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DETERMINATION OF THE ESCAPE VELOCITY OF A PARTICLE ON A RIVERBANK

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Abstract : The erosion of the river bank is a complex mechanism and sediment particles are subjected to a number of forces. Among those forces, force of cohesion between the particles plays a very significant role, and, until now, not much progress has been made to analyze the cohesive force in a comprehensive manner. It is imperative that a particle is surrounded by a family of similar sort of particles and all are bounded together under this force of cohesion. In this article, a review of the already existing equations available for determination of the escape velocity of a particle on the riverbank is made and a new equation has been suggested. The proposed equation takes into account the micro-level variations in the system comprising of a host of particles in dynamic equilibrium.

Keywords : River bank, erosion, particle shape, escape velocity.

1. Introduction

Rivers and streams are products of their catchments. A river is often referred to as dynamic system because it is in a constant state of change. The factors controlling river and stream formation are complex and interrelated. These factors include the amount and rate of supply of water and sediment into stream systems, catchment geology, and the type and extent of vegetation in the catchment. As these factors change over time, river systems respond by altering their shape, form and/or location. In stable streams the rate of these changes is generally slow and imperceptible. Rivers are dynamic systems that change over time. Stream banks erode for many reasons Stream bank erosion is a natural process that over time has resulted in the formation of the productive floodplains and alluvial terraces. Paradoxically, even stable river systems have some eroding banks. However, the rate at which erosion is occurring in stable systems is generally much slower and of a smaller scale than that which occurs in unstable systems. Events like flooding can trigger dramatic and sudden changes in rivers and streams. However, land use and stream management can also trigger erosion responses. The responses can be complex, often resulting in accelerated rates of erosion and sometimes affecting stability for decades. Overclearing of catchments and stream bank vegetation, poorly managed sand and gravel extraction, and stream straightening works are examples of management practice that result in accelerated rates of bank erosion.

Bank erosion consists of two processes - basal erosion due to fluvial hydraulic force and bank failure under the influence of gravity. The degree of saturation of bank material increases with river stage; therefore, the frequency of bank failure is often correlated to the frequency of the flooding. Consequently, the rate of bank erosion is related to both the basal erosion and the bank failure, and bank failure is a probabilistic phenomenon.

2. Erosion Rate of River Bank due to Flow

Basal erosion is referred to as the fluvial entrainment of bank material by flow-induced forces, including drag force, resistance force, and lift force that act on the bank surface. Cohesive force between sediment particles resists erosion of bank material. This article describes an analytical method to calculate the rate of basal erosion of cohesive bank material by applying the concept that bank surface erosion occurs when entrainment of sediment particles from the bank surface is greater than deposition. In this work, authors employ the concept that bank surface is considered as being eroded when sediment particles depart from the bank surface as the rate of entrainment is greater than the rate of deposition.

Sediment particles resting on the riverbed and banks are subject to entrainment by flow-induced forces. In the meantime, these sediment particles tend to deposit on bed or bank surface because of gravity. If the rate of entrainment exceeds the rate of deposition, erosion occurs. Otherwise, deposition takes place. The channel bed or bank remains stable when the exchange of sediment particles between entrainment and deposition reaches a dynamic equilibrium. Duan [1] devised an approach to calculate the erosion rate considering the equilibrium.

3. Submerged Weight

The submerged weight considering the effect of channel slope as well as bank slope can be expressed as

$$W_{sn} = \frac{1}{6}\pi d^3(\rho_s-\rho)g\cos\sqrt{(\cos^2\beta-\sin^2\alpha)} \tag{1}$$

Where W_{sn} = submerged weights normal to the bank surface; d = particle diameter; g = acceleration of gravity; α = angle of channel slope; β = angle of the bank, and ρ_s, ρ = densities of sediment particles and water, respectively. It is assumed that the channel slope is negligible with comparing to the bank slope, and thus Eq. (1) is simplified as

$$W_{sn} = \frac{1}{6}\pi d^3(\rho_s-\rho)g\cos\beta \tag{2}$$

4. Lift Force

The lift force can be calculated by

$$F_L = \frac{C_L}{4}\pi d^2\frac{\rho u^2}{2} \tag{3}$$

Where F_L = lift force; C_L = coefficient of lift force; and u = velocity near bank surface. The lift force is perpendicular to the bank surface. According to Einstein (1950), when the velocity,, is chosen to be the flow velocity with a distance,, above the reference bed surface, the lift coefficient, C_L, is equal to a constant of 0.178 for a uniform sediment resting on the bed surface. If the riverbank material is composed of graded grains, is also a function of the Reynolds number for the grains. The equation is rewritten as

$$F_L = \frac{C_L'}{4}\pi d^2\frac{\rho u_{*b}^2}{2} \tag{4}$$

Where u_{*b} = frictional velocity at the bank surface. The logarithmic distribution of velocity profile was assumed to be valid near bank. Flow velocity at 0.35d above bank surface was then correlated to the friction velocity. The coefficient of lift force can be obtained as,

$$C_L' = C_L\ln^2\frac{\left(0.35d/k_s\right)}{\kappa^2},$$

where C_L = coefficient of lift force, κ = Von Karman constant; and k_s = roughness height equal to the mean size of sand grain.

5. Cohesive Force

For cohesive bank material, interactions among fine-grained particles exert a cohesive force on an individual grain being lifted. The cohesive is a function of particle size and density and other factors, such as the porosity of bank material. Cohesive force can be expressed as

$$F_C = m_s f_C(d,\rho_s,\lambda,\ldots) \tag{5}$$

Where f_C = cohesive force per unit mass;

$$m_s = \frac{1}{6}\pi d^3\rho_s,$$

which is the mass of sediment particle; and λ = porosity of the bank material.

6. Escape Velocity

When particles are lifted by flow to a distance equal to the diameter of the sediment particle, they are considered being entrained. The momentum conservation law gives

$$(F_L - W_{sn} - F_C)\frac{d}{V_{sn}} = m_s V_{sn} \tag{6}$$

Where V'_{sn} = sediment particle escape velocity from the bank normal to the surface. From Eq. (1), (2), (3) and (4), the following equation is obtained.

$$V'_{sn} = \sqrt{\frac{\rho_s-\rho}{\rho_s} g d} \sqrt{\left[\frac{3C_L \alpha u_{*b}^{2}}{4gd(\rho_s-\rho)} - \cos\beta - \frac{\rho_s}{(\rho_s-\rho)g} f_c\right]} \tag{7}$$

7. Capillary Cohesion

Most expressions of the capillary force are based on assumptions of toroidal or parabolic shape of the liquid bridge and on the geometrical characteristics of the liquid bridge (such as the filling angle or the internal or external curvature radii). According to Soulie et al. [2], the relevant parameters are the radii R_1 and R_2 of the grains (where R_2 is the radius of the larger grain, the inter-particle distance D, the volume V of the liquid bridge, the contact angle θ, and the liquid/air surface tension σ. The capillary cohesion is expressed as

$$F = \pi\sigma\sqrt{R_1 R_2}\left[c + \exp\left(a\frac{D}{R} + b\right)\right] \tag{8}$$

Where the coefficients a, b and c are the functions of the volume V of the liquid bridge, the contact angle θ, and $R = \max(R_1, R_2)$:

$$a = -1.1\left(\frac{V}{R^3}\right)^{-0.53} \tag{9a}$$

$$b = \left(-0.148\ln\left(\frac{V}{R^3}\right) - .96\right)\theta^2 - 0.0082\ln\left(\frac{V}{R^3}\right) + 0.48 \tag{9b}$$

$$c = 0.0018\ln\left(\frac{V}{R^3}\right) + 0.078 \tag{9c}$$

8. Determination of the Escape Velocity

Considering dynamic equilibrium

$$F_L - W'_{sn} - F_C = m_s a_{sn} \tag{10}$$

Where m_s is the mass of the particle and a_{sn} is the impending acceleration in that direction.

Assuming the particle to be spherical in shape the expression of the escape velocity comes out to be

$$V_{sn} = \sqrt{\frac{3}{4}C_L'\frac{\rho}{\rho_s}u_*^2 - \left[2R_n\left(1-\frac{\rho}{\rho_s}\right)g\cos\beta + \frac{3}{2}\frac{\sigma}{\rho_s}\frac{\sqrt{R_{n-1}R_n}}{R_n^3}\left[c + \exp\left(a\frac{D}{R} + b\right)\right]\right]} \tag{11}$$

Here n indicates the particle for which the escape velocity is calculated and n-1 implicates its neighbouring particle.

9. Conclusion

In the present work, a new equation for determination of the escape velocity of a particle on a riverbank from the already existing relationships has been developed. The equation relates the escape velocity to the flow rate, the particle size as well as the properties of water like density, surface tension and so on. Thus, the rate of bank erosion can be correlated with the velocity of river and other relevant parameters. The knowledge of change in the velocity of river can be utilized to study the bank erosion. A continuous survey of river velocity can throw light on the bank erosion rate and also the frequency of riverbank failure.

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