Laboratory Experiments of Bank Collapse: The Role of Bank Height and Near-Bank Water Depth

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Abstract We set up a laboratory experiment to reproduce flow-induced bank erosion and bank collapse and to study the role of bank height (Hb) and near-bank water depth (Hw) on bank stability. Five laboratory experiments were conducted in a plexiglass-walled soil tank, using silt collected from natural tidal channel banks (D30 = 75 µm). During each experiment, the bank was subject to a steady and uniform flow. We measured the variations in total soil stress, pore water pressure (when negative, called matric suction), and water content inside the bank and flow velocity and suspended-sediment concentration upstream and downstream of the bank. Results show that the experiments can reproduce four failure types commonly observed in nature including toppling, tensile and shear failures, and erosion and failure driven by loss of matric suction. The patterns of bank failure can be related to Hb/Hw. For large Hb/Hw (> = 2), we observe a cantilever-shape bank profile. For small Hb/Hw (<2), we first observe cracks on the bank top, followed by shear failures along a vertical or inclined surface separating the cantilever block up from the bank top. When accounting for our results in the context of previous experimental studies, we find a transition point characterized by a maximum normalized bank retreat rate. For toppling failures, we also find a positive correlation between the ratio Hb/Hw and the geometrical contribution to bank retreat from bank collapse (Cbc). Our research quantifies the role of Hb/Hw on bank collapse, bank retreat rate, and the overall Cbc.

Plain Language Summary The stability of river banks is a key process in river morphodynamics and of great relevance to river engineering and management. Progress in this area of research is hampered by the difficulty in obtaining measurements. Bank collapse is in fact a fast and often massive event, which is difficult to capture in the field. Using sediment collected next to a channel experiencing bank retreat, we set up a laboratory experiment to study and quantify the effect of the geometry of the channel on bank stability. Our experiments resulted in different types of bank collapse and indicate that the ratio between the height of the exposed part of the bank (bank height) and the height of the submerged part of the bank (near-bank water depth) controls bank stability. The role of the ratio between bank height and near-bank water depth has been long neglected, but our study shows that it plays a major role on bank collapse and retreat and so on the morphodynamic evolution of the entire channel.

1. Introduction

Bank erosion is of fundamental importance to the morphodynamics of fluvial, estuarine and coastal environments, affecting a wide range of physical, ecological, and socioeconomic processes. Bank erosion drives channel width changes (Deng et al., 2018; Deng et al., 2019; Eke et al., 2014; Lopez Dubon & Lanzoni, 2019; Zhao et al., 2019), serves as a major source of sediment load creating riparian habitats (e.g., floodplain and alternate bar) (Daly et al., 2015; Florsheim et al., 2008), and induces farmland and wetland loss (Deegan et al., 2012; Qin et al., 2018; Turner, 1990). Bank erosion is commonly categorized into flow-induced bank erosion and bank collapse (Simon et al., 2000; Thorne & Tovey, 1981). Bank collapse occurs when the driving forces that tend to move soil downslope (e.g., the weight of soil and plants, positive pore water pressure, and seepage forces) exceed the resisting forces of the bank (e.g., soil cohesion, matric suction, hydrostatic pressure, and vegetation roots) (Fox & Wilson, 2010; Langendoen & Simon, 2008;
Rinaldi & Darby, 2007; Thorne, 1982; Yu et al., 2020). On the basis of failure patterns, three principal mechanisms of bank collapse are defined as shear, toppling (beam) and tensile failure (Thorne & Tovey, 1981).

Bank collapse has been studied in both fluvial and tidal systems. For fluvial environments, a number of empirical and process-based numerical models have been proposed to investigate the role of different factors on bank collapse. For example, riparian vegetation (Simon & Collison, 2002), pore water pressure (Deng et al., 2018; Rinaldi et al., 2008), seepage flow (Rinaldi & Nardi, 2013), fluvial erosion (Motta et al., 2014), and bank stratification (Lai et al., 2015) have all been shown to play a major role in bank morphodynamics. In previous physical experiments, bank collapse/erosion has been suggested to be a trigger for river bank retreat, channel meandering, and cutoff (Braudrick et al., 2009; Dulal & Shimizu, 2010; Friedkin, 1945; Li et al., 2019; Li & Gao, 2019; Schumm & Khan, 1972; van Dijk et al., 2012; Visconti et al., 2010). Subsequently, many studies were carried out to analyze the failure mechanism of bank collapse in response to different driving forces. Wilson et al. (2006), for example, explored the impact of hydrologic properties on seepage erosion and the resulting streambank failure. Studies on the influence of bank height and slope, root reinforcement, and bank stratification on bank collapse in response to seepage flow were carried out by Fox et al. (2006), Fox et al. (2007), Cancienne and Fox (2008), and Lindow et al. (2009). The effect of soil physical and chemical properties on seepage erosion is highlighted by Masoodi et al. (2017, 2019). They suggested that with the development of seepage erosion, the riverbank may be subject to a cantilever failure (e.g., shear, toppling, and tensile failure).

Taking into account water level changes, Nardi et al. (2012) investigated the basic processes and possible factors of instability of relatively coarse (sandy-gravel) riverbanks. Contrary to cohesive banks for which bank failure commonly occurs during the falling water stage, they suggested that the reduction of apparent cohesion during the rising water stage accounts for the instability of banks composed of coarse material. This marks a significant difference in bank failure mechanisms between sandy-gravel and sand-clay banks. Arai et al. (2018) and Chen et al. (2017) explored the influence of bank height and slope on bank failure patterns by means of a compacted sandy bank exposed to an increasing or decreasing water level. Although these studies simulated bank collapse in response to flow infiltration and consequent variations in soil properties (e.g., soil density, water content, and pore water pressure), they did not consider the effect of lateral flow velocity and so of flow-induced bank erosion.

To explore the effects of fluvial erosion on the patterns of bank collapse, several laboratory studies were conducted (Patsinghasanee et al., 2015; Yu et al., 2015). Samadi et al. (2013) replaced fluvial erosion processes with artificial undermining and tested the importance of soil density and material type in the pattern of cantilever failures. The study shows that the occurrence of toppling failures is more probable than the simple shear-type mechanism. More recently, laboratory experiments have been conducted at much smaller scales than natural river channels (Patsinghasanee et al., 2017; Qin et al., 2018). Although downscaled physical modes are useful to obtain data on bank failure patterns (Wood, 2014), uncertainties on how to interpret the results remain partly because of the inconsistency between geometrical scaling and physical properties.

Seminal work on bank collapse in tidal environments was carried out by Van Eerdt (1985) and Gabet (1998), investigating the stability of cantilever-shape salt marsh banks and cliffs using beam failure analysis. Ginsberg and Perillo (1990) showed how bank collapse can lead to the development of erosional cuspatate shapes, suggesting that a large slope angle is the main cause for the slumping of the tidal channel bank. Recently, numerical models have been developed taking into account bank collapse from a combined perspective of geotechnics and soil mechanics. For instance, applying stress-deformation analysis, Gong et al. (2018) and Zhao et al. (2019) demonstrated that the bank failure pattern is related to bank height, and for cantilever failure a significant linear relation is found between bank height and the contribution of bank collapse to bank retreat. On the basis of an empirical relation obtained from the Western Scheldt, van Dijk et al. (2019) numerically investigated the role of shoal-margin collapse on channel-shoal dynamics, stating that shoal-margin collapse increases channel-shoal interactions.

With respect to physical experiments, many studies have been conducted to explore the influence of bank erosion/collapse on the initiation and development of tidal creek networks in response to different factors (Iwasaki et al., 2013) including tidal range (Stefanon et al., 2010) and tidal asymmetry (Geng et al., 2019). For toppling failure in salt marshes, Fracalanci et al. (2013) and Bendoni et al. (2014) stated that the
most critical conditions triggering marsh/cliff collapse under the action of wind waves depend on the presence of water inside the tension cracks and low water levels in front of the bank.

Although bank collapse resulting from fluvial erosion is explored in many experimental studies, few of them attempt to capture the variations in soil parameters (e.g., soil stress and pore water pressure) during bank collapse and further to relate the measured data to the observed bank collapse patterns. Besides, the scale of these experiments may preclude detailed observations and quantitative analysis of bank collapse. For instance, tension cracks and tensile failure occurring on the front surface of the bank (e.g., Figure 1a) are not reported. Therefore, developing laboratory experiments with limited scaling effects is imperative to capture the details of bank collapse. Here, we set up a laboratory experiment with a scale similar to natural systems, to reproduce bank collapse under the action of lateral fluvial erosion. The objectives of the present study are (1) to gain insight into the bank failure patterns in response to different ratios between bank height and near-bank water depth; (2) to analyze the role of bank height and near-bank water depth on bank retreat rate, and the overall contribution of bank collapse to bank retreat; and (3) to investigate the effect of bank collapse/erosion on flow velocity and suspended-sediment concentrations (SSCs).

2. Material and Methods

2.1. Study Background

Tidal channels in the Jiangsu coast (Jiangsu province, eastern China) are selected as a study case. The seaward part of the channels is unvegetated and subject to bank failure especially during ebb tide (Figures 1a and 1b). The objective of the present study is to set up a laboratory experiment with a scale similar to natural systems, to reproduce bank collapse under the action of lateral fluvial erosion. The focus of this study is to investigate the effect of bank collapse/erosion on flow velocity and suspended-sediment concentrations (SSCs).

Table 1

| N  | Date            | L   | \(\rho_s\) | \(\omega\) | c  | \(\phi\) | \(k_s\) | \(D_{50}\) | CF | MF | SF |
|----|-----------------|-----|------------|------------|----|--------|--------|---------|----|----|----|
| 1  | August 2016     | S6-u| 32.61      | 25.18      |    |        |        |         |    |    |    |
| 2  | July 2018       | S6-u| 1.85       | 45.12      | 18.23| 26.6   | 1.17   | 12.1    | 3.88| 87.63| 8.47|
| 3  | S6-l            | (--)| (--)       | (--)       | (--)| (--)   | (--)   | 9.2     | 6.61| 90.96| 2.43|
| 4  | S6-b            | (--)| (--)       | (--)       | (--)| (--)   | (--)   | 78.6    | 0   | 23.78| 72.45|
| 5  | S6-f            | (--)| (--)       | (--)       | (--)| (--)   | (--)   | 14.1    | 4.97| 89.32| 5.69|
| 6  | S7-u            | 1.96| 33.12      | 11.21      | 32.57| 7.21   | 62.2   | 0       | 44.15| 55.86|
| 7  | S7-m            | (--)| (--)       | (--)       | (--)| (--)   | (--)   | 61.9    | 0   | 45.37| 54.3|
| 8  | S7-I            | (--)| (--)       | (--)       | (--)| (--)   | (--)   | 64.1    | 0   | 40.46| 59.52|
| 9  | S7-f            | (--)| (--)       | (--)       | (--)| (--)   | (--)   | 84.9    | 0   | 16.96| 81.21|
| 10 | S7-u            | 1.99| 26.73      | (--)       | (--)| (--)   | (--)   | 79.8    | 0   | 10.28| 89.71|
| 11 | October 2018    | S7-u| (--)       | (--)       | (--)| (--)   | (--)   | 74.7    | 0.21| 38.26| 61.52|

Note. N: sample number; L: location; \(\rho_s\): soil density; \(\omega\): water content; c: soil cohesion; \(\phi\): internal friction angle; \(k_s\): saturated hydraulic conductivity; CF: clay fraction (<2 μm); MF: silt fraction (2–63 μm); SF: sand fraction (63–200 μm); u: upper part of the tidal channel bank; m: middle part of the tidal channel bank; l: lower part of the tidal channel bank; b: channel bottom; f: adjacent tidal flats. We refer the reader to the supporting information for the location of field data collection and soil material used for the laboratory experiment and the measurement method for the parameters listed in Table 1.
and 1b). At the sampling sites, the height of the scarp (i.e., bank height) ranges from 0.1 to 1 m and vegetation cover is sparse. The maximum flow velocity over the adjacent tidal flats ranges between 0.5 and 1.0 m/s (Gong et al., 2017).

Three field data collections have been carried out to achieve a general characterization of soil properties of the bank and the adjacent tidal flats (Table 1). Tidal channel banks are characterized by sand and silt...
without significant stratification. We observed a significant landward increase in soil cohesion, water content, and clay fraction, while soil density, internal friction angle, saturated hydraulic conductivity, and sediment grain size (e.g., $D_{50}$) decrease consistently landward. Nearly 9,000 kg of soil materials of the upper part of the bank (less than 0.5 m from the bank top) was collected and packed in Nylon bags and transported by boats and trucks to the laboratory.

2.2. Experimental Setup

The experiments were conducted in a glass-wall current flume 25 m long, 1.2 m wide, and 0.6 m deep (Figure 2a). Two water tanks were built at both ends of the flume and connected through an iron tube. A tailgate was set at the downstream end of the flume to control the water level. To ensure that the flow regime was steady and uniform before passing through the simulated channel bank, elements causing energy dissipation (i.e., gravels and cobbles) were placed at the upstream end of the flume.

A soil tank made of plexiglass was placed on one side of the flume with dimensions (length × width × height) of $3 \times 1.2 \times 0.6$ m (Figure 2a). To facilitate soil layer compaction, a wooden plate was fixed in front of the soil block using screws. Also, to reduce friction between soil block and the wooden plate, a plastic film was used.
to cover the whole wooden plate thus facilitating the removal of the plate after soil construction. After the construction of a soil block, the wooden plate was carefully unscrewed.

The bank was simulated using the soil materials collected from the field site. Following Nardi et al. (2012), the bank was progressively built by creating a series of 20-cm-high layers. For each layer, 1,440 kg of bank soil was packed to achieve the expected soil density (2.0 g/cm³). Two hand hammers with an area of 100 and 300 cm² were used to compact each soil layer. During the first experiment (EXP1 in Tables 2 and 3), we observed that under the beat of the hammers, soil liquefaction took place. This process makes it hard to keep material scaling dimensionally consistent between laboratory model and prototype (see Samadi et al., 2013, and Wood, 2014, for more details). While we focus on the role of bank height and near-bank water depth on bank collapse patterns and resultant bank retreat rate, we also need to acknowledge, despite our efforts, the possibility of scaling effects due to the difficulty of reproducing natural material. To facilitate soil layer compaction while minimizing liquefaction, we made several 1-cm-diameter holes at the back wall of the soil tank to drain the excess water. Each layer was left under self-weight for about 16 hr after compaction to allow for sufficient drainage and consolidation. The final achieved soil density of the simulated bank (around 1.85 g/cm³) is lower than the designed one (2.0 g/cm³) with water content decreased by nearly 16.9%. When achieving the prescribed bank height, the soil block was left under self-weight for another 60 hr before the removal of the front wooden plate. We also considered the option of a static load similar to that employed by Nardi et al. (2012) and Francalanci et al. (2013), but this option was excluded for two reasons. First, the area of the compaction surface is so large (1.2 × 3 m) that would require several static load plates causing problems at the junction between adjacent plates. Second, the method of static load hardly achieves the designed soil density, possibly leading to the occurrence of mass failure immediately after the removal of the front wooden plate (see Nardi et al., 2012). After the construction of the soil block, a set of white orthogonal grid lines was painted on the front and top surface of the middle part of the bank (from 0.3 m to 2.7 m in x direction, see Figure 4) with a spacing of 0.4 m in the longitudinal and 0.1 m in the latitudinal directions (Figure 3). These grid lines were used to quantify bank retreat distance and the size of tensile failure on the front surface of the bank. Contrary to Samadi et al. (2013), the built bank is used to conduct experiments without releasing the focused stress at the soil-tank boundary. The focused soil stress is induced by soil layer compaction and might be a reason for the arcuate-shaped bank line observed in previous and present studies (e.g., Figures 3b-3 and 4 and Patsinghasanee et al., 2017). To reduce the above effects, only the central part of the bank (i.e., bank with white grid lines) is used to analyze collapse patterns and to calculate bank retreat rates. The built bank soil profile is shown in Figures 3a-1 and 3c-1.

Flow velocity probes (CSY02-8, made by Nanjing Hydraulic Research Institute with accuracy around 0.01 m/s) to measure the near-bank and midchannel flow velocity were located 1 m away from the bank in the upstream and downstream directions. To measure the real-time variations in SSC before and after the bank, two optical backscatter sensors (OBS-3+) were installed upstream and downstream of the bank. Pore water pressure, total stress, and water content of the bank soil were measured by a series of tensiometers, stress, and soil moisture sensors, positioned at different distances from the bottom and front surface of the bank. In EXP2, the soil moisture sensor was not used and the tensiometers were installed at the back of the bank. In EXP3-5, we used the soil moisture sensor and the tensiometers were installed near the front surface of the bank. Planimetric and vertical positions of each instrument during the five experiments are listed in Table 2.

To record the deformation and failure process of the soil block, we used (1) a digital camcorder SONY AX45 recording at a rate of 24 frames per second (fps) installed in front of the soil block at the opposite side of the flume for continuous recording (with 3,840 × 2,160 pixels resolution); (2) a digital camcorder SONY CX680 for continuous photographing of the top of the soil block (with 1,920 × 1,080 pixels resolution); and (3) a mobile phone to record images of small-scale bank failure (e.g., tensile failure on the front surface of the bank).

2.3. Experimental Procedures and Data Collection

Five laboratory experiments were carried out with different bank height and near-bank water depth. A bank height of 0.6 m was applied in EXP1-3, then the bank height was decreased to 0.4 and 0.2 m in EXP4 and EXP5, respectively. The near-bank water depth was set to 0.15 m in all experiments except for EXP2 (when it was set to 0.3 m). Other variables (e.g., soil density and water content) before and after each experiment are summarized in Table 3.
To be consistent with field observations at the location where the material was collected, the surface layer flow velocity in the flume was set to 0.4 m/s. Because the flume bottom is flat, a “return flow” was observed when the flow approaches the tailgate. Large turbulence may be present in front of the bank resulting from

Figure 3. Photos of bank profile evolution during each experiment: (a) EXP1: bank height ($H_b$) = 0.6 m and near-bank water depth ($H_w$) = 0.15 m; (b) EXP2: $H_b$ = 0.6 m and $H_w$ = 0.3 m; (c) EXP3: $H_b$ = 0.6 m and $H_w$ = 0.15 m; (d) EXP4: $H_b$ = 0.4 m and $H_w$ = 0.15 m; (e) EXP5: $H_b$ = 0.2 m and $H_w$ = 0.15 m. L1 and L2 in subplot d-6 are used in Figure 6 to indicate the position of the flow velocity probe. The different colors of the bank surface are caused by the use of different light sources.
“return flow” at the beginning of the experiment, leading to significant bank erosion. To eliminate this effect, a low flow discharge was applied until the water surface was higher than the tailgate.

For each experiment, flowing water upstream and downstream of the bank was sampled to calibrate the two OBSs. The time of sampling was selected as follows: (1) at the beginning of the experiment when water was relatively clean; (2) when significant bank erosion was observed; (3) when small-scale bank failure was observed (e.g., tensile failure of the cantilever); (4) when collapsed bank soil was eroded resulting in a significant increase in SSC; and (5) at the end of the experiment. The soil moisture sensor was calibrated using the oven drying method.

After each experiment, soil samples were collected to measure the geotechnical parameters, including soil density (core cutter method), water content of the bank top soil (oven drying method), soil cohesion and internal friction angle (direct shear test), and saturated hydraulic conductivity (falling head method).

We also used a soil lysimeter to measure the flow-induced bank erosion rate in response to different combinations of near-bank flow velocity, soil density, and hydrostatic pressure (Figures 2d and 2e). The soil lysimeter was divided into several 5-cm-high layers, to minimize the occurrence of bank failure (Figure 2e). The rate of flow-induced bank erosion was calculated according to the difference in soil mass before and after the lysimeter experiment. We repeated the lysimeter experiment in response to different flow velocity with constant soil density (1.7 and 1.9 g/cm³) and hydrostatic pressure (5 cm between water surface and the upper boundary of the soil).

All the data collected during each experiment were processed and analyzed through the following four steps: (1) systematic identification and classification of all bank failures; (2) analyzing evolution of bank line extracted from videos and photos; (3) analyzing temporal trends of geotechnical parameters (total soil stress, pore water pressure, and water content); and (4) analyzing temporal trends of hydrological parameters (flow velocity and SSC). To facilitate the description of the results, the observed patterns of bank failures during each experiment are defined and classified following Thorne and Tovey (1981) and Nardi et al. (2012) and summarized as follows:

1. Tensile failures. This type of failure is the most frequently observed bank failure, commonly occurring in the middle and lower part of the front surface of the bank. Characterized by the presence of a tension
crack, tensile failure can be described as a combination of detachment of bank material under tensile stress along a horizontal or cuspate shape and a slight rotational component, leading to the collapse of bank material and the formation of an alcove–shaped surface (we use the term “cuspate” to indicate a planar shape and “alcove” to indicate a three-dimensional erosional surface. See videos in the supporting information).

2. Erosion and failure resulting from loss of matric suction. This process can be considered as the consequence of tensile failures and results in the commonly observed cuspate shape close to the water surface.

3. Toppling or beam failures. Characterized by a rotational component of the movement, toppling is often the consequence of small-scale bank failures, accompanied by one or several deep tension cracks on the bank top.

4. Shear failures. Shear failures can be defined as failures occurring by shear along a vertical or inclined surface delimiting the cantilever block up from the bank top.

Videos of each failure type are available in the supporting information providing the best means of visualizing the processes as they occurred.

To draw a more generic conclusion, we define a dimensionless normalized bank retreat rate as

$$r = \frac{R_r}{v} \frac{w_t}{w_c}$$

where $r$ is the dimensionless normalized bank retreat rate, indicating the type of mechanisms of bank retreat which is related to bank collapse patterns and frequency, $R_r$ is bank retreat rate (m/s), $v$ is flow velocity (m/s), $w_c$ is the channel width (m) and $w_t$ is the overhanging block width (m). $w_t/w_c$ accounts for the effect of slump blocks on bank retreat rate.

The contribution of bank collapse to bank retreat ($C_{bc}$) can be calculated as

$$C_{bc} = 1 - \frac{R_e}{R_r} \frac{H_w}{H_p}$$

where $R_e$ is the rate of flow-induced bank erosion and $R_r$ is the rate of bank retreat.

| Table 4 | Summary of Failure Types and Time in Each Experiment |
|---------|--------------------------------------------------|
| EXP1    | EXP2    | EXP3    | EXP4    |
| Failure type | Time (s) | Failure type | Time (s) | Failure type | Time (s) | Failure type | Time (s) |
| SF      | 699     | SF      | 918     | SF      | 918     | SF      | 611     |
| SF      | 790     | LF      | 949     | SF      | 943     | SF      | 632     |
| SF      | 855     | SF      | 1,483   | SF      | 1,018   | SF      | 657     |
| SF      | 875     | SF      | 1,597   | SF      | 1,099   | SF      | 665     |
| SF      | 897     | SF      | 1,646   | SF      | 1,178   | SF      | 711     |
| SF      | 983     | SF      | 1,747   | SF      | 1,388   | SF      | 797     |
| SF      | 1,108   | SF      | 1,789   | SF      | 1,531   | SF      | 839     |
| SF      | 1,114   | LF      | 2,002   | SF      | 1,560   | SF      | 866     |
| SF      | 1,118   | SF      | 2,461   | LF      | 2,045   | SF      | 896     |
| SF      | 1,280   | LF      | 2,980   | SF      | 964     |      |
| SF      | 1,330   | SF      | 979     | SF      | 1,055   |      |
| SF      | 1,390   | LF      | 1,081   | SF      | 1,112   |      |
| SF      | 1,550   | SF      | 1,361   | LF      | 2,147   |      |
| SF      | 1,626   | LF      | 2,007   | LF      | 2,848   |      |
| SF      | 2,007   | LF      | 2,397   | LF      | 3,271   |      |

Note: LF: large-scale bank failure (toppling failure in this research); SF: small-scale bank failures including tensile failure, shear failure, and erosion and failures because of loss of matric suction. Since more than 50 shear failures are observed during EXP5 without any other types of bank failure, we omitted it from the table.
3. Results

3.1. Occurrence of Bank Failure

The evolution of bank profiles and the occurrence of bank failures during each experiment are summarized using the photos reported in Figure 3 and the description of failure types in Table 4.

EXP1 ($H_b = 0.6$ m, $H_w = 0.15$ m, and $H_b/H_w = 4$). EXP1 was conducted without probes inside the soil block, hence could be used as a reference case to show the effect of probes on bank failure patterns. The start time was defined as the moment when bank started to be submerged by flowing water. After about 11 min, a small tension crack occurred in the left and lower portion of the bank, initiating a progressive deformation of the local bank profile. A small-scale tensile failure was observed after about 30 s (elapsed time 11 min 39 s), due to the weight of the soil below the crack (Figure 3a-1). Over the following 7 min, a series of tension cracks and consequent small-scale tensile failures developed in the lower part of the bank. The small-scale tensile failures did not cause significant accumulation of collapsed bank soil in front of the bank. The above small-scale tensile failures resulted in an arcuate alcove-shaped surface of the rest of the bank. The alcove-shaped surface was then eroded possibly as a result of (1) loss of matric suction and (2) an increase in the weight of soil mass. At elapsed time 25 min 37 s, a horizontal long tension crack occurred in the middle of the bank, immediately followed by a large-scale tensile failure leading to large collapsed bank soil at the bank toe (Figure 3a-2). During the following 8 min, several small-scale tensile failures and one large-scale tensile failure were observed, causing an evident cantilever shape of the bank. The cantilevered bank was unstable and a toppling failure was observed immediately after the occurrence of a tension crack on the bank top (elapsed time 39 min 57 s, Figure 3a-3). At 54 min 31 s, another toppling was observed involving the left part of the bank and no other bank failures occurred until the end of the experiment (Figure 3a-4).

EXP2 ($H_b = 0.6$ m, $H_w = 0.3$ m, and $H_b/H_w = 2$). When flow velocity achieved the designed value (0.4 m/s in the surface layer), an increase in SSC near the bank was observed (Figure 3b-1). At 15 min 18 s, a small-scale tensile failure developed in the left and lower part of the bank just above the water surface, leading to the formation of an arcuate alcove-shaped surface (Figure 3b-2). Subsequently (elapsed time 15 min 49 s), a long and deep tension crack was observed on the bank top (Figure 3b-3), immediately followed by a massive toppling failure resulting in a nearly 0.2 m bank retreat of the whole bank. The collapsed bank soil became the bank toe, weakening the near-bank flow velocity and so providing protection to the rest of the bank (Figure 3b-4). After about 10 min (from elapsed time 24 min 43 s to 29 min 49 s), a succession of small-scale tensile failures destabilized the rest of the bank (Figure 3b-5). Consequently, a toppling failure occurred on the right part of the bank (elapsed time 33 min 22 s). The collapsed bank soil depositing at the bank toe (resulting from previous toppling) was not submerged, protecting the bank from direct bank erosion (Figure 3b-6). Over the next 16 min the collapsed bank soil was progressively eroded, and another toppling was observed on the left part of the bank at 49 min 40 s (Figure 3b-7). The shape of the final bank profile was characterized by a gentle slope region (i.e., bank toe) and a vertical scarp, agreeing well with the shape observed in natural channels (see Figure 2 in Gong et al., 2018).

EXP3 ($H_b = 0.6$ m, $H_w = 0.15$ m, and $H_b/H_w = 4$). A series of small-scale tensile failures was observed at 15 min 18 s, followed by erosion and failures (Figure 3c-1). Two large-scale tensile failures appeared in the middle of the bank at 18 min 19 s and 19 min 38 s respectively, significantly changing the shape of the bank profile (Figure 3c-2). Fourteen minutes later (elapsed time 34 min 5 s), several deep tension cracks were observed on the bank top, leading to a massive toppling failure with the maximum bank retreat distance around 0.4 m (Figure 3c-3). No other bank failures occurred under the protection of the collapsed bank soil until the end of the experiment (Figure 3c-4). Since bank failure patterns were identical between this experiment and EXP1, we could conclude that the installation of soil probes has a negligible effect on bank failure.

EXP4 ($H_b = 0.4$ m, $H_w = 0.15$ m, and $H_b/H_w = 2.67$). Significant bank erosion occurred at 4 min 26 s, indicated by a near-bank increase in flow turbidity (Figure 3d-1). During the next 13 min, we observed a succession of bank failures including small-scale tensile failures with both linear and cuspatte shapes (Figure 3d-2), followed by erosion and failure in the cusps of the arcuate alcove-shaped surface (Figure 3d-3). These failures commonly started at the interface of different sublayers of 0.2 m built during the compaction procedure, as also reported in previous studies (Nardi et al., 2012). Subsequently, four toppling failures accompanied by a small-scale tensile failure were observed at 18 min 1 s, 22 min 41 s, 35 min 47 s, and 47 min 28 s (Figures 3d-4...
to 3d-7). The range of those toppling failures was around 1 m in the longitudinal direction (x direction in Figure 2) with the maximum bank retreat distance less than 0.2 m. Although the bank failure patterns were identical to the previous experiments (i.e., tensile failures in the middle and lower part of the bank followed by a toppling failure), the bank with smaller bank height seemed to be more stable (collapse-induced bank retreat distance was less than half of EXP3). Like previous experiments, the final bank profile was composed of a gentle slope region and a vertical scarp.

EXP5 ($H_b = 0.2$ m, $H_w = 0.15$ m, and $H_b/H_w = 1.33$). Contrary to previous experiments, tension cracks and tensile failures were absent in the front surface of the bank, possibly due to the small size of the cantilever (less than 0.05 m in the vertical direction) after flow-induced bank erosion. Instead, tension cracks were firstly observed on the bank top (Figure 3e-1), followed by a viscous-like slow movement of the soil along a vertical or inclined surface separating the cantilever block up to the bank top (Figure 3e-2). This type of failure could be classified as shear failure and was commonly observed in small-scale tidal creeks where bank height was small, less than 0.4 m, with a relatively large near-bank water depth (Figure 1b). This type of failure was observed only during EXP5 where the ratio of bank height to near-bank water depth was relatively small. The behavior of the previously described shear failures was partly similar to soil creep which was commonly reported in salt marshes although with a faster rate of deformation (Mariotti et al., 2019). Since the ratio of bank height to near-bank water depth was small, hydrostatic pressure exerted to the rest of the bank after bank erosion was large resulting in the absence of toppling failures. As a result, bank retreat was characterized by a progressively slow and parallel movement without a locally sudden change in bank width (Figure 3e-3). More than 50 shear failures were observed until the end of the experiment, and the final bank was characterized by a gentle slope with a negligible scarp (Figure 3e-4).

3.2. Temporal Change of the Bank Line

The evolution of the bank line for each experiment is shown in Figure 4. Since there was no toppling failure in EXP5 and no detailed data were recorded in EXP1, only bank lines in EXP2-4 are presented. The bank line after the first toppling failure was characterized by an arcuate shape with the maximum bank retreat distance ($D_m$) commonly occurring in the middle of the failure region. During the first toppling failure, both EXP2 and EXP3 underwent a significant bank retreat covering the whole region of the photo, while the failure length (x direction) of EXP4 was around 1.2 m (Figure 4a). $D_m$ observed in EXP3 was around 0.4 m during the first toppling failure, nearly twice as large as that observed in EXP2 and EXP4. The smallest failure region was observed in EXP4 indicating that bank stability increases with a decrease in bank height. Compared to EXP2, a larger failure region and $D_m$ were found in EXP3, indicating a nonnegligible effect of near-bank water depth on bank stability. An increase in near-bank water depth implied a larger hydrostatic pressure, which provided a supporting force and prevented the bank from a massive failure. This was also indicated by the similar $D_m$ observed in EXP2 and EXP4 where the ratio of bank height to near-bank water depth was almost the same but with different bank height.

A large increase in the area of the failure region and in $D_m$ was detected at the end of the experiment, as bank height increased (except for EXP3, Figure 4b). $D_m$ observed in EXP2 and EXP3 was around 0.4 m, nearly twice as large as EXP4 and EXP5. The arcuate-shaped bank line induced by the first toppling failure gradually turned into the nearly linear shape parallel to the x axis, resulting from subsequent flow-induced bank erosion and bank failures. We expected the area of failure region in EXP2 to be larger than that observed in EXP3 at the end of the experiment (water depth was initially larger in EXP2 than in EXP3). Since the collapsed bank soil was eroded more frequently during EXP2 (larger near-bank water depth), other types of bank erosion occurred leading to continuous bank retreat. Instead, during EXP3, the collapsed bank soil was still present at the end of the experiment (Figure 3c-4), and no changes of the bank line was observed after the first toppling failure.

3.3. Geotechnical Parameters

Results reported in Figure 5 show the temporal trends of total soil stress, pore water pressure, and water content and the occurrence of bank failures during each experiment.

EXP2 ($H_b = 0.6$ m, $H_w = 0.3$ m, and $H_b/H_w = 2$). During the first 5 min, soil stress measured at T1 increased rapidly as a result of bank toe erosion (Figure 5a). Subsequently, bank soil over T1 and below T3 was eroded by flowing water, accounting for the continuous decrease at T1 and T3. Contrary to T3, soil stress at T1 was
larger than 0 due to the formation of the new bank toe. A slight increase at T2 and T4 was observed during the first 15 min resulting from a slow infiltration of the flowing water. Since the near-bank water depth was 0.3 m, soil material surrounding T2 and T4 could be saturated. At 15 min 49 s, a toppling failure occurred leading to a release of soil stress, indicated by the sudden decrease at T2 and T4. T2 and T4 continued to increase because of flow infiltration. Unfortunately, the power supply of the stress sensors broke at 29 min and the trends of soil stress during the next toppling failures could not be recorded. As expected, pore water pressure increased with time (Figure 5b). Since the tensiometers were installed at the back of the bank, pore water pressure of P1, P2, and P3 were less than 0, indicating they were not saturated. EXP3 ($H_b = 0.6$ m, $H_w = 0.15$ m, and $H_b/H_w = 4$). The trends of the total soil stress were identical to EXP2, except for a slower increase rate of T4 resulting from the smaller near-bank water depth (Figure 5c). As expected, pore water pressure increased with water content (Figure 5d), and the magnitude of pore water pressure at the tensiometers P1 and P3 was much larger than at P2 and P4. The fluctuations of the pore water pressure were induced by the fluctuation of the water surface and the imperfect adherence between the material and the porous cup of the tensiometers. At 12 min, pore water pressure became positive at P1, and the material surrounding the soil moisture sensor was close to saturation, with a water content equal

Figure 5. (a–h) Temporal evolution of total soil stress, pore water pressure, and water content. Arrows indicate the occurrence of bank failure. The gray line indicates water content (not available in EXP2). Large arrows represent toppling failure, while the small arrows indicate tensile failures, erosion, and failures resulting from a loss of matric suction. Position of sensors can be found in Figure 2 and Table 2. Since more than 50 shear failures are observed during EXP5 without any other type of bank failure, we omitted them from the figure.
to 41.4%. The soil moisture sensor was partly exposed to the air due to previous bank failures, and the measured water content decreased. At 34 min 5 s, the pore water pressure measured in the middle and lower part of the bank (P3) reached its maximum, followed immediately by a toppling failure, possibly indicating the contribution of matric suction on bank stability.

EXP4 ($H_b = 0.4$ m, $H_w = 0.15$ m, and $H_b/H_w = 2.67$). Like previous experiments, soil stress at T1 first increased and then decreased asymptotically (Figure 5e). At 10 min, pore water pressure became positive at P1, followed by a sequence of tensile failures (Figure 5f). The occurrence of tensile failures in turn facilitated cantilever formation, leading to a significant increase in total stress at T3 (more details are provided in section 4.1). At the same time, pore water pressure measured in the middle of the bank (P3) gradually increased, weakening the strength of the bank soil. Subsequently, an instantaneous sharp reduction at T3 was observed due to the occurrence of a toppling. At 35 min 47 s, the tensiometer P3 fell into the water together with the collapsed bank soil, leading to a significant increase in P3. The water content of the saturated material for this test was 39.4%.

EXP5 ($H_b = 0.2$ m, $H_w = 0.15$ m, and $H_b/H_w = 1.33$). The trends of the total soil stress were identical to previous experiments and are not described here (Figure 5g). A continuous increase in pore water pressure at P1 was observed, followed by several shear failures which separated the cantilever block up to the bank top. Subsequently, the tensiometer P1 fell into the water and no data could be used. At 30 min, the pore water pressure at P2 started to increase, indicating low saturated hydraulic conductivity of the bank soil. The measured water content (around 35%) was lower than the saturation moisture content observed in previous experiments (around 40%). It is possible that the soil moisture sensor was affected by localized phenomena such as drier material (water content not uniform) or imperfect adherence between the material and the soil moisture sensors.

### 3.4. Flow Velocity and Suspended-Sediment Dynamics

Figure 6 shows the flow velocity and the occurrence of bank failure for each experiment. The midchannel and near-bank flow velocities were measured at locations M and N (characterized by different vertical positions, see Figure 2a and Table 2). At the beginning of each experiment, the flow velocity in the surface layer was nearly 0.4 m/s (blue line, Point M) and decreased to around 0.3 m/s in the middle layer (blue line, Point N), as a result of the vertical distribution of the velocity field. A detailed description of the effect of bank failure on flow velocity for each experiment is summarized below.

EXP1 ($H_b = 0.6$ m, $H_w = 0.15$ m, and $H_b/H_w = 4$). During the first 20 min, a similar magnitude of flow velocity was detected upstream and downstream of the bank. Then several large-scale tensile failures occurred, leading to the formation of a bank toe where flow concentrated (Figure 3a-2). Subsequently, we observed a slight increase in midchannel flow velocity downstream of the bank. Afterward, a large-scale tensile failure occurred involving the downstream boundary of the bank and a sharp decrease in near-bank flow velocity, from 0.3 to 0.1 m/s, was measured (elapsed time 27 min 6 s). The collapsed bank soil was then eroded over the next 10 min, with a gradual increase in flow velocity (yellow line in Figure 6b). At 39 min 57 s, a toppling failure occurred involving the right part of the bank (Figure 3a-3), resulting in a large increase in midchannel flow velocity, from 0.4 to 0.6 m/s, together with a remarkable decrease in near-bank flow velocity, from 0.3 to 0.05 m/s. The flow velocity progressively grew to the initial value as a result of the erosion of the collapsed bank soil. After about 15 min (elapsed time 54 min 31 s), another toppling failure occurred involving the left part of the bank which slightly affected the flow velocity.

EXP2 ($H_b = 0.6$ m, $H_w = 0.3$ m, and $H_b/H_w = 2$). Contrary to EXP1, only a slight variation in flow velocity was found in response to the occurrence of the toppling failure. Since the near-bank water depth was relatively large (0.3 m), the collapsed bank soil was immediately submerged (Figure 3b-4) or eroded (Figure 3b-6 and Figure 3b-7) and turned into bank toe (Figure 3b-8). The flow velocity in front of and behind the collapsed bank soil was measured, indicated by the green triangles and blue squares respectively in Figure 6c (sensor positions are shown as L1 and L2 in Figure 3d-6), and further erosion at the toe was prevented as a result of the relatively low flow velocity behind the collapsed bank soil.

EXP3 ($H_b = 0.6$ m, $H_w = 0.15$ m, and $H_b/H_w = 4$). Although several small-scale tensile failures occurred during the first 20 min (Figure 3c-1), a similar magnitude of the flow velocity was observed upstream and downstream of the bank. At 20 min, the tailgate inadvertently moved, resulting in the large decrease in flow velocity.
velocity. Then several large-scale tensile failures occurred (Figure 3c-2) leading to a decrease in near-bank flow velocity downstream of the bank (Figure 6f). At 34 min 5 s, we observed a massive toppling failure involving the whole bank, leading to large variations in the velocity field. Similar to EXP1, the collapsed bank soil increased the midchannel and decreased the near-bank flow velocities, respectively. For example, the midchannel flow velocity sharply increased from 0.3 to 0.55 m/s in response to the toppling failure (Figure 6e). Since the collapsed bank soil occupied a larger portion of the flume compared to EXP2, flow velocity increased significantly as a result of mass continuity (up to 0.6 m/s, green triangle in Figure 6e).

Figure 6. (a–h) Flow velocity during each experiment and occurrence of bank failures. US indicates upstream and DS downstream, and flow direction is consistent with Figure 2a. Arrows indicate the occurrence of bank failure. Large arrows represent toppling failures while small arrows indicate tensile failures, erosion, and failures resulting from a loss of matric suction. Position of sensors can be found in Figure 2 and Table 2. Green triangles and blue squares represent the flow velocity measured in front and behind the collapsed bank soil (see L1 and L2 in Figure 3d-6), respectively. The red circle indicates the flow velocity measured at the bank toe. Since the flow velocity probes were broken during EXP5, only EXP1-4 is shown here.
EXP4 ($H_b = 0.4$ m, $H_w = 0.15$ m, and $H_b/H_w = 2.67$). During the first 20 min, a progressive increase in mid-channel flow velocity was measured downstream of the bank resulting from the formation of a new bank toe. In contrast, the near-bank flow velocity firstly decreased and then increased as a result of the presence of the collapsed bank soil. At 35 min 47 s, a toppling failure involving the downstream boundary of the bank occurred, accounting for an evident decrease in near-bank flow velocity downstream of the bank. Negligible changes of mid-channel flow velocity were observed during the four toppling failures, indicating that the variations in downstream flow velocity depended on the exact location of the bank failure. At the end of the experiment, the near-bank flow velocity decreased to around 0.08 m/s because of the presence of a bank toe (red circle in Figure 6g).

The time series of SSC upstream and downstream of the bank are shown in Figure 7. At the beginning of each experiment, SSC downstream of the bank was at least 1 order of magnitude larger than that observed upstream. The occurrence of tensile and shear failure sharply increased the downstream SSC, particularly when collapsed bank soil was present. Since the collapsed bank soil was more vulnerable than bank soil and bank toe, SSC increased when the collapsed bank soil was present. A significant instantaneous increase in downstream SSC was commonly observed after the occurrence of bank failure, followed by a gradual decrease to the previous value. Taking EXP2 as an example, SSC sharply increased from 1.5 to 20 kg/m$^3$ at 33 min 30 s, then progressively decreased to 2 kg/m$^3$ during the following 12 min (Figure 7a). Then the downstream SSC decreased gradually as the experiment continued. In EXP5, the downstream SSC was even lower than the upstream. This could be attributed to the formation of a new bank toe, which reduced flow velocity (e.g., red circle in Figure 6g) and was hard to erode.

**4. Discussion**

We described the process of bank failure resulting from flow-induced bank erosion observed in each experiment in the previous section. Here, in order to gain more general insight, we consider the following three questions: (1) What drives the observed differences in bank failure behavior? (2) What factors may affect
the rate of bank retreat and the contribution of bank collapse to bank retreat ($C_{bc}$)? (3) What are the effects of bank collapse/erosion on flow velocity and SSCs?

### 4.1. Observed Mechanisms of Bank Failure

Toppling, tensile, and shear failures and erosion and failures caused by loss of matric suction are common types of bank failure reported in previous experimental studies (Arai et al., 2018; Francalanci et al., 2013; Nardi et al., 2012; Patsinghasanee et al., 2015; Samadi et al., 2013), and they have all been observed in our experiments. Several factors, for example, bank height, soil strength (or soil density), root reinforcement, and flow velocity, are evaluated in the above studies to investigate their effects on bank failure type. Hydrostatic pressure has a nonnegligible influence on bank stability (Gong et al., 2018; Simon et al., 2000) and may also affect bank failure patterns. Therefore, the ratio between bank height ($H_b$) and near-bank water depth ($H_w$) is here used to distinguish the two different mechanisms of bank failure (Figure 8).
For large \( H_b/H_w (H_b/H_w \geq 2) \) e.g., EXP1-4, left part of Figure 8), hydrostatic pressure at the bank toe is relatively small at the initial stage, compared to the stress exerted by the bank soil weight. Under the action of a torque, stress is focused near the bank toe after it has been scoured (Stage II, Figure 8b). This is accompanied by an increase in total soil stress at T1 (e.g., blue line in Figures 5a, 5c, and 5e). For example, T1 in EXP2 increases from 20 kPa to nearly 25 kPa in 5 min. However, Nardi et al. (2012) and Qin et al. (2018) argued that the infiltration of flowing water into the bank also facilitates an increase in the weight of bank soil, possibly increasing soil stress close to the bank toe. This hypothesis is rejected through the comparison of T1 and T3. In fact, even though, the planimetric positions of T1 and T3 are the same (Figure 2b and Table 2), the trends of T1 and T3 are different in response to water infiltration (Figures 5a, 5c, and 5e). At the same time, matric suction (indicated by pore water pressure) in the lower part of the bank sharply decreases to 0 as a result of infiltration (e.g., blue line in Figures 5d and 5f), weakening the strength of the bank soil. Consequently, several cracks may be present in the lower part of the bank (e.g., Figures 3a-1 and 3c-1).

During Stage III, tensile failures evolve from previous cracks, resulting in the formation of an alcove-shaped surface (Figure 3a-1), consistent with observations in natural channels (e.g., Figure 1a, Ginsberg & Perillo, 1990, and Perillo et al., 2018). For large-scale tensile failures, the failed bank material is deposited in front of the bank, promoting the formation of a new bank toe (Figures 3a-2 and 3c-2). Subsequently, erosion and failures driven by the loss of matric suction is present at the edges of the arcuate surface, which is close to the water surface (Figures 8c and 8d). This process can also be attributed to the drastic fluctuations of water surface resulting from the occurrence of other tensile failures.

The above two processes change the shape of the bank profile, leading to the formation of a cantilever Soil stress is then focused at the endpoint of the cantilever under the action of a torque (Figure 8d), which is associated with a rapid increase in total soil stress, as measured at T3 (e.g., red line in Figure 5e). Because of the absence of the lower part of the bank and the formation of the new bank toe, flowing water is directly in contact with the middle part of the bank (e.g., yellow line in Figure 5d). Therefore, the cantilever is extremely unstable particularly when deep tension cracks are present on the bank top. During Stage IV, a toppling failure is present immediately after the occurrence of several deep tension cracks on the bank top (Figure 8e). This observation is similar to that reported by Patsinghasanee et al. (2015) where tension cracks on the bank top seemed to develop only when the cantilever was close to failure. The collapsed bank soil deposits at the bank toe and reduces the near-bank flow velocity, thus providing a protection to the bank (e.g., near-bank flow velocity decreases to 0.08 m/s in Figure 6g). For EXP2 and EXP4, the collapsed bank soil is either eroded as suspended sediment or submerged by flowing water and converted into bank toe. Therefore, the cycle of bank retreat continues until the formation of a new gently sloped bank toe which is hard to erode. The final geometry is characterized by a gentle slope region (i.e., bank toe) and a vertical scarp (Figure 8i).

For small \( H_b/H_w (H_b/H_w < 2) \) e.g., EXP5, right part of Figure 8), a large hydrostatic pressure is present at the initial stage compared to the stress exerted by bank soil weight. During Stage II, soil stress is still focused on the bank toe but with lower magnitude, as a result of the smaller bank height (Figure 8g). For example, the increase in T1 is less than 2 kPa in EXP5 (blue line in Figure 5g). Because of the supporting forces provided by hydrostatic pressure, tensile and subsequent toppling failures are absent. Instead, cracks are present on the bank top, since matric suction in this region progressively decreases to 0 as a result of water infiltration (blue line in Figure 5h). During Stage III, shear failures occur along a vertical or inclined surface separating the cantilever block up to the bank top (dashed line in Figure 8g). The failed bank soil subsequently deposits and forms a new bank toe, which depending on \( H_w \) may or may not protect the bank from further erosion (Figure 8h). If the new bank toe is eroded, the cycle of bank retreat continues. The final geometry is characterized by a gentle slope region (i.e., bank toe) and an almost negligible vertical scarp.

### 4.2. Factors Affecting Bank Retreat Rate and \( C_{bc} \)

Bank retreat is commonly driven by flow-induced bank erosion and bank collapse in both fluvial and tidal environments (Darby et al., 2007; Gong et al., 2018). The rate of flow-induced bank erosion is mainly related to flow velocity and soil properties (e.g., critical shear stress for bank erosion), while the occurrence of bank collapse is subject to soil properties (e.g., soil cohesion and internal friction angle), bank geometry (e.g., bank height, \( H_b \) and bank slope), and near-bank water depth (\( H_w \)). The influences of flow velocity and soil properties on bank retreat rate have been investigated and reported by many studies (Patsinghasanee et al., 2017; Qin et al., 2018), while little attention has been paid to \( H_b \) and \( H_w \). Also, \( H_w \) plays a key role on bank collapse.
and significantly affects the rate of bank retreat. Increasing $H_w$ implies a larger erosion area, leading to more flow-induced bank erosion and consequently more frequent events of bank collapse. On the other hand, an increase in $H_w$ implies a larger hydrostatic pressure, providing supporting forces that reduce the frequency of bank collapse.

Figure 9a shows the correlation between the ratio $H_b/H_w$ and the normalized bank retreat rate ($R^2 = 0.81$). This positive correlation can be attributed to the fact that bank retreat is dominated by bank collapse and $H_b/H_w$ somehow represents the degree of bank stability. For large $H_b/H_w$ ($H_b/H_w > 10$), an increase in $H_b/H_w$ leads to a decrease in the normalized bank retreat rate ($R^2 = 0.9$). Since flow-induced bank erosion is a trigger of bank collapse, small $H_w$ results in small erosion volume and consequently slow bank retreat rate.

The correlation pattern between $H_b/H_w$ and the normalized bank retreat rate also indicates the existence of a transition point where the bank undergoes a maximum normalized retreat rate. In other words, the variation in near-bank water depth alone can remarkably affect bank retreat rate, indicating an inherent difference between fluvial and tidal systems. For river systems, the maximum flow velocity is commonly accompanied by the maximum water depth (i.e., flood), so the flow velocity and the normalized bank retreat rate are not maximized at the same time. For tidal systems, water level rises and falls cyclically and the minimum near-bank water depth during ebb tide changes significantly along the tidal channel (Figures 1a and 1b). Therefore, for tidal channels there might be certain sections where flow velocity and the normalized bank retreat rate reach their maximum at the same time, significantly widening tidal channels.

Previous studies (Gong et al., 2018; Samadi et al., 2013) applied stress-strain models and physical experiments to investigate the role of soil properties, flow velocity, and $H_b$ on the contribution of bank collapse to bank retreat ($C_{bc}$). However, few of these studies attempt to consider the influence of $H_w$, which significantly changes bank failure patterns through hydrostatic pressure and the loss of matric suction. Taking into account both $H_b$ and $H_w$, $C_{bc}$ can be calculated using equation 2 (see section 2.3). The value of $R_e/R_c$ is related to soil properties and hydrodynamics, and indicates the pattern of bank failures. If $R_e/R_c < 1$, toppling failure is present (e.g., EXP2-4). If $R_e/R_c = 1$, shear failure is present (EXP5). If $R_e/R_c > 1$, the bank is characterized by a cantilever shape as commonly observed in composite or salt-marsh channel banks (Gabet, 1998; Samadi et al., 2013).

Figure 9. Relation between $H_b/H_w$ and (a) the normalized bank retreat rate and (b) the contribution of bank collapse to bank retreat ($C_{bc}$). $H_b$: bank height; $H_w$: near-bank water depth.

Figure 10. The correlation between flow-induced bank retreat rate and flow velocity.
A strong linear correlation between flow velocity and the rate of flow-induced bank retreat is shown in Figure 10 \((R^2 = 0.93, \text{ see section 2.3 for more details})\). Flow velocity in the middle layer (0.3 m/s) is used to calculate the flow-induced bank retreat rate and resultant \(C_{bc}\). For EXP2-4, we calculate \(C_{bc}\) when toppling failure occurs. For EXP5, we choose five instances (elapsed time 7 min 31 s, 8 min 19 s, 10 min, 20 min and 30 min) to calculate \(C_{bc}\). The calculated \(C_{bc}\) is then averaged and shown in Figure 9b (detailed information is shown in Table S2 in the supporting information). The theoretical correlation between \(C_{bc}\) and the ratio \(H_b/H_w\) is shown in Figure 9b (red line), where we assume that the failure pattern is shear failure (i.e., \(R_s/R_r\) is set to 1). The measured \(C_{bc}\) for EXP5 lies on the theoretical red curve. With respect to toppling failure, \(R_s/R_r\) should be constant since soil properties and the magnitude of flow velocity are similar in each experiment (Table 3). The fitted \(R_s/R_r\) is equal to 0.35, agreeing well with the assumption that the failure pattern is toppling failure if \(R_s/R_r < 1\).

We expect a positive correlation between \(H_b/H_w\) and \(C_{bc}\) for toppling failures (EXP2-4). The large \(C_{bc}\) for toppling failure demonstrates that previous simplified representations of bank erosion severely underestimate the contribution of bank collapse to the planimetric and cross-sectional evolution of channels. Numerical models separately using near-bank flow velocity (e.g., HIPS model and Delft3D; Ikeda et al., 1981; Schuurman et al., 2013) or angle of incipient collapse and bank height (e.g., Nays2D; Asahi et al., 2013; Jang & Shimizu, 2005) to simulate bank erosion disregard bank collapse which instead should be taken into account from a combined perspective of geotechnics and soil mechanics. The correlation between \(H_b/H_w\) and \(C_{bc}\) is meaningful when simulating channel widening, since the bank retreat rate can be explicitly calculated according to the flow-induced bank erosion rate and bank failure patterns. Further research should be conducted to investigate the relation between \(R_s/R_r\) and soil properties (e.g., soil cohesion, internal friction angle, and water content).

4.3. Effect of the Collapsed Bank Soil

When bank collapse occurs, part of the collapsed bank soil is likely to deposit at the bank toe, changing the local topography of the channel in three ways. First, the collapsed bank soil restricts the flowing water thus affecting the near-bank hydrodynamics. On one hand, flow changes its direction and converges when passing through a cross section where collapsed bank soil is present (Figures 6a and 6e), leading to more bank erosion of the opposite bank in the downstream direction. On the other hand, the presence of the collapsed bank soil reduces the near-bank flow velocity (blue squares in Figures 6c and 6e), resulting in less bank erosion. This initial perturbation is likely to trigger a bend instability migrating in the downstream direction (van Dijk et al., 2012). Second, the collapsed bank soil is more vulnerable than bank soil, and the SSC shows a large increase after the occurrence of bank collapse (Figure 7). For example, SSC increases sharply from 1.5 kg/m³ to nearly 20 kg/m³ due to the presence of the collapsed bank soil (elapsed time 33 min 22 s in Figure 7a). Finally, the lower part of the collapsed bank soil may consolidate into a bank toe reducing bank slope. Since the presence of a bank toe increases bank stability, channel expansion occurs as a result of vertical deepening rather than lateral widening.

We plan further research based on laboratory and numerical experiments to improve the understandings of bank collapse. More laboratory experiment cases should be conducted changing soil properties (e.g., soil density, soil content, and clay-silt-sand fraction), to investigate their influences on \(R_s/R_r\) (equation 2). Second, a bank collapse model, able to take into account the variation in matric suction, is needed to gain more insight on the mechanism of bank collapse and to extend the parameter space over which the relation between \(H_b/H_w\) and bank failure types can be explored. Finally, the variation of water levels during tidal cycles should be considered to study the difference in bank collapse between fluvial and tidal systems.

5. Conclusions

Our research investigates the role of bank height \((H_b)\) and near-bank water depth \((H_w)\) on bank erosion and collapse using a laboratory experiment with a scale similar to natural systems. Our experiments are able to reproduce flow-induced bank erosion and bank collapse. Toppling, tensile, and shear failures, erosion and failures resulting from loss of matric suction are also observed.

For large \(H_b/H_w\) (≥2), cracks and consequent tensile failures are present in the front surface of the bank, mainly as a result of loss of matric suction, and the bank profile is characterized by cantilever shape.
Several deep tension cracks then occur on the bank top, followed immediately by toppling failure. Compared to EXP2 which is characterized by larger $H_w$, tensile failures occurred more frequently before toppling failures during EXP1 and EXP3, manifesting a nonnegligible effect of $H_w$ on bank failure. For small $H_b/H_w$, however, cracks are first observed on the bank top as a result of hydrostatic pressure, and then shear failures occur along a vertical or inclined surface separating the cantilever block up from the bank top.

An increase in $H_b$ or a decrease in $H_w$ leads to an increase in collapse-induced bank retreat distance after the first toppling failure with a maximum bank retreat distance up to 0.4 m. In contrast, the collapse-induced bank retreat distance at the end of the experiment decreases with a decrease in $H_w$, because of the protection effects of the collapsed bank soil.

For toppling failures, a positive correlation is observed between $H_b/H_w$ and the contribution to bank retreat from bank collapse ($C_{bc}$). The large $C_{bc}$ (more than 75%) demonstrates that previous simplified representations of bank collapse severely underestimate the effects of bank collapse on channel evolution.

Considering our results in the context of previous studies, we found a significant positive correlation between $H_b/H_w$ and the normalized bank retreat rate for small $H_b/H_w$ ($H_b/H_w < 7.5$, $R^2 = 0.81$). Instead, an increase in $H_b/H_w$ leads to a decrease in the normalized bank retreat rate ($R^2 = 0.9$) for large $H_b/H_w$ ($H_b/H_w > 10$). This demonstrates the existence of a transition point characterized by a maximum normalized bank retreat rate, indicating that the bank retreat rate is related not only to the flow velocity but also to the near-bank water depth. The role of $H_b/H_w$ has been long neglected but our study shows that this ratio plays a major role on the morphodynamics of bank erosion, collapse, and retreat, and so on the evolution of the whole channel.

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