Computers, Environment and Urban Systems 68 (2018) 97–109

Contents lists available at ScienceDirect

Computers, Environment and Urban Systems

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

Assessing the vulnerability of hydrological infrastructure to flood damage in coastal cities of developing nations

R.I. Ogie[a,*], T. Holderness[b], S. Dunn[c], E. Turpin[b]

[a] Smart Infrastructure Facility, University of Wollongong, Northfields Ave, Wollongong, New South Wales 2522, Australia
[b] The Urban Risk Lab, Massachusetts Institute of Technology, Cambridge, MA 02139, USA
[c] School of Civil Engineering & Geosciences, Newcastle University, Newcastle, Tyne and Wear NE1 7RU, UK

ARTICLE INFO

Keywords:
Vulnerability
Flood
Network
Coastal cities
Floodgate
Infrastructure

ABSTRACT

Hydrological infrastructure such as pumps, floodgates (or sluice gates), dams, embankments, and flood barriers are invaluable assets used for controlling water in flood-prone areas such coastal cities. These infrastructure components are often vulnerable to damage or failure due to the impact of floodwaters, thus leaving people and urban property exposed to flood hazards. To minimise the failure of hydrological infrastructure during intense flooding events, it is important to identify the most vulnerable components and to invest scarce resources in reducing their vulnerability. Using the concepts of exposure, susceptibility and resilience, this study proposes a graph-based network approach for measuring the vulnerability of hydrological infrastructure to flood damage in coastal cities. In this graph-based approach, hydrological infrastructures are represented as network nodes and the waterways as edges. The proposed vulnerability assessment approach is applied to measure and rank the vulnerability of floodgates in one of the most exemplary coastal cities - Jakarta, Indonesia. The results show that the proposed solution is both useful in highlighting the most vulnerable infrastructure components and also providing clues as to what actions can be taken to minimise infrastructure vulnerability. More so, the solution was found to be useful in identifying potential locations within the city of Jakarta, where additional infrastructure are required to improve resilience to flooding. This type of information about infrastructure vulnerability and resilience actions is vital to decision-making authorities responsible for planning, flood preparedness and priority-based allocation of resources for the maintenance of flood control infrastructure in coastal cities.

1. Introduction

Flooding in coastal areas is a frequently occurring problem that must be properly managed to minimise damage to urban property and loss of human lives (Al-Sabhan, Mulligan, & Blackburn, 2003). Floods account for approximately 40% of all natural disasters and affect 20–300 million people every year (Dewan, 2013). It is predicted that the annual global flood losses will hit $1 trillion in 2050 if drastic actions are not taken now (Hallegatte, Green, Nicholls, & Corfee-Morlot, 2013). Coastal cities, particularly those situated in the developing nations of Asia are expected to suffer a higher proportion of these flood losses because of the rapid processes of population growth, urbanization, and land subsidence that increase their exposure to flood damages (Dewan, 2013; Dewan & Yamaguchi, 2008). Coastal cities in developing nations are therefore faced with a greater need to mitigate potential damage caused by fluvial and coastal inundations.

A common flood control strategy involves structural measures or the use of hydrological infrastructure assets such as pumping stations and floodgates (Hung, Babel, Weesakul, & Tripathi, 2009; Ogie, Holderness, Dunbar, & Turpin, 2017). Generally, pumping stations are used to remove accumulating floodwaters from low-lying areas where gravity-fed drainage is not possible (Hardoy & Pandiella, 2009; Tingsanchali, 2012). Floodgates are used to control the flow of water by either keeping them closed or opened, depending on potential flood threats (Sims, 2013). Under normal drainage conditions, the floodgates operate by remaining open. However, as rainfall intensifies and storm surge builds, the floodgates are closed to prevent rising waters from flowing through and flooding dry lands and populated areas located downstream (Sims, 2013).

One major issue with floodgates is that they require regular maintenance during the monsoon season, without which they may fail to operate properly when needed to defend the coastal community against severe flooding events. The need for regular maintenance stems from the fact that floodgates are vulnerable to damages caused by large impact forces from floodwaters (Ke, 2014). The likelihood of damage is particularly higher in cases where aging and inadequate maintenance

* Corresponding author.
E-mail address: rogie@uow.edu.au (R.I. Ogie).

https://doi.org/10.1016/j.compenvurbsys.2017.11.004
Received 23 February 2017; Received in revised form 9 November 2017; Accepted 15 November 2017
Available online 21 November 2017
0198-9715/

have resulted in infrastructure fragility (Turpin, Bobbette, & Miller, 2013). For instance, aged and poorly maintained floodgates may experience damage to wheels, lower bumpers, and other hydraulic components as a result of high velocity flows and debris impact (Grega, Stender, & Fulsaas, 2010). Gates may get stuck or fail to close fully when debris are wedged between the wheels or deposited under the gates (Grega et al., 2010). Regular maintenance is therefore required to ensure the floodgates are operable, particularly during the monsoon season (Caljouw, Nas, & Pratiwo, 2005).

However, in coastal cities situated in developing nations, the shortage of funding and available resources limit the scope and frequency of maintenance of the hydrological infrastructure (Lall & Deichmann, 2010). The failure of poorly maintained hydrological infrastructure has been reported as a major cause of flooding in coastal cities situated in developing nations (Hardoy & Pandiella, 2009; Lall & Deichmann, 2010). Examples of cities that often experience flooding as a result of the failure of flood control infrastructure include Manilla, Jakarta, Mumbai, Dhaka, Tokyo, and Shanghai, to name a few (Dewan, Islam, Kumamoto, & Nishigaki, 2007; Ke, 2014; Mulyasari, Shaw, & Takeuchi, 2011; Stalenberg & Vrijling, 2009; Uitto, 1998). Critically, in cities which are dependent on flood control infrastructure, fluvial and coastal inundation may be caused or exacerbated by the failure of one or more infrastructure components, potentially resulting in significant damage to urban property and loss of human lives (Dawson et al., 2008). It is therefore crucial that the limited resources available for maintenance and upgrade of the hydrological infrastructure be judiciously allocated in a manner that improves resilience and minimises failure during extreme flooding events (Sadoff et al., 2013). Ideally, such resource allocations should be effectively targeted at the most vulnerable components in the hydrological infrastructure network, and thus by spending scarce resources on the most vulnerable components in the flood control network, infrastructure failure resulting in flooding can be minimised (Hall, Meadowcroft, Sayers, & Bramley, 2003).

A quantitative assessment of vulnerability can aid decision makers in identifying the most vulnerable components within a system, which should be prioritised for preventative actions (Balica, Wright, & van der Meulen, 2012). The concept of vulnerability assessment has been widely discussed in the literature, particularly as it relates to people and community (e.g., Chakraborty & Armstrong, 1995; Ciurean, Schröter, & Glade, 2013; Dewan, 2013; Green, 2004; Huang et al., 2012; Jenelius & Mattsson, 2015; Khan, 2012; Masuya, Dewan, & Corner, 2015). However, physical infrastructure assets that are crucial to the safety and day-to-day operation of modern society are also vulnerable to damage associated with natural hazards (Kawamura et al., 2014). Hence, similar assessments that focus on the vulnerability of different types of infrastructure networks to natural hazards have received significant attention in the research community (Johnston, Slovinsky, & Yates, 2014; Tonmoy & El-Zein, 2013; Wei, Wang, Wang, & Tatano, 2015). For example, using the geographical layout of graph models and polynomial-time algorithms, Neumayer, Zussman, Cohen, and Modiano (2011) show how to highlight the areas in a fiber-optic communication infrastructure network that are most vulnerable to natural disasters in terms of maximum disruption to capacity and connectivity. Ezell (2007) proposed Infrastructure Vulnerability Assessment Model (I-VAM) based on the mathematics of multi-attribute value theory and show how the vulnerability for each component in a clean water supply network can be quantified by using the protection measures of deterrence, detection, delay, and response. Other infrastructure systems that have benefited from vulnerability assessments to natural hazards include road transport (Taylor, Sekhar, & D'Este, 2006), aviation (Wilkinson, Dunn, & Ma, 2012), and electric power (Holmgren, 2006) networks. However, no standardised processes yet exist for quantitatively assessing and ranking the vulnerability of hydrological infrastructure components to damages caused by floodwaters. The lack of a standardised process of finding suitable metrics combined with the data scarcity in developing countries complicate this task (Balica et al., 2012; Brecht, Dasgupta, Laplante, Murray, & Wheeler, 2012).

Motivated by this problem, this study proposes a graph-based network approach for measuring and ranking the vulnerability of hydrological infrastructure components to damage caused by the impact of floodwaters. The graph-based network utilized in this study is a directional graph (digraph) in topological vector format, showing how elements of the hydrological infrastructure network are connected within the city. Graph theory is considered appropriate for this problem because it provides a rigorous mathematical basis for computing vulnerability (Dunn, Fu, Wilkinson, & Dawson, 2013), using very little data obtainable at the time and allowing for further improvement from the initial results as additional data becomes available in the future (Bunn, Urban, & Keitt, 2000). In exploring this technique, a general equation for computing the vulnerability of floodgate to floodwater damage is first established, based on the concepts of exposure, susceptibility and resilience. Using the derived equation, a case study implementation is then carried out to assess and rank the floodgates in the city of Jakarta, Indonesia, according to their vulnerability to damage caused by floodwaters.

In applying the derived equation to Jakarta's case study, suitable metrics are systematically derived using a constructed spatio-topological network model of the city's hydrological infrastructure system. The results of the application are Hydrological Infrastructure Flood Vulnerability Index (HIFVI) values representing the degree to which each floodgate in the city of Jakarta is vulnerable to damage caused by the impacts of floodwaters. The computed HIFVI values are stored in a spatial database table and accessible for visualisation using geographical information system software. Such detailed analysis results are useful to decision makers in coastal communities when planning and prioritising infrastructure maintenance and resource allocation for flood preparedness (Odeh, 2002). The remainder of this paper is organised as follows: In the next section the process followed to derive the equation for computing HIFVI is presented. Section 3 presents a case study application to Jakarta's floodgate infrastructure. In Section 4, the results are presented and their implications discussed. Finally, Section 5 concludes the paper, presents major limitations, and makes suggestion for future studies.

2. Equation derivation for computing hydrological infrastructure flood vulnerability index

The study of vulnerability to natural hazards is a burgeoning research area that cuts across several fields of study including health, social science, psychology, policy development, climate science, economics, disaster management, engineering, etc. (Brooks, 2003). This multidisciplinary nature of vulnerability research has resulted in fragmentation in the conceptualisation of vulnerability and indeed, the methodological approaches for assessing it (Brooks, 2003; Dewan, 2013). There is, in fact, no universally accepted definition for the term, vulnerability and attempts to provide a unified framework are often constrained by numerous conceptual linkages to an array of terms such as resilience, risk, sensitivity, and adaptive capacity, most of which are also conceptualised differently in the literature (Cutter et al., 2008; Dewan, 2013). A summary of definitions and the various conceptual frameworks and methodological approaches related to vulnerability assessment are too extensive to be covered in this article without detracting from the focus. A number of studies, with strong focus on reconciling definitions and conceptual linkages within vulnerability research, have already contributed significantly in this regard and the authors would like to refer interested readers to a few of them (Adger, 1999; Brooks, 2003; Cutter, Emrich, Webb, & Morath, 2009; Dewan, 2013).

Nevertheless, an important point to emphasis is that vulnerability is only meaningful when it is discussed in relation to a “specified hazard