Anura3D
MPM Research Community

Paper number: mpm2019.27
www.anura3d.com
www.mpm2019.eu

The need for experimental studies on breaching flow slides

Said Alhaddad[1,*], Robert Jan Labeur[1], Wim Uijttewaal[1]
[1]Environmental Fluid Mechanics Section, Faculty of Civil Engineering and Geosciences, Delft University of Technology, Delft, The Netherlands

[*] E-mail: S.M.S.Alhaddad@tudelft.nl

ABSTRACT

Recent studies have revealed that breaching, rather than liquefaction, is the dominant failure process in underwater slopes of fine sand and the main driver of observed flow slides in nature. As a result, breaching is getting more attention from hydraulic and geotechnical researchers. Measurements of breaching-generated turbidity currents are substantial for understanding the interaction between the turbidity current and the slope surface, as well as for the validation of numerical models. However, these measurements are scarce in the literature. To this end, laboratory experiments are planned to be carried out in the water lab of Delft University of Technology, the Netherlands. This paper describes the special experimental setup that will be employed to obtain the required data.

KEY WORDS: Flow slide; breaching; turbidity current; sediment entrainment.

INTRODUCTION

Flow slides and slope instabilities are common problems in geotechnical and hydraulic engineering, causing significant damages around the world. A flow slide is a phenomenon in which a large amount of soil, present in an underwater slope of a certain steepness and height, moves down the slope and eventually redeposits on a gentler slope. The term “flow slide” is used to describe this type of slope failure, as when the soil is released from the slope, it is transported as a soil-water mixture rather than as a soil mass (Beinssen & Mastbergen, 2017). Submerged infrastructure and flood defenses along coastlines and riverbanks could be under a severe threat of a flow slide, which is able to destabilize an entire hydraulic structure (Figure 1), resulting in significant unwanted consequences. Moreover, flow slides of submerged slopes play an important role in dredging activities and may thus threaten the stability of coastal foreshores. The ability to predict the risk of flow slides is an important consideration for the design, construction, maintenance and safety assessment of flood defenses. This provides motivation for the development of advanced numerical tools such as the Material Point Method (MPM).
It is common in the literature to assume that flow slides are induced by soil liquefaction, which takes place in loosely-packed sand. Nonetheless, it has been observed in recent years that flow slides also take place in densely-packed sand by a less-known failure mechanism referred to as breaching. In contrast to liquefaction, breaching occurs slowly and perhaps takes several hours or even exceeds a day. Recent studies have revealed that breaching, rather than liquefaction, is the dominant failure process in underwater slopes of fine sand (Van den Berg et al., 2017) and the main driver of observed flow slides in nature (Beinssen & Mastbergen, 2017). This conclusion makes it substantial to further investigate the breaching failure mechanism.

Figure 1 Example of damage to a river dike due to a flow slide (Rogers, 2012)

The breaching process is usually accompanied by generation of a turbidity current. This current may further enhance the erosion of the sand surface, picking up more and more sediments, thereby increasing in speed. Turbidity currents belong to the category of gravity-driven flows, a general term for any flow governed by gravitational forces due to the density gradient in a fluid. Turbidity currents are traditionally defined as sediment-laden gravity-driven underflows in which particles are largely or wholly suspended due to fluid turbulence. The source of turbulence is the forward motion of the current along the lower boundary of the sediment bed (Meiburg & Kneller, 2010). The motion of breaching-generated turbidity currents is mainly generated by the action of gravity on the density difference between the sand-water mixture and the ambient water.
The next section presents a detailed explanation of the breaching process, followed by a brief description of the influence of turbidity currents on breaching.

BREACHING PROCESS

The term "breaching" is a very common term in coastal engineering, which usually refers to the process of retrogressive erosion and to the eventual failure resulting from overtopping of embankments, dams and sand barriers (Eke et al., 2011), but it is used here in a more restrictive manner. Van den Berg et al. (2002) specifically referred to breaching as a gradual retrogressive failure of a very steep subaqueous slope that is steeper than the angle of repose. This failure mechanism was first identified in the 1970s by the Dutch dredging industry as a production mechanism for stationary suction dredgers. These days, breaching is considered an important failure mechanism and incorporated into safety assessments in the Netherlands (Van Duinen et al., 2014).
Breaching occurs in densely-packed sand due to its dilative behaviour under shear (Van Rhee & Bezuijen, 1998; Van den Berg et al., 2002). Dilatancy is the increase in volume of a granular substance during deformation, caused by an increase in pore volume. Dilatancy results in a negative pore pressure, with respect to hydrostatic pressure. This increases the effective stress and thus retards the erosion process severely. It also results in an inward hydraulic gradient, forcing the water to flow into the pores, which restores the hydrostatic pressure (Figure 2). Consequently, the grains located at the sand-water interface lose their stability and peel off one by one. The falling grains mix with water and generate a turbulent sand-water mixture, a turbidity current, flowing over and interacting with the slope surface (Eke et al., 2011; Van den Ham et al., 2013).

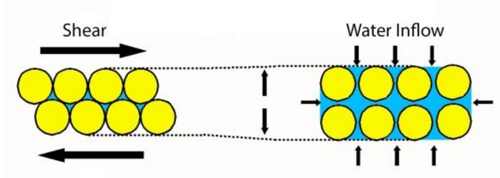


Figure 2 Behaviour of densely-packed sand under shear (modified from Schiereck & Verhagen, 2012)

During the grain-by-grain failure, the negative excess pore pressure is released locally, weakening the deposit near the soil-water interface and resulting in a thin surficial slide, which leads to a drop in the pore pressure. This strengthens the deposit and switches the failure process back to grain-by-grain failure. Van Rhee & Bezuijen (1998) observed the surficial slides in their flume tests for a breaching failure. The variant of grain-by-grain failure and periodic sliding was named "dual-mode slope failure" by You et al. (2014). Nevertheless, Van den Berg et al. (2017) considered this term misleading, arguing that the grain-by-grain failure and the thin surficial slide are inextricably linked to each other and are intrinsic properties of breaching.

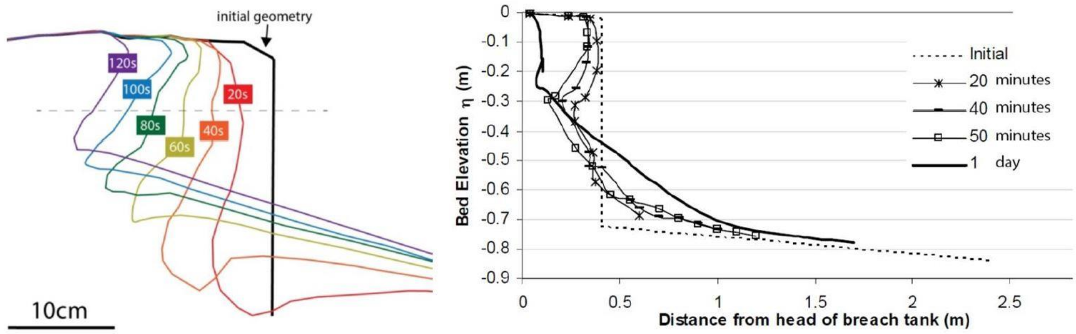
SLOPE EROSION DURING BREACHING

Estimating the erosion rate of sediments throughout breaching flow slides is challenging since many parameters play a role in the erosion process, such as: soil characteristics, breach height, slope angle and the associated turbidity current. To this end, Breusers (1977) introduced a term representing the horizontal propagation speed of a vertical underwater slope due to breaching process and called it the active wall velocity. This wall velocity can be derived from the balance of forces on a sand particle along a slope (the reader is referred to Van der Schrieck (2012) for a detailed derivation). The resulting expression of the wall velocity reads:

$$v_w = \frac{\sin(\varphi - \alpha)}{\sin\varphi}\frac{\rho_s - \rho_w}{\rho_w}\frac{(1 - n_0)k_l}{\Delta n} \qquad (1)$$

where n_0 is the in-situ porosity of the sand, ρ_s is the density of the particles, ρ_w is the density of water, 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.
Direct application of Equation 1 in practical cases is somewhat limited since it does not take into consideration the frequent surficial slides nor the sediment entrainment by the associated turbidity current. The calculated erosion rate only accounts for failure of an over-steepened slope due to the gravitational force. Van Rhee and Bezuijen (1998) found that the expression of the wall velocity was not valid for their large-scale model test. They reasoned that frequent surficial slides and the entrainment of sediments by the turbidity current explained the mismatch. Experimental studies even suggest that the expression of the wall velocity may not be valid for relatively small breach heights, where one could expect that the formed turbidity current is not erosive. Figure 3shows two examples where the erosion rate is not uniform along the breach face, conflicting with the notion of a uniform wall velocity. Erosion velocity increases downstream due to increased velocity of the turbidity current. In addition, the periodic surficial slides substantially increase sand erosion and thus strengthen the formed turbidity current.



(a) Breach height=30 cm, D_{50}=140 µm (You, 2013) (b) Breach height=70 cm, D_{50}=70 µm (Eke, 2008)

Figure 3 Traces of the breach front: non-uniform erosion along the sand-water interface

In conclusion, sediment entrainment by the turbidity current and surficial slides should be incorporated in erosion models of breaching to better estimate the total erosion rate along the sand-water interface and better predict the failure evolution.

Sediment Entrainment by Turbidity Current

Turbidity currents have the ability to carry sediments over long distances and to pick up sediments from the bed. They erode the bed mainly through shear stress exerted on the erodible bed (Pratson et al., 2000). When more sediments are entrained into the turbidity current, its velocity increases, which promotes further sediment entrainment in a process called ignition (Parker et al., 1986; Sequeiros et al., 2009).Bed erosion and the fate of the transported sand are highly affected by turbulence. Turbulence energy keeps the particles suspended while eroding new sediments from the bed.
Breaching-generated turbidity currents induce additional shear stress on the sloping bed, leading to an increase in the erosion rate (Mastbergen & Van Den Berg, 2003). Steep slopes composed of fine sediments are typical features in the breaching process. Yi and Imran (2006) found that steeper slopes with finer sediments present lower values of ignition velocity and sediment concentration. This may indicate that breaching-generated turbidity currents start eroding the slope at earlier development stages than turbidity currents generated due to other triggering mechanisms. This reinforces the necessity to include sediment entrainment by turbidity currents in breaching erosion models.
Very few studies have focused on sediment entrainment by the turbidity current from the bed. The boundary layer of the turbidity current near the bed (the near-bed region) has relatively high particle concentrations, where the particle-particle and particle-fluid interactions increase the mass and momentum exchanges between the current and the sediment bed (Zordan et al., 2017). The dynamics of this boundary layer are still poorly understood.

Breaching Erosion Models

Some attempts are available in the literature to extend Equation 1 to include sediment entrainment by the turbidity current by adopting a sediment pick-up function accounting for the dilatancy effect (e.g. Mastbergen & Van Den Berg, 2003; Van Rhee, 2015). The breaching erosion formula suggested by Mastbergen & Van Den Berg (2003) was modified from the work of Winterwerp et al. (1992). However, the data presented by Mastbergen & Van Den Berg (2003) was too limited for a proper validation of their erosion formula. In a similar way, the numerical model of Van Rhee (2015) incorporated a breaching erosion formula modified from the work of Van Rhee (2010) and Van Rhee & Talmon (2010). Nonetheless, validation of this model is still missing.

To investigate how the breaching erosion models compare to each other, breaching erosion rate is computed for a 60-degree slope with different flow velocity magnitudes (Figure 4); other parameters are listed in Table 1. As expected, the expression of wall velocity renders the same erosion rate for all flow velocities, as it is independent of the flow dynamics. The formula of Mastbergen & Van Den Berg (2003) results in higher erosion rates than that one of Van Rhee (2015) and the difference is magnified at high flow velocities. Differences in the prediction of the erosion rate could have important implications for numerical computations of the breaching-generated turbidity current, as there is a feedback between the hydrodynamics of the current and the morphological changes of the slope. Therefore, experimental data is required for proper validation of breaching erosion models.

Table 1 Parameters used in the calculations of erosion rates

D_{50}(mm)	n_0	n_l	φ	α	ρ_s (kg/m^3)	ρ_w (kg/m^3)
0.135	0.401	0.517	36	60	2650	1000

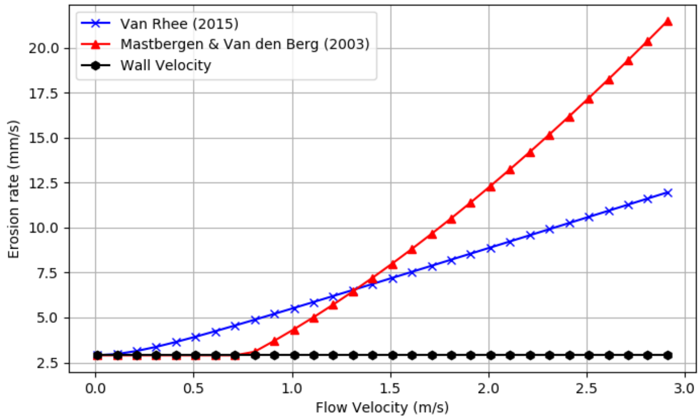


Figure 4 Comparison between erosion formulations based on the flow velocity

Existing breaching erosion models use sediment pick-up functions derived from experiments with steady, uniform flow conditions and fully-developed boundary layers; these conditions are not consistent with turbidity currents. The development of turbidity currents is typically an unsteady phenomenon, meaning that current kinematics and inner density distribution are time-varying. To the best of our knowledge, no sediment entrainment functions were developed directly from experimental measurements of turbidity currents ascribed to the difficulty of obtaining sufficient measurements.

Detailed measurements of the generated turbidity current are instrumental for the development of an erosion model compatible with the problem's conditions and for the validation of numerical models, such as MPM-based models. Toward this end, laboratory experiments are planned to be carried out in the water lab of Delft University of Technology, the Netherlands. As obtaining data for turbidity currents is challenging, different measuring techniques will be tested to identify the most appropriate option.

EXPERIMENTAL SETUP

The experimental setup was designed specifically to study breaching flow slides. It consists of several elements: breaching tank, confining wall, false floor, damping tank, and sedimentation tank. Figure 5 and Figure 6 show a schematic of the experimental setup.

The breaching tank (4m long, 0.2m wide and 2m high) was made sufficiently deep to accommodate relatively high breach heights. These conditions can produce sufficiently high flow velocities to entrain sediments from the slope surface. The basic concept behind a sufficient breach height is that the turbidity current becomes turbulent as it propagates over a steep slope of adequate distance. The tank was also made sufficiently long to provide scope for observations of the failure evolution. The back side of the breaching tank is dark-coloured and made of steel, but the front side is made of glass to facilitate failure tracking and flow visualization.

The confining wall is a sliding mesh gate covered with geotextile, which allows water to pass through it while holding sediments in place. This allows water to escape from the pores through the wall to the ambient water during the compaction process, creating a fully-saturated densely-packed deposit. The confining wall is also used

to shape the targeted slope angle.
The downstream end of the breaching tank is left open and connected to a deeper damping tank to allow the turbidity current to flow freely from the breaching tank into the damping tank. The level of the soil-water mixture in the damping tank should be kept below the bottom of the breaching tank in order to avoid the reflection of the turbidity current from the damping tank back upstream. For this purpose, the turbidity current will be drained from the bottom of the damping tank at the downstream end, while a flow of clear water will be supplied at the top of the damping tank to guarantee a constant water level throughout the experiment.
The false floor can be set to a specified slope, as to increase the sediment transport capacity of the turbidity current versus the existing flat bottom. Accordingly, less sand will accumulate at the toe of the initial sand deposit, maintaining an adequate breach height. Lastly, the sedimentation tank (adjacent to the damping tank, not shown in Figures 5 or 6) is used for collecting the sand-water mixture pumped out from the damping tank.

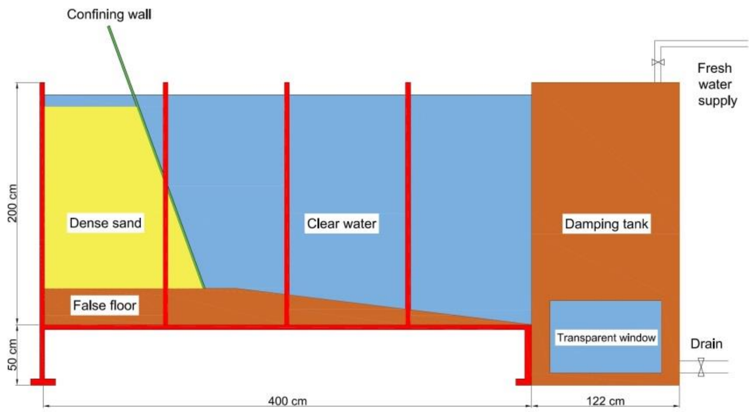


Figure 5 Side view of the experimental setup

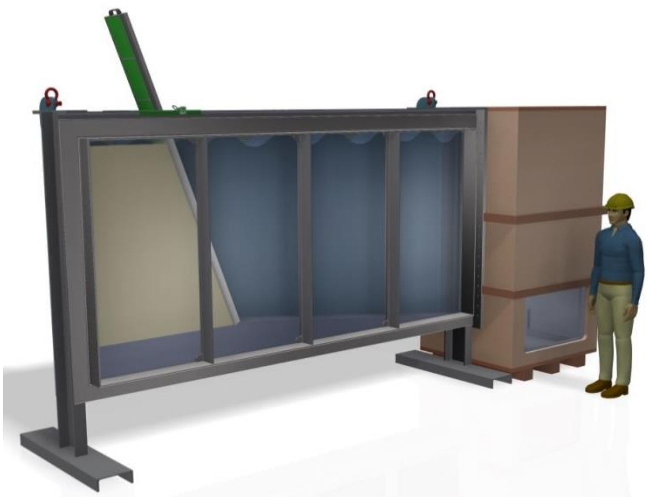


Figure 6 3D diagram of the experimental setup

A deposit of dense fine sand up to 1.5m high will be constructed inside the breaching tank after filling it with water. A selected slope, steeper than the angle of repose, will be created and supported by the confining wall. The deposit will be built layer by layer and each layer will be compacted using a vibrator needle to ensure that the sand will be homogeneous and densely-packed. The breaching will be initiated by quickly pulling out the confining wall between the deposit and the ambient water from the breaching tank.

CONCLUSION AND OUTLOOK

Breaching flow slides are still not sufficiently understood as they exhibit a complex failure mechanism involving both geotechnical and hydraulic processes. Looking from the hydraulic side, an empirical relationship describing the entrainment of sediment by the turbidity current is needed. Developing an advanced erosion model for breaching will be instrumental to enhancing the accuracy of the numerical computations.

We aim to obtain detailed measurements of breaching-generated turbidity currents. This will give us deeper insight into the development of the current and its interaction with the slope surface. Additionally, the outcome of the experimental work can be used to evaluate the performance of advanced numerical models for underwater sandy slopes. As breaching results in a high-concentrated turbidity current, among other reasons, it is challenging to measure velocities and concentrations of the current. Therefore, different measuring techniques will be tested to pick out the most appropriate one.

ACKNOWLEDGEMENTS

This study was conducted as a part of the MPM-Flow project “Understanding flow slides in flood defences”. This project is funded by The Netherlands Organisation for Scientific Research (NWO), Deltares, Royal Boskalis Westminster N.V., Van Oord Dredging and Marine Contractors, Rijkswaterstaat, StichtingIJkdijk and Sibelco.

REFERENCES

Beinssen, K., & Mastbergen, D. R. (2017). Flow Slides: Understanding their geo-mechanical mechanisms, the threats they pose and how these threats can be managed. In *13th Hydraulics in Water Engineering Conference* (p. 132). Engineers Australia.

Breusers, H. N. C. (1977). Hydraulic excavation of sand. *Proceedings International Course in Modern dredging*.

Eke, E., (2008), *Breaching as a mechanism for generating sustained turbidity currents*. M.S. thesis, Urbana, University of Illinois at Urbana-Champaign.

Eke, E., Viparelli, E., and Parker, G., (2011). Field-scale numerical modeling of breaching as a mechanism for generating continuous turbidity currents. *Geosphere*, 7, 1063-1076. Doi: 10.1130/GES00607.1

Mastbergen, D. and Van Den Berg, J. (2003). "Breaching in fine sands and the generation of sustained turbidity currents in submarine canyons". *Sedimentology* 50(4), 625-637.

Meiburg, E., & Kneller, B. (2010). Turbidity Currents and Their Deposits. *Annual Review of Fluid Mechanics,42*(1), 135-156. doi:10.1146/annurev-fluid-121108-145618

Parker, G., Fukushima, Y., &Pantin, H. M. (1986). Self-accelerating turbidity currents. *Journal of Fluid Mechanics*, *171*, 145-181.

Pratson, L. E., Imran, J., Parker, G., Syvitski, J. P., & Hutton, E. (2000). Debris flows vs. turbidity currents: a modeling comparison of their dynamics and deposits. *Special Publication-SEPM*, *68*, 57-72.

Rogers, D. (2012). Levees. Retrieved September 27, 2018, from http://web.mst.edu/~rogersda/levees/Mississippi Delta Region.htm

Schiereck, G. J., Verhagen, H, J. (2012). *Introduction to bed, bank and shore protection*. VSSD: Delft, the Netherlands.

Sequeiros, O. E., Naruse, H., Endo, N., Garcia, M. H., & Parker, G. (2009). Experimental study on self-accelerating turbidity currents. *Journal of Geophysical Research: Oceans*, *114*(C5).

Van den Berg, J. H., Martinius, A. W., &Houthuys, R. (2017). Breaching-related turbidites in fluvial and estuarine channels: Examples from outcrop and core and implications to reservoir models. *Marine and Petroleum Geology*, *82*, 178-205.

Van Den Berg, J. H., Van Gelder, A., & Mastbergen, D. R. (2002). The importance of breaching as a mechanism of subaqueous slope failure in fine sand. *Sedimentology*, *49*(1), 81-95.

Van den Ham, G. A., Groot, M. B., & Mastbergen, D. R. (2013). A Semi-empirical Method to Assess Flow-Slide Probability. *Submarine Mass Movements and Their Consequences Advances in Natural and Technological Hazards Research,* 213-223.

Van der Schrieck, G. L. M. (2012). *Lecture notes dredging technology*. Delft University of Technology.

Van Duinen, A., Bezuijen, A., van den Ham, G., & Hopman, V. (2014). Field measurements to investigate submerged slope failures. In *Submarine mass movements and their consequences*(pp. 13-21). Springer, Cham.

Van Rhee, C. (2010). Sediment entrainment at high flow velocity. *Journal of Hydraulic Engineering*, *136*(9), 572-582.

Van Rhee, C. (2015). "Slope failure by unstable breaching". In: *Proceedings of the Institution of Civil Engineers- Maritime Engineering.* Vol. 168. 2. Thomas Telford Ltd, 84-92.

Van Rhee, C. , & Bezuijen, A. (1998). The Breaching of Sand Investigated in Large-Scale Model Tests. *Coastal Engineering 1998*.

Van Rhee, C. V., &Talmon, A. M. (2010). Sedimentation and erosion of sediment at high solids concentration. In *Proceedings of the 18th International Conference on Hydrotransport* (pp. 211-222). BHR Group, Cranfield, UK.

Winterwerp, J. C., Bakker, W. T., Mastbergen, D. R., & van Rossum, H. (1992). Hyperconcentrated sand-water mixture flows over erodible bed. *Journal of Hydraulic Engineering*, *118*(11), 1508-1525.

Yi, A., & Imran, J. (2006). The role of erosion rate formulation on the ignition and subsidence of turbidity current. In *Proceedings of the 4th IAHR symposium on River, Coastal and Estuarine Morphodynamics* (pp. 543-551).
You, Y. (2013). *Dynamics of dilative slope failure.* . PhD thesis, The University of Texas at Austin.
You, Y., Flemings, P., &Mohrig, D. (2014). Mechanics of dual-mode dilative failure in subaqueous sediment deposits. *Earth and Planetary Science Letters*, *397*, 10-18.
Zordan, J., JUEZ, C., SCHLEISS, A. J., & Franca, M. J. (2017). Experimental Results on Sediment Entrainment by Gravity Currents. In *Proceedings of the 37th IAHR World Congress* (No. EPFL-CONF-230427, pp. 1453-1458).