Daniele Fabrizio Bignami · Renzo Rosso
Umberto Sanfilippo

Flood Proofing in Urban Areas

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Foreword

Flood proofing (often indicated as Floodproofing) is a term indicating a large number of different measures, tools, and procedures, which can be implemented to reduce the flood risk by decreasing the exposure and/or the vulnerability of people, buildings, infrastructures, and goods during a flood event.

Although the origin of flood proofing is historically far antecedent, and much literature was already available at that time, in 2012 a precise definition of this concept has been reported in the Issue No. 15 of the Integrated Flood Management Tools Series of the Associated Programme on Flood Management (APFM), which is a joint initiative of the World Meteorological Organization (WMO) and the Global Water Partnership (GWP).

According to that milestone document, flood proofing includes both structural and non-structural measures against flood damage before or during flooding. Essentially, flood proofing covers two purposes of flood management: flood resistance and flood resilience; flood resistance keeps out flood water to prevent damages, while the flood resilience minimizes the impacts of flood water once a flood occurs.

In general, as it is getting difficult to bear the increasing costs of investing in structural flood protection, governments need to rely more on non-structural measures of regulations and incentive mechanisms in addition to conventional large-scale flood prevention measures. Furthermore, residents and communities need to make more in terms of individual efforts on flood proofing to protect their properties.

Definitively, flood proofing approaches are a valuable and modern way to help to meet the main target of protecting the territory against flooding, by means of smaller widespread diffused interventions which are cost-effective and integrate large-scale flood control infrastructures.

So, a lot of problems of civil protection can be handled by the right solutions, with a quite low socioeconomic impact in almost any urban context that flood proofing offers to everybody responsible for planning flood management, designing flood defense systems, and operating flood control systems in the public and private sectors.

In this framework, I am glad to say that the present book is a remarkable summary of the state of the art of flood proofing principles, methodologies, tools, norms, and tests, including a large number of tables, schemes and pictures.

Moreover, the book proposes a rational redefinition of flood proofing classification, suggesting that operative criteria about the most suitable kind of flood proofing intervention could be adopted in practice, case by case, at point or areal scale.

An interesting review of the physics of stability and instability of both human beings and buildings under flood conditions completes the book contents.

I do hope that the readers of this book will appreciate the efforts carried out by my estimated colleagues Renzo Rosso, Daniele F. Bignami, and Umberto Sanfilippo to provide such a useful and clear description of the different flood proofing aspects including some innovative issues too.

Bologna (Italy), May 3, 2019

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Preface

The disasters caused by inundations all over the world may have quite different impacts on territories and people. It depends on flood magnitude, exposure and resilience of the threatened land, and the effectiveness of the measures (permanent and/or temporary) adopted to protect human settlements.

Traditional approaches to cope with floods deal with creating or reinforcing risk reduction measures. These can be structural and/or non-structural. The first ones (raising levees, enhancing hydraulic conveyance, creating overflows and diversions, either building or improving dams and storage facilities, forest and agricultural adjustments) are essentially permanent (sometimes including real-time control features for overflows, diversions, impounding facilities). Non-structural measures include source control, including watershed and landscape structure management; laws and regulations, including zoning; economic instruments such as insurance plans; flood forecast and warning systems; and a comprehensive system of flood risk assessment, awareness raising, flood-related databases, and safety evacuation procedures. Like structural measures, the non-structural ones also require continuous care to provide the best performance in case of disasters.

One can integrate this approach with temporary measures that are often capable of substantially enhancing the performance of the permanent defense measures. In the last few decades, flood proofing showed to provide quite satisfactory results in terms of damage reduction. After the United States pioneered this approach, many countries have progressively introduced flood proofing among flood risk reduction measures and, most of all, adapted it to specific urban and rural landscape, with features changing from case to case.

Flood proofing usually refers to a large number of interventions, such as building repositioning or lifting, dry or wet flood proofing of the buildings, self-mobile barriers, emergency dikes and/or berms, and even the old-fashioned sand sack walls. All these measures or devices aim at reducing or at least controlling flood impact at the local or municipal scale. This requires taking care of people's safety, building damage, and infrastructural protection during an inundation.

This book reviews literature on flood proofing concepts, techniques, and devices. This includes physics of stability and instability of both human beings and buildings under flood attack, criteria and models to assess flood strain, and safety margins for flood proofing devices and facilities. An updated and enhanced classification of flood proofing methods and devices is presented here to better identify the appropriate solutions to specific risk scenarios and to address the most effective ones from both technical and economical point of view. The focus on temporary flood proofing techniques descends from their capability to meet performance efficiency under a satisfactory cost to benefit framework. Most of examples shown are real case studies, without mentioning manufacturers or commercial products. The book finally reports a resume of norms, guidelines, and laboratory test recommendations for flood proofing devices currently in use in different countries, given that diversity of landscape and social patterns requires a multifaceted and flexible approach.

The purpose of this book is to encourage authorities, stakeholders, and end users to develop appropriate flood proofing solutions to mitigate flood risk under a pragmatic approach.

Milan, Italy
May 26, 2019

Renzo Rosso
Daniele Fabrizio Bignami
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In addition, the authors most gratefully acknowledge the former support by Italian CNR-GNDCI, which fostered pioneering research in the area of flood mitigation.

And, last but not least, we wish to thank our dear families; they are always by our side, giving us reasons to cheer and to go ahead.

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Chapter 1
Introduction

In the context of natural disasters, the scientific community agrees that risk is the product of the probability of a hazard and its adverse consequences. There is no risk if there are no people or values that an extreme event can strike. Similarly, an event is only termed a catastrophe if it hits people and/or it damages their possessions.

The intensity and frequency of a natural phenomenon (hazard) is only one of three factors that determine the overall risk. The amount of values present in the area concerned (exposure) as well as their loss susceptibility (vulnerability) are crucial for the resulting risk. Hence, one can express the risk formula as a function of these three quantities. If risk is insured, a fourth factor, insurance penetration, also plays a role.

All factors that determine the risk are variable. While man cannot influence occurrence and intensity of a natural phenomenon, one may reduce ground effects by land use, agricultural practices and engineering works; and we may control the exposure, e.g. by avoiding hazard-prone areas. One can reduce vulnerability by increasing the structural resistance of objects, with measures depending on specific hazard, e.g. floodplain propagation, flash flood surge or mudflow. Insurance penetration generally increases the geographical spread of risks, but may also increase the probability of higher accumulation losses.

The current approaches deal with analyzing these factors separately, and merging the results under a purely holistic framework. The major objective is ranking risk levels under a merely geographical perspective. The approach further takes the assumption of mutually independent factors as a postulate without exploring their mutual relations also in designing remediation measures. Thus, actions reflect this approach; and risk reduction projects do not account for complexity nor provide a comprehensive fusion to integrate hazard reduction, exposure conscious planning, and enhancements to decrease vulnerability.

Is the approach satisfactory? Mainstream thinking states that flood-risk-related science and technology requires further amelioration in computational practices, decision-making procedures, topographic detail, observational facilities, and so on. That is, one must travel the conventional routes only, assuming that the roads not taken are no exit roads, definitely. Is it time to overcome this assumption?

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No doubt, in last 50 years hydrological science improved both knowledge of underlying physical processes and computational capability to achieve detailed information on hazard and provide predictions in both real-time and long-term scenarios. Flood management, economy and post-catastrophe recovery practices are much more sophisticated than those available 50 years ago. In spite of fundamental advances in many disciplines involved in flood assessment meteorology, flood hydrology, risk assessment, water engineering, urban planning, disaster related social assessment flood catastrophes are increasingly challenging human society worldwide.

Data display an increasing challenge to man's file all around planet Earth. Floods have caused the largest portion of insured losses among all natural catastrophes during recent decades, causing losses worth USD55 billion in 2016 alone around the world. The updated report by European Environment Agency (Floodplain management: reducing flood risks and restoring healthy ecosystems, 2016) examined data on floods dating from 1980 to 2010, and found significant increases in flooding, which will only get worse as time goes on. In addition, by 2050 flood losses may increase fivefold, because of climate change, of increasing value of land around the floodplains, and of urban development. People in coastal areas are more aware of flood threats than those living in inland flood zones; and populations in inland areas are increasing in USA (Qiang et al. 2017).

Preliminary estimates for insured global losses resulting from natural and manmade disasters in 2017 are around USD136 billion, well-above the annual average of the previous 10 years, and the third highest since sigma records began in 1970. Total economic losses soared in 2017 to USD306 billion from USD188 billion in 2016. The accumulation of economic and insured losses ramped up in the second half of the year, due primarily to the three hurricanes Harvey, Irma and Maria that hit the US and the Caribbean, and wildfires in California. Globally, more than 11,000 people have died or gone missing in disaster events in 2017, similar to 2016. Extreme weather in the US led to a high number of severe convective storms (thunderstorms). Five separate severe thunderstorm events from February to June caused insured losses of more than USD1 billion each. The most intense and costly event was a 4-day long storm in May with heavy damage to property inflicted by hail in Colorado and strong winds in other parts of southern and central states. The economic losses of this storm alone were USD2.8 billion, with insured losses of USD2.5 billion (see, Swiss Re, Preliminary sigma estimates for 2017: global insured losses of USD136 billion are third highest on sigma records, 2017).

Global warming is a not negligible forcing factor of flood hazard, capable of augmenting flood risk in the next future. Cities are particularly vulnerable to climate risks due to their agglomeration of people, buildings and infrastructures. Guerreiro et al. (2018) assessed future changes in flood impact for all 571 European cities in the Urban Audit database using a consistent approach. To capture the full range of uncertainties in natural variability and climate models, they used all climate model runs from the Coupled Model Inter-comparison Project Phase 5 to calculate Low, Medium and High Impact scenarios, which correspond to the 10th, 50th and 90th percentiles of each hazard for each city. For the low impact scenario, drought conditions intensify in southern European cities while river flooding worsens in northern European cities. However, the high impact scenario predicts that most European cities will see increases in both drought and in river flood risks. Over 100 cities are particularly vulnerable to two or more climate impacts. Moreover, the magnitude of impacts exceeds those previously reported, highlighting the substantial challenge cities face to manage future climate risks, as further shown by Alfieri et al. (2018): "A considerable increase in flood risk is predicted in Europe even under the most optimistic scenario of 1.5 °C warming as compared to pre-industrial levels, urging national governments to prepare effective adaptation plans to compensate for the foreseen increasing risks".

Peduzzi et al. (2009) showed that human vulnerability from natural disasters is mostly linked with country development level and environmental quality. Some social groups display higher vulnerability than others in both developed countries (Cutter and Finch 2008; Fekete 2009; Dzialek et al. 2016) and developing ones (Adger 2006; Rasch 2015; Salami et al. 2017). Are these factors properly accounted when developing vulnerability, exposure and hazard reduction plans and projects? The interactions among natural hazard, man-made risk enhancements and social issues are not straightforward. For example, Hispanic immigrants have the greatest likelihood, and non-Hispanic Whites the least likelihood, of residing in a flood prone zone in Houston, Texas, USA; conversely, in Miami (Florida, USA) non-Hispanic Whites have a significantly greater likelihood of residing in a flood zone when compared to Hispanic immigrants (Maldonado et al. 2016). Risk perception itself is subject random attitudes, as shown by a recent assessment of social vulnerability in the most flood-prone country of Africa (Kablan et al. 2017). One must notice: "man's attitude against flood risk over last 150 years cannot be disjointed from country's cultural and social attitude, this including politics and religion throughout history" (Rosso 2017). This applies to the most disaster-prone country of Europe, Italy (Dickie et al. 2002). However, one can apply this concept to major flood disasters in Europe and United States (e.g. the Great Flood of Paris in 1910 or the Katrina catastrophe in 2005) as well as to those occurred in Far Eastern countries [e.g. the deadliest dam disaster of Banqiao in China (1975) or the 2016 Assam flood in India]. From ancient times, major floods have an impact on culture, politics and religion (Seppilli 1979) and the feedback involves manmade modification that affect hazard, exposure and vulnerability. One should envisage that a novel approach should consider qualitative and quantitative knowledge under a comprehensive and coherent framework to ameliorate man's capability to cope with floods.

The mutual relation between hazard, exposure and vulnerability is usually missed by current approaches, although it has a clear influence in risk assessment (Danielsson and Zhou 2016). There is the need for merging knowledge from different areas, e.g. hydrology and social sciences (Sivapalan et al. 2012; Di Baldassarre et al. 2015; Gober and Wheater 2015) or ecology and hydrology (Eagleson 2002; D'Odorico and Porporato 2006; Good et al. 2015). However, complexity arising from these interactions requires a step-ahead, because traditional quantitative approaches cannot properly provide an insight of the mechanisms and feedbacks involved, independently from deterministic or stochastic methods adopted in the challenge. When investigating the apparent chaos that arise between nature and man, one must take in mind the famous statement by Henry Adams “Chaos was the law of nature; Order was the dream of man”.

Are the present knowledge and state-of-the art mathematical methods capable to provide the most efficient information on hazard? Is urban planning aware that floods are the first thread among natural disasters? Is there enough and coherent perception of vulnerability by the multifaceted environmental, social and political stakeholders? Trends observed in new millennium worldwide provide a negative answer. In addition, urban resilience (Godschalk 2003) is still a missed issue in urban planning and management in spite of the strong acceleration of urbanization worldwide.

In order to mitigate flood risk, resilience plays a major role if one must properly address the challenge by climate change (Klein et al. 2003):

> The concept of adaptive capacity, which has emerged in the context of climate change, can then be adopted as the umbrella concept, where resilience will be one factor influencing adaptive capacity. This improvement to conceptual clarity would foster much-needed communication between the natural hazards and the climate change communities and, more importantly, offers greater potential in application, especially when attempting to move away from disaster recovery to hazard prediction, disaster prevention, and preparedness.

In particular, one must approach resilience at two different scales: the regional scale and the local scale, the latter in opposition to the concept of resistance. As introduced below, three main factors assess the risk due to catastrophic events of natural origin, i.e. hazard, exposure and vulnerability.

1. Hazard, H, is the probability that a phenomenon with a given intensity I will occur in a given period of time and in a given area: H = H(I).
2. Vulnerability, V, is the level of the losses caused to a given element or to a given group of elements which can be affected by phenomena of a given intensity, as a function of such an intensity I and of the kind of element E at risk: V = V(I, E).
3. Exposed Value, W, that is the economic value or the number of units, related to each one of the elements at risk in a given area and depending on the kind of elements: W = W(E).

The total risk, R, related to a particular element at risk E and to a given intensity I, is the result of a convolution like R(E, I) = H(I)*V(I, E)*W(E). In general, R is the expected value of the losses in terms of human lives, wounded persons, damages to properties and interferences with economical activities due to the occurrence of a particular phenomenon of a given intensity.

This book addresses flood vulnerability under a comprehensive but problem oriented approach to reduce it in urban areas. The key measure to decrease flood vulnerability is flood proofing. The primary objective of flood proofing is to reduce or avoid the impacts of coastal ad river flooding upon structures and infrastructures. This may include, for instance, elevating structures above the floodplain, employing designs and building materials that make structures more resilient to flood damage, and preventing floodwaters from entering structures in the flood zone, amongst other measures. It includes any combination of structural and nonstructural additions, changes, or adjustments to structures and infrastructures, which reduce or eliminate flood damage to real estate or improved real property, water and sanitary facilities, energy and communication networks, structures and their contents. An obvious extension of flood proofing deals with dense human settlements with continuous urbanized areas, both residential and non-residential, because a single block or multiple blocks can be flood proofed under a unified approach. This plays a major role in reducing flood damage in ancient cities with historic buildings under the commitment of preserving heritage and landmarks.

Developing an appropriate flood proofing strategy for protecting property (and people) from flood hazards requires evaluation of the risks, technical considerations, costs, and personal preferences. (a) First appropriate regulations must be issued at the municipal scale and municipal building officials must be aware of the need to disseminate information and guidelines, and to avoid or balance conflicting issues among stakeholders. If an existing building in the regulated floodplain has been substantially damaged or is substantially improved, regulations require that the entire structure be brought into compliance with current floodplain development standards, which precludes the use of some flood proofing techniques. Other building code requirements will also apply to the project. (b) The accurate assessment of hazard plays a fundamental role in developing the appropriate flood proofing technique under a well-assessed municipal strategy. The desired depth of flood protection is a central consideration, since both the technical challenges and the costs for flood proofing measures may increase with water depth. The potential for high water velocities, scouring, ice, and debris flows should also be taken into account. The amount of warning time must also be considered, because protective measures that require time to implement are not appropriate if the area is prone to flash flooding. (c) One must address the identification of feasible options after assessing an operative and detailed knowledge base on flood processes. The applicability of any flood proofing technique depends on the nature of the flood hazard (depth, velocity, debris potential, warning time), site characteristics (size, location, slope, soil type), and building or block characteristics (structural condition, type of foundation, type of building construction). (d) The accomplishment of flood proofing initiatives must involve the overall economic capacity of citizens to afford the costs to install and maintain flood proofing facilities over a long time horizon. Accordingly, one must clearly assess the costs and benefits. Some flood proofing options may be too costly and others may not provide the desired amount of risk reduction. (e) Finally, flood proofing requires developing a strategy for managing flood risks. The decision regarding a flood proofing project must also be based on the personal preferences and concerns of the people who will be living with the results on a day-to-day basis. Are there aesthetic preferences? Concerns about the accessibility of the building? Special considerations related to historic structures? Would someone be available and able to implement protective measures prior to a flood? How much risk are you willing to live with? One must merge these considerations with technical and financial assessments to develop the most appropriate strategy for managing the flood risks in a particular situation (Southern Tier Central Regional Planning and Development Board 2017).

Flood proofing is quite popular in those countries where flood insurance is a major mitigation measure because of nation-wide politics. For example, in an effort to restore fiscal soundness to the National Flood Insurance Program, the Congress of the United States of America enacted program reforms in July 2012. These changes resulted in dramatically higher flood insurance costs for many policyholders, which led to additional reforms in March 2014. As a result, insurance subsidies are being phased out for older buildings that do not comply with current floodplain development standards. The objective is to move toward "full-risk rate" premiums that reflect the flood risk for each building. The impact of these reforms is minor for some policyholders, but it could result in significantly higher insurance costs for others. Accordingly, subsidized rates mitigation push to consider options using updated flood proofing measures and facilities.

In Europe, facing with floods was generally in last two centuries. After the great floods such as those devastating Wien in 1847, Rome in 1870, Paris in 1910, London in 1928, Florence in 1966, Prague in 2002 huge engineering works were carried out to reduce flood hazard. These are partially successful, because they actually reduced flood hazard and the cities did not suffer destructive impacts as those mentioned, but recent events (e.g. Paris in 2016, Rome in 1937 and 2014) show that further measures are needed to achieve acceptable risk levels, but both physical and economic issues indicate that engineering works can hardly accomplish these goal. In this context, adaptation efforts should give priority to measures targeted at reducing the consequences of hazardous events, rather than trying to avoid their occurrence. This will include a deeper insight of the dynamic behavior of floodplains as human-water systems (Di Baldassarre et al. 2013).

As stated by Alfieri et al. (2017) "The adaptation efforts should favor measures targeted at reducing the impacts of floods, rather than trying to avoid them. Conversely, adaptation plans only based on rising flood protections have the effect of reducing the frequency of small floods and exposing the society to less-frequent but catastrophic floods and potentially long recovery processes". Relocation would provide the most effective results, but it has human costs that European countries can afford under extensive and pervasive policies. Under the adaptation commitment, the reduction of vulnerability appears to be an effective and realistic measure towards flood risk mitigation from country-aggregated data for Germany, France, United Kingdom and Italy (see Fig. 1.1).

An interesting overview of the important integrated aspects of flood proofing in urban areas comes up also from the quite recent English manual on flood hazard edited by Lamond et al. in 2011. As a matter of fact, flood proofing refers to a large number of interventions, these including building repositioning or lifting, dry or wet flood proofing of the buildings, self-mobile barriers, emergency dikes and/or berms and even the old-fashioned sand sack walls. All of those flood proofing measures or devices aimed to reduce or at least to control the flood effects at a local or areal scale, due to people loosing stability when hit by the flow, buildings damaged by water flow, vehicles and other materials mobilized and transported by water stream during

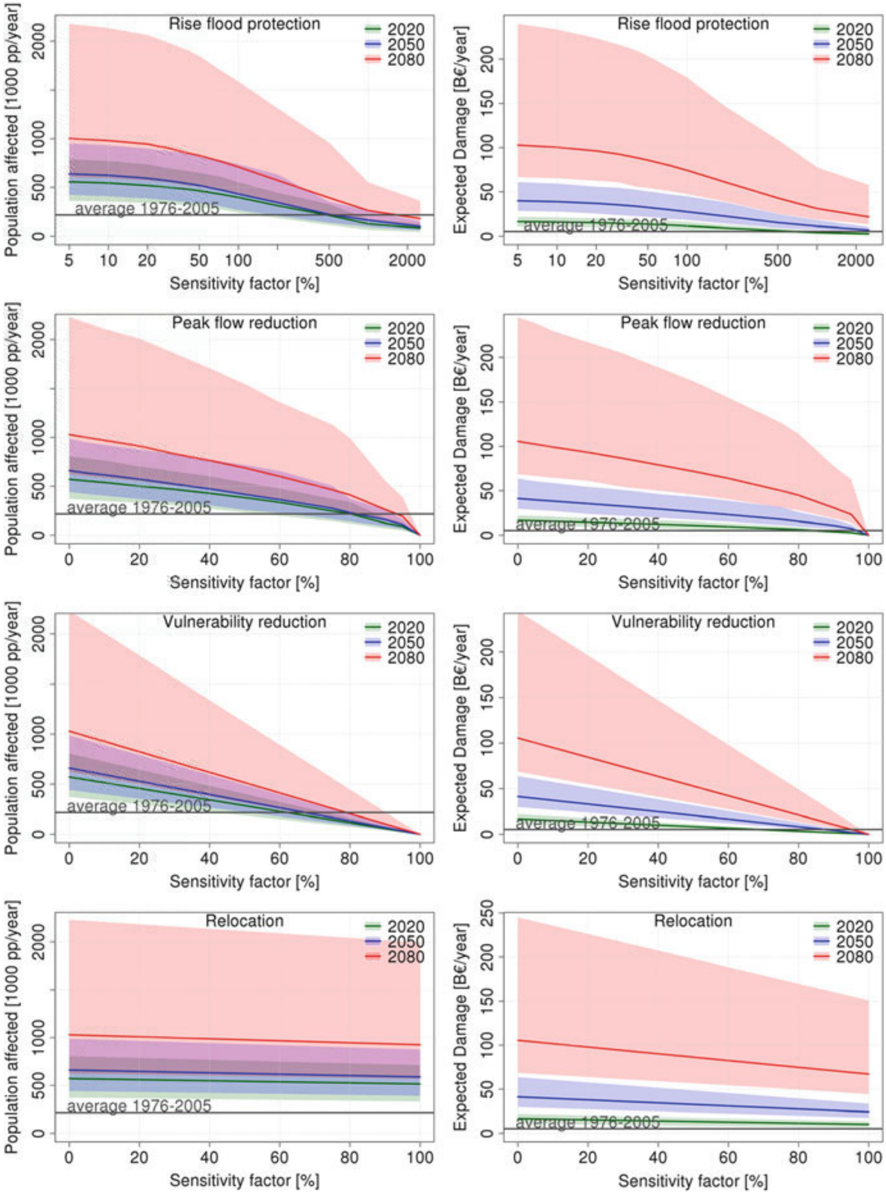

Fig. 1.1 Benefits of four adaptation strategies on ensemble annual estimates of population affected (left) and expected damage (right) in Europe in time slice 2020, 2050 and 2080 (adapted from: Alfieri et al. 2017)

flood conditions. Because most people developed flood proofing measures under holistic approaches, the book first approaches physics of stability and instability of both human beings, objects and buildings under flood attack, this including possible criteria to evaluate stability and safety (see Chaps. 2–6).

Chapter 7 provides an updated classification of possible flood proofing methods and devices under a strategic planning perspective. Both temporary and permanent measures are considered, and the specific situations for effectiveness. Then, we focalize on temporary flood proofing techniques, which display the best performance in terms of cost-benefits. A number of practical examples are presented, most of them are real case studies, without mentioning manufacturers or commercial product names. Finally, we address economic issues associated with insurance discount, premium reduction and tax handle.

Chapter 8 deals with planning of temporary flood proofing measures. We discuss arrangement and activation approaches, this including decision-making to be addressed under a coherent modeling framework. One must consider possible flooding scenarios in order to implement suitable flood proofing system. This is described in detail using a case study for a historic landmark in Italy, the city of Pisa. Chapter 9 provides an extensive review of state-of-the-art device and facilities suitable for temporary flood proofing developments. Chapter 10 reports a review of Tests, Guidelines and Norms adopted by different countries where flood proofing is currently implemented. This can help encouraging authorities, municipalities, technicians, stakeholders and end users to improve their capability to cope with floods under the goal of reducing vulnerability at the municipal, block and building scales.

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Chapter 2
Flood Impact on Buildings

2.1 Introduction

A building stressed by water flow is affected by three main actions: (i) buoyancy, (ii) hydrostatic force, (iii) hydrodynamic force. The first one, sometimes also called Archimedes force, is due to the tendency of a submersed building to float because of the weight of the water that could be in its volume. The second one is due to the mass of water as (statically in quiet) that is in direct contact with the structure, it is isotropic and its direction is locally perpendicular to the contact surface, causing effects on both the vertical elements of the structure (walls, pillars and so on) and on the horizontal elements of the structure (girders, roofs and so on). The third one is provided as the result of the forces related to the water movement and affects the upstream surface of the structure, that is the surface directly facing the flow: it tends to drag the structure toward the flow direction and to scour the foundations, with an additional destabilizing effect due to local whirling eddies and possible negative pressure on the downstream surfaces of the structure.

Until now, literature has not yet payed a lot of attention to the study of the effects of flooding events on single buildings and on residential, industrial and commercial areas in general (Smith 1994). To ensure the structural safety of the buildings towards flooding phenomena by means of consolidation measures specifically designed to this aim, it must be kept into account that such measures are effective and economically viable only when the flow velocities don't exceed 3 m/s (Lardieri 1975).

2.2 Evaluation Criteria

2.2.1 Analysis of Stormwater Effects

Sangrey et al. (1975) developed a procedure to forecast the interactions between flood water and structures in the inundated plan, on the basis of the experience of the

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inundation in the Chemung watershed (Elmira, NY, USA) caused by the Agnes cyclone in 1972. Hence, they analysed 155 buildings and structures of different kinds, out of the more than 1000 ones existing there. In particular, nine categories have been defined according to their weight W, of course approximated (Table 2.1). The assessment of the damages was carried out by examining both of the available aerial photos in a detailed way and by ground surveys (recognition of the structures and interviews with the inhabitants). So, the buildings and the structures have been classified according to just a binary criterion: either *survived* or *destroyed*.

Then, the hydrodynamic characteristics of the inundation, in terms of velocity U and water depth h, have been simulated by means of a standard 1D model, that is HEC-2, modified in order to take into account the effects of the structures on both soil roughness and cross section shape. So the maximum values of U and h have been found out for each structure in the watershed.

The stream creates both a horizontal load and a vertical load against a flooded structure. In particular, the horizontal load F_H is given by the drag along the flow direction, expressed by Sangrey et al. (1975) as:

$$F_H = C_D(1/2)\rho U^2 b\left(h - h_{fo}\right) \tag{2.1}$$

where C_D is the drag coefficient, assumed equal to 2; ρ is the water density as kg/m^3; U is the stream velocity as m/s, b is the structure width in the direction orthogonal respect to the flow as m; h is the water depth as m, and h_{fo} is the foundation depth as m. The load on the foundation is neglected, because the damages are usually due to the separation between the emerging structure and the foundation itself; moreover the stabilizing effects due to minor connections (nails, screws, wires, and so on) between those two elements are negligible.

The analysis is focused on the relationship between the lateral load, represented by the adimensional drag parameter F_H/W, and the corresponding normal load, represented by the di buoyancy parameter $(h - h_{fo})/(10s)$, where s indicates the number of the floors in the structure under analysis. The results are shown in Fig. 2.1, which shows a quite sharp separation between the destroyed buildings (black points) and the buildings that survived (white points). Figure 2.1 also shows how it is possible to find an empirical criterion about the damage, based on the parameters

Table 2.1 Classification of the structures according to Sangrey et al. (1975)

Type	Description	Weight (kgf)
A	1 floor building, light wood-made structure	7800
B	1 floor building, heavy wood-made structure	11,100
C	1 and ½ floor building, light wood-made structure	11,100
D	1 and ½ floor building, heavy wood-made structure	16,300
E	2 floors building, light wood-made structure	12,300
F	2 floors building, heavy wood-made structure	18,800
G	Light wood-made 1 floor appendices (garage and similars)	1000
H, V	1 or 2 floors structures, concrete made	Individual assessment

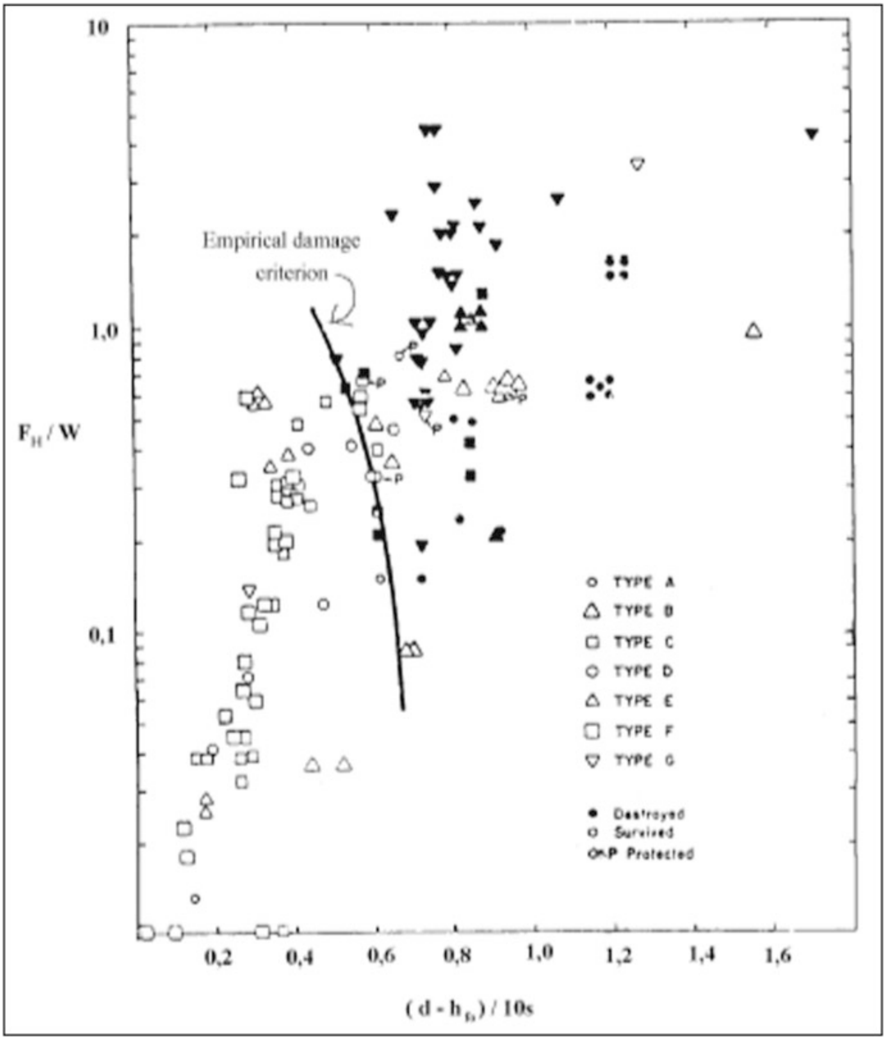


Fig. 2.1 Results of the experimental investigation and consequent empirical criterion about damage assessment according to Sangrey et al. (1975)

F_H/W and $(h - h_{fo})/(10s)$: for example, if the buoyancy parameter is equal to 0.8 and the parameter F_H/W is equal to 1, the structure is likely to be destroyed during a flood.

A study by Lorenzen et al. (1975) examined 15 farms flooded by the same Agnes cyclone in 1972 in four different watershed of the State of New York, each one consisting of a number of buildings between 1 and 4. The structures of the buildings under analysis (were both wood-made, metal-made and concrete-made). The flooding characteristics (water depth and water velocity, that reached 1.5 m/s) had been estimated on the bases of both eye-witnesses and flood evidences, as the surface water levels were marked on some of the walls by the inhabitants.

The analysis includes the assessment of:

1. Floating thresholds for the wood-made buildings,
2. Static and dynamic pressures,
3. Collision load and debris flow impact load assuming that the buildings are not anchored to their foundations.

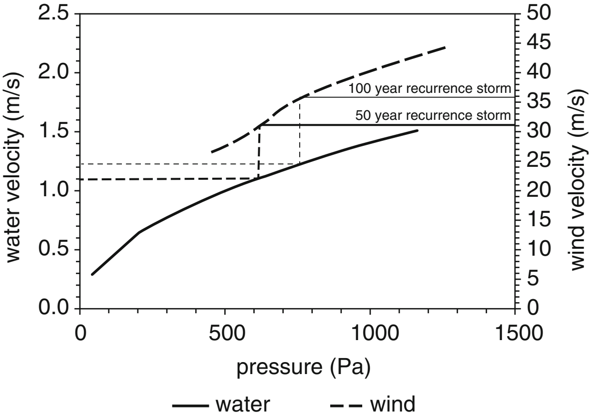
The floating line of a typical single floor ranges between the ground floor and a little bit more than 1 m above the foundation platform. Nevertheless, the wooden buildings and mobile buildings tend to float in a vertical direction, so a building that is not anchored can be removed from its foundations well before the floating condition is achieved. On the contrary, buildings made of concrete do not float but tend to slip and to roll.

The hydrostatic pressure due to the flood water has a high capacity to drag and destroy walls (of) basement floor, especially if such walls are sealed. The water pressure in the saturated soil in subbasement with a deep of 1.8 m can reach, at the floor level and below the pavement, about 1800 kgf/m^2: this is enough to lift the pavement, creating large cracks in the walls, deforming and even breaking them.

In Fig. 2.2 you can see the comparison between the hydrodynamic pressures due to flood waters and to winds. In the examined area of the State of New York, the wind velocity for a return period of 50 years is estimated to be equal to about 31 m/s while for a return period of 100 years it becomes 37 m/s. As a wind velocity of a 31 m/s causes the same pressure of a water flow having a velocity of 1.1 m/s, this means that a building resisting such a velocity should be able to cope with a stream flow characterized by this velocity.

In Fig. 2.3 you see the impact action due to a floating wooden rafter of 45 kgf. Moreover, if the value is 90 kgf and the velocity is about 0.9 ÷ 1.2 m/s that is enough to penetrate a wall made of wood, to crack 5 × 10 cm pillar or to damage a concrete wall.

Fig. 2.2 Comparison between the pressure values due respectively to flood water velocities and wind velocities [from: Maijala (2001), based on Lorenzen et al. (1975)]



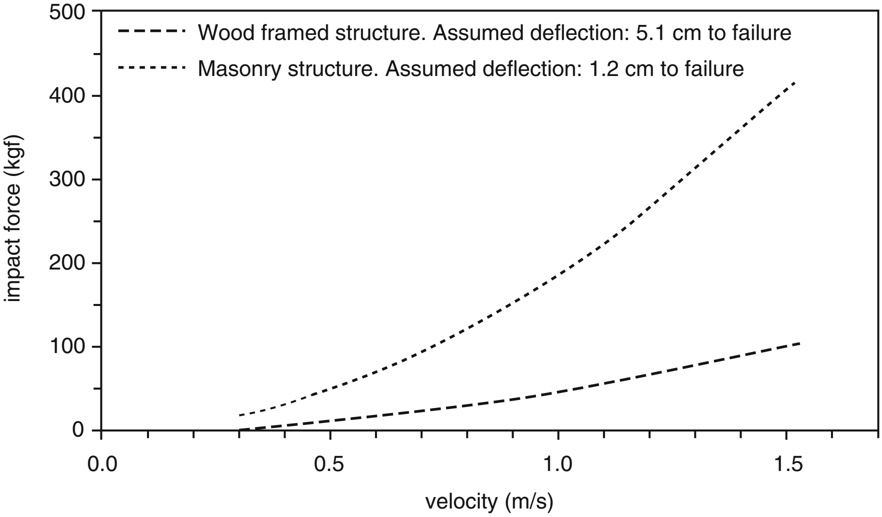


Fig. 2.3 Action due to a floating wood made rafter [from: Maijala (2001), based on Lorenzen et al. (1975)]

Definitively, the study of Hurricane Agnes creates the following conclusions.

Metal Structure Buildings Those buildings (garages, stockrooms and so on) usually survive without too much damage. Nevertheless, the stream flow can drag them, while both floating materials and sediment transport can damage their perimeter. But a solid anchoring of their pillars to the foundation and the empty interblocks of such buildings (if present) tend to mitigate the inundation damages. The buildings with a light metal structure, without impervious walls, with good foundations and effective anchorage, suffer minor damage, essentially because they allow the hydrostatic pressure to become equal on both sides of the structural elements.

Wooden Made Buildings with Concrete Foundations These buildings have very different kinds of reactions to flooding events. As they are usually quite light, in comparison to water, the buoyancy can cause their structural failure. The main reasons for their structural failure are due to insufficient foundations and inadequate anchorage, while the damages observed in buildings that are solidly anchored to strong foundations are quite limited.

Concrete Made Buildings They can resist quite well to an inundation event if they have solid foundations and, at the same time, are not influenced by buoyancy. However, many basement walls are subject to damages because they are sealed and do not allow for the hydrostatic pressure to be equalized until cracks are created in the walls. It is also important to note that concrete foundations and other elements made of concrete are far less resistant in comparison to similar elements reinforced by concrete.

Table 2.2 Threshold values of the submergence water depth for floating (Black 1975)

Kind	One floor (m)	One floor and a half (m)	Two floors (m)
Light	1.9	2.7	2.9
Heavy	2.8	3.5	4.7
Heavy with masonry stiffenings		5.2	

2.2.2 Buoyancy and Hydrodynamic Force

To evaluate the buoyancy effect, Black (1975) studies three different kinds of small buildings made of wood (with respectively one floor, one floor and a half, and two floors) anchored to a foundation platform of 7.3 × 9.8 m. For each kind of building, two different construction techniques are considered, *light* and *heavy*. Their overall weight varies between 7100 and 17,000 kgf. Moreover, the additional effect due to masonry stiffenings made of bricks is examined.

A building begins to float when the buoyancy exceeds the weight. As the buoyancy is a function of the submergence water depth and, Table 2.2 shows the results in terms of water depth threshold, that is buoyancy equal to weight. It can be seen that light houses start to float when the submergence is equal to about half time their height, while the heavy houses when the submergence is equal to about 3/4 times their height.

In addition, Black (1975) studied the combination of buoyancy and dynamic force, in order to assess the relationship between velocity and water depth in terms of building threshold stability. The results summarized in Fig. 2.4 shows how the buildings become unstable because of the combination of those two effects. A flow rate of 1.8 m/s creates a dynamic pressure of 1.7 kPa: likely, it is enough to create structural damages to the different components of the building and erodes the foundations in a significant way, as the foundation soil usually is not able to resist a velocity higher than 1.5 m/s for more than 1 h.

Figure 2.5 summarizes the calculations of the bending moment due to the combination of those two different actions, that are compared with the allowed values (related to the allowed stress values, that are respectively 6895 and 13,790 kPa[1]) usually adopted in wood made buildings. A water depth of 90 cm is enough to compromise a light building even in still water conditions! A wooden wall can sustain higher pressure, about 41,000 ÷ 55,000 kPa in terms of breaking point. When the water enters a building, the hydrostatic pressure on the vertical walls becomes equal; so, Fig. 2.6 shows the relationship between the bending moment due to just the dynamic pressure. If, for example, the flow rates has a velocity of 2.4 m/s, the lower stress limit of the material is exceeded for a water depth of 1 m and the higher stress limit for a water depth of 1.6 m.

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[1] The corresponding allowable stress values for a pilaster of 5 × 10 cm are respectively 347 and 694 Nm.