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Maximum overtopping forces on a dike-mounted wall with a shallow foreshore

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ABSTRACT

The impact force induced by waves overtopping a dike with a vertical wall on its crest, and with a shallow foreshore seaward of the dike, was studied. To this end, physical model tests were performed in a wave flume at a typical scale of 1:25. The goal of this study was to develop a method to estimate the maximum forces on the wall during a known storm peak. The time series of water depth at toe of the dike, flow thickness at seaward edge of the dike crest and impact forces were measured. An empirical Generalized Pareto distribution is verified as the best distribution for the extreme overtopping wave forces.

1. Introduction

Many low-lying coastal towns are protected by defence structures (e.g., seawalls and dikes). Urban development along the waterfront is attractive, although the space is restricted. For example, the residential and commercial developments along UK and Mediterranean shorelines are just behind the seawall (Allsop et al., 2008); Whereas, the development in Belgium and the Netherlands typically is on the top of a sea dike (Van Doorslaer et al., 2015), see Fig. 1 (a). Due to climate change and sea level rise, violent storms are expected which would aggravate the coastal flooding risk. The buildings and people within these densely populated waterfront areas would experience significant impacts from overtopping waves induced by the storms (see Fig. 1 (b)). However, users and owners of the waterfront buildings may be unaware of the potential threats (Allsop et al., 2008).

The coast of the Netherlands and Belgium is characterized by very shallow water foreshore in the front of the coastal dike to dissipate the incoming wave energy (Verwaest et al., 2010). Recent studies reveal that the shallow water environment may contribute to the generation of infragravity waves. The combination of large waves and infragravity waves would result in the exacerbation of the coastal flooding during strong storms (Suzuki et al., 2012). This flooding mechanism is expected to occur, but not brought to the forefront until the super typhoon Haiyan hit the Philippines on early November 2013 (Roeber and Bricker, 2015). The coastal town of Hernani in the Philippines with coral reef in the front was reported struck by a destructive long-period tsunami-like wave with an extreme damage. The mechanism of this significant damage has never been accounted for before (e,g., Shimozono et al., 2015; Roeber and Bricker, 2015), because a coral or artificial reef is normally seen as a protection of the tropical coastal areas against flooding and erosion by dissipation wave energy (Ferrario et al., 2014). Based on the field survey and numerical modeling afterwards, Shimozono et al. (2015) and Roeber and Bricker (2015) published their new results to indicate the tsunami-like wave in Hernani is the result of a superposition of the infragravity wave and sea-swell components (Shimozono et al., 2015) or surf beat generated during the wave breaking process (Roeber and Bricker, 2015). Through the further understanding of the damage caused by typhoon Haiyan, a coral or artificial reef can exacerbate the damage during large storms (Quataert et al., 2015; Roeber and Bricker, 2015). This suggestion is in line with the potential extreme coastal flooding of Belgian and Dutch coast with a shallow foreshore. Therefore, to evaluate the wave overtopping impact induced by the combined large wave and infragravity waves on waterfront buildings has become more interesting and important.

The literature and design guidelines for coastal structures mainly focus on the impact of non-breaking and breaking waves on vertical seawalls or breakwaters, and on the statistic distribution of the

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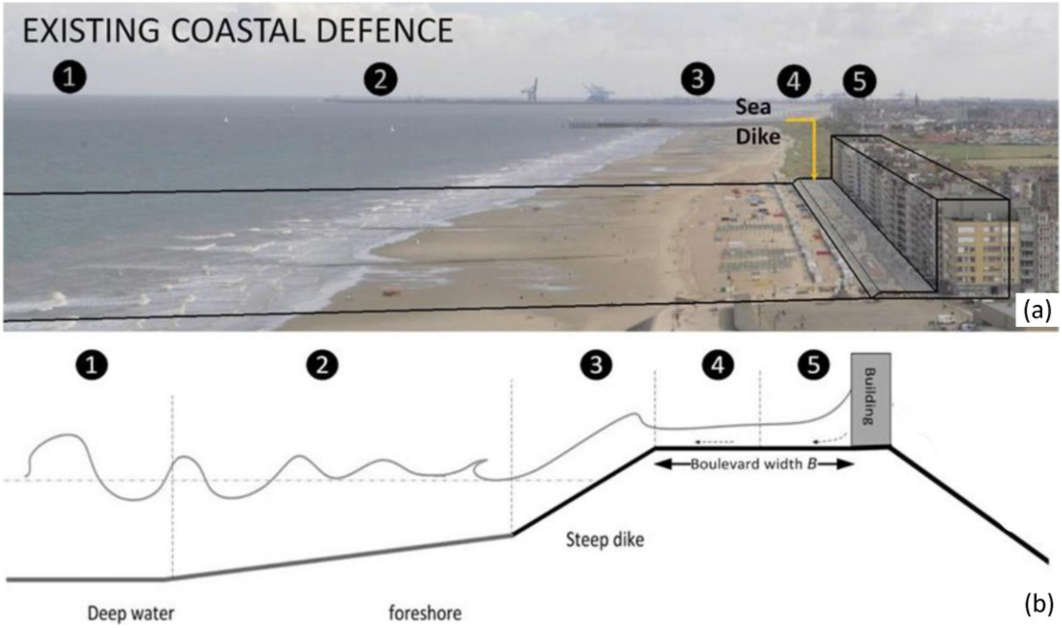

Fig. 1. (a) An example of a coastal dike with buildings on top (Wenduine, Belgium); (b) Sketch of an overtopping impact process. The whole process of overtopping flow impacting on the building, adapted from Chen et al. (2015): ① wind generates waves far away from shoreline; ② offshore waves coming into the shallow foreshore area, increasing wave height, decreasing wave length. Finally, most waves breaking and wave energy dissipating in the form of turbulence bore. ③ Turbulent bore (broken wave) running up on the seaward slope of a dike and overtopping the crest of the dike; ④part of the overtopping flow continue propagating along the dike crest and the other part flowing back seaward; ⑤ overtopping wave impacting on the building eventually.

impact forces (Oumeraci et al., 2001; Cuomo et al., 2010, 2011, et al). Only few studies on broken wave load have been done by Martin et al. (1999) and Nørgaard et al. (2013) in both deep water and shallow water condition. Oumeraci et al. (1993) and Martin et al. (1999) compared the differences of the impact force evolution shape and mechanisms caused by non-break waves, breaking waves and broken waves. In which, broken wave impact is believed to represent the impact of an overtopping wave. However, most of the studies of broken waves are especially for the design of rubble mound breakwater crown wall (Pedersen, 1996; Martin et al., 1999; Nørgaard et al., 2013), but not a vertical wall on a impermeable dike.

The most relevant research work on the topic of overtopping impact force carried out so far consists of the experimental model tests. Chen et al. (2012, 2015, 2014), De Rouck et al. (2012), and Ramachandran et al. (2012) used regular waves and Van Doorslaer et al. (2012) used the overtopping simulator. The aim of these tests was to investigate the characteristics of the overtopping impact forces. A double-peaked evolution shape of a single impact force (e.g., 'dynamic impact peak' and 'quasi-static peak') is recognized and reported by the researchers mentioned above. The two-peak shape of overtopping force is similar to the proposed church-roof breaking wave impact by Oumeraci et al. (1993), but without the significant magnitude difference between the two peaks exhibited by the breaking wave. Chen et al. (2015) proposed an empirical formula to predict the quasi-static peak of the overtopping force, which decays exponentially along the dike crest. Certain relationships between the overtopping force and overtopping discharge and individual overtopping volume were investigated by Ramachandran et al. (2012) and Van Doorslaer et al. (2012), which bring a possibility of using the existing work of overtopping volume and discharge to predict the force. The studies mentioned above conducted by far have improved the understanding of the impact process of overtopping wave and the prediction of the single force, but still not enough. From the point of practical design, we are particularly interested in determining the expected maximum overtopping force during a storm. In order to answer such a design question, statistical study of the overtopping forces is needed, which can be used to develop a procedure to determine the expected maximum force for a given condition.

By far, the statistical studies of wave overtopping has been mainly focused on how to predict the representative significant or the maximum individual overtopping volumes and discharge based on a considerable laboratory work for both smooth gentle and steep slopes of dikes without vertical structures on the crest (e.g., Van der Meer and Janssen, 1995; Pullen et al., 2007; Hughes and Nadal, 2009; Victor et al., 2012; Hughes et al., 2012; Pan et al., 2015); and rubble mound breakwaters (e.g., Zanuttigh et al., 2013). They recommended the use of 2-parameter Weibull distribution family (one of the commonly used extreme value distributions) to estimate the individual overtopping volume, and an empirical shape parameter of Weibull distribution which is related to hydraulic condition and dike structure properties. A common procedure for defining the extremes is using the upper percentiles of the distribution of the individual overtopping volume, such as: Hughes et al. (2012) selected the upper 10% of the overtopping volumes; Victor et al. (2012) chose the 50% of the values; and Nørgaard et al. (2014) used the upper 30% and Pan et al. (2015) applied the full distribution. It seems that the choice of the upper percentiles of the distribution is arbitrary and non-consistent among different studies depending on the specific settings. Moreover, most of the extreme overtopping volume studies made a subjective a priori choice of using Weibull distribution. Coles (2001) argues the non-necessity a priori judgment about the adoption and recommends to use the Generalized Extreme Value (GEV) distribution (contains three forms of distribution families: Gumbel, Frèchet and Weibull) and Generalized Pareto distributions (GP) to do the extreme value analysis. Based on these statistical works mentioned above, and the existence of the relationship between the overtopping forces