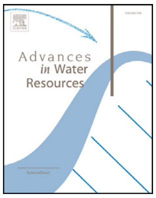
Advances in Water Resources 98 (2016) 97–113

Contents lists available at ScienceDirect

Advances in Water Resources

journal homepage: www.elsevier.com/locate/advwatres



High-fidelity numerical modeling of the Upper Mississippi River under extreme flood condition

Ali Khosronejad[a], Trung Le[a], Petra DeWall[b], Nicole Bartelt[b], Solomon Woldeamlak[b], Xiaolei Yang[a], Fotis Sotiropoulos[a,*]

[a] Civil Engineering Department, Stony Brook University, Stony Brook, New York, USA
[b] Minnesota Department of Transportation, Minneapolis, Minnesota, USA

ARTICLE INFO

Article history:
Received 11 April 2016
Revised 13 October 2016
Accepted 24 October 2016
Available online 27 October 2016

Keywords:
Data-driven simulation
Coupled flow-bed simulation
Turbulent flow
Bed morphodynamics
Large-eddy simulation
The Mississippi River
Extreme flood event

ABSTRACT

We present data-driven numerical simulations of extreme flooding in a large-scale river coupling coherent-structure resolving hydrodynamics with bed morphodynamics under live-bed conditions. The study area is a ∼ 3.2 km long and ∼ 300 m wide reach of the Upper Mississippi River, near Minneapolis MN, which contains several natural islands and man-made hydraulic structures. We employ the large-eddy simulation (LES) and bed-morphodynamic modules of the Virtual Flow Simulator (VFS-Rivers) model, a recently developed in-house code, to investigate the flow and bed evolution of the river during a 100-year flood event. The coupling of the two modules is carried out via a fluid-structure interaction approach using a nested domain approach to enhance the resolution of bridge scour predictions. We integrate data from airborne Light Detection and Ranging (LiDAR), sub-aqueous sonar apparatus onboard a boat and in-situ laser scanners to construct a digital elevation model of the river bathymetry and surrounding flood plain, including islands and bridge piers. A field campaign under base-flow condition is also carried out to collect mean flow measurements via Acoustic Doppler Current Profiler (ADCP) to validate the hydrodynamic module of the VFS-Rivers model. Our simulation results for the bed evolution of the river under the 100-year flood reveal complex sediment transport dynamics near the bridge piers consisting of both scour and refilling events due to the continuous passage of sand dunes. We find that the scour depth near the bridge piers can reach to a maximum of ∼ 9 m. The data-driven simulation strategy we present in this work exemplifies a practical simulation-based-engineering-approach to investigate the resilience of infrastructures to extreme flood events in intricate field-scale riverine systems.

1. Introduction

Extreme river flooding events are becoming more likely due to impacts of the global environmental change and can lead to enormous economic losses and loss of life (Chiang et al., 2010; Georgakakos and Krzysztofowicz, 2001). There are numerous hydrological-based forecasting tools that enable governments and local authorities to estimate the timing and magnitude of flood events and use this information to set up an efficient flood alarm system to enhance the public safety, avoid human losses, and mitigate social damages (Merkuryeva et al., 2015). In addition, however, to the need to have scientific information about the approximate timing and magnitude of flood events, it is also important to be able to assess the risk flooding poses on waterway stability and infrastructure resilience (Liang, 2010; Meesuk et al., 2015; Seyoum et al., 2012). Such predictions require the use of hydraulic engineering numerical models, which are the focus of the present work.

For decades, computational fluid dynamics (CFD) has been utilized as an effective hydraulic engineering tool to study flow and sediment transport processes in rivers and streams under base-flow conditions (see e.g., Abad et al., 2008; Baranya et al., 2013; Jia et al., 2005; 2009; Keylock et al., 2012; Kim et al., 2014; Liu and Garca, 2008; Minor et al., 2007; Nagata et al., 2005; Olsen and Kjellesvig, 1998; Roulund et al., 2005; Salaheldin et al., 2004; Tseng et al., 2000; Wu, 2008; Wu et al., 2000). Most of these studies employ sequential numerical models that run on single computer cores. Despite their great success in hydraulic engineering research, the applicability of such models to performing high-resolution simulation of large-scale rivers under flood conditions is limited by the excessive computing resources that would be required. Most, if

---

[*] Corresponding author.
E-mail address: fotis.sotiropoulos@stonybrook.edu (F. Sotiropoulos).

http://dx.doi.org/10.1016/j.advwatres.2016.10.018
0309-1708/

not all, of the aforementioned computational studies of field-scale rivers have employed rather coarse numerical resolution and statistically averaged turbulence closure models (see, e.g., Abad et al., 2008).

For rivers under flood conditions, on the other hand, the flow is highly turbulent and it is dominated by highly energetic large-scale coherent structures. As such, the interaction among the turbulent flow, river bathymetry, hydraulic structures, and migrating bedforms becomes even more challenging to simulate numerically. It is presumably because of such challenges that most of the existing numerical studies of river flooding in field-scale rivers utilize two-dimensional (2D) models, which solve the so-called shallow-water equations to predict the flood flow (see e.g., Begnudelli and Sanders, 2006; Chen et al., 2012; Gallegos et al., 2009; Horritt and Bates, 2002; Meesuk et al., 2015; Mignot et al., 2006; Sanders et al., 2008; Seyoum et al., 2012; Soares-Frazao et al., 2008; Valiani et al., 2002; Yu and Lane, 2005a,b). 2D models are not computationally demanding and can thus run on sequential computers and swiftly obtain results. Despite their many successful applications and wide-spread use in the hydraulic engineering practice, 2D models are inherently unable to simulate the dynamics of 3D energetic coherent structures and their effect on sediment transport and scour processes near complex hydraulic structures. Yet such predictive capabilities are critically important for accurately assessing the risk extreme flooding poses to hydraulic structures and other infrastructures.

Recent advances in computational algorithms and increasingly growing computing power, however, have set the stage for developing powerful simulation-based tools for tackling such intricate hydraulic engineering problems. In this work we leverage recent computational advances to demonstrate for the first time that data-driven, coherent-structure resolving simulations of turbulence and morphodynamics during extreme flooding events are now possible for field-scale rivers. More specifically, we seek to numerically probe the dynamics of scour near a geometrically complex bridge foundation under a 100-year flood event and live-bed conditions in a $\sim$ 3.2 km long reach of the Upper Mississippi River in Minnesota, USA (see Fig. 1). To do so, we fuse together site specific data from LiDAR, subaqueous sonars and laser scanners to generate a digital terrain model (DTM) of the flood plain, river bed and bridge foundation geometry–a similar approach is also used by Meesuk et al. (2015) to obtain DTM of river reaches for 2D flood modeling. The so-constructed DTM provides a virtual test-bed in which 100-year flooding in the Upper Mississippi River reach and its impact on bridge foundation scour can be studied with unprecedented numerical resolution. The computational framework we employ is the Virtual Flow Simulator (VFS-Rivers) code, which resolves energetic coherent structures, bed morphodynamics and scour in real-life rivers with complex hydraulic structures using large-eddy simulation (LES). The numerical simulations are carried out on a grid with over 100 million computational grid nodes the scour depth prediction takes into account both the local scour development induced by local eddies near the bridge piers and sediment transport throughout the study reach due to the bulk flow of 100-year flood. To increase the resolution of scour predictions we further employ a nested grid strategy by which the study reach is divided into two regions in accordance to proximity to the bridge foundation: near- and far-field. The coupled simulation of the far-field yields the scour depth development due to the mass transport of the sediment material (both the suspended and bed-load) along the $\sim$ 3.2 km long reach of the river and also provides boundary conditions for the near-field simulation. The near-field simulation obtains the scour depth development due to the bridge pier induced turbulence. A linear combination of the scour depth evolution obtained from far- and near-field simulation is then used to estimate the total scour depth near each bridge pier.

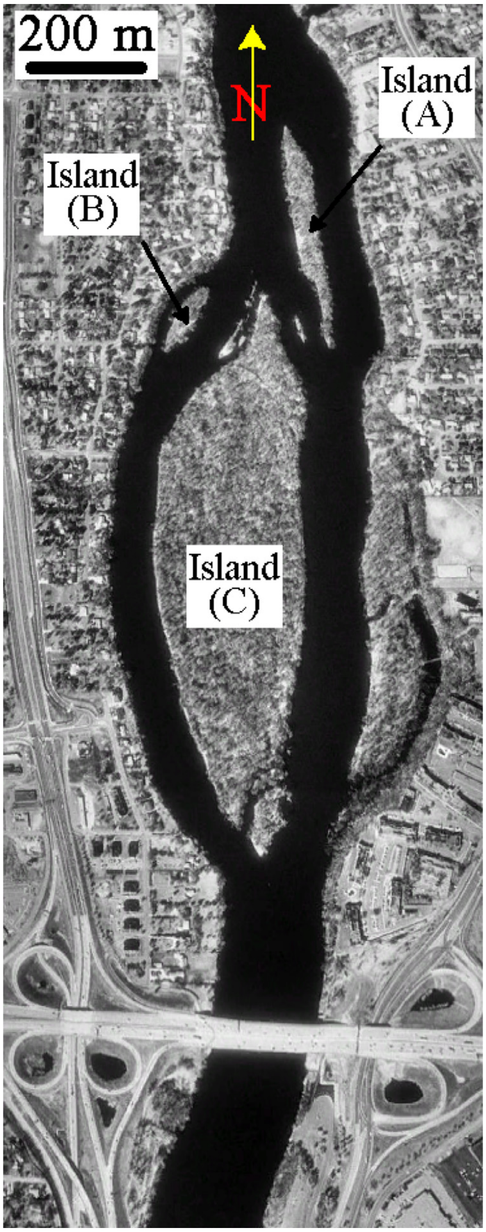


Fig. 1. An aerial picture from Google Earth illustrating the limits of the study reach, which is located in the Upper Mississippi River, Minnesota, USA. The river (the dark area), in this picture, is under base-flow condition and flows from top (north) to bottom (south). Several islands and a bridge can be seen in the study reach. The main island (C) and two smaller islands shown as (A) and (B) are out of water during base-flow condition, while they become fully submerged during 100- and 500-year flood events.

In order to validate the flow field calculations of the VFS-Rivers model, we performed a field campaign to measure the velocity field of the river under base-flow conditions. Measurements are carried out at upstream of bridge piers using Acoustic Doppler Current Profiler (ADCP), which were installed on board of a boat. VFS-Rivers model simulation results with its LES module for the base-flow condition are successfully compared with the ADCP measurements at different locations upstream of the bridge piers.

In what follows we first briefly present the governing equations of the VFS-Rivers model. Subsequently we briefly describe the field campaign to acquire the geometrical information and measure the flow field data under the base-flow condition. Then we present flow field simulation and model validations for the base-flow con-