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Hydrodynamic modelling of flow impact on structures under extreme flow conditions*

Qiuhua LIANG[1,2], Kai-cui CHEN (陈恺翠)[1], Jingming HOU[2], Yan XIONG (熊焱)[1], Gang WANG (王岗)[1], Juan QIANG (羌娟)[1]
1. Key Laboratory of Coastal Disaster and Protection, Ministry of Education, Hohai University, Nanjing 210098, China
2. School of Civil Engineering and Geosciences, Newcastle University, Newcastle upon Tyne, England, UK,
E-mail: Qiuhua.Liang@ncl.ac.uk

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Abstract: Apart from the direct threat to human lives, the flood waves as a result of the rapid catchment response to intense rainfall, breaches of flood defences, tsunamis or storm surges may induce huge impact forces on structures, causing structural damage or even failures. Most existing design codes do not properly account for these impact forces due to the limited understanding of the underlying physical processes and the lack of reliable empirical formulae or numerical approaches to quantifying them. This paper presents laboratory experiments to better understand the interaction between the extreme flow hydrodynamics and the hydraulic structures and uses the measured data to validate a numerical model. The model solves the two-dimensional shallow water equations using a finite volume Godunov-type scheme for the reliable simulation of complex flow hydrodynamics. New model components are developed for estimating the hydrostatic and hydrodynamic pressure to quantify the flow impact on structures. The model is applied to reproduce two selected experiment tests with different settings and satisfactory numerical results are obtained, which confirms its predictive capability. The model will therefore provide a potential tool for wider and more flexible field-scale applications.

Key words: wave-structure interaction, extreme flow conditions, flood hazards, shallow flow model, laboratory experiments

Introduction

The flood events as a result of the rapid catchment response to intense rainfall, failure of flood protection measures, tsunamis or storm surges are usually highly transient in nature and have the features of extreme flow conditions. Apart from their direct threat to human lives, the resulting rapidly varying flood waves may also create tremendous impact forces on structures, causing structural damage or even failures. For instance, the 2011 east Japan tsunami killed more than 15 000 people and significantly damaged or destroyed numerous buildings, bridges and other infrastructures, in a country which can be described as one of the most advanced economies and most earthquake-prepared nations. A large number of papers and reports were published to document the field surveys to show the significant structure damage caused by this and other tsunami events[1-3]. In 2005, Hurricane Katrina together with subsequent floods caused a death toll of at least 1 833 people and the property damage of $\$1.08\times10^{11}$ (USD in 2005). Then in 2012, Superstorm Sandy, the largest Atlantic hurricane on record, affected 24 states in the USA and several other countries, killed 286 people along its path and left over $\$6.8\times10^{10}$ (USD in 2013) in damage. In the UK, a flash flood following an intense rainfall event caused substantial damage to the historic Cornish town of Boscastle in 2004, with some 70 properties flooded, and over 100 cars, caravans, and several boats washed into the sea. There are numerous similar events worldwide that can be also listed here. Supported by a number of recent studies, it is generally recognized that meteorological and hydrological extremes, inclu-

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Biography: Qiuhua LIANG (1974-), Male, Ph. D., Professor

ding storms and different types of floods, will become more frequent and cause more significant economic losses throughout the 21st century[4]. Therefore, it is necessary to review the current building practice and update our design and construction approaches in order to build more resilient communities under climate changes.

In urban areas, some researches were carried out for different types of loading induced on buildings due to floods[5]. Kelman and Spence[5] gave a good overview of the various potential forces that arise during a flood event, and pointed out that the most important factors in the flood damage assessment are the lateral pressure imparted by the different height of water inside and outside of the building and the lateral pressure due to the water velocity. However, how to quantify these flood impacts remains to be explored and the current practical design still commonly relies on the use of empirical formulas to obtain rough and unverified estimations of these hydraulic loadings.

On coastal flooding, assessments were made for the modes of structural failure due to storm surges or tsunamis, e.g., in New Orleans after Hurricane Katrina in 2005[6,7]. However, as pointed out by Nistor et al.[3], most of the existing design codes do not properly take into account the impact forces under extreme hydraulic conditions caused by tsunamis and other analogous events. Similar to the urban applications, the existing empirical formulas for quantifying these forces for design are in a significant disagreement with observations. Therefore, there is an urgent need to fill the current knowledge gap. The new knowledge and tools are crucial for evaluating more reliably the possible structure damage caused under extreme flow conditions by tsunamis or other extreme disastrous events, which will in turn provide better guidelines and codes for city planning and structural design.

In the last two decades, numerous two-dimensional hydrodynamic modelling tools have been developed and widely applied to simulate different types of floods[8-11]. Most of these applications focus on the flood extent and water depth, from which flood damage is estimated without considering the actual hydraulic impacts on structures. These models, particularly, the shock-capturing hydrodynamic flood models, can well predict the detailed velocity field and flow depth in a simulation, which may be extended to directly evaluate hydraulic loads on structures caused by different types of floods. Ghadimi and Reisinezhad[12] reported an attempt to assess the flood impact on cylindrical piers using a finite element shallow water model integrated with a formula derived from the Bernoulli principle for calculating pressure forces.

Based on the current research need, this paper presents laboratory experiments to better understand the interaction between the extreme flow hydrodynamics and structures, with experimental measurements to validate a two-dimensional depth-averaged shallow flow model. The model solves the two-dimensional shallow water equations and a finite volume Godunov-type scheme for automatic tracking of wet-dry fronts[13]. A new component is developed to calculate hydrostatic and hydrodynamic pressures and the corresponding forces. The model can be used to evaluate the flood impacts for different types of floods, including those extreme events driven by tsunamis, storm surges and flash floods. The formulas for pressure calculation are different from those used by Ghadimi and Reisinezhad[12] and are validated by new experimental measurements. The model may provide a robust tool for more flexible field-scale applications.

1. Numerical model

1.1 *Governing equations*

The shallow water equations (SWEs) are used to describe a wide range of flow hydrodynamics with horizontal dimensions much larger than water depth, including the discontinuous dam-break waves. Therefore, the hyperbolic conservation laws of the SWEs are adopted in this paper in the mathematical model for quantifying the fluid-structure interaction under extreme flow conditions. In a matrix form, the governing equations may be written as

$$\frac{\partial \boldsymbol{q}}{\partial t}+\frac{\partial \boldsymbol{f}}{\partial x}+\frac{\partial \boldsymbol{g}}{\partial y}=\boldsymbol{s} \tag{1}$$

where t, x and y, respectively, represent the time and the two horizontal coordinates, $\boldsymbol{q}$, $\boldsymbol{f}$, $\boldsymbol{g}$ and $\boldsymbol{s}$ are the vectors of the flow variables, x- and y-direction fluxes and the source terms, which, when neglecting the Coriolis effects and the surface stresses, can be expressed as follows:

$$\boldsymbol{q}=[\eta \quad uh \quad vh]^{\mathrm{T}},$$

$$\boldsymbol{f}=\left[uh \quad u^2h+\frac{g\left(\eta^2-2\eta z_b\right)}{2} \quad uvh\right]^{\mathrm{T}},$$

$$\boldsymbol{g}=\left[vh \quad uvh \quad v^2h+\frac{g(\eta^2-2\eta z_b)}{2}\right]^{\mathrm{T}},$$

$$\boldsymbol{s}=\left[0 \quad -C_f u\sqrt{u^2+v^2}-g\eta\frac{\partial z_b}{\partial x} \quad -C_f v\sqrt{u^2+v^2}-g\eta\frac{\partial z_b}{\partial y}\right]^{\mathrm{T}} \tag{2}$$

where η is the water level above the datum, u and