Development of a tool to estimate individual building vulnerability to floods

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Abstract

The likelihood that buildings will be flooded and the frequency and severity of the inundation are calculated as part of the general flood predictions for urban and other areas. However, there is no reliable method to estimate the vulnerability of an individual building to damage from flooding. This makes it difficult for building owners and designers to calculate what appropriate measures should be taken to enhance resilience against floods. This paper, developed in the context of the current EC FP7 project FloodProBE, discusses the current estimation methods used in the UK, Germany, USA and Australia, and suggests ways to improve on these to make a model capable of estimating damage to individual buildings, particularly non-domestic ones.

Flood damage to buildings and contents are dependent on a number of variables in relation to the flood events. The major variables are over-floor depth, velocity, rate of rise, debris, contaminants, frequency and duration of inundation and timing. Other variables relate to the building characteristics, such as structure, construction, materials and their drying characteristics, services and their locations, and the condition of the building prior to being flooded.

A flood damage estimation tool that can deal with all these variables is likely to be very complex and difficult to manage, though oversimplification of the variables is likely to lead to inaccurate estimations. A balance must therefore be drawn between excessive complexity and accuracy. The output of the model should express the damage in cost form to be consistent with existing damage methodologies. This will enable calculations to be made in order to assess the cost/benefit analysis of installing flood mitigation/resilience measures to the building and/or its surroundings.

Keywords: flood, prediction, cost/benefit analysis, flood mitigation, stochastic methodology, building construction, building flood vulnerability, vulnerability grades, damage grades.

1 Introduction

This paper examines the state of the art of estimation of damage to buildings on account of flooding and suggests the development of a flood damage prediction tool that is aimed at individual buildings according to their construction types. Non-domestic buildings are targeted owing to the variety in their constructions. In order to do this, the variables involved in damage estimation due to flooding of buildings are explored, the various existing damage methods are reviewed, and a blueprint for an individual building damage prediction tool is outlined.

2 Flood damage estimation

Flooding can have far reaching consequences, not only economic but also social and health related. As the range of damages is so large and many aspects will be very difficult to estimate, it will be necessary to be selective in any method devised to estimate flood damage to buildings and limit the factors to those that can be realistically calculated.

The direct costs are directly related to the physical fabric of the buildings, the structure, construction and materials employed. These are relatively easy to survey and record accurately at various levels of detail by building specialists such as architects and surveyors. The contents of the building and their value and vulnerability to flood damage are more likely to be known by the building occupant, so are not considered here. Similarly, indirect costs of flooding can also best be estimated by the occupants according to the nature of their business and the effect of the flood on the services they provide.

Flood damage to buildings is dependent on several variables in relation to the flood events. The most commonly used is over-floor depth; with velocity, rate of rise, debris, contaminants, frequency of inundation and duration of inundation being also significant, but often ignored [1].

Variables relating to the building characteristics are the structural system, the materials of which the building is constructed, the drying characteristics of the materials, the types of construction used and the condition of the building prior to being flooded [2]. To this can be added the planning of the spaces within the building (basements, level of ground floor above ground etc.) and the services and their positions within the building (air conditioning equipment, circuit boards, boilers etc.).

On account of the variety of variables, a tool that can predict the extent of flood damage to a particular building could become very complex and difficult to manage, though oversimplification of the variables is likely to lead to inaccurate estimations. A balance must therefore be drawn between excessive complexity and accuracy in order that the tool will be both user friendly and sufficiently reliable to provide useful outputs.

3 State of the art of flood damage estimation methods relevant to buildings

Much research has already been carried out on flood damage prediction methods for residential buildings, with less research on non-domestic buildings. A review of these methods was carried out in order to avoid repeating research and for building on the state of the art in this subject. The most relevant methods to this project are described briefly below, and their possible usefulness for individual non-domestic building flood damage estimation is assessed.

3.1 ANUFLOOD methodology

This methodology is Australia's most commonly used commercial flood damage estimation model. It uses potential stage-damage curves based on actual data from flooding in Australia and UK. Stage damage curves are categorised into different building sizes, types and uses. The commercial properties in the database are classified by size and value class that reflects the vulnerability to flood damage of the business's contents. The damage is only based on over-floor flood depth. As the data is based on averages, they tend not to reflect the variability of individual buildings. In fact, damages can vary greatly in non-residential buildings, and analysts need to ascertain the size and type and content of each building. The damage to the individual properties often diverged considerably from the line of regression; hence the results tend to be inaccurate for individual buildings [1].

3.2 USACE velocity-damage curves

Floodwater velocity is rarely taken into account in calculating damage curves. The USACE (U.S. Army Corps of Engineers) Portland District velocity-based building collapse curves are one of the few that do [3]. These curves predict the collapse potential of buildings based on their types of construction, i.e. wood frame, masonry and concrete load bearing walls, steel frame, correlated with floodwater depth and floodwater velocity. The only output of the model is at what point the buildings are likely to collapse. There is no estimate of the range of partial damage to the building or costs of repair.

3.3 HAZUS-MH flood model – adaptation of earthquake 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 and floods).The HAZUS Flood Model is used to characterise riverine and coastal flooding as a basis for damage and loss estimation in relation to buildings. This damage and loss capability includes a library of more than 900 damage curves for use in estimating damage to various types of buildings and infrastructure. The model uses estimates of flood depth along with depth/damage functions to calculate likely damage to buildings. The building occupancy type and ground floor elevation are required as inputs to make the calculation. The output is in the form of area-weighted estimates of damage as a percentage of replacement cost, at block or individual building scale [4]. However, the flood damage data and damage curves highest resolution is census block level so damage predictions are more reliable for large groups of buildings and unsuitable for use on individual buildings.

3.4 Stochastic methodology using Monte Carlo simulation

This stochastic methodology has been developed by Nadal *et al.* [5] that takes account of flooding hydrodynamics – waves, turbulent bores, debris impacts, time dependent local soil scour as well as depth of flooding. The building vulnerability is modelled using analytical representations of the failure mechanisms of individual building components. The flood actions of recent events have been assessed and compared to the resistance of each building component. Monte Carlo simulation was then used to expand available building data and perform load/resistance analysis and to account for the uncertainty of input parameters. The output estimates the average expected flood damage to individual buildings due to both floodwater depth and velocity on the basis of 10,000 hypothetical buildings. The outputs are expressed as three dimensional functions dependent on floodwater depth and floodwater velocity. The main feature of this methodology is the important distinction it makes between flood damages caused by hydrodynamic actions and floodwater depth. It shows that floodwater velocity can increase the damage to buildings by up to 100–190% depending on the type of event. Although the study concentrates on reinforced concrete frame domestic buildings with infill concrete-block walls (including doors and windows), it could be applied to other structures using the same methodology, but lacks the flexibility to cope with combinations of different construction types and materials in individual buildings.

3.5 Damage and loss prediction based on and engineering evaluation system of building construction types

A study by Schwarz and Maiwald [6, 7] at the Bauhaus University in Weimar uses an engineering evaluation system in order to predict damage and losses based on the vulnerability of building construction types. This takes into account the inundation level, flow velocity, duration and building type [8]. The buildings are classified into six types by material used for the construction and the structural system. The study was based on data gathered after the flood in Saxony in 2002, which featured some very high water velocities. The dataset included about 1220 residential buildings, most of substantial size with multiple accommodation units. The buildings were categorised into type according to their main construction material: clay (referring to earth construction - cob, adobe or rammed earth), prefabricated (presumably referring to open timber panel construction), timber frame (meaning heavy timber frame, e.g. oak frame), and masonry (brick or stone construction) and reinforced concrete. A range of damage grades were compiled, from D1, the lowest, to D5 the greatest damage requiring complete rebuilding, based on physical, chemical, structural damage and resulting requirements for repair and replacement. The different building types were allocated to five flood vulnerability classes, with specification of the range of probable scatter into adjacent classes depending on factors such as building condition, quality of workmanship, types of building material etc. From this, damage curves were derived according to the depth of water. The developed tool is based exclusively on data from residential buildings and, owing to considerable variations in predicted possible extent of damage in individual buildings, is best suited for general damage prediction of different building construction types in urban areas. This can identify critical zones, and aid short and long term disaster management decisions. The predictions are however not sufficiently reliable for making precise damage predictions for individual buildings, particularly those featuring several different construction methods.

4 Discussion and development of individual building damage prediction tool

Despite a plethora of data from various parts of the world, it is evident that there is no established damage prediction tool for individual non-domestic buildings that can account in any detail for their different types of construction. Unlike domestic buildings, non-domestic buildings often feature several different types of construction within the same premises. This makes categorisation of buildings simply according to construction types insufficient. It would therefore be a better approach to estimate damage at an elemental level – e.g. wall, floor, ceiling, services etc., rather than a whole building level. This would give a 'menu' that could be used to select the particular construction types used for the various elements of an individual building, and the particular building materials used, thus leading to far greater accuracy in the estimates of damage and consequent costs for repair or replacement.

Damage predictions rely on accurate measurements of the effects of flooding on buildings of different constructions either from past events or as estimates based on technical information and laboratory tests on the different building materials. Owing to the wide range of building types represented in non-domestic buildings, a great amount of detailed information will be required. This volume of data has the potential to make any calculations required to provide reliable estimates very complicated and user unfriendly unless a sophisticated system is devised to facilitate the necessary inputs.

Most damage predictions at present only take into account flood depth (i.e. they are stage-depth predictions). This will not be sufficient in cases where high velocities and levels of pollution are anticipated. Therefore the tool should take into account these additional flood characteristics that cause different kinds of damage to buildings, such as velocity, duration, different types of pollution, e.g. oil, sewage, sediment, as well as debris. Therefore, the function of the proposed damage estimation tool is to predict the extent of damage to individual buildings depending on the severity of the flooding and the construction type of the building. The output of the tool should express the damage in cost form. This will enable calculations to be made in order to assess the cost/benefit analysis of installing flood mitigation measures to the building and/or its surroundings. The tool will be designed for the use of people with sufficient technical knowledge of the planning and construction of buildings in question, such as surveyors, architects and other building designers, quantity surveyors and property managers.

A simple diagram of the principles of such a tool is presented in Figure 1.

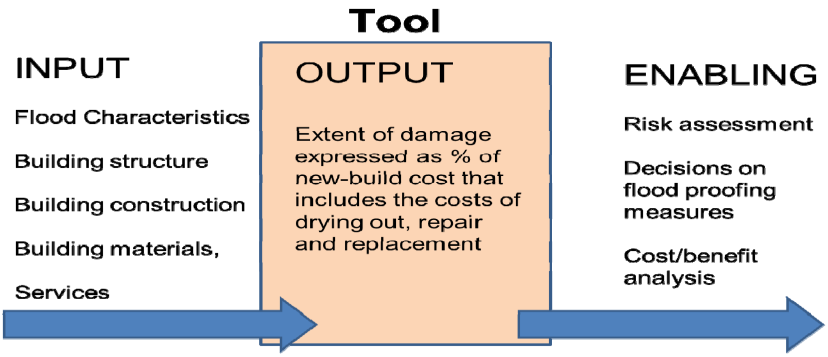

Figure 1: Building damage estimation tool principles.

The aim is to produce a simple-to-use system that will encompass the elements likely to be affected by flood water, namely the basement and foundations, the external walls, the ground floor, the internal partitions including the internal doors and joinery, the external doors and windows, as well as the associated services such as electrics, plumbing and ventilation.

The basic data required to be input into the system by the user are:

- Identification of the structural system
- Identification of the building materials used in the construction of the different elements of the building
- Identification of the different build-up of layers of the different constructions
- Identification of the materials used in the layers of the construction
- Identification of services
- The depth, duration and dynamic characteristics of the flooding and type(s) of pollution

The basic data that are contained in the system are:

- A list of common building materials and their vulnerability grades and recovery grades.
- The information of the protection grade of layers in a range of element constructions.
- The ease of access to building materials layers for drying out measures.
- A list of different services and their vulnerability grade to water damage, protection level and ease of access.

The system will calculate the amount of damage to the building materials and services according to their position within the construction, and the effect of this on the ability of the construction to be dried out, the degree of repair or demolition required, based on a percentage of cost of total demolition and replacement, all depending on the depth, duration and dynamic characteristics of the flooding. Unlike most prediction tools, this will not initially produce general depth/damage curves, from which you need to calculate the damage to a particular type of building. It will predict the actual damage to an individual building according to the nature of the flooding and its construction and equipment. The output, predicting the cost of cleaning, repair or replacement, will be expressed as a percentage of the new-build cost of each element. The percentage can be greater than 100%, reflecting the costs of demolition and disposal of materials, as well as cleaning costs prior to rebuilding. An approximate indication of the actual cost of returning the building to use, depending on where it is and when the flooding occurs, can be produced by the tool when it is combined with calculations using the current or predicted rates of construction prices.

This tool can be used to compare the implications of flooding for different types of building construction, and to assess the value/cost of installing flood protection installations to the building to reduce the damage from future flooding.

5 Collection of necessary flood damage data

It is evident that much detailed data on the effects of flooding on different building materials depending on their use in different constructions will be required to make this model accurate in its predictions. The aim of this research project is to devise the calculations required by the tool to make predictions from inputted and stored data, using available technical data, and then to test the outcomes against real building flood damage records from past flood events. The data contained in detailed records of these damages will be compiled from several sources. Permission has been gained to explore the flood records of the leading international insurance company AXA Insurance, and links have also been established with relevant organisations and building owners who coped with the flooding in the Humber Estuary in the UK.

The data contained in the HOWAS21 database is also being used [9]. HOWAS 21 is a database (Bavarian Water Management Agency) that contains flood damage information of almost 6,000 buildings in numerous floods since 1978 in Germany. The database was compiled according to damage values estimated by damage surveyors of insurance companies who completed a standard questionnaire form on the importance of a great number of criteria. As a result, a list of 20-30 core criteria was identified for each sector, including buildings, businesses, infrastructure, agriculture and others. The data is divided into sub-sets by building functions, and is used to develop depth-damage curves. The database concept contains object-specific flood damage and damage determining factors using four core criteria: event information (type of flood, date, water level etc.); object information (building type, building materials etc.);

damage information (repair and replacement costs for buildings and contents etc.); information about loss reduction (flood mitigation measures, advance warning time etc.) [10].

5.1 Data contained within the system

In order to produce the data required by the system to calculate the predicted flood damage, the following data need to be produced:

- **Assessment of building material grades according to vulnerability to water, pollution and contaminants, drying out time, subsequent performance and level of repair required. The cost element is then added according to percentage of new-build construction cost.**

The proposal is to allocate grades from 1–5 for vulnerability according to the following descriptions:

Table 1: Building material vulnerability grades.

Grade 1	Not vulnerable.	Impervious - no or negligible water take-up. No deterioration to material, structural performance or thermal performance when wet. Lightly affected by pollution and contamination. Minimal drying out required. No dimensional changes or distortion. Full recovery of thermal performance. Simple cleaning of pollution and contamination. No need for repair or replacement.	A low cost element for cleaning and drying required: say 2% of new-build costs
Grade 2	Slightly vulnerable.	Some water take-up. No deterioration to material or structural performance, slight reduction in thermal performance when wet. Moderately affected by pollution and contamination. Moderate drying out time required. Minimal dimensional changes or distortion. Some discolouration. Full recovery of thermal performance. Thorough cleaning of pollution and contamination required. Slight repairs or treatment required, no need for replacement.	Moderate cost element for cleaning, drying and repair: say 15% of new-build costs
Grade 3	Moderately vulnerable.	Considerable water take-up. No deterioration of material or structural performance, severe reduction in thermal performance when wet. Severely affected by pollution and contamination. Considerable drying out time required. Permanent distortion and discolouration when dry. Moderate reduction of thermal performance. Difficult to remove pollution and contamination. Considerable repair and treatment required, and upgrading of thermal performance. Replacement not normally necessary.	Considerable cost for cleaning, drying and repair: say 45%
Grade 4	Extremely vulnerable.	Total soak-up of water. Severe deterioration to material and structural performance. Complete loss of thermal performance. Severely affected by pollution and contaminants. Extremely long drying out time. Severe distortion and loss of structural properties. Thermal performance permanently lost. Impossible to remove pollution and contamination. Replacement required.	High costs for removal and replacement of material: say 110%
Grade 5	Destroyed.	Complete breakup and collapse through soaking. Loses all material, structural and thermal performance. Not possible to dry out. Complete replacement required.	High costs for removal and replacement of material: say 150%

- **Assessment of protection due to situation within the construction build-up according to amount of ingress of water.**

The proposal is to allocate grades from 1-3 for protection according to the following descriptions:

Table 2: Protection grades within construction.

Grade 1	Complete protection from flood water.	Long term protection – no seepage. No need for drying out.	Factor for reduction of repair costs – 100%
Grade 2	Moderate protection.	Protected from flood water for short time and at low pressures. Some seepage.	Factor for reduction of repair cost – Depending on duration of flood 10 - 60%
Grade 3	No protection from flood water	Flood water quickly inundates the material	Full repair/replacement costs

- **The ease of access to building material layers for drying out measures**

The proposal is to allocate grades from 1-5 for ease of accessibility for drying out materials according to the following descriptions:

Table 3: Ease of access for drying.

Grade 1	Material on inside or outside surface.	Complete access to one face for drying out treatment. No building work required.
Grade 2	Material easily accessible by non-destructive demounting of covering layer(s).	Good access to one face of material after exposing. Demounting and remounting work required.
Grade 3	Material accessible by destructive removal of covering layer(s). No loss of structural integrity.	Good access to one face of material after exposing. Demolition and rebuilding of covering layers required
Grade 4	Material accessible by destructive removal of structural layers. Structural integrity compromised, so temporary support necessary.	Moderate access to one face of material for drying. Demolition, temporary support, rebuilding of structural layers required.
Grade 5	Impossible to access material without destruction of construction.	Access holes may be possible. Drying out process made impossible or very difficult, with uncertain results.

- **The characteristics of the flooding**

The characteristics of the flood event are based on 5 different factors:

Table 4: Characteristics of flood event.

Characteristic	**Type of measurement**	**Units of measurement**
Flood depth	In 0.3 metre increments	0.3m – 4.5m
Flood duration	In days	1 – 5+
Speed of flow	In 3 levels of severity	1 = negligible, 2 = moderate, 3 = severe
Debris content	In 3 levels of severity	1 = none, 2 = small, 3 = large
Types of pollution	In 4 types (several possible at the same time	1 = none, 2 = oil, 3 = sewage, 4 = mud and silt

Table 5: Inputs for damage prediction tool.

Flood characteristics	**e.g.**
Depth of flood in metres (0.3 – 4.5m in .0.3m increments	1.5
Duration of flood (in days)	2
Flow speed (1-3)	1
Debris (1-3)	2
Pollution (1-4)	3, 4

Type of structure	**Steel frame with composite steel/concrete floors**			
Element construction type	**Building material per layer (from outside or from top)**	**Vulnerability grade(V) 1-5**	**Protection grade (P) 1-3**	**Access grade (A) 1-5**
e.g. External masonry cavity wall				
	112mm fair-faced brick	2	0	1
	20mm cavity	-	-	-
	30mm extruded polystyrene insulation	2	2	5
	100mm aerated blockwork	3	3	5
	19mm gypsum plaster	4	3	3
	Emulsion paint	2	3	1
Other element construction types as necessary ...				
Service installations				
Electric power and light	Switchboards	5	1	1
	Circuits	3	2	3
Telecommunications	Equipment	5	1	1
	Circuitry	4	2	3
Air-conditioning/ ventilation	Equipment	4	1	3
	Ducting and terminals	2	1	2
Heating	Boilers, cylinders etc.	4	1	1
	Piping	1	2	2
	Heat emitters (radiators)	1	1	1

6 The tool and how it works

The tool aims to provide an easy method of estimating the amount of damage and likely cost of repair of individual buildings according to their construction. Non-domestic buildings normally employ several different construction types, according to element, e.g. floors of in-situ reinforced concrete, and within elements e.g. the external wall may be masonry construction in parts and metal cladding construction in others.

Information about the flood characteristics must first be inserted into the tool. The type of structure used for the building is then inserted. The user of the tool will have to select the types of construction for each element or part of element from a list of typical constructions and then select the building material types for each layer corresponding to the actual built construction. The program will then automatically assign the grades for vulnerability (V), protection (P) and access (A) according to installed data. A separate section is used to describe the types and extents of the service installations likely to be affected by the floodwater. Table 5 provides an example of these inputs.

The tool first needs to calculate whether the structure will withstand the flood (i.e. whether the building will collapse) then if not, what percentage of new build cost will be incurred to bring the affected elements back to normal use. These calculations will take into account the level of need to remove layers and dry out and replace as necessary. Algorithms are being developed that weigh up the different grades and the position of the materials within the construction, the time and energy taken to dry out the materials, based where possible on data from real cases of flooding. It is intended that the tool will be continuously refined as more real case data is collected and checked against outputs. The values in the algorithms will be adjusted so that the outputs match the real outcomes as nearly as possible.

7 Conclusion

Existing damage prediction tools are aimed at producing damage curves for building types and contents, useful for groups of buildings at an urban level rather than individual buildings. They are therefore not precise enough to make accurate predictions about individual buildings. This lack of a flood damage prediction tool for individual non-domestic buildings has made it difficult for owners and managers to estimate the likely extent and costs of damage to their buildings caused by flood events. Without knowing these, it is impossible to make informed judgements on the cost/benefits of introducing flood protection and other mitigation measures to the buildings in order to minimise the costs of these damages and subsequent repairs, and reduce the time that the buildings are inoperable.

One of the focuses of the EC 7th Framework Programme project, FloodProBE, is to examine the effects of flooding on critical infrastructure in urban areas, such as power systems, communications, essential supplies, emergency services and healthcare etc. If these infrastructure types are seen as networks, then the nodes are represented by the buildings and concentrated facilities that are connected together by communicating lines of various types (e.g. cables, roads, radio, pipes etc.). The development of a flood damage estimation tool that is particularly designed to calculate the extent and costs of damage of individual infrastructure buildings according to the construction of their various elements was part of this project. The tool will also be suitable for use on any other type of building, and particularly useful for those built with a variety of construction systems.

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