Building Damage Estimation due to Riverine Floods, Storm Surges and Tsunamis: A Proposed Methodology

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Abstract
This article describes the methodology that has been proposed to estimate direct flood damage to buildings located in riverine and coastal zones. Flooding data have been identified and will be used to develop a database including parameters such as topographic elevation, flood elevation, flood depth, flow velocity, soil type, and land use. Methodologies have been defined to effectively estimate the direct impact of flood actions on buildings, including hydrostatic and hydrodynamic forces, buoyancy, debris impact, waves, surges and tsunamis. These force magnitudes will be compared to the resistance of the structural components in buildings in order to estimate their vulnerability or failure potential. This comprehensive analysis of flood actions would permit to estimate and calculate more accurately the potential damage from flood events (i.e. 10-yr, 50-yr, 100-yr, and 500-year recurrence intervals) and allow to properly account for these uncertainties.

Keywords
Flood, Storm Surge, Tsunami, Building Damage

1. Introduction
Throughout history, floods have lead all natural disasters in the number of people affected and have caused incalculable economic losses. Every year, flooding causes more property damage than any other type of natural disaster. In fact, in the United States alone, flooding accounts for over 90 percent of the disaster-related property damage, and for over 75 percent of all Presidential disaster declarations (FEMA, 1998). Floods can be categorized in two main types: riverine and coastal. In the case of riverine floods, they are mainly caused by the over flow of channels. Riverine floods can also be produced by accidental situations, such as the breaking of a dam. Extreme damages can be expected when flood prone areas have been developed without proper care of the inherent flood risks of these developments. The largest and most significant riverine flood event ever to occur in the United States is known as the Great Midwest Flood of 1993. Tens
of thousands of people were evacuated, and 50 flood-related deaths occurred. At least 10,000 homes were totally destroyed, hundreds of towns were impacted with at least 75 towns totally and completely under floodwaters, and damages approached $15 billion (Larson, 1993). It affected several States, including North Dakota, South Dakota, Nebraska, Kansas, Minnesota, Iowa, Missouri, Wisconsin, and Illinois. Hundreds of levees failed along the Mississippi and Missouri Rivers causing record flooding in nearly 150 major rivers and tributaries.

On the other hand, coastal floods can be a result from storm surges, unusually high tides, or tsunamis. On December 26, 2004 a large earthquake off the coast of Sumatra triggered the deadliest tsunami in recorded history. According to news reports, billions of dollars were lost in property damages, and over 300,000 people lost their lives. Similarly, the recent Hurricane Katrina made its second landfall on the morning of August 29, 2005 in southeast Louisiana, United States. Hurricane Katrina impacted approximately 93,000 square miles and its storm surge caused catastrophic damage along the coastlines of Louisiana, Mississippi, and Alabama. The storm surged also breached the levees separating New Orleans, Louisiana from Lake Pontchartrain, flooding approximately 80 percent of the city and many surrounding areas. Hurricane Katrina is the first flood disaster in the United States to approach an estimated $100 billion in property losses, and devastated more residential properties than any other hurricane in recorded history (Fragos-Townsend, 2006). Hurricane Katrina completely destroyed or made uninhabitable approximately 300,000 homes, resulting in an estimate of $67 billion in residential damage alone.

Because of the geographical setting, countries in tropical regions are exposed to a range of flood inducing natural hazards. Any year, Puerto Rico can experience the threats of hurricanes or slow moving tropical systems that move near the region. Historically, these atmospheric phenomena have caused concern at least once every five years, leaving heavily damaged areas and several deaths behind it, due to extreme riverine and storm surge floods. Recent events such as: Hurricanes Hugo-1989, Marilyn-1995, Hortense-1996, Georges-1998 and Jeanne-2004 are remainders of our vulnerabilities and needs for preparedness against hurricanes and storms. Nevertheless, Puerto Rico has not been included yet in any of the nationwide flood risks assessment studies such as Hazus MH (FEMA, 2003). In 1918 one of the most severe earthquakes known to strike Puerto Rico during the last century generated a landslide tsunami that affected most of the west and northwest coasts. The tsunami caused extensive property damage in the region and almost 150 deaths (O’Loughlin and Lander, 2003).

2. Objectives

The objectives of this study are to: identify and classify the available information about known flood variables and flood risks; develop a database including flood-related parameters such as topographic elevation, flood elevation, flood depth, and flow velocity distribution; estimate the direct impact of flood actions, including hydrostatic and hydrodynamic forces, buoyancy, debris impact, and waves on buildings; define a methodology to effectively estimate soil scour caused by flooding on buildings; determine the resistance of structural elements in buildings to loads caused by flooding; develop the scheme to estimate the vulnerability of buildings, and building elements, located in areas subjected to riverine and coastal flooding (such as 10-yr, 50-yr, 100-yr, and 500-year recurrence intervals) including storm surges and tsunamis.
3. **Flood Damage Assessment (Previous Approaches)**

Comprehensive assessment of risks from flooding is necessary for society to better understand the hazards that it faces daily. However, most flood assessment studies are based on estimation of bulk monetary losses. These studies normally focus on the analysis of economic factors, such as cost of repair or replacement, shelter needs, temporary housing, vehicles, crop and livestock losses, business interruption, days lost from work, and changed spending patterns. Studies that in fact analyze direct building damage tend to focus on damage from floodwater contact. The flood characteristic most frequently analyzed in detail is the water depth from slow-rise floods. Therefore, flood dynamics are often overlooked.

3.1 **Depth-Damage Curves**

Most flood damage studies use depth-damage curves to represent the average building damage that occur at different flooding depths. Information on value, damage as a function of depth, and flood depth at the site are necessary to develop these curves for buildings and other properties (USACE, 1996). Depth-damage curves are normally developed from systematically applied survey procedures, but can also be derived from historical flood data analysis, or through analytical descriptions of flood damage considering the possible damage ratio to a given flood depth. Other depth-damage curves are summing up statements of economic losses for specified regions or river reaches and often include other flood parameters such as inundation duration; such is the case of Hazus MH (FEMA, 2003). Flood parameters other than depth and duration are usually suggested as being significant but have not been analyzed as thoroughly and as systematically. There is currently the need to define, categorize, and fully analyze direct floodwater actions on buildings, including flooding dynamics.

4. **Information Requirements**

The analysis of building damage requires at least two main parameters: floodwater depth and velocity field. For the case of riverine flood damages, hydraulic analyses were performed for five of the mayor rivers in Puerto Rico: Río Guanajibo, Río Yagüez, Río Grande de Añasco, Río Grande de Arecibo, and Río Grande de Manatí. These analyses were performed using the HEC-RAS software developed by the U.S. Army Corps of Engineers (USACE). The input parameters used for each riverine system included: topography of the watershed, channel geometry, land use, and peak flows for recurrence periods of 10, 50, 100, and 500 years. The land use data were obtained from a previous study performed in the Civil Engineering Department (Vélez, 2003). The peak flow data were obtained from the recently published update of the Flood Insurance Study (FEMA, 2005). The watershed topography and land used data were pre-processed using HEC-GeoRAS which was developed in cooperative effort by ESRI and USACE. The water surface profile and velocity data were exported from HEC-RAS simulations and post-processed using HEC-GeoRAS. GIS layers of the five watersheds analyzed were created for each period of recurrence as an example of flood-risk zones in the western and northern parts of Puerto Rico. Examples of the developed GIS layers are presented in figure 1 for Río Grande de Añasco. These results were adjusted to match the regulatory data presented in FEMA’s Flood Insurance Study and Flood Insurance Rate Maps.
5. Riverine Floods

The forces generated during a riverine flood include hydrostatic, hydrodynamic, buoyancy, and the forces generated by the impact of waterborne debris. These forces are illustrated in figure 2.

![Figure 2: Typical forces generated by flooding](image)

Hydrostatic forces occur when slow rising floodwater comes into contact with a building or its components. Lateral hydrostatic forces are generally not sufficient to cause deflection or displacement of a building unless there is significant difference in water elevation on opposite sides of the wall in contact with the floodwater. The hydrostatic force, $F_S$, due to riverine flood acting on a wall are determined from:

$$F_S = \int \rho g h \, dA$$  \hspace{1cm} (1)

where: $\rho$ = mass density of water; $g$ = gravitational acceleration; $h$ = depth of floodwater; and $A$ = surface area of the wall in contact with water.

Hydrodynamic forces are induced by moving floodwater. These forces are a function of floodwater velocity and the building geometry. The location of a building within a floodplain can help to establish whether or not to analyze it for hydrodynamic forces, since the floodwater velocities tend to decrease as the distance from the main channel to the building increases. The hydrodynamic force, $F_D$, due to riverine flood with water velocity $\hat{U}$ is defined as:

$$F_D = 0.5 \int C_D \rho \hat{U}^2 \, dA$$  \hspace{1cm} (2)
The drag coefficient is a function of the ratio between the width of the wall and the floodwater depth. Studies have shown that this coefficient typically ranges from 1.25 to 2.0 (FEMA, 2000). The net result of hydrostatic forces acting in a vertical direction on the bottom of buildings is known as buoyant force. These uplift forces could result in the building, or parts of its structure, to float if the building is not properly anchored. Lateral pressures may then displace the floating building or part of the structure, potentially causing damage, destabilization, or even complete destruction. The buoyant force, $F_B$, acting on the bottom area, $A_b$, is determined as follows:

$$ F_B = \int \rho g h \, dA_b $$

Debris impact forces are imposed on a building by objects carried by moving floodwater. The magnitude of the debris impact force can be large enough to cause substantial, or even catastrophic, damage to the buildings (Haehnel and Daly, 2004). This magnitude is very difficult to predict since there are several uncertainties, including: floodwater velocity, velocity of the waterborne object, geometry and weight of the object, section of the building being impacted, and duration of the impact. The most recognized equation for estimation of debris impact force, $F_I$, is the expression of impulse-momentum:

$$ t F_I = \int d(m_d \hat{U}) $$

where: $m_d$ = mass of the debris; and $t$ = contact time between object and wall. The Coastal Construction Manual (FEMA, 2000) recommends different contact time values accordingly to the type of construction material, ranging from 0.2 (reinforced concrete) to 1.1 seconds (wood). A limitation of this impulse-momentum equation is that it gives the average impact force, not the maximum force, an important point that is not explicitly stated in the FEMA guidance. For example, Laboratory data by Haehnel and Daly (2004) of woody debris have show that the maximum impact force was associated with a log striking a rigid structure with its end. The expression for the maximum debris impact force $F_{I,\text{max}}$ is:

$$ F_{I,\text{max}} = \hat{U}_d \sqrt{k \left( m_d + C m_f \right)} $$

where: $\hat{U}_d$ = velocity of the debris; $C$ = added mass coefficient; $m_f$ = mass of the displaced fluid; and $k$ = effective contact stiffness of the collision. Studies by Delft Cluster (Roos, 2003) used the same maximum impact theory, but the effective contact of the collision was defined analogous to a spring system.

### 6. Storm Surges

Storm surges are abnormal water level fluctuations generated by the barometric depression and winds from tropical storms or hurricanes. This type of flooding constitutes a greater hazard to properties and lives than hurricane winds, and can have disastrous effects on coastal and inland areas. The extreme fluctuations in water level produced during the passage of a storm system are a combination of numerous oceanic, astronomic, and meteorological effects. Measurements of the storm surge generated by the recent Hurricane Katrina demonstrated that it reached 27 feet of height in parts of the Gulf Coast. Some of the estimates elevated the mark to more than 30 feet. Even the height of the wind-generated waves was significant above the storm surge elevation. Figure 3 shows examples of building damage caused by Katrina’s storm surge. The equations used to estimate hydrostatic and hydrodynamic forces due to currents generated by a storm surge are the same used for the riverine flood case. However, the values of mass density and specific weight of water should be varied accordingly. One of the most difficult tasks in calculating these
forces is determining the floodwater velocities, since they vary significantly throughout the passage of a single storm system. Velocities can vary from near zero to extreme magnitude, depending on: topography and slope; distance from the source of flooding; and proximity to other buildings or obstructions. The analysis of storm surge vulnerability should be conservative, assuming that floodwaters approach the building from the most critical direction and that the upper bound velocity due to storm surge current \( U_s \) is given by \( U_s = \sqrt{gh} \).

Figure 3: Building damage caused by Katrina’s storm surge in Waveland, MS.

6.1 Breaking Wave Forces on Walls

Studies have shown that only highly engineered, massive structural elements are capable of withstanding breaking wave forces generated during a storm surge, destroying virtually every wood-frame or unreinforced masonry wall below the wave crest elevation. FEMA (2000) suggests the use of the procedures outlined by Walton et al (1989) to calculate breaking wave forces on building walls. This procedure assumes that the building wall causes a reflected or standing wave to form against the seaward side of the wall. The relationship for the total breaking wave force on walls, \( F_{BW} \), including the hydrostatic component is given by:

\[
F_{BW} = (1.1C_W + 2.41)\rho gh^2 b
\]

where: \( C_W \) = dynamic pressure coefficient which varies from 1.6 to 3.5 (Walton, 1989).

7. Tsunamis

Tsunamis are caused by any disturbance that displaces a large amount of water, more commonly by fault motion during seismic events, but can also be produced by the motion caused by volcanic eruptions, massive landslides, explosions, or meteor impact. A tsunami can be described as a wave, or a series of long solitary waves, which can approach the shoreline and generate breaking waves capable of inundating the shoreline as high-velocity currents or turbulent bores (Ramsden, 1996). In many cases tsunamis have reached a shoreline as breaking waves as large as 100 ft, or even greater, and with velocities of more than 50 fps. Although, there is no general consensus in the literature for a methodology to estimate forces generated by the impact of tsunamis, the literature presents recent studies that have been conducted to estimate such forces. Arnason (2005) concurred that the forces induced by a tsunami’s turbulent bores, \( F_T \), can be modeled as those from extreme-velocity currents:
8. Local Scour around Buildings

Floodwater currents and waves are capable of creating localized scour around a building and its foundation. This scour can cause the loss of bearing capacity or anchoring resistance of the foundation elements. Examples of localized scour around buildings can be seen in figure 4:

![Figure 4: Localized soil scour generated due to the breached levees in New Orleans, LA.](image)

Currently, there is no adequate method for estimating local scour depths in the immediate vicinity of buildings. After performing an extended literature search it has been concluded that the best suited methodology for estimating soil scouring at buildings is to adapt the scour effects on buildings from known effects on bridge piers that are geometrically and hydraulically similar. In fact, FEMA’s Coastal Construction Manual (FEMA, 2000) suggests the use of a modified version of the Colorado State University (CSU) pier scour equation:

\[
F_r = 0.5 \left[ C_r \rho U_r^2 \right] dA
\]

where: \( C_r \) = coefficient of resistance; and \( U_r = 2\sqrt{gh} = \text{tsunami generated current velocity.} \)

Arnason (2005) suggests that the values of the resistance coefficient values range from 1.0 to 2.3, depending on the depth of the bore and the geometrical configuration.

\[
T_C = \text{coefficient of resistance; and}
\]

\[
gh^{UT} = \text{tsunami generated current velocity.}
\]

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\[
z_{max} = 2.2h \left( \frac{b}{2} \right)^{0.65} F_r^{0.43} \cdot K_a
\]

where: \( z_{max} \) = maximum local scour depth; \( b \) = width of the building; \( F_r \) = Froude number; and \( K_a \) = correction factor for flow approach angle.

However, there are problems with the applicability of the CSU equation, since it estimates ultimate scour, which many studies have demonstrated that it could take up to 10,000 hours for this scour to develop. Therefore, the CSU equation without additional modifications is not suited for estimating the local scour depth at buildings during a single flood event. The current work is proposing the incorporation of the Melville & Chiew (1999) time-scale factor to correct the methodology proposed by CSU. However, Melville & Chiew only used circular piers for their laboratory experiments. Thus, it is necessary to incorporate data for non-circular piers such as the obtained from laboratory experiments conducted by Barkdoll (2000). It is worth noting that there are other factors that are not considered by the current local scour equations but are relevant to the scouring process, such as the presence of land cover in the immediate vicinity of buildings.
8.1 Proposed Local Scour Model

The proposed model involves the modification of the CSU equation presented in FEMA’s CCM by incorporating two additional correction factors:

\[ z(t) = 1.4b^{0.65}Fr^{0.43}h^{0.35} \cdot K_t, K_n \]  

(9)

where: \( z(t) \) = local scour depth at buildings as a function of time; \( K_t \) = time scale correction factor for non-circular configurations; and \( K_n \) = land cover correction factor. Both the time-scale and the land-cover correction factors are discussed in the following sections.

8.2 Time-Scale Correction Factor

The Melville and Chiew (1999) expression accounts for the time-scale effects and can be incorporated into the existing equations as the ratio of scour depth at a given time. For this study, the local scour data for non-circular structures obtained by Barkdoll (2000) were isolated in order to develop an appropriate time-scale factor based on the Melville and Chiew expression. The coefficients in the following expression were obtained by means of regression analysis (envelope curve) of the Barkdoll data:

\[
K_t = \exp \left\{ -0.145 \frac{U_c}{U} \ln \left( \frac{t}{t_u} \right)^{1.36} \right\}
\]

(9)

where: \( U_c \) = critical velocity for entrainment of sediment; and \( t_u \) = time for ultimate scour depth to develop.

8.3 Land-Cover Correction Factor

Velocity data is normally obtained from hydraulic studies that embark relatively large watersheds, thus estimating the velocity field around individual buildings may not be feasible. Floodwater velocity, and consequently the local scour depth, can vary significantly depending on the type of land cover present around each building. Most local scour equations are developed for barren sand soils. However, if there is vegetation securing the soil from detachment, these equations can greatly overpredict scour depths. Thus, it is necessary to develop a correction factor to account for these specific situations.

The land-cover factor can be defined as the ratio of scour depth generated when land cover is present to the depth of scour under experimental conditions. For this study, the Manning’s roughness coefficient has been proposed as the measurement of the land-cover factor based on:

(1) the CSU equation considers the depth of scour, \( z \), to be proportional to the flow velocity, \( U \), elevated to a power of 0.43, and (2) the flow velocity is inversely proportional and linearly related to Manning’s roughness coefficient, \( n \):

\[
K_n = \frac{z_{\text{land cover}}}{z_{\text{experimental}}} = f \left( \frac{U_{\text{land cover}}}{U_{\text{experimental}}} \right)^{0.43} \rightarrow \left( \frac{n_{\text{experimental}}}{n_{\text{land cover}}} \right)^{0.45}
\]

(10)

Since the smallest median size of bed material used in laboratory experiments (as found in literature) is 0.01mm, \( n_c \) should be approximately 0.010:

\[
K_n = n_c^{0.43} / n_c^{0.43} = 0.138 / n_c^{0.43}
\]

(11)

where: \( n_c \) = Manning’s coefficient for experimental conditions; and \( n_c \) = Manning’s coefficient for actual field conditions.
9. Vulnerability of Buildings

To determine the vulnerability of a building it is necessary to compare the magnitude of the loads induced by the floodwater with the structural strength of the main building elements: walls and columns. For this purpose two methods will be employed: (1) structural mechanics and (2) yield line analysis.

9.1 Structural Mechanics

The estimation of the strength of buildings is related to their structural design. These data provide information about the materials used, dead loads, and geometrical factors, among others. The shear forces and bending moments induced by the floodwaters are calculated based on structural mechanics theory. The input for these calculations is the resultant force generated by the floodwater and its point of application.

9.1.2 Normal Load Acting on Columns and Load-Bearing Walls

In order to calculate the strength of the building it is necessary to first determine the normal forces acting on the analyzed element:

\[ N = n q_c l_c + (q_{rs} + q_{rs}) d_m \lambda + (n-1)(q_{fd} + q_{fs}) d_m \lambda \]  

where:  
- \( N \) = normal force;  
- \( n \) = number of floors;  
- \( q_c \) = self weight of column/wall;  
- \( l_c \) = height of column/wall;  
- \( q_{rs} \) = self weight of roof;  
- \( q_{rd} \) = dead load of roof;  
- \( q_{fs} \) = self weight of floors;  
- \( d_m \) = mean depth of building; and \( \lambda \) = geometrical factor of load.

9.1.3 Structural Strength of Reinforced-Concrete Columns (RCC)

The bearing capacity in terms of shear forces \( V_u \) and bending moments \( M_u \) of RCC are determined as follows:

\[ V_u = \nu t_w b \]  
\[ M_u = T (t_u - 0.5 a_u) + N (0.5 t_w - 0.5 a_w) \]

where:  
- \( \nu \) = shear stress;  
- \( t_w \) = thickness of the column;  
- \( T \) = tensile force;  
- \( t_u \) = useful thickness of the column; and \( a_u \) = width of the compressive zone. The shear stress and the tensile force on the column are calculated from:

\[ \nu = 2 \left( 1 + \frac{N}{2000 t_w b} \right) \sqrt{f_c'} \]  
\[ T = A_s f_y \]

where:  
- \( f_c' \) = compressive strength of concrete;  
- \( A_s \) = area of steel reinforcement; and \( f_y \) = tensile strength of steel.

9.1.4 Structural Strength of Concrete-Block Walls (CBW)

The bearing capacity in terms of shear forces \( V_u \) and bending moments \( M_u \) of CBW are determined as:

\[ V_u = f_v t_w b \]  
\[ M_u = (f_v + \sigma_c) \left( t_w^2 b / 6 \right) \]

where:  
- \( \sigma_c \) = compressive stress;  
- \( f_v \) = shear strength;  
- \( f_t \) = tensile strength. The compressive and shear strength of the concrete blocks are calculated as follows:
\[ \sigma_c = \frac{N}{t_w b} \quad (19) \quad \text{and} \quad f_v = 0.5(f_i + \sigma_c) \quad (20) \]

9.2 Yield Line Method

The yield line method proposes that a concrete-block panel under a load develops a plastic hinge in a region of high moment. This hinge resists the moment, transferring any increase in the load to other regions which then yield and become part of the hinge. This region of the hinge is known as a yield line. These yield lines are formed across the panel, dividing it into slabs that rotate plastically under the applied load and causing the panel to collapse. The fundamental principle is the static equilibrium of an unreinforced concrete-block panel in the collapse limit state under external loads (Kelman, 2002; Martini, 1998). The work method is adopted to define the equilibrium equations by analyzing a small, arbitrary displacement of the panels in the direction of the applied load:

\[
\text{Dissipated Energy} = \text{Internal Energy Expended} = \sum (L \times \delta) \quad \text{over all regions} = \sum (M \times l \times \theta) \quad \text{over all regions} \quad (21)
\]

where: \( L \) = load acting within a particular region; \( \delta \) = horizontal displacement generated by the loads on the region; \( M \) = moment of resistance of the region; \( l \) = length of the yield line; and \( \theta \) = rotation of the region. As part of the current work, the yield line method will be adapted to evaluate concrete-block panels with openings (doors and windows). This is an advantage over the structural mechanics method.

9.3 Magnitude of Structural Damage

The total damage suffered by a building is estimated by the combined effects of all applicable forces acting during a flood event. The magnitude of the structural damage is established based on the vulnerability of individual structural components. The damage magnitude is represented by means of vulnerability matrices, in which a value of structural damage is assigned to different combinations of floodwater depth and floodwater velocity. For this purpose, engineering judgment should be used along with historical data, whenever available.

11. Quantification of Direct Flood Losses

The direct losses (or cost of damages) suffered by a building during a flood event can be quantified by means of Expected Annual Loss and the Probable Maximum Loss indexes. Both of these indexes are measurements of the damage risk, or in other words, the vulnerability of a building exposed to flood hazard.

11.1 Expected Annual Loss (EAL)

The EAL is the average value of the expected annual flood damages over the lifespan of a building. It is computed by weighting the damage due to any given flood by the probability of that flood and adding the products over the range of floods (50-year, 100-year, and 500-year recurrence intervals). Also, FEMA (1986) has suggested the use of the EAL as an index for homeowners to determine whether or not to retrofit flood prone properties.
11.2 Probable Maximum Loss (PML)

The term probable maximum loss (PML) is one of the most widely used terms in the property insurance industry, which aim is to assess the amount that no claim is likely to exceed, protect the companies against high losses and assure their survival. PML calculations are based on scenarios that assume a major event hitting a large area or an area with high concentration of values (Kron, 2002). For each company a different scenario may determine the PML, which are typically based on scenarios generated from 10-year to 200-year flood events. The PML is also used as a natural risk index. The procedure for estimating PML for natural catastrophes has evolved over the past few decades from a rather simplistic deterministic basis to methodologies based on loss exceedance probability. In fact official entities, such as the Natural Disaster Coalition (NDC, 1995), have defined PML in this probabilistic manner, setting the PML to a low annual exceedance probability of 0.002 (equivalent to a 500-year return period). For this study, the PML definition proposed by the NDC has been adopted.

12. Conclusions

The proposed methodology promises to become an effective and useful tool to assess structural damages caused by floods due to rivers, storm surges, and tsunamis. The relevance of the different flood actions generated during these events, including local soil scour, has been acknowledged. It has the capacity to evaluate the vulnerability of buildings to the different flood actions, individually or collectively. In the case local scour, concepts from scour at bridge piers have been incorporated. In order to advance the assessment of structural vulnerability, yield line analysis will be adapted to evaluate wall panels enclosing door and window openings. This study will help both practitioners and researchers to implement the necessary prevention and mitigation measures to alleviate flood impact and damages. This could also help the insurance industry to evaluate insurance policies and rates for damages caused by floods.

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14. References


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