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Numerical assessment of flood hazard risk to people and vehicles in flash floods

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ABSTRACT

Flash flooding often leads to extremely dangerous and sometimes catastrophic conditions in rivers due to characteristics such as: short timescales, the limited opportunity for issuing warnings, and the frequent high average mortality. Many past extreme flood events have been accompanied by flash floods, and they have also been one of the main sources of serious loss of human life among the world's worst natural disasters. Flash floods can also cause large loss of property, such as the recent floods in Pakistan and the damage to vehicles in the 2004 Boscastle flood in the UK. It is therefore desirable to be able to assess the degree of safety of people and vehicles during flash floods using numerical models. In the current study, an algorithm for assessing the flood hazard risk to people and vehicles has been integrated into an existing two-dimensional hydrodynamic model capable of simulating flash floods. In the algorithm, empirical curves relating water depths and corresponding critical velocities for children and adults, developed by previous researchers, are used to assess the degree of people safety, and a new incipient velocity formula is used to evaluate the degree of vehicle safety. The developed model was then applied to three real case studies, including: the Glasgow and Boscastle floods in the UK, and the Malpasset dam-failure flood in France. According to the analysis of model predictions, the following conclusions have been obtained: (i) simulated results for the Glasgow flood showed that children would be in danger of standing in the flooded streets in a small urban area; (ii) simulations for the Boscastle flood indicated that vehicles in the car park would be flushed away by the flow with high velocity, which indirectly testified the predictive accuracy of the incipient formula for vehicles; and (iii) simulations for the Malpasset dam-failure flood showed that the adopted method for the assessment of people safety was applicable, and some local people living below the dam would have been swept away, which corresponded well with the report of casualties. Therefore, the developed integrated model can be used to evaluate the flood hazard risk to people and vehicles in flash floods, and these predictions can be used in flood risk management.

1. Introduction

Flash floods are often caused by heavy or excessive rainfall over a short period of time, which is distinguished from a regular fluvial flood by a timescale of less than 6 h (NWS, 2009). In the UK flash floods are regarded as having a time to peak of less than 3 h within catchments of 5–10 km^2, whereas in the USA times to peak of up to 6 h for catchments of 400 km^2 are regarded as potential flash flood catchments (Georgakakos and Hudlow, 1984). Flash floods are usually characterized by raging torrents after heavy rainfall flows over river beds, through urban streets, or mountain canyons in geomorphic low-lying areas, and almost sweeps through everything. They can occur within minutes, or a few hours, after excessive rainfall, and can also occur even if no rain has fallen; for instance after a levee or dam has failed or breached, or after a sudden release of water by debris or ice jam. Due to their rapid occurrence, flash floods usually result in a very limited opportunity for warnings to be prepared and issued, and therefore they are extremely dangerous events, often leading to catastrophic consequences and particularly in the form of loss of human life and property (Collier, 2007).

From 1975 to 2001, there were 1816 reported inland flood events, including such events as flash and river floods, which resulted in the loss of life of over 175,000 people around the world (Jonkman and Penning-Rowsell, 2008). Other types of floods, such as dam-break flows, storm surges and tsunamis can be even more catastrophic in terms of loss of life (Jonkman and Penning-Rowsell, 2008). Throughout the 21st century about 127 reported flood events occurred in East Asia, of which 25 events belonged to the category of flash floods, and accounted for almost 30% of the total

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deaths; and about 14 large floods occurred in the UK, of which 3 events were categorised as flash floods (EM-DAT, 2008). Jonkman and Vrijling (2008) divided floods into three types: drainage floods, river floods and flash floods, and statistical data have shown that the average mortality is highest for flash floods because they are generally unexpected and rapidly evolving events. In the UK, the Department for Environment, Food and Rural Affairs (Defra) and the Environment Agency (EA) have published figures showing that the UK's assets at risk from fluvial flooding are valued at £81.7 billion (Defra and EA, 2005). Although much of this value is associated with flooding in large rivers, such as the River Severn, flash floods are the main source of danger to human life (Collier, 2007).

Hand et al. (2004) pointed out that many of the extreme events occurring in the 20th century were accompanied by flash floods, and such flood events generally occurred in summer and early autumn. For example, a flash flood that occurred in 1967 in Lisbon, Portugal, killed 464 people; and the flash flood occurring in 1975 caused by the Banqiao dam failure in China resulted in about 231,000 deaths. Recently a small town, named Boscastle, in the UK was struck by a devastating flash flood on 16 August 2004, which was caused by heavy rainfall of over 200 mm falling in 5 h (Brigandi et al., 2007). This is one of the best recorded extreme flood events in the UK in recent years. The local Environment Agency (2004) and North Cornwall District Council (2005) reported that millions of pounds of damages were made and about 116 vehicles were washed away. During this flood event, some vehicles and other large-size debris were caught under a local bridge, blocking the main flow passage and finally causing the bridge to collapse. Based on the above examples, it can be concluded that flash floods often lead to serious loss of human life and loss of vehicles, especially in densely populated urban areas. Therefore, it is desirable to be able to assess the degree of safety of people and vehicles caused by flash floods in urban areas using a numerical model, from the viewpoint of enhanced flood risk management.

The processes of flood propagation in urban areas are often simulated by two-dimensional (2D) hydrodynamic models (Bates and De Roo, 2000; Liang et al., 2007; Soares-Frazao and Zech, 2008; Hunter et al., 2008; Neal et al., 2009; Wang et al., 2010; Yu, 2010). BC Hydro's Life Safety Model (LSM) provides the capability to produce a comprehensive range of simulations of possible dam-failure emergency scenarios, and the present default version of the LSM accepts the product of depth and velocity as the argument for person stability (Johnstone et al., 2005). Di Mauro and Lumbroso (2008) recently conducted hydrodynamic studies and loss of life modelling for the 1953 Canvey Island flood in the Thames Estuary using the LSM proposed by BC Hydro. Previous flood risk maps obtained using these numerical models usually depict the distributions of maximum water depths or velocities for a specified flood, and cannot account for the mechanical equilibrium of people and vehicles on the flooded streets and roads. Therefore, the estimation module of hazard degrees for people and vehicles needs to be integrated with a hydrodynamic module in order to predict the flood risk in urban areas, which is the aim of the current study reported in this paper.

In this study, an existing two-dimensional (2D) hydrodynamic model, capable of simulating flash floods, is outlined briefly and previous studies on the assessment of people and vehicle instability are also reviewed. Then an algorithm for assessing the flood hazard risk has been integrated with the existing 2D hydrodynamic model outlined herein, and this algorithm includes function curves between water depths and corresponding critical velocities for people instability, as proposed by Keller and Mitsch (1993), and an incipient velocity formula for various vehicles developed recently by Xia et al. (2010a). Finally, the integrated model has been applied to simulate the conditions for three flash floods and to assess the corresponding hazard degrees for people and vehicles, including the recent Glasgow flood, the 2004 Boscastle flood, and the Malpasset dam-failure flood in 1959. The first two floods occurred in the UK and the last flood occurred in France.

2. Description of an integrated model

This section introduces an existing 2D hydrodynamic model, assessment methods for people and vehicle safety, and the quantification method of the corresponding flood hazard degrees, which comprises an integrated model capable of assessing the hazard degrees for people and vehicles in flash floods.

2.1. 2D hydrodynamic model

For flows in natural rivers, floodplain systems and urban catchments, a set of shallow water equations for two-dimensional flows over a horizontal plane can be deduced, with these flows meeting most of the key underlying hypotheses, including: a hydrostatic pressure distribution, a free surface, a small vertical acceleration and a small bed slope (Tan, 1992). However, it is worth mentioning that these hypotheses would not be verified near a bore or for curved bed topography. The depth-averaged 2D shallow water equations used in the current model can be written in a general conservative form as given below:

$$\frac{\partial U}{\partial t}+\frac{\partial E}{\partial x}+\frac{\partial G}{\partial y}=\frac{\partial \tilde{E}}{\partial x}+\frac{\partial \tilde{G}}{\partial y}+S \tag{1}$$

where U = vector of conserved variables; E and G = convective flux vectors of flow in the x and y directions, respectively; $\tilde{E}$ and $\tilde{G}$ = diffusive vectors related to the turbulent stresses in the x and y directions, respectively; and S = source term including: bed friction, bed slope and the Coriolis force. The above terms can be expressed in detail as:

$$U=\begin{bmatrix} h \\ hu \\ hv \end{bmatrix}, E=\begin{bmatrix} hu \\ hu^2+\frac{1}{2}gh^2 \\ huv \end{bmatrix}, G=\begin{bmatrix} hv \\ huv \\ hv^2+\frac{1}{2}gh^2 \end{bmatrix},$$

$$\tilde{E}=\begin{bmatrix} 0 \\ \tau_{xx} \\ \tau_{yx} \end{bmatrix}, \tilde{G}=\begin{bmatrix} 0 \\ \tau_{xy} \\ \tau_{yy} \end{bmatrix} \text{ and } S=\begin{bmatrix} q_s \\ +hfv+gh\left(S_{bx}-S_{fx}\right) \\ -hfu+gh\left(S_{by}-S_{fy}\right) \end{bmatrix} \tag{2}$$

where u and v = depth-averaged velocities in the x and y directions, respectively; h = water depth; q_s = source (or sink) discharge per unit area; g = gravitational acceleration; f = the Coriolis acceleration due to the earth's rotation; S_{bx} and S_{by} = bed slopes in the x and y directions, respectively; S_{fx} and S_{fy} = friction slopes in the x and y directions, respectively; and τ_{xx}, τ_{xy}, τ_{yx} and τ_{yy} = components of the turbulent shear stress over the plane.

The model used a finite volume method (FVM) to solve the governing equations based on an unstructured triangular mesh. In this FVM model, the study region was first divided into a set of triangular cells, to form an unstructured computational mesh. A cell-centred FVM was then adopted in this model, in which the average values of the conserved variables are stored at the centre of each cell, with the three edges of each cell defining the interface of a triangular control volume. At an interface between two neighbouring cells, the calculation of flow fluxes can be treated as a locally one-dimensional problem in the direction normal to the interface, thus the fluxes can be obtained by an approximate Riemann solver. In the current model, a Roe's approximate Riemann solver, with the scheme of monotone upstream scheme for