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Position Paper

A preliminary combined simulation tool for the risk assessment of pedestrians' flood-induced evacuation

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ABSTRACT

Flood risk assessment in urban regions does not account for human behaviours during emergency. Understanding behaviours during floods and developing related simulators highlight critical phenomena for individuals' safety, during and after the flood, and suggest risk-reduction strategies aimed at helping evacuees. The proposed Flooding Pedestrians' Evacuation Dynamics Simulator (FlooPEDS) combines flood hydrodynamics (based on Nonlinear Shallow Water Equations) and individuals' evacuation (by modifying the Social Force Model). FlooPEDS capabilities are illustrated with reference to an important case study. Results focus on evacuees' motion and path choices. This preliminary simulator implementation, still raw for practical use by planners and authorities, is already mature to guide the design of innovative resilience-increasing urban solutions (i.e.: architectural components like handrails, raised flooring systems) in specific hazardous urban areas, as support to traditional strategies (i.e.: early warning systems; evacuation plan communication).

Software availability

Title: FlooPEDS
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E-mail: g.bernardini@univpm.it; m.dorazio@staff.univpm.it; e.quagliarini@univpm.it
Software availability: The executable file is only available for the behavioural model ("beta version" available in the journal supplementary materials, by including the case study scenario inputs); for the hydrodynamic model, please contact authors (m.brocchini@univpm.it; m.postacchini@univpm.it)
Sourcecode language: Java
Software required: Recommended JRE 1.8.0_20 or later
System required: Any personal computer with MS Windows 7 or MS Windows 8

1. Introduction

Studies on risk and damage due to a urban flood are mainly based on hazard and vulnerability estimations (Jha et al., 2012; Leskens et al., 2014). The occurrence probability of the flood depends on its type and causes (Jha et al., 2012) and it can also include related uncertainties (Bazin et al., 2017). Territorial features are generally accounted for by vulnerability analyses (Jiang et al., 2009). They mainly involve: plano-altimetrical layouts (including mapping activities (Morelli et al., 2012)); land use highlighting economic factors, their sensitiveness to flood effects (Jiang et al., 2009) and ecological impacts (Jha et al., 2012); population densities and demographic data (Koks et al., 2015). Studies concerning the estimation of damages (Molinari et al., 2014) and life losses (Jonkman et al., 2009) in different scenarios are also available, as well as GIS-based applications (Qi and Altinakar, 2011).

Modelling studies have been devoted to the determination of the flood-inundation extent, especially in urban areas. Such models have to deal with the spatial scale of the urban tissue, which ranges from 0.1 m to 10 m for significant urban details and between 1 m

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and 100 m for a relatively large floodplain (Soares-Frazao et al., 2008). Hence, the modelling of such an environment is fairly complex and needs some specific approximations. Models typically range from simple approaches based on the intersection between a plane, which represents the water surface, and a Digital Elevation Model (DEM) of sufficient resolution, e.g. reconstructed using LiDAR (Guidolin et al., 2016), to three-dimensional solutions of the Navier-Stokes equations, e.g. used for the description of water flow (e.g. open-channel flows (Thomas and Williams, 1995)). Simple models are usually characterized by limitations (Cobby et al., 2003), e.g. the unrealistic one-dimensional approach to model out-bank flows (Goutière et al., 2008), or they do not account for specific urban areas and neglect important smaller-scale features, e.g. section reductions and energy losses due to the presence of buildings (Goutière et al., 2008), while three-dimensional models are characterized by large computational costs. This means that a proper trade-off is needed to obtain useful and realistic outputs, in terms of flood characterization, at a reduced computational cost. Shallow-water, depth-averaged, approaches seem to be the most promising. They are often used to simulate floods in urban environments characterized by a porosity that acts on both water storage and fluxes (Guinot, 2012). Typical flood simulations are characterized by moving boundaries. These are accounted for by using appropriate wet-and-dry techniques, which are properly implemented in shallow-water models (Brocchini et al., 2001). In particular, Nonlinear Shallow Water Equations (NSWE) models, according to the recent literature (Bazin et al., 2017; Soares-Frazão and Zech, 2008), seem to own the required skills to properly reproduce a urban flood, even if they are not as accurate as three-dimensional solvers (Wang et al., 2017).

On the other hand, human aspects are usually accounted for by introducing an exposure factor (Koks et al., 2015). Previous works underlined how human behaviours are influenced by the flood evolution and the environmental modifications during the event, because individuals interact with “dynamic” scenario conditions (due to the flow propagation and its effects) (Chanson et al., 2014; Opper et al., 2010). These interactions affect: a) quick abandon of hazardous areas; b) individuals' possibility to maintain safe conditions while moving (Ishigaki et al., 2009); c) survivors' rates (Jonkman et al., 2009); d) reach of refuge points (Jiang et al., 2009). Supplementary aspects that influence the evacuation are connected to the urban scale complexity. Such “human” factor (also from a behavioural point of view) becomes a fundamental issue to be accounted for in case of: a) compact urban fabrics (Hubbard et al., 2014); b) touristic areas (Tsai and Chen, 2011); c) inefficient (or missing) Early Warning Systems (EWS) and evacuation procedures, which could lead exposed people to significantly retard the evacuation starting and thus face critical scenario conditions, e.g. for treacherous flow conditions, given in terms of stream depth and speed (Cools et al., 2016); d) interactions between pedestrians' flows and vehicles and/or transportation evacuation (Di Mauro et al., 2013). Some studies tried to tackle the issues of: a) human behaviours in different types of flood events, mainly by defining risk-perception aspects (Bodoque et al., 2016); b) psychological attitudes, by including social influences and attachment to belongings (Riad et al., 1999); c) actions during the evacuation timeline, by considering rescuers’ strategies and evacuation effectiveness (Opper et al., 2010); d) level of risk for pedestrians (including instability), depending on floodwaters velocity and depth (Chanson et al., 2014); e) motion speed for pedestrians moving in floodwaters, depending on specific flow forces (Ishigaki et al., 2009); e) life losses and hazardous behaviours (Jonkman et al., 2009). Most of these studies involves laboratory experiments (Ishigaki et al., 2009) and interviews (Bodoque et al., 2016; Riad et al., 1999). Those based on real-life emergency analyses (Chanson et al., 2014; Jonkman et al., 2009) seem to be limited if compared to those devoted to other urban emergencies (e.g.: earthquakes (Bernardini et al., 2016b).

Despite the importance of the “human” factor, current guidelines for governmental and local authorities on emergency management planning and risk-reduction strategies do not seem to account for similar aspects (Opper et al., 2010).[1] Nevertheless, combined hazard, vulnerability and exposure evaluations are essential for defining: a) possible risk-reduction policies to minimize the impacts of floods (Jha et al., 2012) by including private and public interventions (Milman and Warner, 2016), and b) emergency management strategies, such as (mass) evacuation plans and procedures (Opper et al., 2010). To this aim, flood evacuation software tools should be developed to highlight critical phenomena for the individuals' safety, like for other kinds of urban disasters (Bernardini et al., 2016a; Kunwar et al., 2014). Simulation models useful to study different types of flood events are already available (Kunwar et al., 2014; Matsuo et al., 2011), by including tsunami (Di Mauro et al., 2013) and hurricane (Chen et al., 2006) emergencies. Most of these models describes pedestrians' evacuation choices by establishing coded paths, while density-speed diagrams are used to define total motion times (Kunwar et al., 2014; Lämmel et al., 2010). A “macroscopic” approach (Bernardini et al., 2016a; Kunwar et al., 2014) is often used, because the simulator takes advantage of its low computational cost and it is well suited to represent large urban areas. Although these models generally use macroscopic pedestrians' movement rules (mainly: the fundamental diagram of pedestrians' dynamic) supported by wide experimentally-based analysis, their main limits concerns the representation of heterogeneous population, environmental conditions, and complex behaviours (e.g.: evacuation counterflow; individuals' age and specific movement features; group phenomena; interactions with surrounding environmental elements) (Lämmel et al., 2010; Thompson et al., 2015). An additional limit could be represented by the implementation of general (i.e.: no-flooding conditions) macroscopic motion rules in the simulators, e.g. evacuation flow diagrams referring to no-emergency movement, fire escape, general purpose evacuation, indoor movement (Bernardini et al., 2016a; Shiwakoti et al., 2008). Solvers working at a smaller scale could take advantages of a “microscopic” representation of human evacuation interactions (Chen et al., 2006; Rabiaa and Foudil, 2010), by assigning the evacuation behaviours (and possible psychological rules) to each involved pedestrian. Agent-based models could solve this issue by attributing the time-dependent role of the flows characteristics on individuals' speeds and stability (Matsuo et al., 2011). Nevertheless, current simulators generally do not provide a validation process (even if based on real world rules for pedestrians' evacuation (Matsuo et al., 2011) or are limited to comparisons between the produced outputs and the ones of other models (Di Mauro et al., 2013). Within microscopic approaches, the Social Force Model could offer significant advantages since it uses a continuous spatial and temporal description of the evacuation scenario (Helbing et al., 2005). It models each evacuee's movement as the resultant of man-man and man-environment interactions: behaviours could be modelled in a separate way by means of experimental analysis (i.e.: real event videotapes analyses

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[1] Hazus Flood Model and Methodology, by FEMA (https://www.fema.gov/hazus-mh-flood-model); http://ec.europa.eu/clima/policies/adaptation/what/docs/swd_2013_137_en.pdf; CFPA-E No 1:2012, by Confederation of Fire Protection Associations Europe, (http://www.cfpa-e.eu/wp-content/uploads/files/guidelines/CFPA_E_Guideline_No_1_2012_N.pdf); Evacuee Support Planning Guide, by Federal Emergency Management Agency (2009; FEMA P-760); Guidelines for Reducing Flood Losses, by UNISDR (2002) (https://www.unisdr.org/we/inform/publications/558) (last access: 7/2/2017).