International Journal of Sediment Research ∎ (∎∎∎∎) ∎∎∎–∎∎∎

Contents lists available at ScienceDirect

International Journal of Sediment Research

journal homepage: www.elsevier.com/locate/ijsrc

Original Research

Experimental investigation on cohesionless sandy bank failure resulting from water level rising

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ARTICLE INFO

Article history:
Received 25 August 2016
Received in revised form
5 June 2017
Accepted 22 August 2017

Keywords:
Riverbank erosion
Matric suction
Cohesionless bank
Tensile strength

ABSTRACT

In the last decade, sediment replenishment forming cohesionless sandy banks below dams has become an increasingly common practice in Japan to compensate for sediment deficits downstream. The erosion process of the placed cohesionless sediment is a combination of lateral toe-erosion and the following mass failure. To explore cohesionless bank failure mechanisms, a series of experiments was done in a soil tank using a compacted sandy soil mass exposed to an increasing water level. Two types of uniform sand (D_{50} = 0.40 mm and 0.17 mm) and two bank heights (50 cm and 25 cm) were used under the condition of a constant bank slope of 75°. The three dimensional (3D) geometry of the bank after failure was measured using a handheld 3D scanner. The motion of bank failure was captured using the particle image velocimetry (PIV) technique, and the matric suction was measured by tensiometers. The compacted sandy soil was eroded by loss of matric suction accompanying the rise in water level which subsequently caused rotational slide and cantilever toppling failure due to destabilization of the bank. The effect of erosion protection resulting from the slumped blocks after these failures is discussed in the light of different failure mechanisms. Tensile strength is analyzed by inverse calculation of cantilever toppling failure events. The tensile strength had non-linear relation with degree of saturation and showed a peak. The findings of the study show that it is important to incorporate the non-linear relation of tensile strength into stability analysis of cantilever toppling failure and prediction of tension crack depth within unsaturated cohesionless banks.
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1. Introduction

The sediment deficit below a dam has negative environmental and socioeconomic impacts on downstream areas (Fan & Springer, 1993). In the last decade, sediment replenishment below dams has become an increasingly common practice in Japan to compensate for these sediment deficits downstream (Ock et al., 2013). Cohesionless sand or gravel, which is generally used for sediment replenishment, is arranged along the channel bank margin so that the placed sediment is transported downstream without producing extra turbidity during a flood event (Ock et al., 2013). The erosion process of the placed sediment is generally a combination of lateral toe-erosion and the following mass failure (Kantoush et al., 2010). Therefore, it is important to understand the erosion process and the subsequent failure mechanism of cohesionless banks.

Previous studies have attempted to predict river bank erosion and failure by using numerical simulation based on non-cohesive sediment transport models. In conventional two-dimensional (2D) or three-dimensional (3D) simulation of non-cohesive sediment transport, a simple slope collapse model is applied to calculate the gravitational bank failure processes (e.g., Iwasaki et al., 2016; Schuurman et al., 2016). In this model, if the angle of bed slope along the bank line exceeds a critical angle (e.g., the angle of repose), the bank failure and the corresponding local deposition on the bed are computed so as to become smaller than the critical angle. This approach treats the bank failure process without considering geotechnical factors of the bank such as matric suction and shear strength. However, Nardi et al. (2012) found various types of bank failure caused by a loss of matric suction even in cohesionless material. Therefore, prediction models of bank failure should consider these geotechnical effects.

Unlike conventional non-cohesive sediment transport models, numerical models such as the Bank Stability and Toe Erosion Model (BSTEM; Simon et al., 2000) and the Conservational Channel Evolution and Pollutant Transport System (CONCEPTS; Langendoen &

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http://dx.doi.org/10.1016/j.ijsrc.2017.08.002
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Please cite this article as: Arai, R., et al. Experimental investigation on cohesionless sandy bank failure resulting from water level rising. *International Journal of Sediment Research* (2017), http://dx.doi.org/10.1016/j.ijsrc.2017.08.002

Simon, 2008), which were developed by the U.S. Department of Agriculture (USDA), and the model of Darby et al. (2007) compute bank failure on the basis of geotechnical factors at the target bank. These models consider actual riverbank geometry, the effect of bank material heterogeneity (i.e. composite structure), hydraulic erosion, and the effect of saturated–unsaturated conditions for bank stability in analyzing bank stability based on the limit equilibrium method. In fact, many researchers have successfully applied these models to actual riverbanks (e.g., Daly et al., 2015; Luppi et al., 2009; Midgley et al., 2012; Rinaldi et al., 2008). However, to the best of our knowledge, these models have not been applied to the failure of cohesionless banks, which is in the focus of the present work.

Many researchers have done experiments with meandering channels consisting of non-cohesive sand (e.g., Friedkin, 1945; Schumm & Khan, 1972; van Dijk et al., 2012). Most of these experiments focused on the bank erosion caused by bed shear stress rather than bank failure related to geotechnical factors. Although many experimental studies have focused on seepage erosion induced by lateral subsurface flow towards the riverbank and the related bank failure (e.g., Chu-Agor et al., 2009; Fox et al., 2006; Karmaker & Dutta, 2013), only a few experimental studies have focused on the bank failure process (i.e. Nardi et al., 2012; Samadi et al., 2013). Samadi et al. (2013) did experiments of cantilever failure by manually removing the lower parts of a compacted soil mass in an experimental box. Nardi et al. (2012) assigned bank space and water tank space in an experimental box. They supplied water into the tank space and caused the soil mass to collapse due to saturation and loss of matric suction resulting from the increase in water level. They reported that loss of matric suction can trigger large-scale bank failure even in static water. Their experimental method is suitable for observation of the failure mechanism of cohesionless banks because it was able to generate various types of failure including cantilever failure, slab failure, slide, and dry granular flow. However, the experimental conditions used in Nardi et al. (2012) and Samadi et al. (2013) were limited; knowledge of the bank failure process remains insufficient. In particular, the influence of bank materials and bank height remain unclear, which are important for modeling of bank failure.

In the present study, a series of bank failure experiments were conducted in a soil box to explore cohesionless bank failure by focusing on the influence of sand type and bank height in consideration of the matric suction. Moreover, the study attempts to determine the velocity of collapsing bank blocks and 3D geometry of a failed bank to quantitatively examine the effects of bank height and particle size.

2. Experimental methodology

The experimental soil box, 1.00 m, 2.00 m, and 1.00 m in width, length, and height, respectively, was composed of wood except for one lateral wall of acrylic glass constructed to enable observation of the failure mechanism in detail (Fig. 1(a)).The soil box was divided into bank space and tank space (Fig. 1(b)). For uniformity in the frictional condition between the lateral wall and bank, clear polycarbonate sheets were affixed on both sidewalls. A pipe was installed to supply water, and a drainpipe with a flowmeter (FD-V70, Keyence Co., Ltd.) was installed to adjust the water level. A high-permeability vanishing wave mesh was inserted to absorb

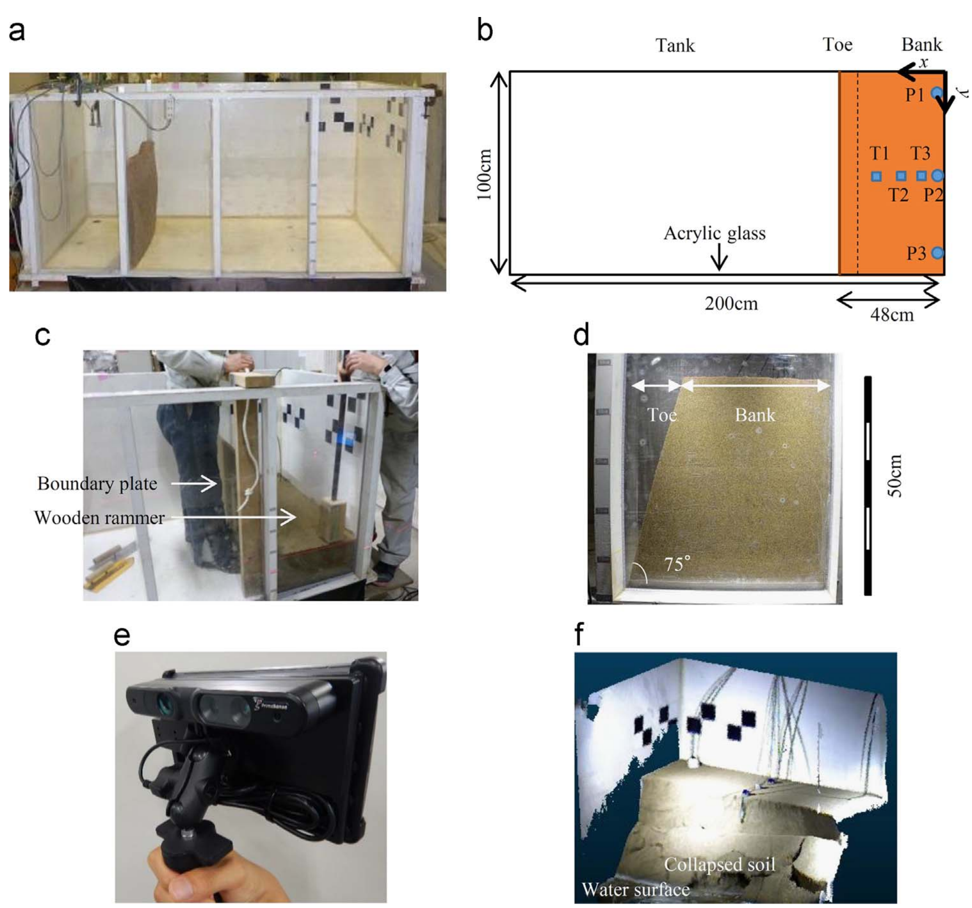

Fig. 1. Experimental soil box and 3D scanner. (a) Lateral view; (b) plan view (P: soil moisture probe, T: tensiometer); (c) compaction using a wooden rammer; (d) side view in which the bank was cut at an angle of 75°; (e) 3D scanner; and (f) example of point cloud data captured by the 3D scanner. The order of failure in (f) is III in EXP1 (Table 3), and the failure type is (b) corresponding to Fig. 3 (i.e. rotational slide).

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