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The Importance of Various Parameters on River Bank Stability Prediction

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Abstract

The erosion of channel banks causes damages to fertile agricultural land and the infrastructures located near destabilized river banks, leads to channel widening. So, the stability analysis of river bank is an important issue in river engineering problems. There are many factors have to be considered on the bank stability analysis; i.e. bank geometry, bank material properties, the level of water surface in the river and at the ground, and so on. Among the bank geometry parameters, the location and the depth of tension crack are two essential issues for determining bank geometry and the amount of river bank erosion and sedimentation. However, there are a few researches in literacy on computing these parameters and their effects on bank stability. in this research, a method to compute the location and depth of tension crack is presented. the sensitivity of safety factor of river banks against planar failure via the variation of some important parameters affecting the bank stability has been investigated. in this regard 51 sites of Mississippi river, USA, have been analyzed with a new model called "Extensive Model of Stability Analysis of Riverbanks (EMSAR)". on the basis of the results of bank stability analysis for available data, it is found that the bank angle, cohesion and the specific weight of bank material, in importance order, are the most important parameters affecting bank stability and the amount of safety factor against bank failure. the results also show that the depth of tension crack has a little influence on the safety factor of bank stability so that in the case of 20% error on estimating both the depth of tension crack and the river bank angle, there is 4% and 25% error on the amount of corresponded safety factors, demonstrating low and high sensitivity of safety factor over the variation of depth of tension crack and the bank angle, respectively.

1. INTRODUCTION

Due to direct benefits for human civilization (e.g. agricultural and industrial water supply, construction of hydro-electric power stations, navigation improvement) as well as protecting against floods and other river disasters, rivers have long been a subject of interest for scientists and engineers. Among different aspects in river engineering, the stream channel width is one of the most reliable and indicative variables for describing stream characteristics and morphology [1], so, the study of stream-bank stability is therefore a very important topic in this field study. the erosion of channel banks causes damage to land and adjoining property. for example, Alonso and Combs [2] reported that bank erosion and related damages are common occurrences along many miles of streams throughout the United States. the U. S. Army Corps of Engineers, in their evaluation of stream instability, reported that erosion is occurring along approximately half a million miles of bank lines within the system of rivers throughout the United States. Bank erosion processes may be responsible for the delivery of large volumes of sediment, with associated sedimentation hazards in the downstream reaches of a fluvial system, which in turn, may represent a significant problem in river management [3]. Odgaard [4] stated that the weight of silt and clay entrained into the water from cut banks is estimated to be 30-40 percent of the suspended load of the East Nishnabotna and Des Moines Rivers in Iowa, USA. Odgaard [4] also reported that the U.S. Army Corps of Engineer's (1983) study of the sediment budget of the Sacramento River, California, showed that, of the 11.5 million tons of total sediment inflow to the system, 6.8 million tons (59 percent) is derived from bank erosion.

Although a wide range of individual processes can contribute to river bank erosion [5-6], the erosion of bank material through mass-wasting is probably the most serious from the perspective of water resources management. This is because mass-wasting involves rapid channel widening and the delivery of large volumes of sediment to the channel.

There are several factors which contribute in bank erosion through mass failure; i.e. changes in the geotechnical characteristics of the bank materials results from loss of cohesion by frost weathering, the development of tension crack [7], streamflow by providing a hydrostatic confining force which acts as a resistance force, time which has conflicting effects, vegetative protection, soil moisture, presence of negative pore water pressure in the unsaturated portion of the bank (consists of cohesive materials) above the water table [3].

From the above factors, the tension cracks and its two specific characters; i.e. the location and the depth, play a significant role on bank stability. the location and the depth of tension cracks are key parameters which define the geometry of failed banks. the depth of the tension crack also reduces the effective length of the potential failure surface and consequently decreases bank stability. in this research, the effects of tension crack on stability of river bank using an Extensive Model of the Stability Analysis of Riverbanks (EMSAR) and data collected from Mississippi River, USA, investigated. Moreover, by comparing the ability of different methods proposed to calculate these two parameters, another method has been introduced to estimate the location and the depth of tension crack.

2. METHODS TO CALCULATE THE LOCATION AND THE DEPTH OF TENSION CRACK

Rankine (1857) proved existence of horizontal tension crack inside top layers behind a vertical wall. Later, Terzaghi (1943) applied the Rankine’s theorem over a vertical bank based on Culmann’s type failure [5]. the depth of tension crack estimated from Mohr-Diagram is represented as:

$$Z_0 = 2\,C \tan\,(45 + \phi / 2) / \gamma_s \tag{1}$$

where Z_0 is the depth of tension crack, γ_s is the specific weight of soil materials, and C and ϕ are the cohesion and internal friction angle of bank materials, respectively. in high banks the amount of Z_0 is only a small percentage of bank height so the presence of tension crack does not change notably the failure plain shape. in low and vertical banks, the failure block leaves the bank from tension crack and slide down along a smooth curved failure plain surface. So, this type of failure mechanism may be defined by using the modified Culmann’s method.

Terzaghi (1943) stated that the maximum depth of tension crack is about the half height of vertical wall [5]. Moreover, the direct tension tests conducted on soil, show that the unconfined tension of resistance is about 10-15 percent of compression resistance [5]. Hence, the soil tension resistance limits the improvement of cracking to the maximum of Z_0. Lohnes and Handy [8] showed that if the resistance tension is maximum at the soil surface, its value decreases to zero at Z_0. Lohnes and Handy's equation to estimate the depth of tension crack in a soil of finite tensile strength is [8]:

$$y = Z_0 (1 - \sigma_{TC} / \sigma_t) \tag{2}$$

where y is the tension crack depth, σ_{TC} is the tensile strength of the soil, and σ_t is the tensile stress at the ground surface. Using Mohr-Diagram, Lohnes and Handy [8] defined σ_t as:

$$\sigma_t = 2\,C \tan\,(45 - \phi / 2) \tag{3}$$

where C is the soil cohesion. Baker (1981) stated that the above equation can not be expected to be applicable to finite slopes [7]. Darby and Thorne [7] reported that, on the basis of using river bank failure geometry and geotechnical data collected from 51 sites in Northern Mississippi, the last three relations were unable to predict accurately the tension crack depth for the banks at those sites.

Also, Thorne and Abt [9] stated that the tension crack depth is usually equal to less than half of the bank height and, if no site-specific data are available, 0.5 may be used as the default value for K_r (the tension crack index, defined as the ratio of tension crack depth to bank height). Moreover, Thorne and Abt [9] also reported that varying K_r from 0.3 to 0.7 (its realistic range) does not change the safety factor (FS) by more than 10 percent.

It should be noted that, on the other hand, due to the relation between tension crack parameters and the failure bank angle (β), there is many attempts to find a relationship to estimate the last mentioned parameter. Taylor [10] stated that at critical conditions, the failure plane angle corresponds to the angle at which the cohesion, C, is fully developed. on the basis of this theory and using a simplified geometry shape for river bank, Lohnes and Handy [8] defined the following equation:

$$\beta = (\alpha + \phi) / 2 \tag{4}$$

where α is the river bank angle before bank failure. Lohnes and Handy [8] stated that as the stress distribution is changed during crack beginning and its development, the above equation gives only an estimated value for failure plain angle. Moreover, by neglecting the effects of positive and negative pore water pressures, hydrostatic confining pressure, and hydrostatic pressure due to water in any tension crack in equations, Osman and Thorne [11] developed the following equation to predict β as:

$$\beta = 0.5 \left(\tan^{-1} \left[(H / H')^2 (1 - K_r^2) \tan \alpha \right] + \phi \right) \tag{5}$$

where H is river bank height, H′ is bank height above the top of a vertical part of the bank located at the river bottom, if there is any. a comparison of failure plane angles predicted using equation (5) with failure plane angles measured at 51 sites shows that the above mentioned equation has a tendency to under-predict the failure plane angle [12]. Amiri-Tokaldany et al. [13], by considering the equality between the present depth of tension crack and its amount after bank failure, present following equation as (Fig. 1):

$$\beta = \tan^{-1}\left(\frac{H_2}{BW + H_3/\tan\alpha}\right) \quad (6)$$

where BW is the failed block width, and parameters H_2 and H_3 are defined in Fig. 1.

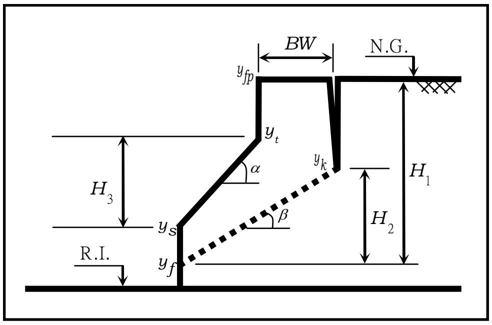

Fig. 1: Introduction of Parameters used for Computing Failure Plane Angle [13]

It should be noted that most existing models for analysis of bank stability of river banks, including the above mentioned models, have a number of technical and conceptual shortcomings. for example, most analyses of the stability of steep, cohesive, eroding banks which fail along planar surfaces have been based on estimating the resultant of both driving and resisting forces acting on incipient failure blocks using a relatively simple, idealized, geometry. Hence, such analyses are somewhat limited when they are applied under conditions encountered in the field. some of the above limitations have individually, or in combination, been addressed in more sophisticated analysis presented in the last 10 years; e.g. Darby and Thorne [12]; Rinaldi and Casagli [3]; and Amiri-Tokaldany et al. [13], among others. However, not only none of them has ability to estimate the critical depth of tension crack, but they have no ability to analyze the stability of the river bank without introducing the depth of tension crack as a known parameter.

In this research, the predicted results from some available models have been compared together and the sensitivity of effective parameters on the safety of factor against planar failure has been investigated. Moreover, in the improved model in this research, three methods for estimating the depth of tension crack have been deployed. As the first method, it is assumed that there is some field data about the amount of the depth of tension crack. So, this data has been used as a known parameters in the improved model. As the second method, if there is no data of tension crack depth, the model uses Equation (1) to estimate the depth of tension crack. As the second case, the model uses the idea presented by Thorne and Abt [9] from which it is assumed that the depth of the tension crack has been limited to half of the bank height. So, the stability analysis has been performed for different tension crack depths starting from the ground surface and increase to its maximum amount by increment of 5 cm. the results for each depth have been considered and the least amount of factor of safety has been recognized as the critical depth. Consequently, the other specifications of the failed block have been computed. As an improvement, the models of Darby and Thorne [12] and Amiri-Tokaldany et al. [13] modified so that they do not need to enter the amount of crack depth as known parameters to analyze the bank stability.

3. RESULTS AND CONCLUSION

To determine the effectiveness of parameters on the amount of the factor of safety against planar failure, several series of sensitivity tests have been performed. in Fig. 2, some results of the above tests have been shown. As shown in Fig. 2a, by increasing 30 percent of the amount of tension crack depth, there is only about 5 percent decrease of the amount of factor of safety. Fig. 2b shows that by increasing of 20 percent on the amount of river bank angle, there is 25 percent decrease of the amount of factor of safety, demonstrating the more effectivity of river bank angle than the depth of tension crack.

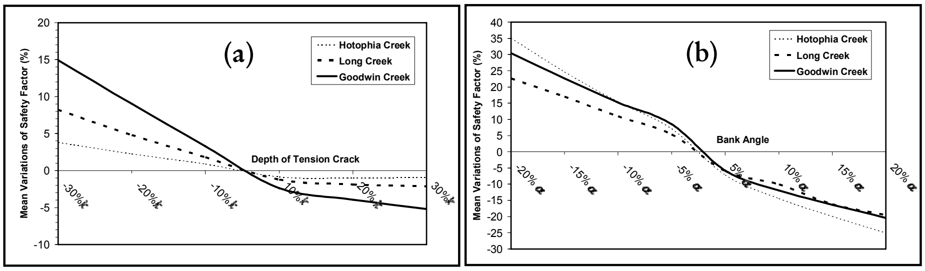

Fig. 2: The Sensitivity of Safety Factor Over the Variations of Bank Geometry: A) Depth of Tension Crack; B) Bank Angle

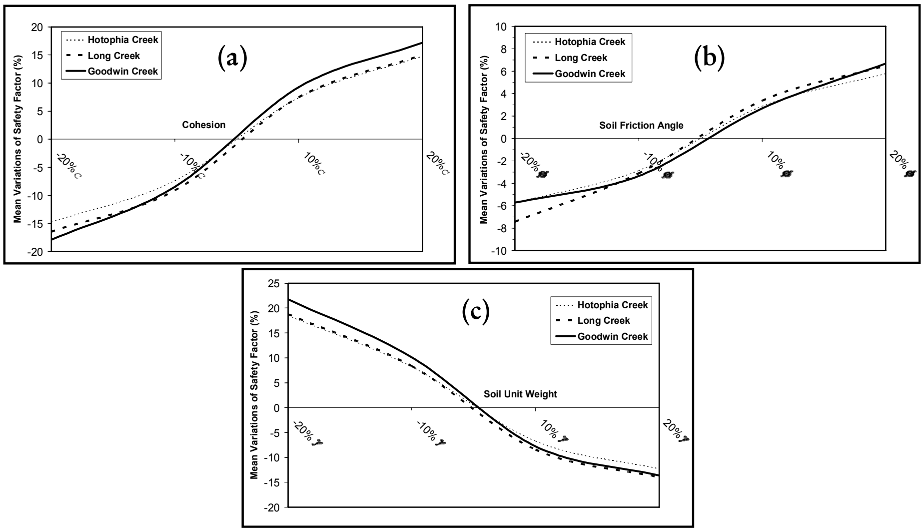

Fig. 3: The Sensitivity of Safety Factor Over the Variations of Bank Material: A) Cohesion; B) Soil Friction Angle; C) Soil Unit Weight

Moreover, as shown in Figs. 3a and 3b, by decreasing 20 percent on the amounts of soil cohesion and internal friction angle, the amount of factor of safety is reduced about 18 and 8 percent, respectively. Also, according to Fig. 3c, an increase of 20 percent on the amount of bank specific weight, the amount of factor of safety is reduced about 14 percent, demonstrating that in case of under-estimating of 20 percent on the amount of specific weight of the river bank materials, the amount of the factor of safety over-estimated around 14 percent.

From the above results, it is found that the bank angle, cohesion and the specific weight of bank material, in importance order, are the most important parameters affecting bank stability and the amount of safety factor against bank failure.

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