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Investigating effect of water level variation and surface tension crack on riverbank stability

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ABSTRACT

During high flow season, the rise and fall of river water level could induce riverbank instability and threaten structural safety of flood-protection facilities on floodplains. Through a flume experiment, this paper investigates the influences of three factors (namely, drawdown rate of river stage, initial water elevation, and riverbank slope angle) on riverbank stability due to the fall of river water level. From the laboratory experiments it was observed that tension crack appeared in all riverbank failure cases and all failure patterns were of planar type. Moreover, this paper presents a riverbank stability analysis model that explicitly incorporates the integral effect of all forces acting upon the failure plane and tension crack. The prediction accuracy of the proposed model is examined by using experimental data obtained in this study and field data of the Hotophia Creek in the USA and the Sieve River in Italy. A comparison of model simulation results with and without considering tension crack clearly indicates the importance and necessity of including tension crack for achieving good accuracy in riverbank stability simulations. For practical application of the improved riverbank stability model, two empirical formulas for estimating tension crack location and failure plane angle were examined and modified to enhance their appropriateness in riverbank stability simulation. Finally, the improved model with the modified empirical formulas was verified to show its good prediction in riverbank stability analysis.

1. Introduction

Human activities and developments in floodplains are generally restricted. The lands are often used for agriculture productions, parking lots, or recreational uses. Major floods can cause riverbank failure due to high flow velocity and pore-water pressure build-up inside the bank soil media. The process could induce riverbank instability which threatens the safety of flood-protection structures on floodplains.

Chu-Agor et al. (2008) conducted a flume experiment to investigate the influences of groundwater level gradient within the bank soil media on riverbank failure pattern. Their findings were that when change in groundwater level gradient is relatively mild, the riverbank soil body will fail in the form known as the planar failure (see dash line in Fig. 1). When change in groundwater level gradient is relatively large, the soil particles near the toe of riverbank can be removed resulting in a hollow bottom section of the riverbank in the form of a cantilever structure. Eventually, the riverbank collapsed under its own weight, known as the cantilever failure. The second type of failure pattern is not considered in the current study. Casagli et al. (1999) and Rinaldi and Casagli (1999) analyzed the change in pore-water pressure inside the riverbanks of the Sieve River, Italy and found that matric suction, which reflects unsaturated pore-water pressure, greatly contributes to riverbank stability, particularly when groundwater levels were low. Fox et al. (2007), through the analysis of soil properties of the Goodwin Creek riverbank in the USA, indicated that riverbank soil could appear in layers resulting from sediment erosion and deposition of multiple flood events. The stratified soil structure could create anisotropy in hydraulic conductivity which could induce preferential lateral flow movement in layered soil leading to riverbank instability.

The aforementioned experiments focused primarily on the effects of changing groundwater levels on riverbank stability. However, during flood seasons, the rise and fall of river water level and

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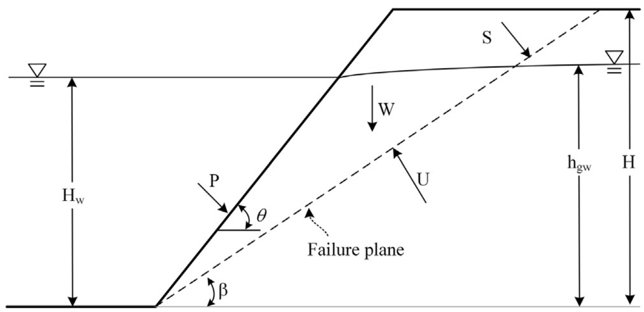

Fig. 1. Forces acting on the failure plane without tension crack.

groundwater table inside the bank have significantly different rates. The former could be in the order of meters per hour, whereas the latter is in milli-meters per hour. Thus, investigating the effect of forcing on riverbank stability resulting from significantly different scales in water level change poses a considerable challenge. As of now, most laboratory studies investigating the effect of relative change in river water level and riverbank groundwater table on bank stability focus on cantilever failure type due to erosion at the toe of the bank. Nardi et al. (2012) in their series of laboratory experiments observed that when river stage rises riverbank can lose its stability from toe erosion and reduced matric suction of soil particles inside the riverbank. As for planar failure, no studies can be found to investigate the combined effect of changing river water level and its interaction with groundwater level on riverbank stability.

In hydraulic design and analysis involving riverbanks knowledge about the processes and characteristics of riverbank failure is essential. Such knowledge can be directly obtained from laboratory experiments because such tests offer useful insights about the failure process and provide data to develop physically creditable simulation models or to improve existing ones. This study reviews presently available riverbank stability analysis models, their theoretical foundations in light of riverbank failure process observed in the experiment.

Study and analysis concerning riverbank failure typically adopt limited equilibrium approach to assess riverbank stability in which factor of safety (*FS*), defined as the ratio of resisting force (*FR*) to driving force (*FD*) on the failure plane (i.e., $FS = FR/FD$), is used as the indicator for the state of riverbank. When $FR < FD$ (or $FS < 1$), riverbank failure would occur. However, most riverbank stability models developed earlier do not consider tension crack. Fig. 1 illustrates the forces acting upon the failure plane without tension crack and they involve uplift force (*U*), matric suction (*S*), mass of failed block (*W*), and hydrostatic-confining force (*P*). Uplift force and matric suction are, respectively, due to pore-water pressure of saturated and unsaturated soils - they are closely related to groundwater level (h_{gw}). On the other hand, the hydrostatic-confining force is related to river water level (H_w). Rinaldi and Casagli (1999) and Chiang et al. (2011) indicated that hydrostatic-confining force and matric suction provide resistance against riverbank failure while mass of failed block and uplift force tend to induce bank failure.

Early developments for riverbank stability models largely focused on the mass of failed block (Lohnes and Handy, 1968; Spangler and Handy, 1973; Osman and Thorne, 1988; Thorne and Abt, 1993). Later, two other factors (i.e., river water level and groundwater table) were included (Simon et al., 1991; Darby and Thorne, 1996; Darby et al., 2000). In doing so, other than the weight of failed soil mass block, hydrostatic-confining force and uplift force in the saturated region below the groundwater level are also included in riverbank stability assessment. This extension, however, is still incomplete because it fails to consider the effect of matric suction in the unsaturated part of riverbank above the groundwater table inside the river bank. To incorporate the effect of matric suction on bank stability Rinaldi and Casagli (1999) developed a model to consider water level change in the river and within the bank. In their model groundwater level is assumed to move with the same rate upward as the river water stage during the rising period of flood whereas during the falling period the groundwater is kept at the level when river water starts to drop. This treatment will under-estimate matric suction within the bank soil media which leads to a prediction of bank failure sooner than what would actually occur. Simon et al. (2000) investigated the effect of matric suction by analyzing long-term data of the Goodwin Creek in the USA to explain the change in matric suction during the rise and fall of river flow as well as its influences on riverbank stability. It should be pointed out that all of the above-mentioned studies treated groundwater level as a horizontal line during the flood event. Although this treatment simplifies the riverbank stability analysis, the results of analysis could not reflect the fact that the rate of groundwater level changes differ from that of river water level by several order of magnitude and, thus, could not capture the relative dynamic changes in uplift force and matric suction inside the riverbank and their combined effects on riverbank stability.

Through one-dimensional Boussinesq equation for unconfined groundwater flow, Chiang et al. (2011) considered the change in groundwater level inside the riverbank and included the influences of all the forces (see Fig. 1) to develop a comprehensive riverbank stability model. However, Chiang's model is still inadequate in that the presence of tension cracks and their effects on riverbank stability are not considered. Thorne (1982) indicated in a case study that tension crack typically occurs with riverbank failure, which is also the phenomenon observed in this experimental investigation (described in Section 2). Although the model developed by Rinaldi and Casagli (1999) incorporates tension crack in riverbank stability analysis, it however treats the tension crack location and failure angle as known inputs. Therefore, their model is more suitable for postmortem assessment of riverbank failure events rather than for prediction. To enhance predictive capability of the riverbank stability model, means to accurately estimate tension crack position and riverbank failure plane angle must be incorporated in the simulation model along with all the forces acting upon the failure plane.

The paper consists of three main parts in which the first part describes a flume experiment to gain a better insight of riverbank failure process, to elucidate the influence of relative change between river water level and groundwater table on riverbank stability, and to collect data on riverbank failure characteristics (e.g., failure pattern, tension crack location, failure angle, etc.). In the second part, experimental data are used to examine the adequacy of existing riverbank stability models. An improved model is established from modifying a previous model to closely capture actual bank failure conditions observed in the experimental study. Finally, the improved riverbank stability model and the experiment data are used to assess the applicability of two frequently used empirical formulas for estimating tension crack location and failure plane angle in riverbank stability analysis. The empirical formulas with deficiency are modified if necessary, and the improved riverbank stability model with modified empirical formulas is verified with independently collected field data from the literature for its validity and generality.

2. Experimental setup and methodology

2.1. Bank stability parameters and design experiment

2.1.1. Bank stability parameters

The factors influencing the FS of a riverbank stability can be expressed as (Osman and Thorne, 1988; Darby and Thorne, 1996; Casagli et al., 1999; Rinaldi and Casagli, 1999; Simon et al., 2000; Simon and Thomas, 2002; Chiang et al., 2011):