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Experimental and numerical investigation of the stability of overhanging riverbanks

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ABSTRACT

Although different types of riverbank mass failure have been studied by many researchers, many uncertainties remain in predicting cantilever failures, in part because of a lack of detailed observations of this type of bank collapse. In this study, a laboratory study of cantilever failure was carried out using two types of materials to form overhanging banks with three different densities. The laboratory results show that the occurrence of toppling failures is more probable than the simple shear-type mechanism that has been analyzed most frequently by prior researchers. We go on to model these toppling failures numerically. Specifically, a Mohr-Coulomb model, within the framework of SIGMA/W software (ver. 7.17), was used to simulate the stress–strain behavior of the experimental banks. The numerical results for loess materials are in good agreement with the laboratory observations, but the simulations do not replicate experimental failures observed in higher density, more cohesive soils.

1. Introduction

Riverbank erosion is an important source of sediment production and remobilization in rivers, and as such, this phenomenon plays a key role in floodplain development and water resources management. Bank erosion also causes damage to agricultural lands and adjacent infrastructure and may be responsible for the delivery of large volumes of sediment, with associated sedimentation hazards in the downstream reaches of fluvial systems (Rinaldi and Casagli, 1999). Odgaard (1987) stated that the weight of silt and clay entrained into the water from cutbanks is estimated to be 30–40% of the suspended load for the East Nishnabotna and Des Moines Rivers in Iowa, USA. In the loess area of the Midwest United States, bank material contributes as much as 80% of the total sediment eroded from incised channels (Simon et al., 1996).

Accordingly, the assessment of riverbank stability is important in developing a full understanding of fluvial dynamics and in assessing the need for protection and stabilization of riverbanks in critical regions of erosion. A large number of riverbank stability analyses are already available (e.g., Thorne and Tovey, 1981; Van Eerdt, 1985; Osman and Thorne, 1988; Darby and Thorne, 1996; Rinaldi and Casagli, 1999; Simon et al., 2000; Amiri-Tokaldany, 2002; Micheli and Kirchner, 2002; Langendoen and Simon, 2008; Samadi et al., 2009; among others), but most of them are not able to analyze the overhanging bank profiles that are typically formed in composite or cohesive homogenous riverbanks (Samadi et al., 2011b). Composite riverbanks, typically consisting of a basal layer of relatively erodible material overlain by a less erodible layer (often of finer material), are widely observed on rivers flowing through alluvial deposits. Fluvial entrainment or seepage erosion of the erodible material from the lower bank usually occurs at a much higher rate than erosion of the less erodible material from the upper cohesive bank. In such circumstances this leads to the formation of a cantilevered (overhanging) bank profile, with upper bank retreat taking place predominantly by the failure of these cantilevers. However, relatively few studies have undertaken stability analyses of the overhanging blocks in composite riverbanks, though notable recent contributions have started to address the issue of undermining as a prerequisite for forming overhanging blocks (Fox et al., 2006, 2007a,b, 2010, among others). In addition, some workers have recently developed new bank stability relations for cantilevered riverbanks (Darby et al., 2007; Langendoen and Simon, 2008; Samadi et al., 2011b).

The seminal work on cantilevered riverbanks was by Thorne and Tovey (1981), who defined three possible failure mechanisms for such banks; i.e., shear, tension, and toppling (beam) failures. However, in the three decades since their paper, the critical assumptions

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employed in Thorne and Tovey's analysis and other similar analyses (e.g., Darby et al., 2007; Langendoen and Simon, 2008; Samadi et al., 2011a,b) have not yet been tested rigorously (Van Eerdt, 1985; C. Thorne, Univ. of Tehran, personal communication, 2007). Undoubtedly one of the reasons for this gap is related to the difficulties of undertaking field studies under the special conditions associated with cantilever failures (Samadi et al., 2011b). A particular problem concerns the hazardous nature of measuring the geometry of overhangs, while the situation is still more complicated if the failure takes place during the presence of water flow in the river. Thus, identifying the instantaneous mechanism of failure at the inception of failure is not easy.

By making some assumptions about the effective forces acting on the sliding surface, Van Eerdt (1985) introduced relationships to analyze the stability of toppling failures of overhanging salt marsh cliffs in Oosterschelde, The Netherlands, based on limit equilibrium and beam theorem. However, we can assume that the elastic–plastic behavior of cohesive materials forming overhanging blocks in riverbanks diverges from that of overhanging blocks in salt marsh sediments, meaning that the relationships introduced by Van Eerdt (1985) are unlikely to be transferable to riverbank contexts. Indeed, soil mechanics literature (see, for example, Muir Wood, 2004; Fang and Daniels, 2006) indicates that elastic models are unlikely to be satisfactory except under very restricted conditions. A specific difficulty concerns the assumption (Ajaz and Parry, 1975; Van Eerdt, 1985) of linear elastic stress–strain behavior during compression. A quick comparison of the stress–strain response implied by a linear elastic description of soil behavior with the actual stress–strain response of a typical soil shows that many features of soil response exist that the linear elastic model is unable to capture (Muir Wood, 2004). As such, choosing a soil constitutive relationship appropriate to the problem being considered is important (i.e., cantilever failure).

For these reasons, a study focused specifically on the overhanging failure phenomenon is necessary (see Fig. 1 for detail). Cantilever failure mechanisms have in fact recently been studied by constructing a physical model in the laboratory (Samadi, 2011; Samadi et al., 2011a); the clear advantage of this approach being the detailed observations that are possible. However, this form of physical modeling is limited to exploring a relatively narrow set of conditions because the lengthy times that are often required to construct the experiment. In contrast, numerical models may offer a more rapid setup that, in turn, implies that numerical models can be used to investigate a wider variety of different scenarios. In this paper we seek to employ the advantages of both physical and numerical modeling in a complementary approach designed to provide new insights into the process of cantilever failure. Specifically, herein we present numerical simulations of soil behavior (i.e., Mohr–Coulomb) using a finite element method for evaluating the overhanging failures observed in the laboratory experiments of Samadi et al. (2011a). The availability of high quality observations from the physical modeling provides the ability to evaluate rigorously how the choice of particular constitutive models affects the veracity of the numerical simulations. A particular advantage of the data presented in this paper is that we employ a new experimental procedure to investigate the behavior of fine-grained materials during the formation of overhanging bank profiles, in which digital photography and particle image velocimetry (PIV) techniques are used to quantify spatially explicit bank deformation fields, enabling a detailed comparison of experimentally derived and numerically simulated parameters. To our knowledge, ours is the first study to model overhanging failures using this methodological approach.

2. Methods

In this section of the paper, we provide (i) an overview of the physical modeling and (ii) a description of the implementation of the numerical modeling.

2.1. Laboratory experiments

In recent years increasing interest has been focused on the potential of employing physical models to investigate riverbank erosion processes. For example, mass failures (including different mechanisms of cantilever failure) in a sandy gravel riverbank were investigated recently by Nardi et al. (2009, 2011). In addition, physical modeling of mass failure in riverbanks composed of sand and sandy silt material has been undertaken also by Taghavi et al. (2010). Various works have also been carried out to investigate dam-break flow and associated downstream sand bank failures (Spinewine et al., 2002; Soares-Frazao et al., 2007; Spinewine and Zech, 2007; Zech et al., 2008); and small scale experiments have been carried out on banks composed of fine-grained, sandy sediments, with a specific focus on the occurrence of seepage erosion and related mass failures (Howard and McLane, 1988; Fox et al., 2006; Chu-Agor et al., 2007; Fox et al., 2007a,b; Wilson et al., 2007; Chu-Agor et al., 2008; Lindow et al., 2009; Fox et al., 2010). In this study we use data from the experiments undertaken by Samadi (2011, also reported in Samadi et al., 2011a). Because the experimental design and aim of these experiments have been described previously in those publications, we herein present only a brief overview.

One of the traditional limitations of physical modeling is the effect of scale. Most physical models are constructed at much smaller scales

Fig. 1. (A) Fluvial erosion at the toe of a riverbank (bottom layer) results in the formation of an overhanging profile in cohesive banks of the Kordan River. (B) Destruction of the overhang from cantilever failure.