Building Damage due to Riverine and Coastal Floods

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Abstract: Floods in both riverine and coastal zones can cause significant damage to infrastructure, including possible structural failure of buildings. Methodologies commonly used to estimate flood damage to buildings are typically based on aftermath surveys and statistical analyses of insurance claims data. These methodologies rarely account for flooding hydrodynamics, and thus do not differentiate between the damage caused by floodwater contact and those caused by floodwater velocity. A new stochastic methodology has been developed to estimate the direct impact of flood actions on buildings and to determine the expected damage. Building vulnerability is modeled based on analytical representations of the failure mechanisms of individual building components. The flood actions generated during different flooding events are assessed and compared to the resistance of each building component. The assessed flood actions include: hydrostatic and hydrodynamic forces, waves, turbulent bores, debris impacts, and time-dependent local soil scour. Monte Carlo simulation was used to synthetically expand the available building data, to perform load-resistance analysis, and to account for the uncertainty of input parameters. The primary result from this study is the expected flood damage to individual buildings, and it is expressed as a three-dimensional functions dependent on both floodwater depth and floodwater velocity. The results show how floodwater velocity can increase the magnitude of the flood damage outcome compared to those that solely consider water depth. This demonstrates the real need for considering floodwater hydrodynamics in the vulnerability assessment of buildings located in flood prone areas. Although the present study focuses on the vulnerability of reinforced concrete frame buildings with infill concrete-block walls, the methodology can also be applied to other types of structures. This methodology could serve as a decision-making tool to assist engineers and emergency management agencies to identify zones of high risk, and to implement the necessary preventive measures and mitigation strategies to minimize the adverse impact of potential flooding events.

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Introduction

Throughout history, floods have led all natural disasters in the number of people affected and have caused incalculable damage and economic losses. Although some natural extreme events, like earthquakes, may cause extreme damage at any particular time, floods occur at a much higher frequency. Close to 90% of all natural disasters in the past 10 years have been the result of hazards such as floods, tropical cyclones, and severe storms; floods in particular have accounted for 37% of all natural hazards [World Meteorological Organization (WMO) 2005]. Flooding events can be categorized into two main types: riverine and coastal. Riverine floods are mainly caused by the overflow of stream channels. Coastal floods can result from storm surges, unusually high tides, or tsunamis. Floods can also be a result of accidental situations, such as the breaching of a levee or a dam.

Flood actions describe those effects that a flood could directly impose on a building, potentially causing damage or even structural failure. These flood actions include: hydrostatic forces, buoyancy (hydrostatic force acting in the upward direction), hydrodynamic forces, forces generated by the impact of floodborne debris or other objects. In the case of coastal floods, buildings can also be affected by the forces induced by the impact of waves. Also, the adverse effects of flood actions can be aggravated by water-induced scour and by long-term erosion. These can lower the ground surface around the building foundations, which could cause the loss of load-bearing capacity and thus, the loss of structural resistance to lateral and uplift forces. There might also be sediment deposition and aggradation against building components, generating additional unforeseen loading.

Damages caused by floods are broadly classified into two categories: tangibles and intangibles (Dutta and Tingsanchali 2003). Tangible damages are those that can be evaluated quantitatively in economic terms. Conversely, intangible damages are the ones that are difficult to express in economic terms, such as environmental and health related losses (e.g., anxiety, mental suffering to victims, inconvenience, and disruption everyday activities). Tangible damages can be classified in two types: direct damages or indirect damages. Direct damages are those caused by physical contact of

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floodwater, such as damages to buildings, general infrastructure, vehicles, transportation and communication features, agriculture, and others. Indirect flood damages refer to the economic impact caused through interruption or disruption of economic and social activities.

Methodologies currently used to estimate flood damage to buildings are typically based on the analysis of data derived from aftermath surveys and insurance claims. Most of these analyses considered bulk monetary losses that neglect the assessment of direct flood damage to buildings, or do not account for the effects of flooding hydrodynamics. Those studies that have actually analyzed direct building damage often focus on damages from floodwater contact. Flood parameters other than floodwater depth are frequently suggested as being important in the determination of damages, but are yet to be thoroughly and systematically analyzed.

The present study focuses on the assessment of direct physical damage to buildings caused by flood actions during different events, including: riverine flood, storm surge, and tsunami. Buildings located in coastal areas, in particular, are frequently affected by high winds, in addition to the flood actions. In these situations, both flood and wind actions can adversely affect structures and it can be difficult to differentiate the damage caused by hydraulic loading from that caused by wind. However, wind-building interactions and the corresponding damage potential are outside the scope of the present study. A stochastic approach is used as part of this study in order to assess the vulnerability of buildings based on the aggregated damage to individual building components, which are rarely examined and analyzed in detail. The results from this study allow to estimate and calculate more accurately the damage from potential flood events, and to account for many of the uncertainties not considered yet in current flood damage models.

Traditional Flood Damage Assessment Methodologies

Direct flood damages are normally estimated from systematically applied survey procedures, but can also be derived from the analysis of insurance claims data, historical flood data analysis, or any combination of these approaches. The results from these analyses are primarily expressed as depth-damage functions, or curves. One of the most significant problems regarding traditional methodologies is that there are no uniform guidelines for the collection of flood damage data. And, similarly, the methods used to evaluate the compiled data and to report these results greatly vary depending of the evaluating agency or institution. Therefore, as discussed by Downton et al. (2005), the records of historical flood damage data are often inadequate for scientific assessment. The following sections discuss the origins of these curves, as well as some of their limitations. Information about FEMA's HAZUS-HM flood model is provided as an example of an application that employs such curves.

Depth-Damage Curves

Depth-damage curves recount the damage extent for a specific region based on the inundation depth. In some cases where the damage progresses as a function of time, the duration of the inundations might be considered. In the case of buildings, depth-damage curves represent the average building damage that occurs at different inundation depths. These curves also consider building characteristics, including primary construction material (wood frame, steel frame, concrete-block bearing walls, or masonry bearing walls) and location (e.g., riverine A-zone, coastal A-zone, or coastal V-zone). Once developed, depth-damage curves are often used for future events or applied to similar regions since their use require less time, effort, and resources. Depth-damage curves are typically developed isolating the contents damage from the building/structural damage. Individual curves are then made available for each category.

The flood damage estimates provided by depth-damage curves can be highly uncertain due to the fact that these curves represent the aggregated damage caused by several different flood actions, but the damage is expressed just in terms of floodwater depth. As noted by FEMA (2005), the use of depth-damage curves is not recommended "*whenever high velocity flows, ice or debris induced damage, erosion and soil/foundation failure, or unusually long-duration flooding are likely*."

Velocity-Damage Curves

One of the few exceptions where floodwater velocity was considered as part of the development of damage curves is the USACE Portland District's velocity-based building collapse curves [U.S. Army Corps of Engineers (USACE) 1985]. These collapse curves correlate the floodwater depth and floodwater velocity with the collapse potential of building based on their material class: (1) wood frame; (2) masonry and concrete bearing walls; and (3) steel frame. However, the only information provided by these curves is if the buildings could potentially collapse or not. Therefore, the information presented by these curves is very limited and does not provide any guidelines concerning the quantification of flood damage, such as the percentage of building damage, or even failure risk.

HAZUS-MH Flood Model

HAZUS-MH (HAZards U.S. Multi-Hazard) is a nationally standardized methodology and risk assessment software program that comprises three models for estimating potential losses from natural disasters (i.e., earthquakes, hurricane winds, floods). HAZUS-MH flood model was released by FEMA in 2004. It currently comprises methods for the assessment of damages in riverine and coastal settings. These damages include buildings, transportation and utility lifelines, crops, vehicles, among others (Schneider and Schauer 2006). The Federal Insurance Administration's and the U.S. Army Corps of Engineers (USACE) are the sources for most of the HAZUS-MH flood model depth-damage curves (Scawthorn et al. 2006b; Ding et al. 2008).

The detailed methodology for this flood model is discussed by Scawthorn et al. (2006a, b). Some of the shortcomings of using HAZUS-MH are that: (1) the flood damage data and damage curves highest resolution is census block level and that (2) currently, there are very few velocity-damage curves. Although HAZUS-MH flood model is said to account for floodwater velocity (Schneider and Schauer 2006), this is actually done by indirect methods such as the application of adjustment factors.

As discussed by Scawthorn et al. (2006a,b), in theory, the HAZUS's library of damage curves can be applied to individual buildings. However, since most damage estimates are computed at census block levels, damage predictions are more reliable for large groups of buildings. Regarding the limited availability of velocity-damage curves, the building collapse curves developed by the USACE Portland District [U.S. Army Corps of Engineers

(USACE) 1985] are still the only functions included in the current version of HAZUS-MH that account for floodwater velocity. Therefore, the direct impacts of moving floodwaters or hydrodynamic forces are not actually considered by the HAZUS-MH flood model. This limitation is crucial since floods with significant velocity can generate much more damage than inundations alone.

Alternative Flood Damage Assessment Methodologies

Studies proposing either alternative or complementary methods to assess flood damage are uncommon. A study by Kelman (2002) focused on evaluating the physical vulnerability of residences to flood disasters in coastal eastern England. In addition to the typical evaluation of hydrostatic actions, Kelman examined the effects of: (1) hydrostatic forces resulting from floodwater depth differentials between the inside and outside of external walls and (2) floodwater velocity. Kelman's study represents an excellent attempt at providing new knowledge and methods to evaluate the risks from coastal flooding scenarios. However, the actions generated due to waves, debris impacts, or local soil scour, were not modeled. In addition, the study only evaluated the vulnerability of masonry walls and glass windows. The vulnerability of other structural components, such as columns or frames, was not assessed.

Another recent flood damage study was performed by Delft Cluster in the Netherlands (Roos 2003). The study evaluated the vulnerability of masonry and concrete buildings due to several loading cases, including: (1) hydrostatic forces due to floodwater level differentials; (2) floodwater velocity; (3) wave action; and (4) pounding debris. The damage model compares the floodwater loads to the strength of the walls. However, the results from the Delft Cluster study were of qualitative nature. As discussed by Roos (2003), in the final analysis it was assumed that when a load-bearing wall fails, buildings could either collapse partially or totally. Then, "*it is supposed that 70% of the partial collapsed buildings will totally collapse*."

Building Damage Model

The present study provides a comprehensive analysis of physical damage to individual building components, which are rarely examined and analyzed in detail. The primary objective of this study is to define a methodology to assess the vulnerability and flood damage risk of buildings located in areas subjected to riverine or coastal floods. The direct floodwater actions on buildings are defined, categorized, and thoroughly analyzed, considering the source of exposure and the corresponding flooding hydrodynamics. The methodology defined herein could also serve as a complementary approach to current methodologies (e.g., flood damage functions), or for verification purposes. In order to achieve this main objective, the secondary objectives were:

1. Evaluate the direct impact of floodwater actions on buildings, including: hydrostatic and hydrodynamic forces, wave forces, debris impact forces, and localized soil scour;
2. Assess the vulnerability of individual building components, including: reinforced concrete frame, concrete-block walls, doors, and windows;
3. Express the expected flood damage as three-dimensional functions dependent of both floodwater depth and floodwater velocity; and
4. Determine the level of influence that the velocity of floodwater exerts on the flood damage outcome.

This analysis of flood actions enables engineers to estimate and calculate more accurately the damage from potential flood events, and accounts for many of the uncertainties not considered yet in current flood damage models. This is particularly significant to emergency management agencies and insurance companies who can benefit from the assessment of flood damage risk and the categorization of flood damage magnitudes.

Modeling Approach

The methodology developed as part of this study is, in essence, the same for buildings located in either riverine or coastal zones. The particularities of each type of event will be discussed in the subsequent sections. The Monte Carlo simulation technique is initially used to synthetically expand the available building data. Complete sets of synthetic data were generated for 10,000 hypothetical buildings, based on the structural and geometric data collected from 28 typical residential buildings in Puerto Rico (i.e., reinforced concrete frame buildings with infill concrete-block walls). The general building data required for the vulnerability assessment includes, location, plan area, and height of the building, among others. Detailed data are also required for each of the building components assessed: reinforced concrete frame, infill concrete-block walls, doors, windows, and utilities and finishes.

Monte Carlo simulation was also used to perform the load-resistance analysis, which evaluates the interaction between the loading and the resistance of a system (building component). In this analysis the forces and actions induced by floodwater are accounted for and compared to the resistance of each of the five building components in order to determine their vulnerability. In order to account for the uncertainty associated with the loading and the resistance, both are characterized by probability-density functions (PDF). Each parameter used in the simulation is assumed to be a mean value and that its possible deviation from this mean value (random error) is given by the corresponding PDF (e.g., normal distribution, lognormal distribution). Failure of a system is deemed to occur when the resistance is exceeded by the loading generated by the collective flood actions.

Computation of Expected Flood Damage

The flood damage is initially computed for each building component individually, as a function of both the floodwater depth and velocity. The expected flood damage (EFD), defined as the expected value of flood damages, is then computed per building unit by considering the aggregated damage to all five building components at each of the evaluated depth-velocity combinations. In general terms the EFD is defined as

$$\mathrm{EFD} = \int (D)d(\mathrm{BV}) \quad \text{or} \quad \mathrm{EFD} = \sum_{i=1}^{5} (D_i)(\Delta \mathrm{BV}) \tag{1}$$

where D=flood damage (%) and BV=replacing value of the building. One of the key steps in the computation of the EFD is to develop an accurate representation of the building failure sequence. The damage to each building component is methodically examined and combined to form the overall EFD at each depth-velocity combination, and many special situations are considered, as described by Nadal (2007). For example, in the extreme event that a load-bearing column fails due to localized soil scour or the impact of flood-borne debris, the associated damages to all other adjacent building components (walls, doors, windows, utilities, and finishes) are also accounted for and aggregated to the total damage. Also, a structurally compromised wall could fail before the floodwater reaches the windows. In this case, the damage corresponding to the window located within that wall, as well as any door or utility feature, is also accounted for. In addition, buildings are considered a total loss when the EFD reaches 60%. This threshold indicates that the cost of repairing the building is equal to the value of replacing it (new construction).

After the EFD is computed, it is expressed as vulnerability matrices and plotted as three-dimensional damage functions. A vulnerability matrix, which is an actual matrix in its mathematical sense, displays the flood damage resulting from each coordinate pair of floodwater depth and floodwater velocity, i.e., EFD=f (depth, velocity). The Monte Carlo simulation is then performed to simultaneously estimate the EFD to each of the 10,000 hypothetical buildings. The mean of all simulated damages yields the final EFD values. The vulnerability of buildings was assessed for various flooding events and their corresponding loading cases, as discussed in the following sections.

Flood Actions due to Riverine Floods

The damage generated by riverine floods may be due to the action of hydrostatic or hydrodynamic forces, impact of waterborne debris, and local soil scour. Hydrostatic forces are those imposed by a mass of still floodwater acting on a building or building component, such as columns, walls, doors, and windows. The magnitude of the hydrostatic force depends on the floodwater depth difference between both sides of a building component. The hydrostatic force, F_S, acting on a plane surface is determined by integrating the hydrostatic pressure over the surface area

$$F_S = \int \gamma h dA_s \tag{2}$$

where γ=specific weight of fresh water ($9.8\ \text{kN/m}^3$ for freshwater); h=floodwater depth; and A_s=area of the plane surface in contact with the floodwater.

Hydrodynamic forces are those generated by flowing floodwater. These forces are dependent on floodwater parameters such as velocity, depth, mass density of water, and in addition, the geometry of the building component being impacted by the flow. The location of a building within the floodplain is of great significance because floodwater velocity is likely to decrease away from the source of the flood (i.e., main channel of a river, or the coastline in the case of a storm surge). Hydrodynamic forces are comprised of two main components: inertia and drag. The inertial force is proportional to the acceleration of the fluid, while the drag force is proportional to the square of the velocity. The inertial component is omitted due to the difficulty associated with the computation of flow acceleration around buildings in flooding conditions. Therefore, the hydrodynamic force, F_D, acting on a plane surface is determined by

$$F_D = C_D \int \rho U^2 dA_p \tag{3}$$

where C_D=drag coefficient; ρ=mass density of water ($1{,}000\ \text{kg/m}^3$ for freshwater); U=depth-averaged floodwater velocity; and A_p=area of the plane surface perpendicular to the flow. The drag coefficient is a function of the building width to floodwater depth ratio, and it typically ranges between 1.2 and 2.0 (FEMA 2000).

Flood Actions due to Coastal Floods

Coastal flooding can result from unusually high tides, storm surges or tsunamis. The present study focuses on the flooding of coastal zones caused by storm surges and tsunamis. Although these two events are very different occurrences, the effects on the infrastructure of low-lying coastal zones can be very similar. Recent examples of these are the tsunami that affected the Indian Ocean region in 2004 and the storm surge generated by Hurricane Katrina in the Gulf Coast of the United States in 2005. Robertson et al. (2006) stated that: "*Despite the differences in flow velocity and inundation duration, the effects on the coastal infrastructure in the inundation zones of Hurricane Katrina and the Indian Ocean tsunami of 2004 were remarkably similar,. . . for this reason numerous parallels have been drawn between the two events*."

Storm Surges

A storm surge is an oceanographic phenomenon characterized by an abnormal increment in seawater level, which is caused by the atmospheric low pressure and wind field associated with moving storm systems. The winds from tropical storms or hurricanes can pile the ocean water along the coastline and rush it inland, resulting in great heights and potentially causing extensive damage to buildings and coastal infrastructure.

One of the complexities when calculating forces generated by a storm surge is determining the floodwater velocity. Both the velocity and direction of floodwater vary drastically throughout the course of a storm system. The velocities of the floodwater currents can vary from near zero to extreme velocities during a single event. FEMA (2000) recommended that floodwater velocities due to a storm surge should be assumed to lie between specific lower and upper bounds. The lower bound, given by $c_l = h/t$, where h is floodwater depth, and t is defined as 1 s, is recommended as a safety factor for design purposes, instead of considering near zero velocities. The upper bound is given by the wave celerity equation, stated as $c_u = (gh)^{1/2}$.

The hydrostatic and hydrodynamic forces due to the floodwater and currents generated by a storm surge can be estimated using the same equations used for riverine floods. However, the values of mass density and specific weight of water should be adjusted due to the higher density of the salt water. The recommended values of specific weight and mass density of salt water are $10.0\ \text{kN/m}^3$ and $1{,}025\ \text{kg/m}^3$, respectively.

The impact of waves is one of the most important factors in the estimation of flood damage to buildings in coastal zones. As discussed by FEMA (2000): *only highly engineered, massive structural elements are capable of withstanding breaking wave forces*. There are two breaking wave forces cases that are most relevant to buildings: breaking waves on walls, and breaking waves on columns. In the case of breaking waves acting on walls, the magnitude of the force is calculated based on a modified version of the Hom-ma and Horikawa model (Hom-ma and Horikawa 1965). This model is further discussed in details by Walton et al. (1989). The magnitude of the breaking wave force acting on a vertical wall, F_W, can be estimated by

$$F_W = 1.1 C_P \gamma_s h^2 b + 2.41 \gamma_s h^2 b \tag{4}$$

where C_p=dynamic pressure coefficient; γ_s=specific weight of salt water ($1{,}025\ \text{kg/m}^3$); and b=width of the wall. In those cases where the floodwater level is equal at both sides of the wall, the breaking wave force, F_W, is determined from

$$F_W = 1.1 C_P \gamma_s h^2 b + 1.92 \gamma_s h^2 b \tag{5}$$

The dynamic pressure coefficient has been defined as a function of the exceedance probability of the storm surge event, and typically varies between 1.6 and 3.2. The breaking wave forces acting on a column, F_{Wc}, can be calculated as follows:

$$F_{Wc} = 0.5 C_D \gamma_s b_c H_W^2 \tag{6}$$

where b_c=diameter of the column and H_W=height of the waves. According to the wave breaking criteria, the maximum breaking wave height can be assumed as 0.78 times the floodwater depth. The recommended values for the breaking wave drag coefficient are 2.25 for square or rectangular columns and 1.75 for round columns (FEMA 2000).

Tsunamis

A tsunami is a wave, or series of waves, of extremely long wavelength and period which is generated by an impulsive disturbance that vertically displaces a large-scale amount of ocean water. Tsunamis are more commonly triggered by fault motion during seismic events (earthquakes), although they can also be generated by volcanic eruptions or massive landslides near or at the bottom of the ocean. A tsunami can strike a coastal zone as solitary wave, or as a series of waves capable of inundating the coastline as high-velocity currents, known as turbulent bores (Ramsden 1996).

The magnitude of the forces generated due to a tsunami can be approximated by the same equations used for cases of storm surges. However, it is essential to consider the greater magnitude of the floodwater velocity. It is recommended that floodwater velocities due to a tsunami should be assumed to lie between a lower and an upper bound given by Eqs. (7) and (8), respectively

$$c_l = \sqrt{gh} \tag{7}$$

where c_l=lower bound velocity due to a tsunami flooding, given by the equation of wave celerity and g=gravitational acceleration constant, and

$$c_u = 2\sqrt{gh} \tag{8}$$

where c_u=upper bound velocity due to a tsunami flooding. Note that Eq. (8) yields conservative estimates, since it derived based on the speed of a surge-front traveling over a frictionless horizontal plane (Camfield 1980).

Special Flood Actions

This section discusses those actions that are not directly imposed by water, but are driven by the floodwater flow. These special cases include the analysis of forces due to the impact of floodborne debris and local soil scour. In the case of coastal zones, in particular, the adverse effects of flood actions can be aggravated by water-induced scour and by long-term erosion. These can lower the ground surface around building foundations, which could cause the loss of load-bearing capacity and, thus, the loss of structural resistance to lateral and uplift forces.

Debris Impacts

Forces due to the impacts of floodborne debris can be large enough to cause substantial or even catastrophic damage to the buildings. The magnitude of the impact force is very difficult to predict due to the uncertainties of the parameters involved, including: floodwater velocity, velocity of the floodborne debris, weight and geometry of the debris, height of the debris impact, and duration of the impact. The model used in the present study to estimate the forces due to debris impacts was developed by Haehnel and Daly (2004). This model, which was developed based on laboratory studies, is analogous to the behavior of a spring system and is defined as

$$F_I = U\sqrt{k m_d} \tag{9}$$

where F_I=force due to the impact of floodborne debris; U=floodwater velocity; k=effective contact stiffness between debris and structure; and m_d=mass of the debris. In practice, the likelihood of a building being impacted by debris is unknown. Therefore, the parameters k and m_d were varied randomly. Also, the damage due to floodborne debris was computed based on the assumption that one critical structural member is impacted (i.e., load-bearing column).

Local Soil Scour

Currently, there is no methodology, to the writers' knowledge, to estimate local soil scour at a building foundation. As a common practice, buildings are not expected to be located along flood prone areas. However, ideally, local scour effects on buildings can be adapted from those known effects on bridge piers that are geometrically similar and subjected to the same hydraulic conditions. FEMA (2000) proposed the preliminary use of an equation developed at Colorado State University (CSU) to predict scour depths at bridge piers

$$\frac{z_t}{h} = 2.2\left(\frac{b_f}{h}\right)^{0.65} (\mathrm{Fr})^{0.43} \tag{10}$$

where z_t=scour depth at a building foundation; b_f=one-half width of building in the direction of the flow; and Fr=Froude number. Eq. (10) is essentially the CSU equation (Jones 1983; Richardson and Davis 2001), but it already incorporates a correction factor of 1.1 for square-shaped structures. Also, in Eq. (10) the flow-obstruction length is taken as one-half the width of building, b_f, instead of the entire width in the case of a pier. This is due to the fact that, in the case of buildings, it is deemed that one scour hole will develop at each side of the wall facing the floodwater flow, instead of just one hole at the center of the obstruction in the case of piers or other narrow structures.

Zevenbergen et al. (2004) stated that it could take up to 10,000 h, in some extreme cases, for scour to develop into the predicted values with Eq. (10). However, hurricanes and other storms often produce extreme hydraulic conditions for time periods of only a few hours. Therefore, using the current pier scour equations to estimate scour depths under these conditions may not be reasonable.

A new model was sought to estimate local scour while accounting for the time-scale effects, which could result in scour depths being only a small fraction of the ultimate scour depth. Therefore, in order to estimate local scour depths at building foundations as a function of the floodwater flow duration, it is recommended to use the CSU equation, Eq. (10), but with the inclusion of the time-scale correction factor, K_t, developed by Melville and Chiew (1999); i.e., final scour depth is estimated as: Eq. (10) $\times K_t$. The time-scale correction factor was also modified since it was originally developed for circular bridge piers. Therefore, as part of the present study, the K_t factor was adapted for square and rectangular shapes representing typical building geometries. The following is the time-scale factor modified based on laboratory data obtained at the Iowa Institute of Hydraulic Research (IIHR) by Barkdoll (2000)

$$K_t = \exp\left\{-0.25 \cdot \left|\frac{U_c}{U}\ln\left(\frac{t_f}{t_u}\right)\right|\right\} \tag{11}$$

where U_c=critical floodwater velocity [as defined by Melville and Chiew (1999)] and t_f=duration of the floodwater flow. The parameter t_u is the time required for the development of maximum scour depth. It can be obtained experimentally as the time at which the rate of increase of scour depth is less than 5% the diameter (or equivalent width) of the structure, or through the equations developed by Melville and Chiew (1999).

Loading Cases

In order to better understand the possible consequences of the flooding events (riverine flood, storm surge, and tsunamis), each one has been subdivided into two different loading cases according to the different combinations of forces and flood actions. This section discusses each loading case, the corresponding flood actions, and the entailed assumptions.

Riverine Floods

- The slow rise flood represents the typical riverine flood. As the name implies, the floodwater depth increases slowly, allowing for infiltration of water into the building through small openings of doors and windows. This situation causes the floodwater level to be basically equal at both sides of the external walls, resulting in the cancellation of the hydrostatic force. Only the hydrodynamic force acting on the outside of external walls is accounted for in this case; and
- The flash flood, or fast rise flood, represents an atypical situation where the floodwater rises rapidly and moves at very high velocities. This type of flood can be caused by extreme rainstorm events, or by accidental situations such as the breaching of a levee or dam. The key assumption is that the rise of the floodwater is rapid enough to affect the building without allowing significant infiltration of floodwater. Therefore, the inside of the building is considered to be dry. This is a worst-case scenario where it is also assumed that any given combination of floodwater depth and floodwater velocity occurs instantaneously. This would allow us to consider the maximum feasible flood damage due to a riverine event. Both the hydrostatic and hydrodynamic forces are accounted for in this case.

Storm Surges

- The surging flood characterizes the most common type of coastal flood caused by a tropical storm or hurricane. Due to the nature of the storm surge event, the depth of the stillwater increments gradually and flooding of coastal areas can occur hours before the system landfall. This case is similar to the slow rise riverine flood, in which the hydrostatic force is cancelled and only the hydrodynamic force is considered; and
- The breaking waves case applies to coastal zones, where waves are capable of reaching buildings located at the coastlines without any obstruction. The occurrence of breaking waves represents the maximum feasible flood damage due to a storm surge event. This case accounts for breaking wave and hydrodynamic forces.

Tsunamis

- Turbulent bores occur when the tsunami waves break and inundate the coasts as high-velocity currents. These turbulent bores can adversely affect buildings even several miles inland. Due to the rapid development of this type of event, both hydrostatic and hydrodynamic forces are considered; and
- Tsunami waves normally break offshore and approach the coast as turbulent bores. However, when an area has been already flooded by long waves or bores, breaking waves can have a direct impact on buildings. This case considers the effects of breaking waves and hydrodynamic forces.

Building Vulnerability

Although structural analysis is not the focus of this paper, it is vital to discuss briefly the building vulnerability models developed as part the present study.

Reinforced Concrete Frames

The vulnerability of reinforced concrete columns depends on several factors, including: the number and dimensions of the columns, the total area and tensile strength of steel reinforcement, the compressive strength of concrete, and the load supported by the columns. The bending moments and shear forces induced by the floodwater are calculated using structural mechanics theory. The vulnerability analysis focuses on the reinforced concrete columns, since these are the frame elements that are directly impacted by the floodwater actions, and, thus, where the failure is deemed to occur. However, a reinforced concrete frame consists primarily of columns and beams. This beam-column system allows loads to be transferred between the connecting elements. Therefore, when analyzing the flood forces acting on columns, the beams are also taken into consideration.

The magnitude of the floodwater forces acting on the reinforced concrete columns on typical building frames were modeled by J. Agudelo (personal communication, 2006), using the software SAP2000. A two-dimensional linear elastic analysis was performed to determine the bending moments and shear forces acting on both the strong axis and the weak axis of reinforced concrete frames. The flood forces were represented by an equivalent point load acting at different floodwater depths (0.15-m intervals).

Concrete-Block Walls

The vulnerability of the concrete-block walls is estimated by yield line analysis (YLA). This methodology is typically used for the analysis of concrete slabs (Kennedy and Goodchild 2004), but has been successfully used for evaluation of block walls subjected to lateral forces (Martini 1998; Kelman 2002). The term *yield* is used because the concrete slabs are assumed to be ductile (elastic-plastic stress-strain relationship) due to the steel reinforcement. However, when used to analyze masonry walls it is often called *fracture* line analysis. YLA is based on the use of the virtual work method (VWM) to evaluate the failure mechanism of elements at the ultimate limit state, where the virtual external work done by the forces equals the virtual internal work done by the energy dissipation along all the yield lines (Kennedy and Goodchild 2004).

As discussed by Kelman (2002), it is assumed that unsupported wall panels under external forces develop a plastic hinge (or yield line) in a region of high moment. This hinge resists the moment by transferring the force to other regions which also yield and become part of the hinge. The yield lines are formed across the unsupported wall panel, dividing it into slabs that rotate plastically due to the applied force. When the external work exceeds the internal work, the static equilibrium is broken, causing the wall panel to collapse. The VWM defines the equilibrium equations by analyzing an arbitrary horizontal displacement of the slabs. This displacement is often expressed as a fraction of unity. The VWM equations are expressed as follows (Kelman 2002):

$$\text{Internal energy dissipated} = \text{External energy expended}$$

$$\sum (M \times l \times \theta)_{\text{over all slabs}} = \sum (F_e \times \delta)_{\text{over all slabs}} \tag{12}$$

where F_e=resultant floodwater force; δ=horizontal displacement generated by the resultant floodwater force; M=bending moment capacity; l=length of the yield line; and θ=angle of rotation of the slabs. The YLA allows to assess the vulnerability of concrete-block walls of different dimensions (width, height, thickness) and also allows to evaluate walls with openings, such as doors and windows.

Doors and Windows

The vulnerability of doors and windows is assessed considering the damage to their respective connections as the primary failure mechanism. These building components were modeled using two-dimensional rigid-body statics. Equilibrium equations were established to determine the reaction forces in the connections as a function of the magnitude of the flood forces and floodwater depth. Static equilibrium analysis was performed to determine the reactions at the door lock and at three hinges. From this analysis, it was determined that the larger reaction force was that of the door lock. The analysis of the reaction forces on double doors present two cases, with and without bolts. The case of a double door with bolts results in the addition of two reaction forces.

The British Standard (British Standards Institution 1980) *Locks and Latches for Doors in Buildings* states that the resistance of typical door locks ranges from 0.5 to 4.0 kN. Studies discussed in the more recent European Standard (European Committee for Standardization 2004) *Burglar Resistant Construction Products—Requirements and Classification* show that the resistance of the door locks could vary from 1.0 to 5.0 kN. Static equilibrium analysis was also performed to determine the reactions at the window connections. The strength of the window connections is provided by the shear force capacity of the screws that secure the windows to the concrete. Typically, the screws used for this type of connection have a shear stress resistance of 165 MPa and a diameter of 6.35 mm (Breyer 1988).

Utilities and Finishes

The building utilities and finishes division differs from all other building divisions in that its vulnerability cannot be assessed directly by load-resistance analysis. This division includes: electrical and plumbing systems, cement plastering, painting, and wood works, among others. Therefore, an alternate method must be employed. Buchele et al. (2006) discusses various types of damage functions, including: linear polygon function, square-root function, and point-based power function. It is also pointed out that damage to utilities and finishes tends to occur after the floodwater level has risen to a threshold elevation in the building. In some cases, this damage can be negligible until the floodwater affects the electrical installation (power receptacles).

Among all the functions evaluated in the present study, the point-based power function was chosen to represent the damage to building utilities and finishes due to its flexibility and user-defined parameters. Eq. (13) allows establishing the heights at which the initial and the maximum damage to the utilities and finishes occur (Buchele et al. 2006)

$$D = D_{\max}\left[\frac{D_0}{D_{\max}} + \left(1 - \frac{D_0}{D_{\max}}\right)\left(\frac{h - h_0}{h_{\max} - h_0}\right)^{1/C}\right] \tag{13}$$

where D=flood damage; D_0=initial flood damage at height h_0; $D_{\max}$=maximum flood damage at height $h_{\max}$; h_0=height of initial flood damage; and $h_{\max}$=height of maximum flood damage. The user-defined exponent C allows to control the gradient of the damage function.

U.S. Army Corps of Engineers (USACE) (1985) presented damage functions for different types of buildings due to still floodwater, where the velocity is equal to zero. When block-wall buildings are affected by still floodwater, it is reasonable to assume that the gross of the building damage is due to the damage experienced by the utilities and finishes. Since the current research considers flood damage at 0.3-m intervals, the utilities and finishes damage will be initially observed at 0.3 m of floodwater depth (h_0=0.3 m). The damage due to flood depths less than 1 m is estimated by linear interpolation. A user-defined exponent C equal to 1.17 resulted in a correlation coefficient between the point-based power function and the U.S. Army Corps of Engineers (USACE) (1985) damage data of 0.995. For those events where floodwater velocity plays a significant role, the utilities and finishes damage function [Eq. (13)] must be adjusted accordingly to reflect the possible increase in damage.

Results: Expected Flood Damage

The primary result from the present study, which is the EFD, can be expressed as vulnerability matrices or as three-dimensional surface plots. Each of these represents the mean damage suffered by all 10,000 hypothetical buildings due to a unique flooding scenario. Each of the buildings was evaluated at eight different 45°-rotational intervals, according to the directions in which the floodwater can potentially approach the building. For each flooding scenario, matrices are developed for each of the eight intervals, plus an additional matrix representing the average damage considering all eight directions. These average damage matrices state the expected damage regardless of floodwater direction, and its use is adequate for those cases when the direction in which the floodwater approaches a building is unknown. Each vulnerability matrix is represented by a three-dimensional vulnerability surface illustrating the corresponding EFD.

Riverine Floods

The direction-averaged vulnerability surface shown in Fig. 1 shows that the maximum EFD observed for the slow rise flood case (at h=3.0 m and U=3.0 m/s) is 54%. Notice that under the traditional approach, where most of the considered damage is only due to floodwater contact (at h=3.0 m and U=0.0 m/s), just a 36% EFD damage would have been predicted. In theory, this represents a damage underestimation of up to 18%. This difference evidences one of the weaknesses of the traditional flood assessment methodologies, where only hydrostatic effects are considered (i.e., no effect of moving floodwater). In this case, a typical depth-damage function would show damage magnitudes

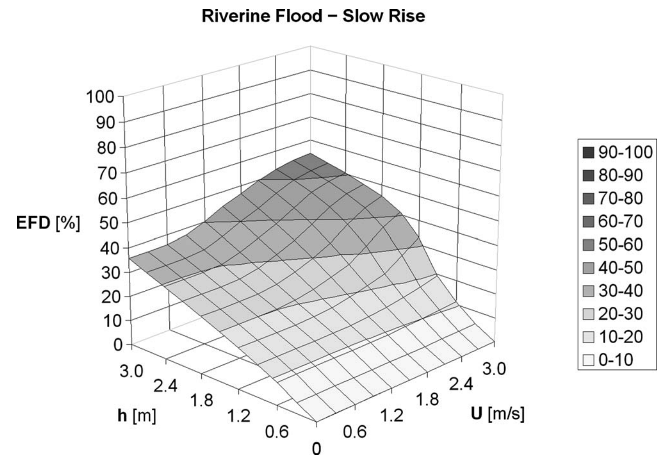

Fig. 1. Expected flood damage due to slow rise floods

comparable to a curve corresponding to zero velocity ($U = 0.0$ m/s), as shown in Fig. 1. The following trends were observed with respect to the EFD outcome:

1. In case of still floodwater (velocity near to zero), most of the damage is due to water contact;
2. At low floodwater depths and velocities, floodwater depth tends to be the controlling parameter, which is the variable that has the greatest influence on the model outcome; and
3. At high floodwater depths and velocities, the flood damage is controlled by both parameters.

The direction-averaged vulnerability surface for the flash flood loading case is presented in Fig. 2. The maximum EFD observed for this matrix (at $h = 3.0$ m and $U = 3.0$ m/s) is 55%. Even though the maximum EFD is just 1% higher than its equivalent for the slow rise flood case, for the rest of the depth-velocity combinations, the maximum EFD due to flash flood can be up to 27% higher. In the case of a flash flood it is observed that, in general, floodwater velocity has less influence in the EFD outcome when compared to the slow rise case due to the assumption that the floodwater rises rapidly enough to affect the building while the inside is still dry. In addition, although the hydrostatic force and the hydrodynamic force are both functions of floodwater depth, the hydrostatic force depends solely on the floodwater depth and its magnitude is much larger than that of the hydrodynamic force. This explains the fact that for any depth-velocity combination, floodwater depth is the controlling parameter (see Fig. 2).

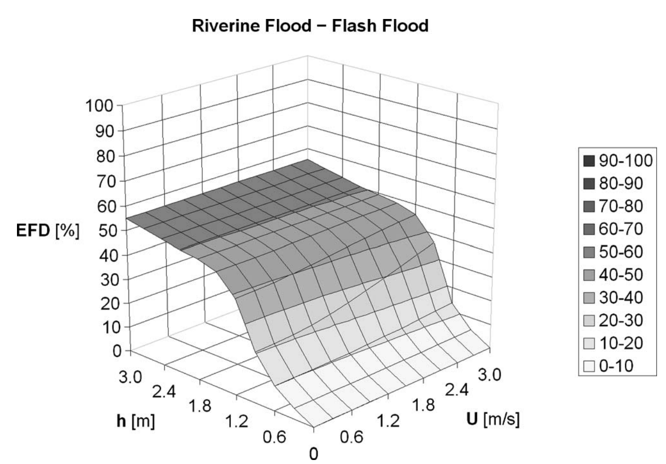

Fig. 2. Expected flood damage due to flash floods

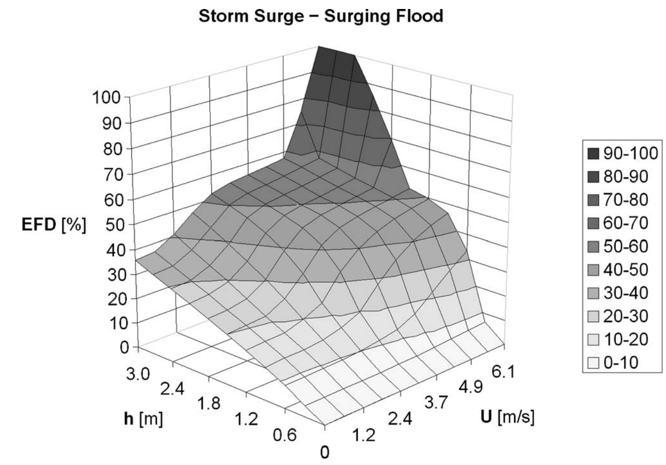

Fig. 3. Expected flood damage due to surging floods

Storm Surges

The flood damage due to coastal storm surges was calculated for floodwater depths up to 3.0 m and velocities up to 6.1 m/s. Floodwater velocity due to storm surges can increase the damage by over 140%, when compared to still floodwater. The direction-averaged vulnerability surface for the surging flood loading case is presented in Fig. 3. The trends observed for this case are similar to the case of slow rise flood. However, significant increase in damage to reinforced concrete frames is observed for floodwater depths greater than 1.8 m and floodwater velocities greater than 5.5 m/s.

The direction-averaged vulnerability surface for the case of breaking waves due to storm surge shows that floodwater depth is the controlling parameter (see Fig. 4). This is due to the large magnitude of the breaking waves force, which, for a given floodwater depth, is between 9 to 11 times larger than the magnitude of the hydrostatic force alone. The breaking wave force is a function of floodwater depth, as is the hydrostatic force. It can also be concluded that floodwater velocity has almost no bearing on the expected flood damage outcome. At high floodwater depths and

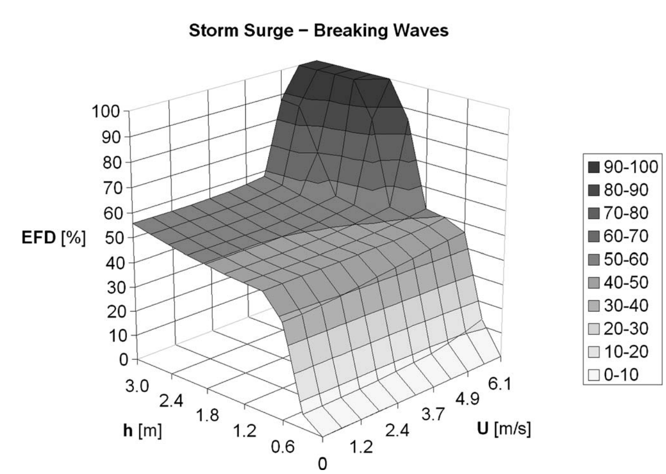

Fig. 4. Expected flood damage due to breaking waves

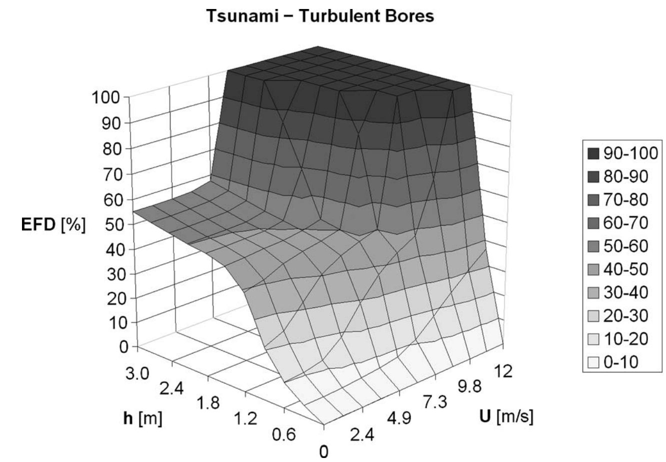

Fig. 5. Expected flood damage due to turbulent bores

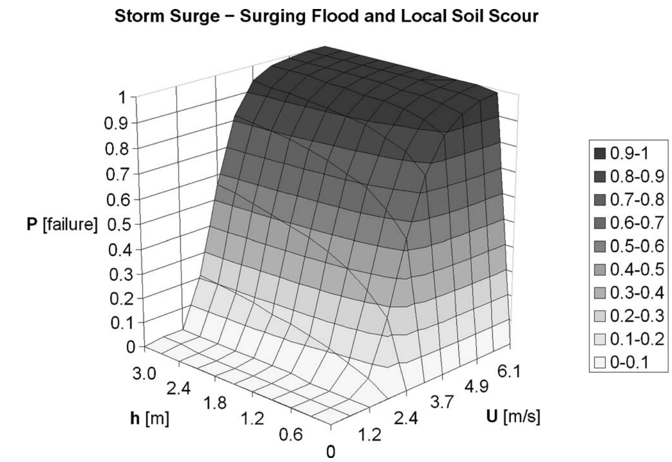

Fig. 6. Probability of foundation failure due to surging floods and local soil scour

velocities (beyond 1.8 m and 4.9 m/s, respectively), significant increase in damage to building frame is initially observed.

Tsunamis

The flood damage due to tsunamis was calculated for floodwater depths up to 3.0 m and floodwater velocities up to 12.2 m/s. In the case of tsunamis, floodwater velocity can increase the damage by up to 190%, compared to the damage by still floodwater. The direction-averaged vulnerability surface for the turbulent bores loading case is presented in Fig. 5. At low floodwater depths and velocities, the expected flood damage due to breaking waves is up to 28.5% higher than the flood damage due to turbulent bores. In the case of tsunamis the floodwater velocity is a function of the floodwater depth. Thus, it can be considered that for both loading cases floodwater depth is the parameter that controls flood damage outcome. Significant damage to the building frames is observed for floodwater depths as low as 1.2 m, for both, turbulent bores and tsunami waves cases. Also, in both cases, major damage to the reinforced concrete frames can be observed for floodwater velocities as low as 6 m/s. Total damage can be observed for floodwater depths and velocities beyond 1.5 m and 7.3 m/s, respectively.

Local Soil Scour

The local soil scour estimates were generated for shallow foundations (column footings) resting on noncohesive soils and subjected to clear-water scour which constitutes a conservative assumption. Two different sets of results were obtained in the case of local scour: the EFD values and the probability of foundation failure. Both of these results are expressed as a function of floodwater depth, velocity, and duration of flow exposition. The vulnerability assessment considered those foundations located at the corners of the buildings and those located at the laterals, immediately adjacent to the corners. Based on the collected building data, the average distance from the center of the corner to the lateral column footings is 2.6 m. A scour hole must develop to a great extent in order to reach and affect the lateral column footings. Therefore, the probability of failure of the lateral column footings is drastically reduced when compared to that of the corner column footings.

The vulnerability surfaces for the case of local scour show the potential damage caused by the local scour, considering a given floodwater flow, in addition to the damage generated by the typical flood actions corresponding to each loading case. From the results, it is evident that the probability of failure rises as the floodwater depth, velocity, and flow duration increase.

In general, the largest increment in failure probability was observed for flow durations between 2 and 4 h (up to 0.35). Although the probability of failure continues increasing for the subsequent durations, the incremental differences tend to decrease. The probability of foundation failure due to the local soil scour generated by storm surges (surging flood), and flow duration of 6 h, is presented in Fig. 6. Note that this vulnerability surface only considers floodwater flow approaching the building at 90° angles with the walls.

Conclusions

This study proposes a new methodology to estimate flood damage to buildings in either riverine or coastal settings, based on the aggregated damage to individual building components. This methodology represents an improvement upon existing flood damage estimation methodologies based on aftermath surveys and statistical analyses of insurance claims data. It can serve as a decision-making tool to assist researchers, designers, and emergency management agencies to identify high-risk zones, and to implement the necessary preventive measures and mitigation strategies to reduce damage and adverse impact of potential flood events.

The flood damage results provide a basis to compare the risk of flood damage between different locations and flood hazards. The results also allow making an important distinction between the flood damages caused by hydrostatic actions (function of floodwater depth) and those damages caused by hydrodynamic actions (function of floodwater velocity). In the case of riverine events, floodwater velocity can increase the damage by an additional factor of over 100% when compared to flood inundations alone, where floodwater velocity is equal to zero. When considering storm surges, it was determined that floodwater velocity can increase flood damage by up to 140%, when compared to still floodwater. Similarly, in the case of tsunamis, floodwater velocity can increase the damage almost 190%. The results from this study demonstrate the need to consider floodwater hydrodynamics as part of the damage assessment of buildings located in flood prone areas.

The specific results from this study should be directly applied only to residential reinforced concrete frame buildings with infill concrete-block walls. These results could be applied to other types of buildings (e.g., commercial or industrial) only if they are comparable to those typical buildings from which the results were generated. However the general concepts, methodological principles, and lessons learned from this study can be effectively applied to other types of buildings and natural hazards.

Recommendations

Additional studies should be carried out in order to improve the structural vulnerability models, accounting for dynamic load redistribution caused by the failure of individual columns. More studies are needed in order to fully understand how local soil scour develops around building foundations and the corresponding failure mechanisms. In addition, further development of the methodology is necessary in order to include other types of building structures, such as shear-wall buildings, wood-framed buildings, and industrial steel buildings.

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