Évaluation probabiliste du risque d'inondation dans les zones urbaines protégées par des digues

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RESUME

Une amélioration du système d'évaluation du risque d'inondation peut s'articuler autour de 2 éléments : (i) l'évaluation de la fiabilité des digues en considérant les multiples mécanismes de rupture potentiels, et (ii) la considération de multiples scénarios de brèches dans les digues. Les mécanismes de défaillance de surverse et d'érosion régressive sont considérés, prenant en compte la variabilité des propriétés géotechniques, pour plusieurs intensités de crues. La méthode proposée se base sur des simulations pour aboutir aux courbes de fragilité des digues. Des simulations hydrauliques reproduisant de multiples scénarios d'inondation et de rupture de digue permettent par une analyse statistique et probabiliste des paramètres d'inondation (profondeur d'eau et vitesse du flux) de générer une représentation spatialisée et probabilisée de l'aléa d'inondation. Les cartes d'inondation permettent l'évaluation de la probabilité d'occurrence de l'inondation et leur combinaison résulte en une représentation probabiliste de l'aléa d'inondation où, pour chaque point de la zone protégée, la distribution probabiliste des paramètres de l'inondation est obtenue. Le risque d'inondation pourra alors être évalué en combinant l'aléa inondation, les enjeux exposés à l'inondation et leur niveau de vulnérabilité.

Mots-clefs Digues, Risque probabiliste d'inondation, Spatialisation, Brèches

I. INTRODUCTION

Every year, floods affect social life and the economy all over the world. Some famous floods include Hurricane Katrina in 2004 (ASCE, 2007), Storm Xynthia in 2010 (Kolen et al., 2013), and the floods in Southern Alberta in 2013 (Pomeroy et al., 2016), which had terrible consequences for human life and assets. The International Panel on Climate Change projected increase of sea level rise and more frequent heavy precipitations throughout the 21st century, which should increase adverse impacts as seen in major floods. To which Field et al. (2014) added that if levee structures are to be a reliable, they can only be effective if they are regularly operated and maintained. In fact, a breach in a levee system may cause more damage due to the flood wave than a gradual rise in water. The International Levee Handbook from CIRIA et al. (2013) identified and explain each step of the process to flood risk assessment. Its main steps are event probability estimation, inundation modeling, analysis of levee system failure, exposure and vulnerability estimation, estimation of level of risk, risk attribution, and assessment of remaining gaps in knowledge. We focus on levee failure and probabilistic flood hazard assessment. Levee system failure is defined as the inability to achieve a defined performance threshold (Allsop et al., 2007, Simm et al., 2012). According to CIRIA et al. (2013), there are 3 types of levee failure mechanisms: external erosion, internal erosions, and slope instability. Levee performance can be conducted through quantitative methods using expert judgment, index based methods, mathematical models based on physical, or empirical equations. Those methods are usually an adaptation or a direct usage of methods developed for dams (e.g. Foster et al., 2000, ICOLD, 2017). We focus on urban fluvial levee structures subject to overflowing and backward erosion as the main failure mechanisms (Mainguenaud et al., 2023).

Studies based on the Netherland's flood risk assessment integrated approach (Van Alphen., 2015) assess flooding while considering potential levee failures. However, their study considers one failure mechanism at a time for one flood event. On the other hand, Maranzoni et al., 2022 consider the probabilistic flood hazard for multiple levee breaches during a single flood event. Maranzoni et al., 2023 provide a review of flood hazard assessment methods dividing them into heuristic, conceptual, and empirical approaches, while flood maps can be either deterministic or probabilistic. To be able to combine both flood hazard and levee failure, we chose a probabilistic approach to flood hazard.

We propose a method to assess levee failure probabilities resulting in a fragility curve for each failure mechanism. Then, assess probabilistic flood hazard considering levee failures for several failure mechanisms and several flood events. The flood probability is combined with levee failure probabilities to provide a flood exceedance probability for every scenario. This study enables the identification of the levee most vulnerable locations.

II. METHODS

A. Levee failure probability assessment for overflowing mechanism

By overflowing failure, is meant the external erosion of the levee crest due to water level until a breach occurs. In contrast to overtopping, where the water flow is perpendicular to the levee structure, overflowing does not consider erosion due to waves. Overflowing is a time dependent mechanism that Visser et al., 1995 describe overflowing in 3 phases: the beginning of the erosion due to overflow, the progression of the erosion, and the collapse of the structure. We chose to consider that failure by overflowing is equivalent to the beginning of a severe erosion of the hydraulic structure for hydraulic peak conditions (i.e. the end of the progression phase). Estimation of overflowing probability based on expert judgement required a group of specialist engineers including at least one specialized in risk analysis. In addition to this condition, each expert in the panel must have knowledge of the geotechnical or hydraulic fields. Each expert independently provided an expert judgement of the probability of failure considering the water level, the soil type, the geometry, the mechanical parameters, and the overflow duration of the levee segment. They estimated the failure probability due to overflow on a qualitative scale from "not probable" to "almost certain probability" (7 grades). Then, a group discussion followed, where misunderstanding of questions and biases were addressed, and the experts selected together in a consensual way the final qualitative scale of failure. Finally, we transposed the qualitative assessment to a quantitative scale using the approach defined by Peyras et al., 2010.

B. Levee failure probability assessment for internal erosion mechanism

Among the different mechanisms of internal erosion (e.g. backward erosion, concentrated leak erosion, contact erosion, suffusion), backward erosion is commonly used as the design criteria for levees (CIRIA et al., 2013). Due to the lack of model for the progression of backward erosion, we consider backward erosion initiation criterion as backward erosion failure. The resulting probability of failure corresponds to the probability of erosion initiation, which is a safe approximation, as erosion does not always lead to failure such as when the process is interrupted. To assess backward erosion, we compare local hydraulic gradients (obtained from a finite element model) with the critical gradient of Terzaghi (Terzaghi, 1943). We evaluate the probability of failure as the probability that the critical gradient is less than the hydraulic gradient obtained by the numerical seepage analysis model. Initiation of backward erosion occurs at the foot of the levee, therefore we select the maximum hydraulic gradients considered to assess backward erosion failure in this area. The evaluation of hydraulic gradients is a source of uncertainty related to the type of hydraulic modeling (e.g. steady state or transient model), numerical aspects (e.g. mesh size, location of hydraulic gradients), and soil parameters for the geotechnical model (e.g. porosity, specific gravity). We consider geotechnical uncertainty by modelling the critical gradient as a random variable normally distributed and defined the distribution parameters from expert judgement and literature (Mainguenaud et al., 2023).

C. Levee breaching model

We used the parametric breach model with Froehlich, 1995 empirical equations to estimate breach final width, slopes, and time of breach opening. We did not consider simultaneous or successive breach failures within a scenario as we assumed that when a breach occurs, it liberates some of the pressure forces on the structure and should be less likely to breach on nearby downstream segments. However, the consideration of multiple breach is relevant for long levees of several kms (Maranzoni et al., 2022).

D. Probabilistic assessment of flood hazard for multiple flood event and breach scenarios

Probabilistic flood hazard is assessed by a cumulative flood exceedance probability curve for every location of the flooded area. First, we compute the probability of the scenario conditional on the flood ($P_{scenario \mid flood}$) : the levee failure probability (P_{breach}, extracted from fragility curves) weighted by the number of levee segments where the breach can be located and by the number of failure mechanisms considered. For every flood of return period (T in years), the sum of the probabilities of the scenarios conditional on the flood is equal to 1. Then, we compute the scenario probability ($P_{scenario}$) as Equation 1.

$$P_{scenario} = P_{flood} \,.\, P_{scenario \mid flood} \quad (1)$$

For every flood scenario, we have a probability of occurrence associated with the maximum depth or velocity map. We cumulate flood exceedance probabilities for each flood parameter (depth, velocity) to obtain this cumulative flood exceedance probability curve.

III. CASE STUDY : ETOBICOKE CREEK

A. Location and hydrology

The Etobicoke Creek watersheds and the study area located in Meadowland Park in Brampton, Ontario, Canada. Toronto Region Conservation Area, 2023 identified the study area as one of the flood vulnerable clusters. Water Office historical database (Government of Canada, 2023) provides water levels and flow values. The hydraulic station 02HC017 is located in our study area provided the data for the flood frequency analysis which determined peak flow values, ranging from 85 to 530 $m^3.s^{-1}$. We simulated flood events associated with return periods 100, 200, 350, 500, 750, and 1 000-yr. The levee is located approximately 80 m away from the river stream steep vegetated banks, creating a flood mitigation floodplain.

B. Geotechnical data for the levee

The levee is approximately 60-year old with a homogeneous silty embankment (Terraprobe, 2023), 2 m high throughout the 500 m of length. The levee slopes are fairly consistent throughout the levee length and consist of 3:1(horizontal:vertical) for the water side, 2:1 for the protected area side of the levee (Figure 1) and covered in grass. Topography and geometry of the levee were the decisive factors for the levee segmentation (5 segments in total in Figure 2). We assumed a constant failure probability through each levee segment.

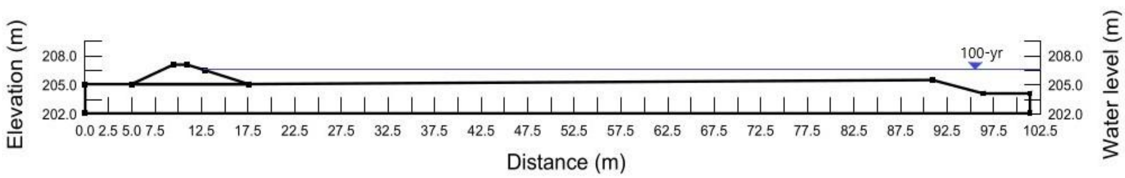

FIGURE 1. Etobicoke Creek levee cross-section (located on segment 3, see Figure 2)

FIGURE 2. Etobicoke Creek levee segments numbered 1 to 5 ; in blue Etobicoke Creek flowing southward ; in green the hydraulic model cross-sections

To assess levee failure probabilities, we used soil parameters based on a geotechnical assessment (Terraprobe, 2023) performed by Terraprobe for the Toronto and Region Conservation Authority (TRCA). The geotechnical assessment indicated a globally homogeneous, slightly plastic, sand and silty soil (gravel 10%, sand 41%, silt 31%, clay 18% as per MIT soil classification), 11% water content, 10^{-8} m.s^{-1} levee permeability, 10^{-6} m.s^{-1} foundation permeability. The earth fill estimated cohesion is 15 kPa and the angle of internal friction to 28°. To compute a critical gradient, we used values based on expert judgment and technical literature: porosity $n \in [0.3; 0.45]$ (Hough, 1969), the solid particle density $\gamma_s \in [2{,}600; 2{,}800]$ kg.m^{-3}, and water density γ_w=1,000 kg.m^{-3}. The computed critical gradient follows a normal distribution N(1.06 ; 0.27), taking into account the range of values found in literature. Therefore, the levee model is a homogeneous soil of permeability 10^{-8} m.s^{-1}, only the shape of the levee changes depending on the levee segment considered.

C. Hydraulic data for the levee and breaching model

The seepage analysis was performed with a numerical model based on the finite elements method to model hydraulic gradients for the backward erosion failure probability. We assumed steady-state flow conditions, as prolonged exposure to the maximum water level creates conditions for the worst case effects on the levee. The levee was designed to withstand a 100-year flood return period. The HEC-RAS software has 2 breaching mechanism options: (i) piping or (ii) overtopping (Hydrologic Engineering Center, 2023). The piping breach option (i) opens from the bottom of the levee, and the erosion will begin on the protected side of the levee because of seepage flow carrying soil particles. As the pipe grows larger, material will detach and fall into the moving water slowly resulting in an open breach. The overtopping breach erosion option (ii) starts on the downstream side of the levee, and was deemed satisfying to model the overflow failure mechanism. We consider the piping option to model backward erosion and the overtopping option to model overflow.

E. Flood propagation model and scenario probabilities

For the case study, we use a High Resolution Digital Elevation Model derived from LiDAR data and satellite imagery provides a Digital Terrain Model (DTM) of 1 m spatial resolution. The corresponding survey 'York 2019' is sourced from National Resource Canada. We use HEC-RAS's 1D/2D model to compute the river water surface for a subcritical flow regime in the 1D area, and Shallow Water Equations (SWE) to propagate the water in the 2D area based on theoretical triangular hydrographs. Therefore, we assumed incompressible flow and negligible vertical velocity. For each simulation, we stored a map of the highest depth and velocity values reached during the flood event. Every flood scenario is associated with a flood scenario exceedance probability conditional on a flood. The cumulative flood exceedance probability curve is computed as described in section II.D.

IV. RESULTS

A. Levee fragility curves

We plotted overflowing and backward erosion fragility curves versus flood return periods (associated with peak water levels) in Figures 3 and 4. There is a fragility curve for every levee segment. We observed an increase of backward erosion failure probabilities after the 350-year return period and only segment 3 (BXS3) shows a steep increase of backward erosion failure probability. On the other hand, overflow probabilities showed a steep increase from the beginning, especially for the middle segments 2, 3, and 4.

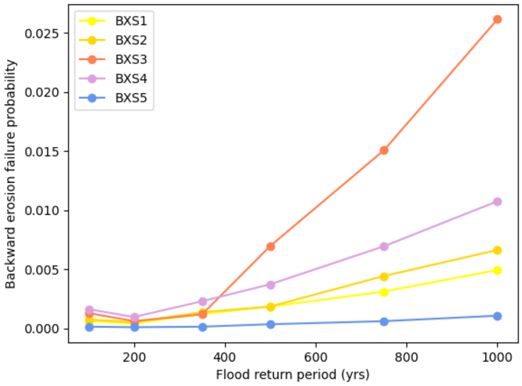

FIGURE 3. Backward erosion fragility curves for Etobicoke Creek

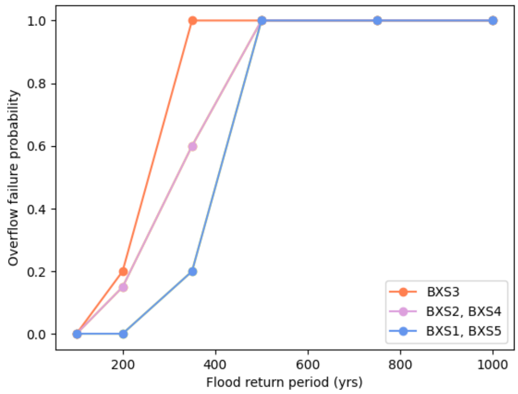

FIGURE 4. Overflow fragility curves for Etobicoke Creek

In this case study, the levee has a high reliability and is not likely to fail. However, this method shows which critical failure mechanism to focus on and which levee segment to pay attention.

B. Probabilistic flood hazard

We compute cumulative flood exceedance probability for depth and velocity. To present the result, we chose 5 locations (Figure 5): point a located in the residential neighborhood, points b and c behind the levee respectively at segment 3 and 4, point d is located on the parking lot, and point e on the main road downstream of the levee.

FIGURE 5. *Locations to present the results point a (residential neighborhood), points b&c (behind the levee), point d (parking), and point e (road)*

Cumulative flood exceedance probabilities shown in Figure 6 for which each graph take into consideration every breaching scenario (no breach and breaching of every levee segment by overtopping and piping), and every flood (return periods range from 100-year to 1,000-yr).

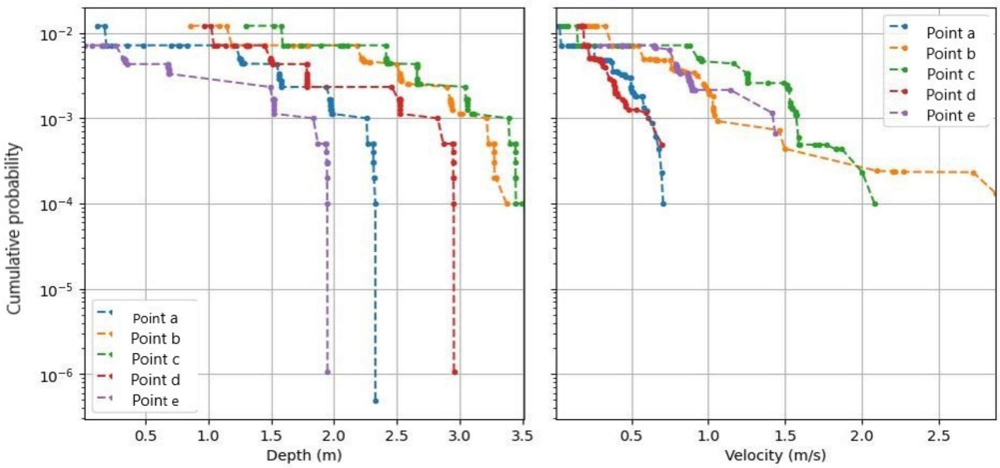

FIGURE 6. Cumulative flood exceedance probabilities for depth and velocity for point a (residential neighborhood), points b&c (behind the levee), point d (parking), and point e (road).

With the aggregated results obtained for backward erosion and overflow failure mechanism, we are able to distinguish various levels of flood hazard in a protected area. For this case study, the level of depth hazard from highest to lowest is locations c, b, d, a, and e (Figure 6, depth graph). The level of velocity hazard depends on the velocity value but in general, ranks from highest to lowest in the following order: location c, b, e, a, and d (Figure 6, velocity graph).

V. DISCUSSIONS

A. Limitation of fragility curve assessments

The assessment of backward erosion failure probabilities proposed has some limitations associated with the use of the critical gradient of Terzaghi defined for cohesionless soils in steady-state conditions. For cohesionless soils, another approach to compute a critical hydraulic gradient was proposed by Indraratua and Radampola (2002). An alternative approach could be to compute the hydraulic shear stress and compare it with a critical hydraulic shear stress value measured from a Jet Erosion Test (JET). If no JET data is available, Regazzoni and Marot (2011) also proposed an estimation of the erosion index based physical parameters proposed by Wan and Fell (2004).

Internal erosion is a time dependent mechanism, however the current model does not account for this. Using an energy approach such as the one proposed by Marot et al. (2011) based on an erosion resistance index could be a suitable approach to assess backward erosion failure probabilities as this index is determined from the whole evolution of the process and not just its initiation.

Contributing factors to backward erosion initiation such as animal burrows, vegetation roots, pipes, or other structures going through the levee are not accounted for either, which could balance our previous statement as such actors may increase backward erosion failure probabilities. Additional work to include contributing factors to backward erosion would improve the fragility curve accuracy. The overflowing assessment method is highly dependent on water levels and overflow duration applied to the levee. Moreover, expert judgement is prone to over- and underestimation of failure probabilities as shown in Hathout et al., 2019, which may explain why the overflowing fragility curve has the steepest increase in this case study.

B. Influence of the distance to the levee on depth and velocity

In general, the higher the water depth, the closer to a breach we are located. However, for the present case study, it seems there is no correlation between depth and distance to the levee. Instead, it shows that topography has a big impact on depth. On the other hand, velocity values lower the further we go from the breach location. In our case study, there is one exception: location e (road) is obstacle free due to straight and flat terrain conditions offered by the asphalt road. With few obstacles to slow water propagation, location e shows similar probabilities to location b (close to the levee). Cumulative probabilities provide maximum depth values, and velocity evolution curve which help choosing appropriate mitigation measures based on which level of hazard one is willing to accept. For example on Figure 6, the water depth of location a (the residential area) does not exceed 2.4 m. Considering depth and velocity probabilities is necessary as both point to different protected areas to focus on. In particular, velocity probabilities should be considered near levee breaches because the values are high.

VI. CONCLUSIONS

A flood risk assessment accuracy relies on each of its component. To improve flood risk assessments, we propose a method to improve flood hazard by considering levee failures. Our approach consists in multiple levee breaching scenarios for various flood intensities. We conduct a levee reliability study for homogeneous levee segments for backward erosion and overflow failure mechanisms, then propagate the flood in the river and through the levee breach, statistically analyzing depth and velocity flood parameters located in the protected area. We propose a new approach to probabilistic flood hazard mapping for flood hazard assessments by developping a probabilistic assessment method of levee failure probabilities able to integrate multiple failure mechanisms. The selection of failure mechanisms (backward erosion, overflowing) must be tailored to the levee studied. We propose a method with an accuracy level meant for city scale and present a case study on Etobicoke Creek, located in the Greater Toronto Area, Canada. The levee shows a high reliability (withstand a 100-yr return period). This method provides information on which critical failure mechanism to focus on for the flood hazard assessment and the maintenance of the levee. Making use of established fragility curves from the levee reliability study, we developed a probabilistic flood hazard assessment method considering various levee failure mechanisms triggered by different flood intensities. The flood propagation in the river and through the levee breach provides flood depth and velocity maps to analyse. We propose a new approach to probabilistic flood hazard mapping, providing cumulative probabilities of every flood and levee breaching scenario. This case study showcases the method ability to identify of the most hazardous location with a probabilistic flood exceedance curve. Moreover, once the hydraulic model is defined properly and run, the next flood propagation simulations will need a shorter running time due to locally saved terrain and other input data. For large scale areas, the post-processing of flood hazard maps would be more efficient if it was integrated in a software but as a first approach, coding is sufficient.

We proposed a methodological framework for systematic levee failure integration to flood hazard studies. Levee failure impact on flood hazard highlights the importance of pursuing regular levee maintenance and include levee reliability into flood assessment routine. This probabilistic flood hazard can then be used as an input to a flood risk assessment.

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