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Mechanics of dual-mode dilative failure in subaqueous sediment deposits

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ABSTRACT

We introduce dual-mode dilative failure with flume experiments. Dual-mode dilative failure combines slow and steady release of sediments by breaching with periodic sliding, which rapidly releases an internally coherent wedge of sediments. It occurs in dilative sandy deposits. This periodic slope failure results from cyclic evolution of the excess pore pressure in the deposit. Sliding generates large, transient, negative excess pore pressure that strengthens the deposit and allows breaching to occur. During breaching, negative excess pore pressure dissipates, the deposit weakens, and ultimately sliding occurs once again. We show that the sliding frequency is proportional to the coefficient of consolidation. We find that thicker deposits are more susceptible to dual-mode dilative failure. Discovery of dual-mode dilative failure provides a new mechanism to consider when interpreting the sedimentary deposits linked to submarine slope failures.

1. Introduction

To understand how submarine slope failures sculpt the Earth's surface and how they are recorded in the sedimentary record, we need to understand the different processes by which they release sediments. Submarine slope failure analysis has emphasized slumping slope failure, typically in mud rich deposits, where large amounts of sediments are released in a short time span and generate debris flow. These failures leave scarps that are up to a few kilometers long and can have runoff distances of hundreds of kilometers (Hampton et al., 1996; Locat and Lee, 2002). They are well documented in deep-marine sedimentary successions. In contrast, breaching is a type of slope failure with no obvious sedimentary record that was discovered during sand mining (de Koning, 1970; Van den Berg et al., 2002). Breaching occurs in densely packed sandy deposits; it is a retrogressive subaqueous slope failure where sediments are released at a slow (∼mm/s) and approximately constant rate from a near-vertical failure surface. Breaching generates sustained turbidity currents and leaves no discernible failure scarp (Van den Berg et al., 2002). It is a potential mechanism for releasing sandy, long shore drift deposits that accumulate at the heads of submarine canyons (Mastbergen and Van den Berg, 2003; Eke et al., 2011) and it may also play an active role redistributing sand in deltaic systems (Torrey III, 1988; Torrey III et al., 1988). Although difficult to study in the field, breaching can be analyzed directly in the laboratory.

Breaching and slumping are driven by different modes of shear deformation (Meijer and van Os, 1976; Van den Berg et al., 2002). Slumping is due to contraction of pores during shear and an ensuing rise in excess pore pressure in the deforming deposit. The rise in excess pore pressure reduces the effective stress, which weakens the deposit and leads to slope failure (Terzaghi, 1951; Hampton et al., 1996; Locat and Lee, 2002; Flemings et al., 2008). In contrast, breaching results from grain-framework dilation during slope failure (Meijer and van Os, 1976; Van Rhee and Bezuijen, 1998; You et al., 2012). Dilation produces negative excess pore pressure behind the failure surface that increases the strength of the deposit resulting in a stable and steep retrograding failure surface. If the amount of dilation is too small, the negative excess pore pressure is insufficient to produce the high effective stress that maintains the near vertical failure surface and the slow release of sediment from it that defines breaching.

We present a new type of slope failure process, dual-mode dilative failure, where breaching and sliding cyclically alternate as the dominant failure process. We show how breaching releases sediments at a constant and relatively slow rate while sliding rapidly releases an internally coherent wedge of sediments from the failure surface. Pore pressure measurements show that sliding induces a large drop in excess pore pressure that temporarily stabilizes the deposit. These large values of negative excess pore pressure then dissipate as breaching proceeds. We combine our observations

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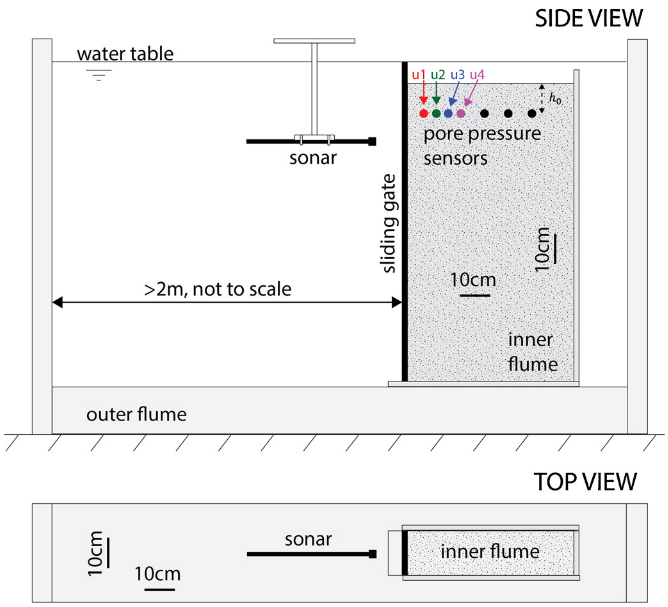

Fig. 1. Side view and top view of the setup of an experiment. The distance from the sliding gate to the left end of the outer flume is not to scale (too large to be included in this figure).

with a poro-mechanical model to show that this dissipation of the excess pore pressure causes sliding and the rate of excess pore pressure dissipation determines the frequency of sliding. Lastly, we use a numerical model to discuss the conditions that could lead to dual-mode failure instead of pure breaching in dilative deposits.

2. Experiment setup

Each experiment begins with the construction of a rectangular deposit out of siliciclastic, well-sorted fine sand ($D_{10} = 0.1$ mm, $D_{50} = 0.19$ mm, $D_{90} = 0.25$ mm) inside a gated-box referred to as the inner flume (Fig. 1). The inner flume is water tight on all sides except for the side with the gate; it rests within a larger, water-filled tank referred as the outer flume. The inner flume is 1.2 m tall, 0.15 m wide, and 0.58 m long and it constrains the deposit on all sides until the narrow vertical sliding gate is removed. The inner flume is positioned in the center of the outer flume with its sliding gate more than 2 m away from the end of the outer flume (Fig. 1, top view). This 2 m distance allows sufficient space for the failed sediments to flow away from the failing deposit.

We build each deposit by raining sediment through the water column at a controlled rate (2 m per hour). Because the sedimentation rate in the lab is much higher than that in the field, the lab deposit can have higher porosities than a deposit built with natural sedimentation rates (Vaid and Negussey, 1988). To densify the deposit, we tap the surface of the deposit under water with a rubber mallet when it was at $\frac{1}{3}$, $\frac{2}{3}$, and full height. At the end of sedimentation, we place 46 kg of deadweights on top of each fully built deposit for 24 hours to further densify the deposit. We place 6 thin (∼0.01 m), evenly spaced, horizontal layers of brown colored medium sand ($D_{50} = 0.3$ mm) to serve as marker beds to visualize deformation in the deposit. The average porosity of the deposit (n), calculated from the dry weight of the deposit and its final size, is ∼36%. The porosity used in the experiment is commonly observed in the field (e.g., Curry et al., 2004). Each final deposit is 0.58 m long, 0.15 m wide, and depending on the experiment between 0.96 m to 1.0 m tall.

We collect three types of measurements in each experiment. First, we record the pore pressure in the deposit with gauge pressure transducers at 7 locations along the length of the deposit and at a constant depth ($h_0 = 10$ cm, Fig. 1). The transducers, whose outer diameters are 2.4 cm, are placed outside of the outer flume and they are plumbed to the deposit with a series of thin tubes, whose outer diameters are 0.32 cm and inner diameters are 0.16 cm, to minimize the disturbance to the deposit. The distance between the sensors and the surface of the deposit varies between 0.08 m to 0.12 cm in different experiments. We place the sensors close to the top of the deposit because the pore pressure signal in the lower portion of the deposit is complicated by the adjacent re-deposition of failed sediments. The transducers record pore pressure at each location at a frequency of 1 Hz and an accuracy of 21 Pa.

Second, we measure the location of the failure surface with an ultrasonic transceiver. The sand–water interface has a large contrast in acoustic impedance that is imaged with the reflected acoustic wave. The transceiver collects acoustic data at a frequency of 10 MHz, and measures the distance between its head and the deposit–water interface to a resolution of 0.14 mm over a footprint of 1.8 cm^2. We orient the transceiver horizontally so that it measured the retreat of the roughly vertical failure surface at a position ∼16 cm below the top of the deposit (Fig. 1). With this configuration, the surface retreat measurements and the pore pressure measurements are collected close to each other. Videos capturing the evolution of the entire failing deposit are also collected during each run.

3. Dual-mode dilative failure

We initiate the experiment by quickly (in ∼2 s) pulling out the sliding gate from the inner flume. The deposit maintains a vertical surface, which we refer to as the failure front (Fig. 2A). The failure front retreats at a slow and steady rate of approximately 0.25 cm/s; as it retreats, sediment grains are released from the failure front (see also supplementary material Video 1). The falling grains generate sustained turbidity currents (Fig. 2A). These observations are consistent with pure breaching slope failure (Van Rhee and Bezuijen, 1998; Van den Berg et al., 2002; Eke et al., 2011; You et al., 2012).

After 10 s a slide plane oriented at 80° to the horizontal emerges (Fig. 2B). The sediment wedge above this plane starts to slide downward as a relatively coherent block. As the wedge slides, it deforms and entrains water until it fully disintegrates and becomes part of the turbidity current. After the wedge slides, breaching begins once again. During each breaching interval, the slope of the failure front steepens from ∼80°to ∼90°. Sometimes the slope even becomes overhanging. We call this cyclic failure process dual-mode dilative failure: the failure mode shifts cyclically between breaching and sliding for the duration of the experiment.

The failure front is imaged by the bright reflector on the ultrasound image (Fig. 2C). For example, point “a” in Fig. 2C shows that the failure front has retreated 8 cm at 25 s since removal of the gate. The steeper line segments record breaching as slow retreat of the failure front with time. Sliding is recorded by the nearly horizontal line segments which record rapid retreat of the failure front. The failure front moves toward the sonar for a few centimeters before it suddenly retreats (circled area in Fig. 2C). Because the wedge is wider near its top, the water-sediment boundary temporarily moves forward as the wider part of the wedge passes through the sonar measuring point. Sliding starts when the failure front moves forward and ends when the next breaching period (slow retreat) begins. The horizontal distance recorded by the sonar during this rapid retreat records the size of the horizontal thickness of the wedge; we refer to it as the sliding size (Fig. 2C). The sliding event that occurs at 62 s shows no forward moving component of the failure surface (boxed area in Fig. 2C) because