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Flood Physical Vulnerability on Buildings

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Abstract—Floods are the one of the most far flung and destructive nature disasters occurring in the world. The annual disaster record shows that the occurrence of flood increasing continuously about ten folds over the past five decades. The impact of floods in coastal area can cause significant damage to RC buildings, including imaginable structural failure of buildings. In this paper the study aims to the necessity to bring out corrective measures that can be adopted to reduce vulnerability before harm occurrences due to floods. This paper is mainly focusing on the consideration of Structural damage due to flood impact, Flood impact on different floors , height and openings of the building, Promoting safer construction, different loading acting on buildings during floods, failure occurring during floods and to adopting the necessary preventive measures and moderation techniques to minimize the adverse impact of flood on RC buildings.

1. INTRODUCTION

The impact of floods has played a very important role, mainly due to their harmful impacts on cultural heritage. Floods lead to the loss of historical repository, desolation of historic sites, changes in the cultural landscape, and also to the disappearance or substantial distortion of impalpable heritage. Due to periodic changes in climatic conditions over recent years, we have witnessed increasingly frequent major floods and related events that pose a substantial threat to cultural heritage worldwide. These include the floods in Central Europe in 2002, the New Orleans flood in 2005, and numerous floods in South Asia in 2007 and 2009, as well as severe floods in Central Europe again in 2010. Engineering experience acquired during the course of major floods has provided comprehensive knowledge and reliable data about the impact of flooding on historic objects and sites. This experience can serve as a basis for establishing guidelines and recommendations for the effective protection of cultural heritage in emergency situations. River floods are the most common type of natural disaster in many European and Asian regions. Recent European studies have pointed to a significant increase in the frequency and severity of river floods due to the apparent development of global warming. However, floods, being highly impactful phenomena, are well documented with details including social and economic impacts. The impact action of floods has dramatically destroyed buildings, especially in countries and villages in mountainous areas. For many years, researchers always thought that the effective time of the impact was short and that the range of the impact was limited. So, the impact of a flood was not considered as a primary factor during the design of the buildings, and the studies about this were absent. Jones (1997) reported on the impact of flood and wind on structures in coastal areas. Kelman studied the damage to unreinforced masonry buildings in England at risk to storm surges (Kelman 2002) and presented an overview of flood characteristics with respect to their applicability for estimating and analyzing direct flood damage to buildings (Kelman and Spence 2004).

2. IMPACT OF FLOOD ON GROUND AND FOUNDATIONS

Strong rainfalls and/or snow melt preceding floods do not only cause a rise of water level in rivers but also a rise of groundwater table as well. Thus, during flood a change of the state of subsoil below buildings and other structures can be expected. Soil becomes water saturated, water menisci between grains disappear, and cemented brittle contacts may dissolve if they are soluble and effective stresses reflecting intergranular forces decrease. There are several phenomena induced by floods which can influence the foundation function and, as a result, endanger stability and integrity of the whole object. Flood effects on foundation subsoil and foundation structures can be roughly divided into the following categories:

- Soil collapse in case of the first time saturation;
- Internal erosion of soil;
- External erosion scours of soil;
- Decreasing soil stiffness due to reduction of effective stresses;
- Soil heave due to water saturation;
- Horizontal pressure on structures;
- Excessive uplift forces on structures; and
- Deterioration of foundation material especially in case of wooden piles.

Not all effects can appear simultaneously and it depends on local conditions, which effects prevail and how severe their consequences will be.

3. COLLAPSE SETTLEMENTS

Collapsible soils are dry or partly saturated soils which become flooded. The most debatable are collapsible soils having an open type structure with large void spaces giving rise to a metastable grain skeleton. Flooding events can lead to a sudden volumetric compression of soil which damages and destroys the overlying structures.

3.1 Internal Erosion

In groundwater flowing with high velocity high hydraulic gradients, fine particles can be washed out from voids between large grains so-called suffusion or piping, which makes the soil skeleton looser and eventually susceptible to collapse. If a layer of fine-grained soil is in contact with a layer of coarse-grained soil, fine particles can be transported by water into the pores of the coarse-grained soil. In this way, the permeability of the coarse grained layer decreases so-called colmatation and the void space in the fine-grained soil progressively grows so-called contact erosion.

3.2 Erosion of Soil Surface Scour

Scour is a gradual removal of soil surface layers by flowing water resulting in a deepening of the soil surface, holes can arise at the ground surface, mostly at the contact with more erosion-resistant materials. It is a common phenomenon not only in bridge abutments or piers Scour is one of the three main causes of bridge failures. It has been estimated that 60% of all bridge failures result from scour e.g., Huber 1991; Kattell and Eriksson 1998, but in foundations of buildings in flooded areas as well National Trust for Historic Preservation 1993. Erosion can lead to the loss of a significant soil volume below foundation structures, thus producing deformations and cracks in the superstructure. An uneven settlement or a collapse of the whole structure can appear.

3.3 Change of Soil Mechanical Properties

Damage to foundations does not need to be limited to direct flood actions. Fluctuations in groundwater table are responsible for changes in soil effective stresses. Since most of the mechanical soil properties depend on effective stresses, rise of groundwater level is related to a decrease of soil stiffness and shear strength and vice versa. Variations of effective soil stresses during groundwater oscillations are equivalent to load cycles, thus yielding a gradual settlement of the ground surface, as can be observed in Venice Gajo et al. 1997.

3.4 Additional Horizontal Pressure

Retaining structures like historic freestanding walls, gravity retaining walls, and basement structures can suffer due to additional horizontal pressures induced by flood water. A baroque wall around the church in Zöbing and terrace walls of historic vineyards in Wachau both in Austria were destroyed by water pressure Kohlert and Huber 2002. A garden wall of the Wesenstein Castle in Saxony Germany collapsed during the flood 2002 too.

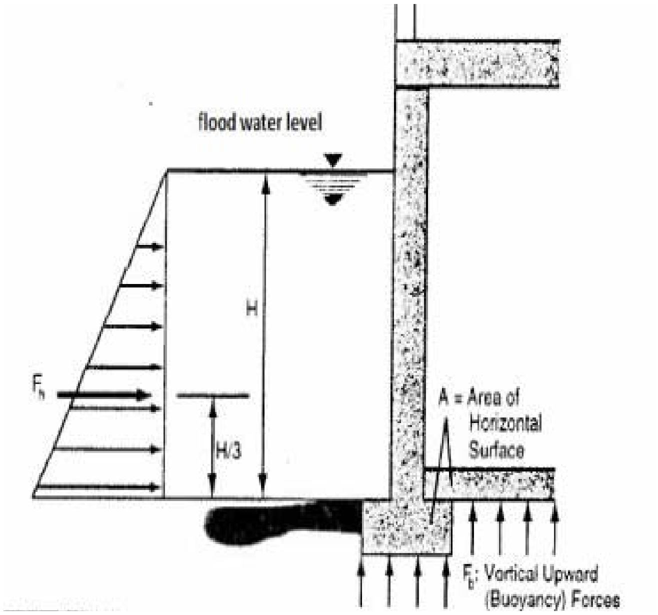

Fig. 1: Static forces acting on building.

3.5 Excessive Uplift Forces

Uplift forces due to a rise of water level pose a serious threat during floods too. Lightweight structures can be uplifted when the building is submerged. In extreme cases the whole building can be heaved by buoyancy. If danger of such a state is approaching, flooding of the basement can counterbalance the uplift force. A further negative impact of uplift forces can be cracks in the foundation. Water inflow into the object can take place through these cracks. If unsuitable grading of the underlying fill exists, internal erosion can take place and cavities below the foundation can be created. Eventually, these cavities might cause an irregular settlement or even collapse of the foundation.

3.6 Deterioration of Foundation Materials

Deterioration of organic foundation material like wood accompanies usually an exposition of submerged wooden piles to air after a lowering of the groundwater table. Nevertheless, also in case of floods, dry sections of wooden piles can be submerged in water for a longer time period. After withdrawal of flood water, increased wood moisture and the presence of air can lead to fungal and bacterial deterioration of pile foundation elements.

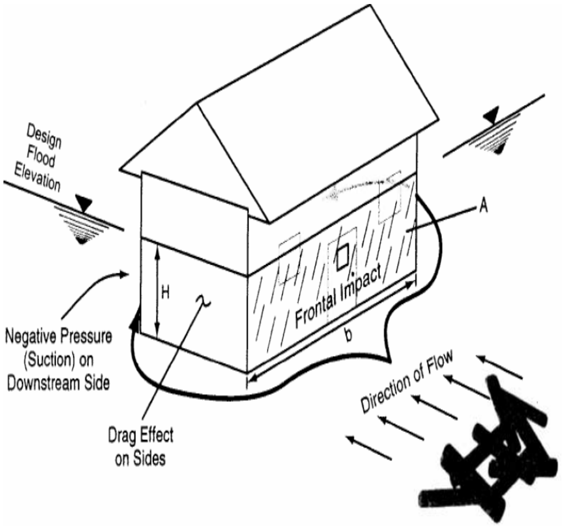

Fig. 2: Dynamic forces acting on building.

4. FLOOD DAMAGE ASSESSMENT METHODOLOGIES

Direct flood damages are normally estimated from systematically applied survey procedures, but can also be derived from the analysis of historical flood data analysis, or any combination of these approaches. 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.

4.1 Depth-Damage Curves

Depth-damage curves recount the damage extent for a specific region based on the flood depth. In some cases where the impairment 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. 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 flood water depth.

4.2 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 flood water depth and floodwater velocity with the collapse potential of building based on their material class:

- Wood frame;
- Masonry and concrete bearing walls; and
- Steel frame.

5. 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:

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

6. BUILDING VULNERABILITY

The building vulnerability is the vital to discuss briefly the building vulnerability models developed as part the present study.

6.1 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.

6.2 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 Good child 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 Good child 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.

6.3 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 in this case, 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. The 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.

6.4 Utilities and Finishes

The building utilities and finishes division differs from all other building divisions in that its vulnerability cannot be accessed 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 user defined parameters. 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 flood water 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.

7. RESULTS: EXPECTED FLOOD DAMAGE

The primary result from the 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, and 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.

8. CONCLUSIONS

This study proposes a new methodology to estimate flood damage to buildings in either riverine or coastal settings, based on the aggregated failure 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 flood water velocity is equal to zero. When considering storm surges, it was determined that flood water velocity can step up 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 and 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.

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