be determined, as shown as a continuous cumulative and density distribution (see Figure 3b); this continuous distribution can also be discretized[2] for analytical simplicity (also see Figure 3b).

Often, it is simply assumed that breach will occur if any flow occurs over the crest (i.e., $W_{x,t} > D_{x,t}$) and will not occur if no flow occurs over the crest (i.e., $W_{x,t} \leq D_{x,t}$). In this case, the 'conditional' probability of failure is a 'step function' of 'freeboard' (see blue dashed line in Figure 4)[3]: P[F | (D-W) >0] = 0.0 and P[F | (D-W) $\leq$ 0] = 1.0 so that P[F | D, W] = P[W >D].



a) b)

Figure 3 Example time-related (Δt) uncertainty in maximum nominal water elevation ($W_{max,x,\Delta t}$) at particular dike segment location (x). Note: simplified discretization in 3b is for subsequent example.

<u>For example</u>, in this very simplified case, the conditional probability of failure for a minimum crest elevation of 3.0 m is the same as the probability of the maximum water elevation exceeding 3.0 m, which as previously discussed was about once every 200 years (on average) or 0.5% per year. Alternatively, if the dike was designed for a maximum 200 year water elevation (i.e., a crest elevation of 3.0 m) plus 0.1 m design excess freeboard, for a total crest elevation of 3.1 m, it would take a 700-year maximum nominal water elevation (0.1% per year) to overtop that design crest and fail the dike.

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[2] A continuous distribution can be 'discretized' by dividing it into a comprehensive and non-overlapping set of 'bins' (Δ ranges) defined by their average (nominal) value and a lower and upper bound, e.g., if linear scale:
p[$W_{max} \pm \Delta/2$] = P[>($W_{max} + \Delta/2$)] - P[>($W_{max} - \Delta/2$)]. Narrower bins in relevant parts improve discretization accuracy.
[3] P[a] expresses 'unconditional' probability of a given event a (e.g., >x); similarly, p[x] expresses 'unconditional' probability distribution of variable x; P[a | b] expresses 'conditional' probability of a given event a <u>if</u> another event b has occurred (or will occur); similarly, p[x | b] expresses 'conditional' probability distribution of variable x <u>if</u> event b has occurred (or will occur).

However, several mechanisms can lead to failure (breach) due to high maximum water levels, which are expected to vary with time at different locations. These mechanisms that can lead to failure include:

- Crest or downstream toe erosion under prolonged overtopping
- Crest erosion when the nominal water elevation is below the dike crest elevation, e.g., due to wave action/wind setup and/or due to porous/cracked dike crest
- Internal erosion when the water level is high enough (not necessarily above the crest) to cause flow through the dike along preferential pathways (internal erosion mechanisms are further described in [2])
- Dike and/or foundation instability triggered by hydraulic loading.

The last three mechanisms represent failure resulting from 'breaching prior to overtopping' [2], which could develop when the water level is below or at the nominal dike crest. On the other hand, a failure of significance will not necessarily occur even if the water elevation temporarily exceeds the dike crest if a protected, less erodible dike surface exists. This failure mechanism would represent a condition of 'overtopping without breach' [2].

Hence, there is a probability (P) of dike failure at a particular location (x) that can be established as a function of the difference in the minimum nominal dike crest elevation (D) and the maximum nominal water level (W_{max}) at a particular time (t), depending on the 'integrity' (including erodibility) of the dike:

$$\mathrm{P}[F_t|(W_t, D)] = \mathrm{P}[F_t|(D - W_t)] = f\{W_t, D\} \text{ if } D \text{ is 'static'} \quad (1)$$

Such a 'conditional' probability of failure ('overtopping fragility curve') might be established for a given dike segment, as shown by the blue solid line example in Figure 4. This more realistic relationship indicates that in this example: the probability of breaching would approach 1.0 as the dike is overtopped by >0.2 m for a significant time; there is about 90% probability of breaching if overtopped by 0.1 m; there is about 60% probability of breaching before overtopping, which may be the result of waves/wind setup, a cracked dike crest, internal erosion, or dike instability as the freeboard decreases to zero; there is about 25% probability of breaching if there is only 0.1 m of freeboard, and there is less than 5% probability of breaching with more than 0.2 m of freeboard. This relationship is expected to vary among dike locations due to their different conditions and should be established using appropriate analyses or by expert engineering judgement (which will not be discussed further here).

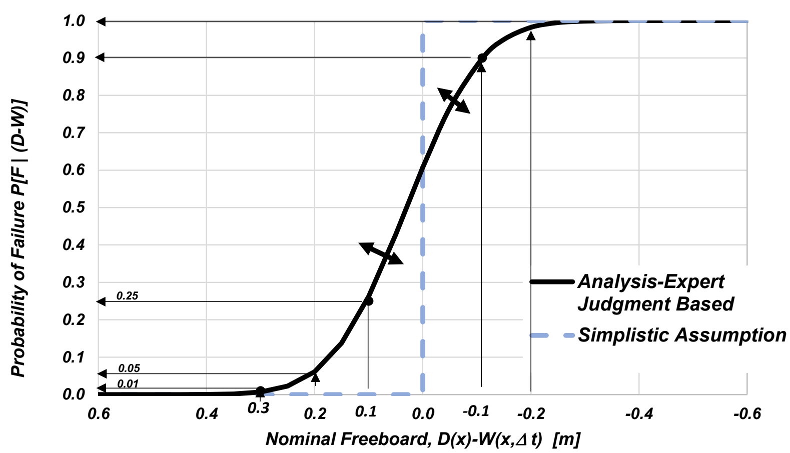


Figure 4. Example 'Overtopping Fragility Curve' showing the probability (P) of dike failure (F) due to difference between the nominal maximum water elevation (W) and nominal minimum dike crest elevation (D), i.e., minimum freeboard (D-W), at particular time (t) and location (x)

Relationships in Figures 3 and 4 can be mathematically combined to determine the probability over a time period (Δt) of future dike failure ($F_{\Delta t}$) due to water overtopping ($W > D$) at a particular location (x), assuming no change (or uncertainty) in the nominal minimal dike crest elevation (D) over that time period:

$$\mathrm{P}[F_{\Delta t}] = \int_{\mathrm{All}\,W} \mathrm{P}[F|(D - W)]\, \mathrm{p}\big[W_{\mathrm{max},\Delta t}\big]\, \mathrm{d}W \text{ where } \int_{\mathrm{All}\,W} \mathrm{p}\big[W_{\mathrm{max},\Delta t}\big]\, \mathrm{d}W = 1.0 \quad (2a)$$

To easily incorporate the more realistic overtopping fragility curve (Figure 4), the continuous distribution of $W_{max,\Delta t}$ can be discretized (as shown simplistically in Figure 3b) for calculation of the probability of failure prior to or after the dike is overtopped (as opposed to only exactly when it is overtopped):

$$\mathrm{P}[F_{\Delta t}] \approx \sum_{\mathrm{All}\,W} \mathrm{P}[F|(D - W)]\, \mathrm{p}\big[W_{\mathrm{max},\Delta t}\big] \text{ where } \sum_{\mathrm{All}\,W} \mathrm{p}\big[W_{\mathrm{max},\Delta t}\big] = 1.0 \quad (2b)$$

<u>For example</u>, for the same hypothetical dike (3.0 m crest elevation) and maximum water elevation uncertainty (Figure 3b), but with the more realistic Overtopping Fragility Curve (blue curve in Figure 4), the annual probability of failure is 0.014 (see Table 1), as compared to 0.005 using the simplified fragility curve.

Table 1. Simplified example calculation of probability of dike breaching due to overtopping with realistic dike Overtopping Fragility Curve in the absence of seismic loading (D=3.0m)

$W_{max,\Delta t}$ (m)	p[$W_{max,\Delta t}$][a]	$D - W_{max,\Delta t}$(m)	P[F | ($D - W_{max,\Delta t}$)][b]	P[F | ($D - W_{max,\Delta t}$)] p[$W_{max,\Delta t}$]
2.5	0.8669	0.50	0.00	0.0000
2.7	0.0963	0.30	0.01	0.0009
2.9	0.0358	0.10	0.25	0.0090
3.1	0.0050	-0.10	0.90	0.0045
Sum=	**1.0000**	**P[$F_{\Delta t}$] = $\sum_{\text{all W}}$ P[F | ($D - W_{\Delta t}$)] p[$W_{\Delta t}$][c]=**		**0.0144**

Notes: [a] from Figure 3b. [b] from Figure 4. [c] from Equation 2b.

SEISMIC SHAKING IMPACTS

In the above, the minimum nominal dike crest elevation (D) during the particular time period (Δt) at any location (x) is assumed to be known and constant over time, and may be easily obtained from field measurements (i.e., a topographic survey). Similarly, it is typically assumed that the dike overtopping fragility curve can be adequately determined and will be constant over time. However, various events and/or processes could occur that could change the minimum dike crest elevation and /or change the dike overtopping fragility curve (as defined by dike integrity). Of particular interest is potential future dike damage (especially reduction in the minimum nominal dike crest elevation, as well as degradation of the dike overtopping fragility curve), due to possible future seismic events.

Earthquake shaking intensity levels can be represented by an Intensity Measure (IM), which could be any one of several ground motion parameters (e.g., peak ground acceleration PGA, peak ground velocity PGV, etc.) that describe the intensity of seismic shaking at a given location. Earthquake-induced damage, e.g., change in crest elevation (ΔD) and degradation of dike overtopping fragility curve (P[F|(D-W)]), can be assessed for a dike as a function of a specific earthquake Intensity Measure (IM) at that location (x), i.e., $\Delta D(x)$ and $\mathrm{P}[F|(D-W)] = \mathrm{f}\{IM(x)\}$. Such relationships for $\Delta D(x) = \mathrm{f}\{IM(x)\}$ can be obtained by performing Newmark-type analyses or by running more comprehensive Finite Element or Finite Difference models, as shown by the dots in Figure 5, whereas such relationships for $\mathrm{P}[F|(D-W)] = \mathrm{f}\{IM(x)\}$ should be assessed by appropriate analyses or expert engineering judgement (in the same way as for the undamaged case).

A common simplistic assumption is that there is a threshold IM below which there is no earthquake-induced damage, but when exceeded, it will result in a constant known level of damage (ΔD and change in Overtopping Fragility Curve) . In this case, the seismic fragility curve is simply a step function, as shown by the blue dashed curves in Figures 5a and 5b. The probability of that earthquake damage level during a particular period is then simply the probability of exceeding the threshold IM over that same time period:

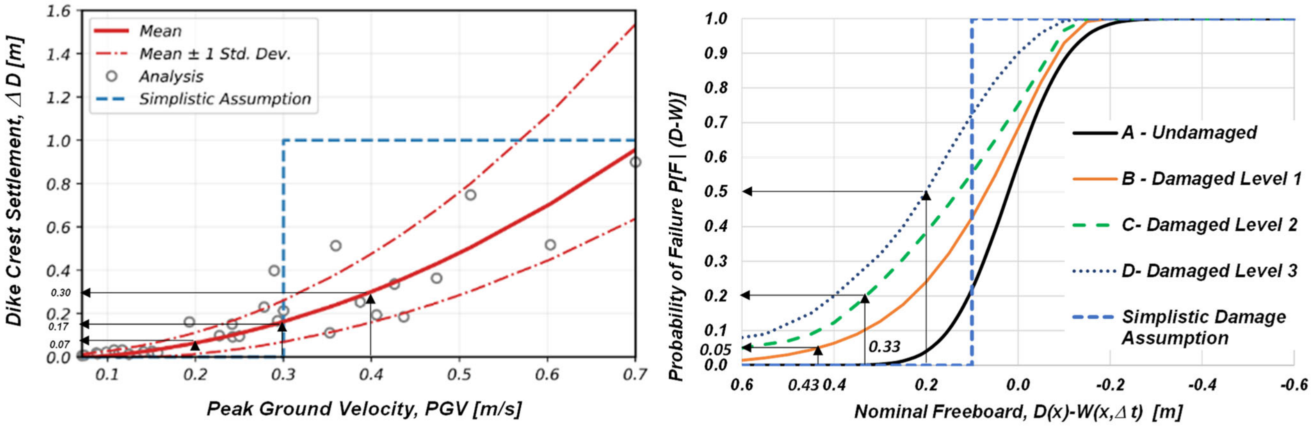
E[ΔD] = 0 and no change in Overtopping Fragility Curve, if $IM < IM_c$ (3a)

= ΔD_c and known change in Overtopping Fragility Curve, if $IM > IM_c$ (3b)

P[ΔD=0 and no change in Overtopping Fragility Curve] = P[$IM < IM_c$] (3c)

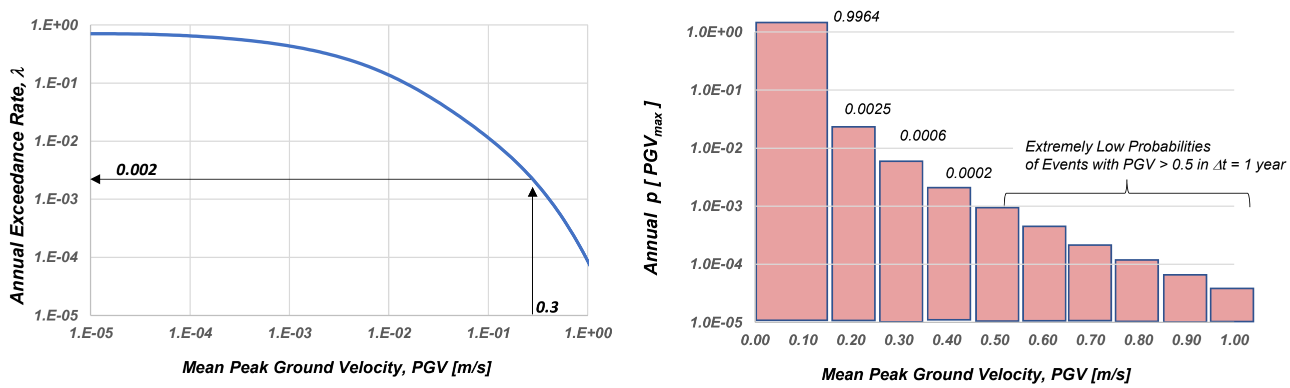
P[ΔD=ΔD_c and known change in Overtopping Fragility Curve] = P[$IM > IM_c$] (3d)

The time-related (e.g., annual) probability of exceeding any particular IM at any location (x) (a 'seismic hazard curve') is calculated (by a seismic hazard analyst) using ground motion attenuation algorithms that relate various IMs to the distance (attenuation) between the seismic source and a given site, and the frequency-magnitude and other characteristics (e.g., rupture type) of the earthquake associated with the source, from the fifth generation Probabilistic Seismic Hazard Model (PSHA), developed by Natural Resources Canada [6] using OpenQuake [7]. An example of this relationship of the annual probability of IM exceedance (λ) is shown in Figure 6a for a particular dike in the Lower Mainland, BC (Canada) using Peak Ground Velocity (PGV) as the IM (although any other IM could have been used if considered appropriate). From this $\lambda - mean\ PGV$ relationship (e.g., Figure 6a), the probability distribution (p[]) for the future maximum mean PGV over a specific time period (e.g., 50 years or annually) can be determined (e.g., Figure 6b), either by differentiation or discretization.



a) b)

Figure 5. Example 'Dike Seismic Damage Function' showing dike damage, i.e., a) reduction in minimum dike crest elevation (ΔD) and b) degradation of dike Overtopping Fragility Curve*, due to Intensity Measure (IM) at particular location (x) – Note: Using PGV (m/s) as IM.*



a) b)

Figure 6. Example Seismic Hazard Curve for a particular site in the lower mainland, BC (49.059,-123.024): a) annual exceedance probability (λ) of mean PGV (uncertainty not shown); b) annual probability of maximum mean PGV. Note: simplified discretization in 6b is for subsequent example.

<u>For example</u>, for the same hypothetical dike (3.0 m initial crest elevation) and maximum water elevation uncertainty (Figure 3b), but subject to seismic shaking, as shown in Figure 5a, the simplistic critical *PGV* is 0.3 m/s, which if exceeded results in 1.0 m dike crest settlement and a reduced Overtopping Fragility Curve of failure if freeboard is less than 0.1 m (as shown in Figure 5b). From Figure 6a, the annual probability of exceeding that critical *PGV* is approximately ~0.002, and the simplistic conditional (on that seismic event happening) annual probability of dike failure (assuming a step function at 0.1 m freeboard, as shown in Figure 5b) is nearly 100% (i.e., from Figure 3, the annual probability that the maximum water elevation will exceed 1.9 m, which is the initial dike crest elevation of 3.0 m minus the dike crest settlement of 1.0 m, minus 0.1 m freeboard). These probabilities combine to an unconditional annual probability of dike failure of approximately 0.002 (for the simplified step function version of the Overtopping Fragility Curve). Using the more realistic damaged Overtopping Fragility Curve (e.g., Curve C – Damaged Level 2, as shown in Figure 5b) would not make a difference in this case because of such a large settlement.

However, the properties and spatial variation of the dike and foundation materials are typically uncertain and the analyses are approximate, resulting in uncertainties in that damage response associated with any particular seismic IM at that location, as expressed by a probability distribution, $\mathrm{p}[\Delta D|IM]$, as illustrated by the mean and standard deviations of the relationship using *PGV* for *IM* in Figure 5a, and similarly illustrated by the revised Overtopping Fragility Curves for various *PGV*s (or simply expressed as a function of ΔD) in Figure 5b.

The development of such seismic vulnerability curves that express the damaged (ΔD) induced by a range of intensity levels characterized by a given *IM* could be carried out for a specific location (x) using finite element or finite difference analyses. The uncertainty in dike settlement response could potentially include the variability in input ground motions and the variability in soil properties as well as other sources of uncertainty (i.e., epistemic uncertainty in ground motion models, constitutive models, etc.)

In this case, 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 throughout the Lower Mainland, BC (Canada). 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 as a function of relevant ranges of select input parameters. 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*), cumulative absolute velocity after application of a 5 cm/sec2 acceleration threshold (CAV_5), and earthquake magnitude (*M*), amongst others. Ultimately, *PGV* was selected as the primary intensity measure based on consideration of performance-based case histories [4], internal evaluations, 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.

The *PGV*-dependent dike damage functions were further conditioned on a number of input parameters that 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, earthquake magnitude (M), and initial freeboard ($D - W$) associated with a given flood level. Foundation 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}). Additional model details are provided in [5].

Using the ANN algorithm and assessments of the significant uncertainties in the input parameters for any location, estimates of *ΔD* and its uncertainty can be assessed for various locations within the Lower Mainland via Monte Carlo simulation An example of the type of output is presented in Figure 5a.

The relationships in Figures 5a, 5b and 6b can then be combined to determine the unconditional probability distribution (p[]) over any time period of future reduction in dike crest elevation (ΔD) and change in overtopping fragility curve (P[$F|(D - W)$]) due to seismicity, which, for simpler calculations, can also be discretized:

$$\mathrm{p}\left[\Delta D_{max,\Delta t}\right] = \int_{\mathrm{All}\,IM} \mathrm{p}[\,\Delta D \mid IM\,]\ \ \mathrm{p}\left[IM_{\max,\Delta t}\right]\ \mathrm{d}IM \approx \sum_{\mathrm{All}\,IM} \mathrm{p}[\,\Delta D \mid IM\,]\ \ \mathrm{p}\left[IM_{\max,\Delta t}\right] \tag{4a}$$

$\mathrm{p}\left[\Delta D_{max,\Delta t} = \mathrm{E}[\,\Delta D \mid IM\,]\right] \approx \mathrm{p}\left[IM_{\max,\Delta t}\right]$ ignoring the secondary uncertainty in ΔD as a function of *IM* (relative to the uncertainty in *IM*) (4b)

p[degraded Overtopping Fragility Curve] = f{*IM*} or f{ΔD} ignoring the secondary uncertainty in the curve (relative to the uncertainty in *IM*) (4c)

Equation 2 can then be rewritten to incorporate these seismic impacts (including damaged fragility curves):

$$\mathrm{P}[F_{\Delta t}] = \int_{\mathrm{All}\,W} \int_{All\ \Delta D} \mathrm{P}[F|(\{D_o - \Delta D\} - W)]\ \mathrm{p}[\Delta D]\ \mathrm{p}\left[W_{\max,\Delta t}\right]\ \mathrm{d}\Delta D\ \mathrm{d}W \tag{5a}$$

$$\mathrm{P}[F_{\Delta t}] \approx \sum_{\mathrm{All}\,W} \sum_{All\ \Delta D} \mathrm{P}[F|(\{D_o - \Delta D\} - W)]\ \mathrm{p}[\Delta D]\ \mathrm{p}\left[W_{\max,\Delta t}\right] \tag{5b}$$

<u>For example</u>, for the same hypothetical dike (3.0 m initial crest elevation), maximum water elevation uncertainty (Figure 3b), subject to seismic shaking (Figure 6), but expressed more realistically in terms of dike damage functions for settlement (Figure 5a) and Overtopping Fragility Curve (Figure 5b) as a function of *PGV* (or ΔD for the fragility curve) (as opposed to simple step functions), the conditional probability of dike failure is calculated first for each combination of potential annual maximum *PGV* <u>and</u> annual maximum water elevation, which are then combined with the annual probabilities of those potential maximum *PGV* and maximum water elevation to determine the unconditional annual probability of failure to be 0.0149 (see Table 2). In this example, the probability of failure considering potential seismic shaking is only a few percent higher than for aseismic conditions (Table 1); however, this increase in the annual probability of failure can vary significantly depending on the various factors involved (e.g., hydro hazard, seismic hazard, dike fragility, etc.).

Table 2. Simplified example calculation of probability of dike breaching due to overtopping with seismic loading and its realistic dike settlement and Overtopping Fragility Curve seismic damage functions (D_o=3.0m)

$PGV_{max,\Delta t}$	p[$PGV_{max,\Delta t}$][a]	$\Delta D_{max,\Delta t}$= E[ΔD | $PGV_{max,\Delta t}$][b]	p[$\Delta D_{max,\Delta t}$] = p[$PGV_{max,\Delta t}$]	P[F | (D-W)] = $f\{\Delta D_{max,\Delta t}\}$	P[F|({D_o-ΔD} – $W_{max,\Delta t}$)][c] for $W_{max,\Delta t}$ = 2.5m[d]
0.1	0.9964	0.01	0.9964	A – Undamaged	0.00
0.2	0.0025	0.07	0.0025	B – Level 1	0.05
0.3	0.0006	0.17	0.0006	C – Level 2	0.20
0.4	0.0002	0.30	0.0002	D – Level 3	0.50
Sum=	1.0000	**P[$F_{\Delta t}$|$W_{max,\Delta t}$] = $\sum_{\text{all } PGV}$ P[F | (D-$W_{max,\Delta t}$)] p[$PGV_{max,\Delta t}$]=**			**0.0004**

$W_{max,\Delta t}$	p[$W_{max,\Delta t}$][e]	P[F | $W_{max,\Delta t}$]	P[F | $W_{max,\Delta t}$] p[$W_{max,\Delta t}$]
2.5	0.8669	**0.0004**	0.0003
2.7	0.0923	0.0110	0.0011
2.9	0.0358	0.2514	0.0090
3.1	0.0050	0.9002	0.0045
P[$F_{\Delta t}$] = $\sum_{\text{all } W}$ P[F | (D – $W_{\Delta t}$)] p[$W_{max,\Delta t}$][f]=			**0.0149**

Note: [a] from Figure 6b. [b] from Figure 5a. [c] from Figure 5b. [d] only showing calculation for $W_{max,\Delta t}$ = 2.5m, but for brevity not showing the similar calculations for the other $W_{max,\Delta t}$. [e] from Figure 3b. [f] from Equation 2b.

RECOVERY TIME

The above analysis (Table 2) can be conducted to determine the probability of a dike breach over a specific time period assuming no additional changes (e.g., repair). However, the damaged dike is expected to be repaired to its original conditions over a certain time period, as shown schematically in Figure 7. Reasonably assuming only one possible dike failure (corresponding to the maximum IM) at a particular location during the time of interest, then that time period of interest (Δt) can be divided into 3 parts (Figure 7): pre-seismic undamaged ($< M$), unrepaired post-seismic damaged ($R - M = \Delta t_R$) and repaired post-seismic damaged ($> R$). Also, reasonably assuming that any dike damage would be repaired and restored to its pre-damage condition, then there are essentially only two time periods required: damaged pending recovery (Δt_R) and undamaged/repaired ($\Delta t - \Delta t_R$).

Similar to the expected earthquake-induced damage (ΔD and degraded fragility curve) , the recovery time (Δt_R) is also expected to be a function of the intensity of earthquake shaking, which may be represented by a given IM (i.e., ΔD and Δt_R are correlated). Alternatively, recovery time could also simply be expressed as a function of ΔD, i.e., strong earthquake shaking is expected to cause more damage when compared to lower intensities, requiring longer recovery times. A relationship between Δt_R and ΔD could be developed, for example, by determining the material volumes that may be required to be sourced and transported to a given dike reach for conducting repairs, plus initiation time (which could be extensive considering other non-dike damage, limited resources and priorities after a major earthquake). Those material volumes could be quantified for a given damage level expressed in terms of deformations (i.e., ΔD).

A relationship of this type, including its uncertainty (which might be significant for such a complex problem), should be developed with the dike owner (reflecting that organization's capabilities and priorities). Each such relationship is also expected to be developed for a specific region, and may vary from region to region. A hypothetical example of a relationship between seismic-induced dike crest settlement (ΔD) and recovery time (and its uncertainty) is shown in Figure 8. This hypothetical relationship expresses an expected recovery time of about 0.5 years (6 months), with a 10% to 90% range of about 0.15 to 0.9 years, to repair an earthquake-induced settlement of 0.1 m.

The unconditional probability of a dike failure (F) over a specific time period (Δt), considering potential seismically-induced damage, can be calculated by separating that time period into two parts (Figure 7):

$$\text{P}[F_{\Delta t}] = \text{P}[F_{\Delta t - \Delta t_R}] + \text{P}[F_{\Delta t_R}] \quad (6a)$$

where:

Δt_R is the time period (years) when the dike is seismically damaged (e.g., Figure 8) (6b)

P[$F_{\Delta t - \Delta t_R}$] is the probability of failure for the undamaged dike =

1 – (1-{annual probability of no dike damage over Δt-Δt_R x P[$F_{\Delta t=1y}$]})$^{(\Delta t-\Delta tR)}$ (e.g., P[$F_{\Delta t=1y}$] from Table 1) (6c)

P[$F_{\Delta t_R}$] is the probability of failure for the seismically damaged dike =

1 – (1-{annual probability of dike damage over Δt x P[$F_{\Delta tR}$]})$^{(\Delta tR)}$ (e.g., P[$F_{\Delta tR}$] derived from Table 2) (6d)

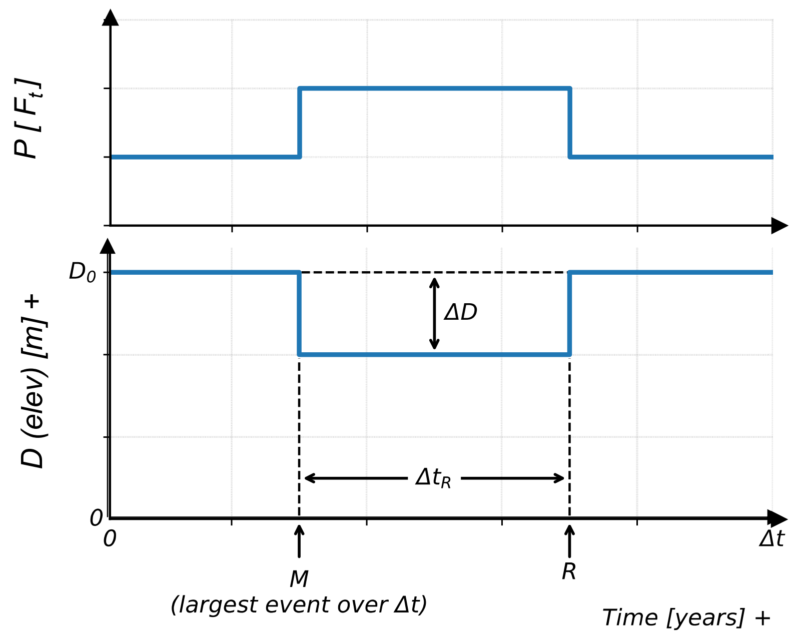


Figure 7. Schematic example showing earthquake-induced seismic damage (ΔD, as well as a degraded Fragility Curve) at specific location (x). M is the random time of earthquake occurrence, R is the time when repairs are completed, and Δt_R (= R – M) is the 'recovery' time. Note: This example assumes that the dike will be repaired to its original condition.

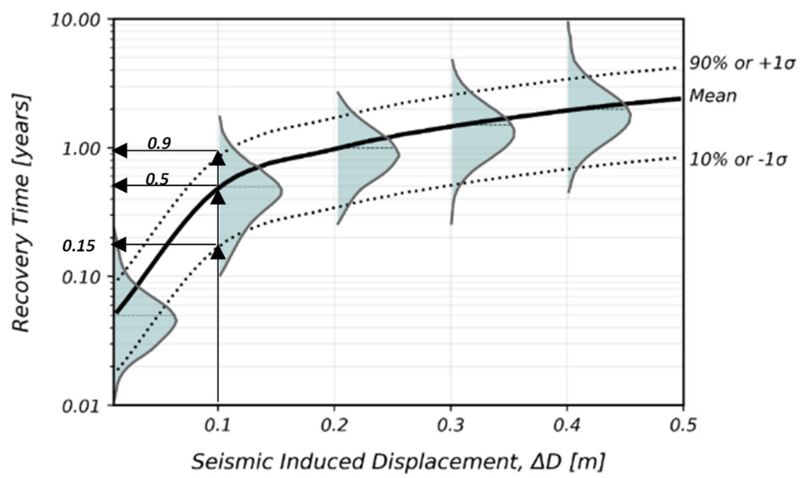


Figure 8. Schematic example of recovery time as a function of seismic induced settlement (ΔD) for a specific organization and region

<u>For example</u>, for the same hypothetical dike (3.0 m crest elevation), maximum water elevation uncertainty (Figure 3b), and realistic undamaged Overtopping Fragility Curve (blue curve in Figure 4), but without considering seismicity, the annual probability of failure is 0.014 (Table 1). For those same conditions, plus the same seismic hazard (Figure 6) and dike damage functions (Figure 5), the annual probability of a 'significant' (i.e., PGV >0.15 m/s such that ΔD > 0.05 m) seismic event is only 0.0033 (and the probability of no damage is thus 0.9967) and the conditional annual probability of failure given such a significant seismic event is 0.147 (see Table 3). For an expected value of recovery time of 0.5 years (derived from Figure 8 and the conditional probability distribution of displacements and thereby recovery times), the <u>annual</u> unconditional probability of failure then equals (from Equation 6): $\{1 – (1 - 0.9967*0.014)^{(1-0.5)}\} + \{1 – (1 - 0.0033*0.147)^{(0.5)}\} = 0.0078$. Similarly, the unconditional probability of failure over 50 years equals: $\{1 – (1 - 0.9967*0.014)^{(50-0.5)}\} + \{1 – (1 - 0.0033*0.147)^{(0.5)}\} = 0.51$.

Table 3. Simplified example calculation of annual probability of dike breaching due to overtopping with realistic dike settlement and Overtopping Fragility Curve seismic damage functions for 'significant'(PGV' if PGV>0.15 m/s so ΔD>0.05 m and degraded Overtopping Fragility Curve) seismic event (D_o=3.0m)

$PGV'_{max,\Delta t}$ >0.15	p[$PGV'_{max,\Delta t}$][a]	$\Delta D_{max,\Delta t}$= E[ΔD | $PGV'_{max,\Delta t}$][b]	p[$\Delta D_{max,\Delta t}$] = p[$PGV'_{max,\Delta t}$]	P[F | (D-W)] = $f\{\Delta D_{max,\Delta t}\}$	P[F|({D_o-ΔD} - $W_{max,\Delta t}$)][c] for $W_{max,\Delta t}$ = 2.5m[d]
0.1	0.9964	0.01	0.9964	A - Undamaged	0.00
0.2	0.0025	0.07	0.0025	B - Level 1	0.05
0.3	0.0006	0.17	0.0006	C - Level 2	0.20
0.4	0.0002	0.30	0.0002	D - Level 3	0.50
Sum=	0.0033	**P[$F_{\Delta t}$|$W_{max,\Delta t}$] = $\sum_{\text{all } PGV}$ P[F | (D-$W_{max,\Delta t}$)] p[$PGV'_{max,\Delta t}$][g]=**			**0.105**

$W_{max,\Delta t}$	p[$W_{max,\Delta t}$][e]	P[F | $W_{max,\Delta t}$]	P[F | $W_{max,\Delta t}$] p[$W_{max,\Delta t}$]
2.5	0.8669	**0.105**	0.091
2.7	0.0923	0.297	0.027
2.9	0.0358	0.679	0.024
3.1	0.0050	1.000	0.005
P[$F_{\Delta t}$] = $\sum_{\text{all } W}$ P[F | (D - $W_{\Delta t}$)] p[$W_{max,\Delta t}$][f]			**0.147**

Note: [a] from Figure 6b. [b] from Figure 5a. [c] from Figure 5b. [d] only showing calculation for $W_{max,\Delta t}$ = 2.5m, but for brevity not showing the similar calculations for the other $W_{max,\Delta t}$. [e] from Figure 3b. [f] from Equation 2b. [g] p[PGV'] conditioned on PGV being significant, i.e., divided by $\sum_{\text{all } PGV}$ p[$PGV'_{max,\Delta t}$]

PROBABILITY OF DIKE BREACHING DUE TO OVERTOPPING FROM SEISMIC SHAKING CONSIDERING ADDITIONAL UNCERTAINTIES

The previous analysis (and its example) has considered the simple 'step function' Overtopping Dike Fragility Curve and the simple 'step function' Seismic Dike Damage Function, as well as more realistic Overtopping Dike Fragility Curves that express the uncertainty in dike failure as a function of freeboard and more realistic Seismic Dike Damage Functions that express the mean dike damage (dike crest settlement and degraded fragility) as a function of *PGV*; the mean of recovery time (which, along with degraded fragility, can be expressed as a function of that damage) is also used. Although the uncertainties in Seismic Damage Functions and in recovery time are not explicitly incorporated, they could be (e.g., by expanding the algorithms and using Monte Carlo simulation to calculate the somewhat larger conditional probabilities). However, it is believed that these uncertainties are much smaller than the uncertainties in the maximum water elevations and maximum seismic shaking events, and, since their mean values are used, those uncertainties can reasonably be ignored.

CONCLUSIONS

Dikes are often the primary protection for otherwise flood vulnerable areas. With this protection, some of those dike-protected areas have over time developed significant population, property improvements, infrastructure, etc. In those areas, the consequences of a dike failure (breach) and subsequent flooding of those previously dike-protected areas could be catastrophic. However, the probability of such a dike failure has not previously been adequately assessed, especially considering the potential seismically-induced dike damage that can occur and might not be repaired before upstream water levels rise. Although dike protection can be enhanced (e.g., by raising the dike, providing a 'spillway' or sacrificial section that discharges into relatively undeveloped areas, hardening the dike to better withstand some overtopping or seismic shaking, shortening recovery time by pre-planning, reducing peak water levels by dredging or upstream controls, etc.), such enhancements can be extremely expensive. Such expensive enhancements should be evaluated in terms of their actual 'risk reduction', which is the combination of their reduction in the probability of dike failure and/or the reduction in the consequences of dike failure. Hence, it is important to first assess the status quo (existing or planned) dike risks (i.e., the combination of probability and consequence of dike failure) and identify the primary aspects driving the risk, to focus on possibly cost-effectively changing those aspects.

Although there are various ways such flood-protection dikes can fail (e.g., internal erosion or instability), all of which should be considered in the risk assessment and management, this paper has focused specifically on overtopping, including consideration of seismic impacts. Overtopping failure (i.e., dike breach) can occur when the upstream water level approaches the lowest vulnerable dike crest level (which would not include, for example, a hardened spillway). The crest and/or downstream toe/slope will progressively erode into a full breach as flow occurs over the crest (or through a cracked, porous crest), unless emergency interventions are successful. The probability of a dike breach occurring as a function of actual sustained minimum 'freeboard' (i.e., the difference between the nominal minimum crest elevation and nominal maximum water elevation, with negative freeboard reflecting overflow), considering potential successful intervention, is termed the 'dike overtopping fragility curve'. The actual time-related (e.g., annual) probability of dike failure can then be calculated by combining that fragility curve with the time-related (e.g., annual) probability of the nominal maximum water elevation, reasonably assuming the nominal minimum crest elevation and fragility curve are constant and known.

However, seismic events can occur that shake and thereby damage the dike, i.e., lowering that nominal minimum crest elevation (reducing freeboard) and reducing the crest's integrity (degrading the fragility curve). The magnitude of that damage (i.e., reduction in minimum crest elevation and degradation of the fragility curve) is a function of the magnitude of the seismic intensity measure (*IM*, e.g., peak ground velocity *PGV*) at the site. The reduction in minimum crest elevation (ΔD) was determined via finite element (FE) analysis (PLAXIS) for a wide range of input parameters, based on which an algorithm (neural net) that adequately replicated those results was developed and used to incorporate (via Monte Carlo simulation) the assessed uncertainties in those input parameters to calculate the uncertainties in that settlement for specified *PGV*s. The mean of settlement (ΔD) and degraded fragility curve for each PGV were assigned the time-related (e.g., annual) probability of that *PGV* and used to determine the increased probability of dike breach in the same way as aseismic. However, this increased probability of dike failure lasts only as long as it takes to repair and restore the seismically damaged dike. This recovery time (which is also uncertain and a function of seismic damage) has also been incorporated into the analysis.

In the above way, the time-related (e.g., annual) probability of dike failure due to overtopping, explicitly considering site seismicity/damage/recovery and its contribution to dike failure (and, when combined with other failure modes and their consequences, contribution to dike risk) can be adequately determined. This information is needed to identify and evaluate the cost-effectiveness of potential dike enhancements/improvements in reducing dike risk.

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