Coastal Engineering 130 (2017) 1–13

Contents lists available at ScienceDirect

Coastal Engineering

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

A simplified physically-based model for coastal dike and barrier breaching by overtopping flow and waves

Weiming Wu[a,*], Honghai Li[b]

[a] Department of Civil and Environmental Engineering, Clarkson University, Potsdam, NY 13699, USA
[b] Coastal and Hydraulics Laboratory, Engineer Research and Development Center, U. S. Army Corps of Engineers, Vicksburg, MS 39180, USA

ARTICLE INFO

Keywords:
Dike
Barrier
Breach
Overtopping
Waves
Overflow
Breach closure

ABSTRACT

The simplified physically-based breach model, DLBreach, has been developed to simulate the overtopping breaching of coastal dikes and barriers, which can occur either from the sea side or the bay side. The breaching process is divided into two stages: intensive breaching and general inlet evolution, in which the flows are calculated using the weir flow equation and the Keulegan equation, respectively. The Keulegan equation is a simplified energy equation for steady nonuniform flow with local head loss due to channel contraction and expansion, revised herein by adding the wind driving force. Empirical formulas are adopted to calculate phase-averaged wave overtopping discharge, wave setup, and wind setup/setdown. The wave overtopping discharge is combined with the surge overflow discharge, and the wave setup and wind setup/setdown are added to the sea and bay water levels for the hydrodynamic and sediment routing. Alongshore sediment is considered as a source boundary condition for the non-equilibrium sediment transport model at the breach. The model has been tested using the 94' field experiment of sea dike breaching by overflow in the Zwin Channel Estuary, a laboratory experiment of sea dike breaching initiated by wave overtopping, and a field observation of the eight-day breaching and closure event of the Mecox Inlet at eastern Long Island of New York during Sept. 10–18, 1985. The model results agree generally well with the measurements.

1. Introduction

Earthen dams, levees, dikes and barriers have been widely used for flood defense along rivers, lakes and coastlines all over the world. However, these embankment structures may fail due to various trigger mechanisms, such as overtopping, piping, and foundation defects, particularly under extreme weather conditions. Failures of these structures can generate disastrous floods causing loss of human lives and damage of properties and infrastructure. Understanding and modeling of embankment failure processes are crucial for risk assessment and decision making. In the last decades, a large number of laboratory and field experiments and case studies have been conducted and numerous models have been developed to understand, characterize and simulate earthen embankment breaches (e.g., MacDonald and Langridge-Monopolis, 1984; Froehlich, 1995; Broich, 1998; Temple et al., 2006; Wang and Bowles, 2006; D'Eliso, 2007; Faeh, 2007; Tuan, 2007; Morris et al., 2009; Xu and Zhang, 2009; Wu, 2013; Marsooli and Wu, 2015). A good summary of those knowledge, experiments, data and models can be found in Singh (1996), Wahl (1998) and ASCE/EWRI Task Committee (2011).

A coastal embankment breach can occur in two directions by either elevated bay water level due to heavy rainfall in the watershed, or elevated sea water level by storm surge and waves. Tidal flow in a coastal inlet and estuary also affects the breach in two directions. This is different from inland dam and levee breaches which usually occur and develop in only one direction. In addition, the setup of water level by strong winds and waves can contribute to overtopping, and the presence of waves in incipient breach increases sediment mobilization and transport. A barrier breach may be closed naturally by the sediments transported from adjacent beaches and shores due to littoral drift, or it may increase in size and become a new inlet or estuary. All these special features need to be considered in a coastal embankment breach model.

Embankment breach models can be classified as parametric, simplified and detailed physically-based breach models (ASCE/EWRI Task Committee, 2011). The parametric models estimate the breach width, peak outflow and failure time using regression equations statistically derived from measurement data (MacDonald and Langridge-Monopolis, 1984; Froehlich, 1995; Xu and Zhang, 2009). Currently available parametric models are mainly for dam breach because data on dike and

* Corresponding author.
E-mail address: wwu@clarkson.edu (W. Wu).

https://doi.org/10.1016/j.coastaleng.2017.09.007
Received 10 September 2016; Received in revised form 8 September 2017; Accepted 9 September 2017

barrier breaches are very limited. Physically-based models simulate embankment breaching processes in detail using one-, two- and three-dimensional (1-D, 2-D and 3-D) hydrodynamic and morphodynamic equations (Broich, 1998; Wang and Bowles, 2006; Faeh, 2007; Wu, 2007; Marsooli and Wu, 2015). Because breach flows are usually in mixed flow regimes and with hydraulic jumps, the numerical schemes often used are the shock-capturing approximate Riemann solvers and Total Variation Diminishing schemes in 1-D and depth-averaged 2-D models (Wu, 2007) and the volume-of-fluid (VOF) and smooth particle hydrodynamics methods in vertical 2-D and 3-D models (Marsooli and Wu, 2015). The detailed multidimensional breach models have potential to obtain more physical insights and more reasonable predictions, but they require significant computation time and capacity. Therefore, a more attractive approach in engineering applications is to simplify the hydrodynamic and sediment transport calculations. For examples, the breach cross-section is usually simplified as a rectangle or trapezoid, and the breach flow is estimated using the weir or orifice flow relation. Such simplified physically-based breach models have been developed for dams (Cristofano, 1965; Ponce and Tsivoglou, 1981; Nogueira, 1984; Fread, 1984, 1988; Singh, 1996; Broich, 1998; Temple et al., 2006; Wang and Bowles, 2006; Morris et al., 2009; Wu, 2013), sea dikes (Visser, 1998; D'Eliso, 2007), and barriers (Kraus and Hayashi, 2005).

Up to now, most of the embankment breach models focus on dams, and only a few for coastal dike and barrier breaches. Each of these coastal breach models has limited capabilities. For example, the sea dike breach model of Visser (1998) does not consider wave effects. The simplified physically-based model of Kraus and Hayashi (2005) is a robust coastal barrier breach model and has been applied in practice, but it uses the Keulegan equation which may have errors for the supercritical flow in the early breaching stage. Basco and Shin (1999) developed a 1-D numerical model consisting of a set of submodels to simulate different stages of barrier breaching caused by storms. It uses the Lax-Wendroff explicit scheme for overland flow and the Preissmann implicit scheme for tidal flow. The model is quite complicated and comprehensive, but the numerical schemes need improvement for mixed-regime flows. Tuan (2007) developed a 1-D numerical model to simulate the growth of breach channel by wave overwash and the barrier breach process due to storm surge overflow. He used a finite volume method with Roe's (1981) approximate Riemann solver to solve the 1-D shallow water equations and proposed a breach growth index model for the ratio of lateral widening and vertical deepening rates. D'Eliso (2007) developed a preliminary model for the breaching of sea sand dike with clay cover, and then improved it to a detailed model by incorporating a RANS (Reynolds-averaged Navier-Stokes equations) VOF solver for overflow and overtopping waves. The model considers a variety of mechanisms, such as wave overtopping, overflow, infiltration, clay cover sliding or uplift, grass cover failure, and headcut. However, it mainly focuses on the breach from seaside and has not been fully tested.

The present study aims to enhance a simplified physically-based dam and levee breach (DLBreach) model (Wu, 2013) to simulate coastal barrier and dike breaching. The previous version of DLBreach is able to simulate the breaching processes of homogeneous and composite embankments due to overtopping and piping in one direction. The enhanced model considers a two-way breach which can occur from either seaside or bayside, or change breach direction when the flow reverses. It considers the effects of waves, tides, wind, subbase erosion, and longshore sediment transport. The enhanced DLBreach model has more capabilities than the existing simplified coastal dike and barrier breach models of Visser (1998) and Kraus and Hayashi (2005), and is much simpler and less costly than the detailed models of Basco and Shin (1999), Tuan (2007) and D'Eliso (2007). The technical details and validations of the developed model are described in the following sections.

2. Approximations of earthen embankment breach

The most common mechanisms for earthen embankment failures are external erosion due to overtopping flow and waves, and internal erosion due to seepage and piping. The breach geometry differs for different failure modes (overtopping or piping), embankment materials (cohesive, non-cohesive or mixed), and structures (homogeneous or composite embankments). Each type of embankment breach is approximated in DLBreach according to the specific breaching processes and characteristics (Wu, 2013). The one-way breaches for homogenous cohesive or noncohesive and composite embankments previously implemented in DLBreach are enhanced to consider two-way breaches where the flow may reverse in coastal and estuarine settings. The two-way piping breach and the corresponding hydrodynamic and morphological evolution are similar to the one-way piping breach except the flow may reverse, and thus are not covered in this paper. Changes made from one-way to two-way overtopping breaches are described below.

As shown in Fig. 1(a), the longitudinal profile of the overtopping breach of homogenous noncohesive embankment is approximated as a trapezoid consisting of a bayward slope, a flat top and a seaward slope. If breaching occurs from the bay side, the bayward slope is the upstream slope and the seaward slope is the downstream slope. If breaching occurs from the sea side or when the flow reverses, the upstream and downstream slopes will switch. The erosion on the upstream slope of the breach is assumed negligible due to the steep inverse slope, whereas the flat top and downstream slope experience downcutting due to surface erosion and widening due to undercutting at bank toe and mass sliding from the breach side slopes. The trapezoid top is kept flat during downcutting while the downstream slope rotates about the downstream toe. Once the breach body is washed away, the erosion will continue into the erodible foundation, as shown in Fig. 1(b).

For the overtopping breach of homogenous cohesive embankment, the surface erosion on the downstream slope in Fig. 1(a) is replaced by headcut erosion. The headcut is a vertical or nearly vertical drop on the bed surface profile, and migrates upstream or opposite to the flow direction. Because the flow may reverse, headcut can occur in either seaward or bayward slope, or both. Similarly, the one-way overtopping breach of composite embankment with a clay core is also revised by allowing seaward or/and bayward shoulders to erode.

The overtopping breach cross-section is still approximated as a trapezoid, as shown in Fig. 2. The side slope of the breach channel is

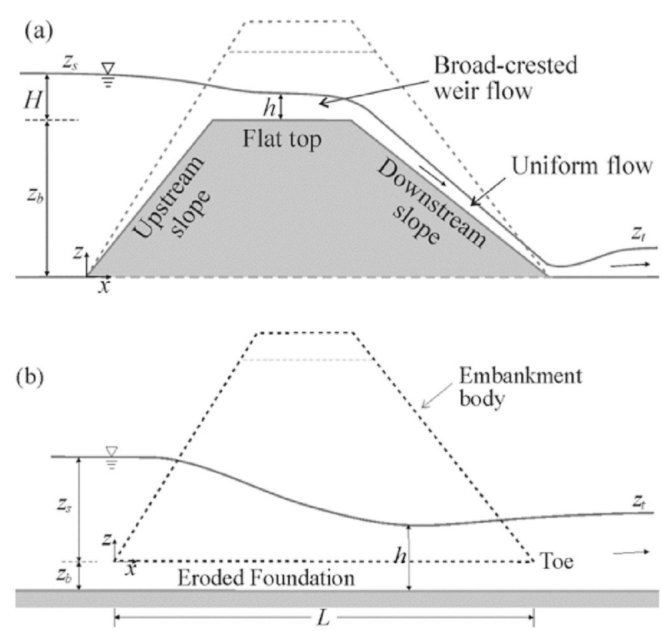

Fig. 1. Longitudinal section of breach with variable definitions: (a) Intensive breaching period; (b) Inlet evolution period (z_s = headwater level; H = headwater level above the breach bottom; z_b = breach bottom elevation; h = flow depth at the breach; z_t = tailwater level).