International Journal of Sediment Research 31 (2016) 220–225

Contents lists available at ScienceDirect

International Journal of Sediment Research

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

Original Research

Critical caving erosion width for cantilever failures of river bank

Yangui Wang [a,*], Shangfu Kuang [a,b], Jialin Su [c]

[a] International Research and Training Center on Erosion and Sedimentation (IRTCES), Beijing, China
[b] China Institute of Water Resource and Hydropower Research (IWHR), International Research and Training Center on Erosion and Sedimentation (IRTCES), Beijing, China
[c] Hydrological Bureau, Ministry of Water Resources, Beijing, China

ARTICLE INFO

Article history:
Received 2 March 2015
Received in revised form
9 May 2016
Accepted 10 May 2016
Available online 16 May 2016

Keywords:
Caving erosion
Cantilever failure
Stability coefficient
Critical caving erosion width

ABSTRACT

The cantilever failure is one of the typical bank failures, in which the lateral caving erosion at the bottom of the bank plays an important role. When the caving erosion width is larger than a certain value, the cantilever failures such as shear, toppling and stress failures may occur. In order to understand the condition of the cantilever failure, the collapse mechanisms of the cantilever failures are studied based on the bank stability theory and flume experiment. According to the bank stability equation with the lateral erosion, the critical caving erosion width (CCEW) formulas for the shear and toppling failures of simple slope bank were derived in this paper. The formulas show that the CCEW increases as the overhanging soil thickness and soil cohesion increase, and decreases as the crack depth on the bank surface and the slope angle of the bank increase. And these formulas were tested with experimental data, which shows the predicted values are good agreement with experimental data. The paper reveals a quantitative expression on the process of the river cantilever failure.

1. Introduction

Bank failure is an important lateral evolvement process, which often occurs in alluvial rivers, such as in the Middle and Lower Yangtze River and the Lower Yellow River. Bank failures occurred in about 35.7% of the Middle and Lower Yangtze River in length in the 1990s, and had still occurred seriously with about 655 times since operation of the Three Gorges Reservoir in 2003 (MWR, 2012). Bank failure also plays an important role in the channel evolution process of the Lower Yellow River, especially since operation of the Xiaolangdi Reservoir in 2001. The beach failures in the Lower Yellow River seriously occur with the channel erosion after water and sediment regulation with the Xiaolangdi Reservoir (MWR, 2008). Bank failures also frequently occur in other country's rivers such as the Niger River in Western Africa (Abam, 1993), the Ohio River in America (Hagerty et al., 1981) and the Lockyer Valley in Australia (Thompson et al., 2013).

Bank failures can be divided into sliding failure, sinking failure, cantilever failure, and Ω failure, etc (Wang & Kuang, 2014) according to the collapsed mechanism and failure forms. The collapsed mechanism is very complicated because there are three kinds of influence factors of bank soil factors (such as bank structure, soil property and slope form), flow factors (such as flow state, water level and its changes) and fluvial process factors (such as bed erosion, lateral caving erosion and river regime) (Wang et al., 2003; Parker et al., 2008). During the flood period, bank soil property and flood level changes play very important roles in bank failures, and the lateral caving erosion at the bottom is more important than other factors during the dry season with low water level. The caving erosion at the bottom generally occurs in the concave bank, and that is why the concave bank rapidly collapses for the bend reach. The caving erosion in the concave bank can be interpreted from three aspects of the water and sediment movement theory, the dynamic theory and the vortex theory (Wang & Kuang, 2005).

As one of the typical bank failures, the cantilever failure mainly occurs at the concave bank of the bend reach during the dry season. Because of the serious erosion at the bottom of bank, especially the lateral caving erosion in the concave bank of the bend reach, the upper part of the bank is in the overhanging state. When the caving erosion width is larger than a certain value, the cantilever failure will occur under the weight of the overhanging soil (ASCE Task Committee on Hydraulic, 1998; Springer et al., 1985; Samadi et al., 2013; Thorne & Tovey, 1981), shown in Fig. 1.

* Corresponding author.
E-mail addresses: wangyg@iwhr.com (Y. Wang), kuangsf@iwhr.com (S. Kuang), jlsu@mwr.gov.cn (J. Su).

http://dx.doi.org/10.1016/j.ijsrc.2016.05.003
1001-6279/© 2016 Published by Elsevier B.V. on behalf of International Research and Training Centre on Erosion and Sedimentation/the World Association for Sedimentation and Erosion Research.

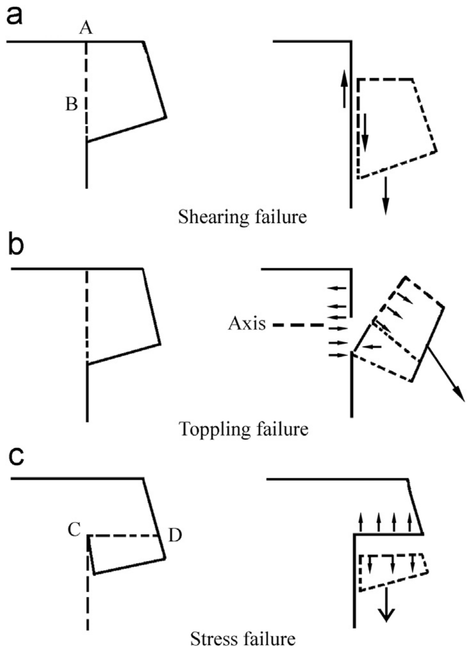

Fig. 1. Types of cantilever failures.

When the weight of the overhanging soil block is more than its shear strength along the line AB, the overhanging soil block will fall down along a vertical face, which is called shear failure. When the weight torque of the overhanging soil block is greater than the cohesive tensile torque of the soil, the overhanging soil block will whirl to fail, which is called toppling failure. When the weight of the lower overhanging soil block exceeds the tensile strength of soil, the lower part will fall down, which is called stress failure.

In natural circumstances, shear failure and toppling failure often occur during the caving erosion of the simple slope bank, so the critical caving erosion width (CCEW) of the shear and toppling failures will be only analyzed in this paper. The CCEW is defined as the caving erosion width of the bank when the cantilever failures occur.

2. Critical caving erosion width for shear failure

In the lateral caving erosion process at the bottom, when the weight of the overhanging soil block is larger than its shear strength, the shear failure will probably occur. The collapse mode of the shear failure is shown in Fig. 2. In general, the collapsed face of the shear failure is upright, shown with the vertical line AB in Fig. 2. The safety of the steep bank is often analyzed with the stability coefficient, which is defined as the ratio of the resistant stress with the soil weight and given as

$$K=\frac{cl}{\gamma A} \tag{1}$$

where, γ is the unit weight of bank soil; l is the length of the failure line AB along the channel cross section, and $l=H-H'$; θ and c are internal friction angle and cohesion of bank soil, respectively; and A is the cross-sectional area of the bank failure block. A can be calculated as

$$A=\frac{H_1^2-H_2^2}{2\ \tan\ \Theta_2}-\frac{H_1^2}{2\ \tan\ \Theta_1}-\frac{H^2-H_2^2}{2\ \tan\ \Theta_0} \tag{2}$$

The stability coefficient of the shear failure is derived from Eqs. (1) and (2) as

$$K=\frac{2c(H-H')}{\gamma\left[\frac{H_1^2-H_2^2}{\tan\ \Theta_2}-\frac{H_1^2}{\tan\ \Theta_1}-\frac{H^2-H_2^2}{\tan\ \Theta_0}\right]} \tag{3}$$

where, H′is the crack depth on the bank surface; H_1 and Θ_1 are respectively depth and angle of the upper slope; H_2 and Θ_2 are respectively depth and angle of the middle slope; H and Θ_0 are respectively river depth and the lower slope angle; shown in Fig. 2. Define $B=-\frac{H-H_2}{\tan\ \Theta_0}$, which is called the caving erosion width. If $K=1$, the CCEW (B_{cr}) for the shear failure is

$$B_{cr}=\frac{2S_t(H-H')}{H+H_2}+\frac{H_1^2}{(H+H_2)\tan\ \Theta_1}+\frac{H_2^2-H_1^2}{(H+H_2)\tan\ \Theta_2} \tag{4}$$

where, $S_t=\frac{c}{\gamma}$, which is called soil intensity coefficient in this paper. From Eq. (4), the CCEW primarily depends on soil characteristics, caving erosion location, slope morphology, crack depth on the bank surface, etc. Generally, the CCEW will be greater when the soil intensity coefficient is larger, the overhanging soil block is thicker, the bank slope is smaller, and the longitudinal crack is shallower. If the other conditions remain unchanged, the CCEW for the non-crack bank is the largest. According to soil mechanics theory (Chen, 1984), the crack depth on the bank surface can be determined as:

$$H'=\frac{2c}{\gamma}\ \tan\left(45^\circ+\frac{\theta}{2}\right) \tag{5}$$

If the above equation is inserted into Eq. (4), the CCEW of the shear failure is

$$B_{cr}=\frac{2S_t\left[H-2S_t\ \tan\left(45^\circ+\frac{\theta}{2}\right)\right]}{H+H_2}+\frac{H_1^2}{(H+H_2)\tan\ \Theta_1}+\frac{H_2^2-H_1^2}{(H+H_2)\tan\ \Theta_2} \tag{6}$$

For the simple bank slope, $H_1=H_2$ and $\Theta_1=\Theta_2=\Theta$. If define $m=\ \tan\ \Theta$, which is called slope coefficient, then the CCEW of the shear failure is

$$B_{cr}=\frac{2mS_t\left[H-2S_t\ \tan\left(45^\circ+\frac{\theta}{2}\right)\right]+H_1^2}{m(H+H_1)} \tag{7}$$

As a special case, when the parallel caving erosion occurs in the simple bank slope, and $H_1=H$, the CCEW is

$$B_{cr}=\frac{2mS_t\left[H_1-2S_t\ \tan\left(45^\circ+\frac{\theta}{2}\right)\right]+H_1^2}{2mH_1} \tag{8}$$

Figs. 3 and 4 show the relationships of the CCEW and the overhanging soil thickness calculating with Eq. (8) for the cases of without and with cracks. The results show that there is a linear relationship between the CCEW and the overhanging soil thickness for the upright bank. The larger the soil intensity coefficient is, the larger the CCEW will be. The CCEW only has a relationship with soil intensity coefficient without cracks on the bank surface. Although the CCEW increases with the overhanging soil thickness for the simple slope bank, it also becomes larger with the increasing soil intensity coefficient for the influence of the overhanging soil thickness on the caving erosion width. The CCEW without cracks on the bank is greater than that with cracks. The CCEW for the gentle slope bank is greater than that for upright slope.

3. Critical caving erosion width for toppling failure

The toppling failure will occur when the weight torque of the overhanging soil block is greater than the tensile torque of the cohesive soil. There are two cases of the stress distribution in the bank failure face, as shown in Fig. 5, due to difference in bank soil