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Preliminary Evaluation of Existing Breaching Erosion Models

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ABSTRACT

The ability to estimate the erosion rate along an underwater breach face is crucial to understand the evolution of breaching failure. To this end, breaching erosion models were developed and applied in numerical models. However, these erosion models have never been validated, owing to the scarcity of direct measurements of turbidity currents that accompany breaching. The aim of this study is to evaluate the existing breaching erosion models using direct measurements of recently performed laboratory experiments on breaching flow slides. We found out that the erosion model put forward by Mastbergen & Van Den Berg (2003) provides good agreement with the data and performs better than the one proposed by Van Rhee (2015). The latter tends to overestimate the erosion rate, particularly at steeper slopes.

INTRODUCTION

Stability of subaqueous slopes is a common problem in the fields of soil and fluid mechanics. Flow slide is one of the possible failure mechanisms, which bring serious hazards to hydraulic structures. It occurs when the sediments of underwater slopes lose their stability and move downslope, forming a much gentler slope. Two types of flow slides are distinguished in the literature: liquefaction flow slides and breaching flow slides (Alhaddad et al., 2020a). The former occurs in loosely-packed sand, as it shows a contractive behaviour under shear forces; the soil structure collapses abruptly and a large amount of the soil body flows downslope. The latter, on the other hand, does not take place as an abrupt collapse. Rather, sand grains peel off particle by particle, forming a turbidity current propagating over the slope surface (breach face).

It is to be noted that the term breaching here does not refer, as conventionally, to the phenomenon of the eventual failure of hydraulic structures due to overtopping. Instead, it is a relatively slow, gradual, retrogressive erosion of submerged slopes steeper than the soil internal friction angle. Breaching has escaped the attention of researchers, because it was confused with soil liquefaction (Eke et al., 2011). This is due to the fact that both failure modes produce very similar post-event morphology. Currently in the Netherlands, breaching is seriously involved in the safety assessments of dikes.

Unlike static liquefaction, breaching is mostly encountered in densely-packed sand, as it dilates under shear forces (Van Rhee, 2015). Dilatant sand undergoes an increase in pore volume under shear deformation, leading to the generation of negative pore pressure, which considerably retards the erosion process. Owing to the pressure difference, an inward hydraulic gradient is generated, forcing the ambient water to flow into the pores, releasing the negative pressure. As a consequence, the sand particles located at the sand-water interface become unstable and gradually peel off, almost particle by particle. These particles mix with the ambient water, creating a turbidity current running along the breach face and then down the slope toe (Eke et al., 2011). Breaching can last for many hours, propagating towards coastlines or river banks and hence posing a severe risk (Figure **1**). Moreover, this mode of failure could cause instabilities during the construction of submerged slopes (Van Rhee, 2015).

Figure 1: Ongoing breaching flow slides: Amity Point captured on 18 August 2014 (**left**), Ameland Island Southwest, the Netherlands, 2017 (**Right**) (Source: Mastbergen et al., (2019)).

Turbidity currents are buoyancy-driven underflows that can be observed in oceans, lakes, estuaries, and reservoirs. The fluid within the turbidity current has a density higher than the density of the ambient fluid, resulting in an excess hydrostatic pressure, which drives the current downstream. The presence of sediments inside the current is the reason for the higher density of the current. When the turbidity current propagates downslope, it interacts simultaneously with the bed at the bottom boundary and with the ambient fluid at the upper boundary, producing turbulence.

Unlike turbidity currents generated by other triggering mechanisms, breaching-generated turbidity currents do not have a distinctive propagating front at the breach face (Figure **2**). This is because the sand particles peel off everywhere along the slope, leading to the simultaneous formation of a current from the upstream end until the breach base. This current induces shear stress over the breach face, thereby promoting sediment erosion and strengthening itself; when more sediments are suspended in the current, it becomes denser and thus faster (Alhaddad et al., 2020b).

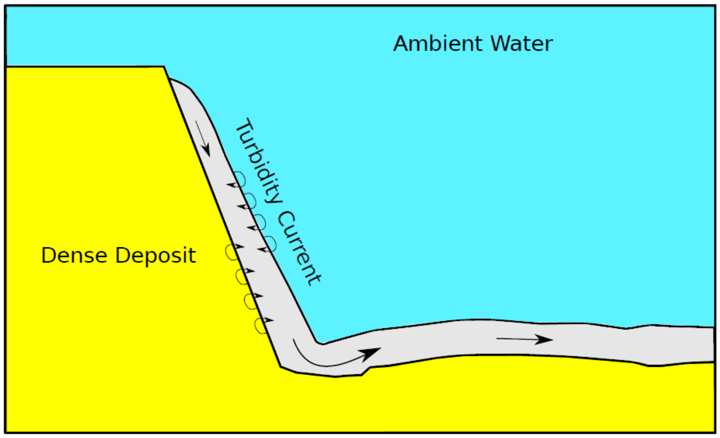

Figure 2: Schematic representation of breaching flow slides and the accompanied turbidity current

The paucity of direct measurements of breaching-generated turbidity currents has resulted in there being no validation of the breaching erosion models used in the literature (i.e. Mastbergen & Van Den Berg (2003) and Van Rhee (2015)). Very recently, Alhaddad et al. (2020b) performed large-scale lab experiments on breaching flow slides, providing the first quantitative data of breaching-generated turbidity currents and erosion rates. In this paper, we utilize these measurements to provide the first insights into the performance of the existing breaching erosion models.

SEDIMENT EROSION

Not only is the ability to predict the variation of erosion rate along the breach face needed to quantify the total erosion, but it is also crucial to better understand the failure evolution. In addition to the grain-by-grain failure, both Van Rhee & Bezuijen (1998) and Alhaddad et al. (2020b) observed a periodic collapse of coherent sand wedges, termed surficial slide, in their experiments. In the case that there are no surficial slides occurring, the total erosion will be the summation of gravity-induced erosion and sediment erosion by the flow motion.

Gravity-induced Erosion (Pure breaching)

Breaching has remained unexplored until it was identified by the Dutch dredging industry in the 1970s. It is considered an important production mechanism for stationary suction dredgers. Balancing the forces acting on a sand grain present on a slope, Breusers (1977) derived the expression of 'wall velocity' to estimate the dredging production. Wall velocity is the horizontal speed of the retrogressive erosion of a vertical underwater slope caused by pure breaching. This expression can be adjusted to represent the sand erosion velocity perpendicular to the breach face and can be written in a general form for variable slope angles:

$$v_{e,g} = \frac{\sin(\varphi - \alpha)}{\sin\varphi}\frac{\Delta(1 - n_0)k_l}{\delta n} \tag{1}$$

where $\Delta = \frac{\rho_s - \rho_w}{\rho_w}$ is the relative grain density, in which ρ_s is the density of the particles and ρ_w is the density of water, n_0 is the in-situ porosity of the sand, k_l is the permeability at the loose state, φ is the internal friction angle, α is the slope angle, and δn is the relative change in porosity $\delta n = \frac{n_l - n_0}{1 - n_l}$, in which n_l is the maximum porosity of the sand.

The gravity-induced erosion is linearly proportional to the permeability, implying that the presence of finer grains within the sand body decreases the gravity-induced erosion rate. Another implication is that the magnitude of the permeability should be carefully measured.

Flow-induced Erosion

Turbidity currents pick up sediments from the slope surface mainly through the shear stress they induce on the bed. Sediment entrainment occurs when the bed shear stress τ exceeds a certain value. The well-known Shields parameter θ represents the bed shear stress in a dimensionless form and reads:

$$\theta = \frac{\tau}{(\rho_s - \rho_w)gD_{50}} = \frac{u_*^2}{\Delta g D_{50}} = \frac{C_f\,\bar{u}^2}{\Delta g D_{50}}$$

where u_* is shear velocity, C_f is dimensionless bed friction coefficient and $\bar{u}$ is the flow velocity averaged over flow layer thickness. At a horizontal bed, erosion occurs when θ is larger than the critical Shields parameter θ_{cr} which can be obtained from Shields curve or readily from the smooth fit given by Brownlie (1981):

$$\theta_{cr} = 0.22{R_p}^{-0.6} + 0.06\exp\left(-17.77{R_p}^{-0.6}\right)$$

where R_p is the particle Reynolds number and defined as: $R_p = \frac{D_{50}u_s}{v}$, in which $u_s = \sqrt{\Delta g D_{50}}$ is Shields velocity for sand grains. The relation between sediment pick-up and the Shields parameter is called the pick-up function ϕ_p. This empirical function is usually derived based on experimental results under specific conditions and reads:

$$\phi_p = \frac{E}{\rho_s u_s}$$

where E is the sediment pick-up rate perpendicular to the bed (kg/s.m^2). The flow induced erosion rate $v_{e,f}$ is given by

$$v_{e,f} = \frac{E}{\rho_s(1 - n_0)}$$

Total Erosion

Given that Equation 1 does not involve the sediment entrainment by turbidity currents, it cannot be directly applied in practice. Therefore, this expression was extended to more realistic erosion models by Mastbergen & Van Den Berg (2003) and Van Rhee (2015). To the best of our knowledge, no other erosion models were developed to suit the breaching conditions. A key feature of these erosion models is that they account for a sloping bed steeper than the internal friction angle as well as the retarded erosion by the dilative behavior of the granular material.

Mastbergen & Van Den Berg (2003) adopted the sediment pick-up function of Winterwerp et al. (1992) and developed a relation to compute the total erosion rate v_e:

$$\frac{v_e}{u_s}\left(1-\frac{v_e}{v_{e,g}}\right)=\frac{0.018(\theta-\theta_{cr})^{1.5}D_*^{0.3}}{\frac{\sin(\varphi-\alpha)}{\sin\varphi}(1-n_0)} \tag{2}$$

where D_* is defined as a dimensionless particle diameter: $D_* = D_{50}\sqrt[3]{\frac{\Delta g}{\nu}}$. Two extreme solutions for Equation 2 were reported in Mastbergen & Van Den Berg (2003):

$$v_e=\begin{cases}\dfrac{0.018(\theta-\theta_{cr})^{1.5}D_*^{0.3}k_l u_s}{\frac{\sin(\varphi-\alpha)}{\sin\varphi}(1-n_0)}, & v_e/v_{e,g}\ll 1\\[2ex] \sqrt{\dfrac{0.018(\theta-\theta_{cr})^{1.5}D_*^{0.3}\sqrt{\Delta^3 g D_{50}}}{\delta n}}, & v_e/v_{e,g}\gg 1.\end{cases}$$

The first extreme condition is never met in breaching and the second condition does not comply with experimental data at lab conditions. To evaluate the erosion model of Mastbergen & Van Den Berg (2003), we provide the general solution for Equation 2, which also includes the transition zone between the two extreme conditions:

$$v_e=u_s\left(\frac{v_{e,g}}{2u_s}+\sqrt{\left(\frac{v_{e,g}}{2u_s}\right)^2+0.018(\theta-\theta_{cr})^{1.5}D_*^{0.3}\frac{\Delta\, k_l}{\delta n\, u_s}}\right). \tag{3}$$

When $\theta \le \theta_{cr}$, Equation 3 gives $v_e = v_{e,g}$.

Van Rhee (2015) developed a breaching erosion model modified from the work of Van Rhee (2010) and the pick-up function of Van Rhee & Talmon (2010):

$$v_e=\frac{0.000616u_s\frac{\theta}{\theta'_{cr}}\frac{1-n_0-c_b}{1-n_0}-w_s c_b\cos\alpha}{1-n_0-c_b} \tag{4}$$

where θ'_{cr} is a modified critical Shields parameter that includes the effect of the slope angle and dilatancy:

$$\theta'_{cr} = \theta_{cr}\left(\underbrace{\frac{\sin(\varphi-\alpha)}{\sin\varphi}}_{the\ effect\ of\ the\ slope\ angle} + \underbrace{\frac{v_e}{k_l}\Delta n\frac{A}{\Delta}}_{the\ effect\ of\ the\ hydroulic\ gradient}\right).$$

A disadvantage of Equation 4 is that v_e is present at both sides, meaning that it can only be solved numerically or iteratively.

LARGE-SCALE EXPERIMENTS

Alhaddad et al. (2020b) conducted large-scale experiments on breaching flow slides at the water lab of Delft University of Technology. The experiments were executed in a 2 m high tank with a submerged sandy slope steeper than the sand internal friction angle. The submerged slope, in the first place, was unstable and initially failed due to the gravitational force. A fine, uniformly-graded sand of D_{50} equal to 0.135 was used in the experiments (see Table **1**). Quantitative data of flow thicknesses, velocities, sediment concentrations and slope profile evolution were presented for various slope angles: 50 degree, 64 degree and 70 degree.

We revisit the experimental data that is relevant to the purpose of this paper: sand characteristics, layer-averaged velocities, and corresponding erosion rates.

The settling velocity of a single grain $w_{s,0}$ is computed using the formula of Budryck and the effect of the hindered settling was taken into account according to Richardson and Zaki (1954) to calculate the settling velocity w_s. The reference of the near-bed concentration c_b is not defined in Van Rhee and Talmon (2010). They assumed a near-bed concentration of 0.15 to evaluate their pick-up function and we follow them here to evaluate the erosion model of Van Rhee (2015). We point out that the near-bed concentration is not incorporated in the erosion model of Mastbergen & Van Den Berg (2003).

Table 1: Properties of sand used in the experiments (Source: Alhaddad et al. (2020b))

D_{50} (mm)	n_0	n_l	φ	ρ_s (kg/m^3)	k_l (m/s)	$w_{s,0}$ (m/s)
0.135	0.40	0.51	36°	2650	0.000307	0.011

No direct shear stresses were measured in the lab experiments of Alhaddad et al. (2020b), and thus, the bed friction coefficient C_f was not defined. Therefore, two reasonable, different values were used in the calculations: 0.005 and 0.01.

RESULTS AND DISCUSSION

The predicted erosion rates by the proposed breaching erosion models are compared against the measured erosion rates in Figure **3**. Clearly, the relationship proposed by Mastbergen & Van Den

Berg (2003) renders good agreement with the data and performs better than the one prosed by Van Rhee (2015). The latter overestimates the erosion rates and this overestimation is magnified at steeper slopes.

A better insight into the predictive ability of existing breaching erosion models can be obtained by advanced numerical simulations, which can reproduce the experimental results. To this end, we are developing a CFD numerical model.

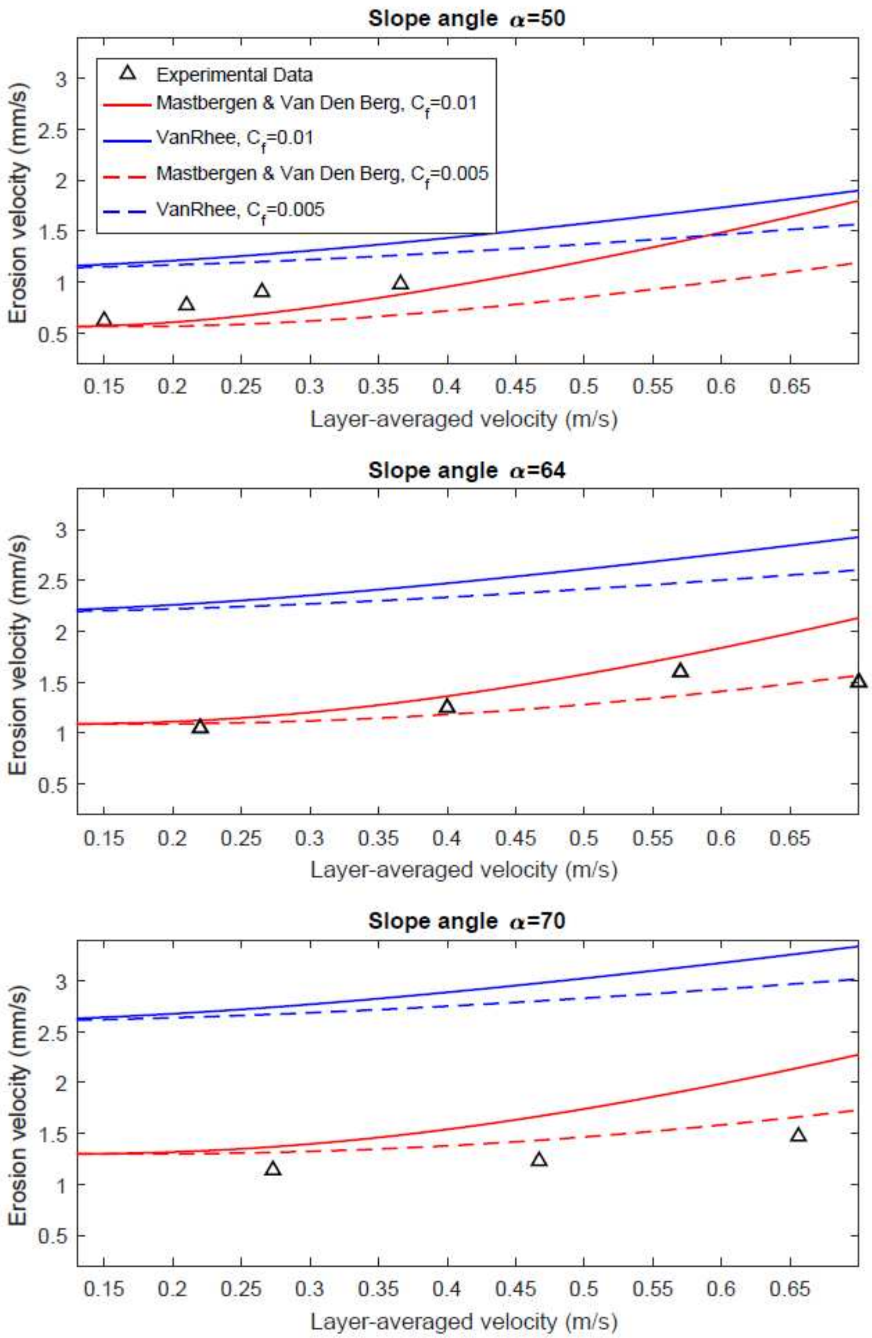

Figure 3: Comparison between the experimental data and proposed breaching erosion models

CONCLUSION

To test the predictive ability of existing breaching erosion models, an independent source of experimental data is utilized. The relationship proposed by Mastbergen & Van Den Berg (2003) perform better than the one proposed by Van Rhee (2015). The former provides good agreement with the data, while the latter overestimates the erosion rate, especially at steeper slopes.

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