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Estimation of time-varying discharge and cumulative volume in individual overtopping waves

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ABSTRACT

The time variation of discharge per unit dike length in an overtopping wave is characterized by a rapid increase to a maximum discharge that can be several times greater than the mean discharge, followed by a slower decrease in discharge until overtopping for that wave ceases. Measurements of wave overtopping acquired during the European small-scale *FlowDike* experiments were analyzed to identify individual overtopping waves using a two-step "supervised" procedure that combines the best features of automated wave determination augmented with manual error correction and validation. The result was a well-vetted data set of 5799 individual overtopping waves represented by time-series of flow depth and velocity near the seaward edge of the dike crest. The model dikes had planar seaward dike slopes of either 1V-on-3H or 1V-on-6H. Instantaneous discharge time series were calculated as the product of the flow thickness and velocity time series. In this paper, the two-parameter Weibull probability density function is adopted to represent the time variation of instantaneous discharge in an overtopping wave. Values of the Weibull scale factors, *a*, and shape factors, *b*, are obtained through nonlinear best-fitting of the Weibull equation to all 5799 waves. Best fits were also performed for the simpler Rayleigh version of the Weibull equation when $b = 2$. An empirical equation was developed for scale factor, *a*, in terms of predicable parameters of the overtopping waves. The shape factor, *b*, could not be successfully parameterized, but it was found that the shape factors are narrowly distributed about the Rayleigh value of $b = 2$. Predictions of time-varying discharge made using the Weibull equation with $b = 2$ (i.e., Rayleigh equation) are assessed in terms of the root-mean-square errors between predictions and measurements. The estimates are reasonable for most of the waves. The capability to estimate the time-varying discharge in individual overtopping waves will improve the art of full-scale wave overtopping simulation, and the resulting empirical equations will contribute to methodologies aimed at quantifying the resiliency of dike erosion protection.

1. Introduction

The capability of grass-covered earthen dikes and levees to withstand tolerable rates of wave overtopping depends almost entirely on the resiliency of the grass/soil system protecting the landward-side slope. The applied hydrodynamic forces occurring during wave overtopping vary greatly with maximum instantaneous velocities being as much as four times greater than the average flow velocity. Furthermore, each successive overtopping wave has different magnitudes of maximum velocity, maximum flow thickness, maximum discharge, and overtopping duration. The time variation of instantaneous discharge in individual overtopping waves typically features a fairly rapid increase in discharge to a maximum value, followed by a much slower decline in discharge down to zero. Thus, the hydrodynamic forces exerted on the structure crest and landward-side slope grass/soil system are unsteady and depend significantly on the time variation of instantaneous discharge that occurs with each overtopping wave.

Development of reliable design guidance for overtopping of grass-covered dike systems requires full-scale field measurements during storm events or full-scale physical model simulations of overtopping events. Acquiring field measurements during actual severe wave overtopping events is extraordinarily problematic, so coastal engineers have instead focused on full-scale wave overtopping simulation using mobile simulators on actual dikes (e.g., Van der Meer et al., 2006; Van der Meer, 2007; Van der Meer et al., 2008; Steendam et al., 2010) and fixed simulators using prepared grass test trays (e.g., Thornton et al., 2011; Van der Meer et al., 2011; Thornton et al., 2014).

Realistic wave overtopping simulations are driven by present understanding of the overtopping processes and being able to replicate these processes with a reasonable level of accuracy. When wave conditions and freeboard remain relatively constant, the overall wave overtopping condition can be represented by the average discharge (q_w) and the

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probability distribution of individual overtopping wave volumes (P_V). Reliable empirical equations describing q_w and P_V in terms of incident wave conditions, structure geometry, and crest freeboard (Pullen et al., 2007) have been developed based on small- and large-scale physical model tests of common dike geometries. Full-scale physical model simulation of individual waves using the Dutch-invented simulator consists of the intermittent release onto the dike crest of prescribed water volumes in such a manner that key parameters of the unsteady flow (i.e., maximum velocity, maximum flow thickness, and release duration) are correctly reproduced for each water volume in the probability distribution. It may be possible to improve wave overtopping simulations by assuring the water release also approximates the actual time-varying discharge on the dike crest. This will lead to improved design guidance and better assessment of grass-covered dike and levee resiliency.

This paper utilizes a comprehensive set of wave overtopping measurements acquired during the European small-scale *FlowDike* experiments to: (1) identify individual overtopping waves; (2) analyze the time-varying discharge per unit dike length in each wave; and (3) establish viable empirical predictive equations for time-varying discharge and cumulative overtopping volume. Section 2 briefly overviews previous research related to individual overtopping waves. Section 3 summarizes the *FlowDike* experiments and describes the data analysis. A theoretical equation based on the two-parameter Weibull probability density function is proposed in Section 4 to represent the time variation of discharge and corresponding time variation in cumulative overtopping volume. The theoretical equation is fitted to measured discharge and cumulative volume time series in Section 5, and empirical relationships for the Weibull parameters are developed in Section 6. The new predictive equations are evaluated relative to measurements in Section 7, and application to a recent dike slope resiliency assessment methodology is illustrated in Section 8. A summary and conclusions are given in Section 9.

2. Previous research

Initial estimates of individual overtopping wave hydraulic parameters were reported in papers by Schüttrumpf et al. (2002); Van Gent (2002); Schüttrumpf and Van Gent (2003); Schüttrumpf and Oumeraci (2005), and Bosman et al. (2008). Relationships were given at the seaward edge of the dike crest for the flow depth ($h_{2\%}$) and flow velocity ($u_{2\%}$) exceeded by 2% of the incident waves. The equations at the seaward edge of the crest ($x_c = 0$) were given by

$$h_{2\%}(x_c = 0) = C_{A,h}\ (R_{u2\%} - R_c) \tag{1}$$

and

$$u_{2\%}(x_c = 0) = C_{A,u}\ \sqrt{g(R_{u2\%} - R_c)} \tag{2}$$

where $R_{u2\%}$ is the vertical run-up elevation exceeded by 2% of the incident waves; R_c is the freeboard (dike crest elevation minus still water elevation); g is gravitational acceleration; and $C_{A,h}$ and $C_{A,u}$ are empirical coefficients. It was necessary to assume $h_{2\%}$ and $u_{2\%}$ are Rayleigh-distributed to estimate values at other percent exceedance.

Van der Meer et al. (2010) measured flow thickness and velocity of eight different wave volume releases from the Dutch mobile overtopping simulator on an actual dike, and they developed relationships for maximum flow thickness, maximum velocity, and overtopping duration in terms of individual wave volume. Van der Meer et al. stated that the resulting equations were strictly valid only for the Dutch mobile simulator. They also recommended additional research to better resolve the dependency of the important wave volume parameters on individual wave volumes, and they questioned the assumption that maximum velocity and flow thickness were Rayleigh distributed.

Hughes et al. (2012) analyzed data from 9 small-scale experiments conducted by Hughes and Nadal (2009) that combined wave overtopping with a low negative freeboard with a 1-on-4.25 planar seaward slope. On the levee crest, time series of instantaneous discharge were calculated as the product of the coincident flow thickness and flow velocity time series. An analysis of nearly 2100 individual wave volumes produced a relationship between maximum instantaneous discharge and wave volume, and an associated equation for overtopping duration.

Hughes (2015a, 2015b) analyzed the extensive *FlowDike I* and *FlowDike II* data sets (described in Section 3), and he proposed new empirical equations for maximum velocity, maximum flow thickness, maximum discharge per unit crest length, and the overtopping duration occurring in individual overtopping wave volumes. Hughes noted the new equations strictly apply at the seaward edge of the dike crest on dikes having planar seaward-side slopes ranging between 1-on-3 and 1-on-6.

There has been hardly any research on the profile shape of time-varying discharge in an individual overtopping wave. Van der Meer (2007) examined raw data from the German regular wave overtopping tests provided by Dr. Schüttrumpf, and he concluded that the time variation of overtopping flow velocity, $u(t)$, and flow thickness, $h(t)$, were essentially triangular in shape for the larger overtopping wave volumes. Multiplying the velocity and flow thickness time series (assuming the maximum peaks coincide) gives the time series of instantaneous discharge that can be integrated to give total volume expressed by Van der Meer (2007) as

$$V_T = \frac{u_{max}\, h_{max}\, T_o}{3} = \frac{q_{max}\ T_o}{3} \tag{3}$$

where u_{max} is maximum flow velocity, h_{max} is maximum flow thickness, T_o is overtopping duration, and $q_{max} = u_{max}\, h_{max}$.

Hughes (2011) formulated an equation for the idealized time-varying discharge in an overtopping wave by assuming the flow thickness and flow velocity were represented by the expressions

$$h(t) = h_{max}\left[1 - \frac{t}{T_o}\right]^m \quad \text{For } 0 \le t \le To \tag{4}$$

and

$$u(t) = u_{max}\left[1 - \frac{t}{T_o}\right]^n \quad \text{For } 0 \le t \le To \tag{5}$$

where $h(t)$ and $v(t)$ are instantaneous flow thickness and velocity, respectively; t is time; and the exponents m and n are positive. Multiplying Eqs. (4) and (5) yields an equation for the time variation of instantaneous discharge given by

$$q(t) = h_{max}\, u_{max}\left[1 - \frac{t}{T_o}\right]^{m+n} = q_{max}\left[1 - \frac{t}{T_o}\right]^{m+n} \quad \text{For } 0 \le t \le To \tag{6}$$

Integration of Eq. (6) gives the total volume in the overtopping wave, i.e.,

$$V_T = \frac{q_{max}\ T_o}{(m + n + 1)} \tag{7}$$

Hughes (2011) agreed with Van der Meer (2007) that the flow thickness and flow velocity profiles were typically well represented by triangular shapes, and he set $m = n = 1$. Thus, Eq. (7) reduced to the same as Eq. (3) proposed by Van der Meer, and Eq. (6) became

$$q(t) = q_{max}\left[1 - \frac{t}{T_o}\right]^2 \quad \text{for } 0 \le t \le To \tag{8}$$