

An Analytical Approach for Determination of Riverbank Erosion under Action of Capillary Cohesion, Viscous Force and Force due to Pore Pressure

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ABSTRACT: Riverbank erosion is a complex phenomenon and sediment particles on the riverbank are subjected to a number of forces. In this paper the behaviour of a particle on a riverbank is analyzed for different types of saline water using a recent analytical model called the Truncated Pyramid Model. The particle is subjected to a number of forces, e.g., capillary cohesion, viscous force, force due to pore pressure and gravitational pull. It is highly influenced by the arrangement of other particles surrounding it. These forces have always been considered as a significant factor in determination of the threshold condition where the particle is about to escape from the riverbank. This limiting velocity of the particle is termed as the escape velocity. The escape velocity is strongly related to other parameters like the volumetric rate of erosion, entrainment rate etc. Here it is shown that the escape velocity changes significantly as the inter-particle distance and the volume of the liquid bridge between the particles change.

KEYWORDS: Riverbank erosion, Truncated Pyramid Model, Capillary cohesion, Viscous force, Pore pressure

I. INTRODUCTION

When a steam-flow takes place over a loose sedimentary bed, hydrodynamic forces are exerted on the sediment particles at the bed surface. Cohesive bank material is usually eroded by the detachment and entrainment of aggregates or crumbs of soil. The motivating forces are the same as those for non-cohesive banks, but the resisting forces are primarily the result of cohesive bonds between particles and aggregates. The Osman and Thorne [1] model correlates basal bank erosion to bank failure and derives an analysis of bank stability for planar bank failure. Darby and Thorne [2] widens the applicability of the model proposed by [1] by considering pore-water pressure and hydrostatic confining pressure terms and then allowing the failure plane to pass through more than the toe of the bank. Darby et al. [3] show that the basal erosion plays an important role in morph-dynamic modeling, and thus, a basal erosion model, like the excessive shear stress model, might prove to be useful in this regard. Darby & Belbono [4] reports the development of a model of flow, sediment transport, grain-size sorting, and bed topography for river bends with erodible banks. Duan [5] shows that the separation speed of the sediment particle on the river bank can be obtained from force analysis considering equilibrium condition, and the predominant forces acting on the particle are lift force, submerged weight of the particle & cohesive force between the particles. The Truncated Pyramid Model proposed in Mukherjee & Mazumdar [6],[7] analyzes the response of a particle on a cohesive river bank in different situations. It also takes into account several degrees of freedom in the geometry setting of the particle, which was not addressed in previous research.

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II. TRUNCATED PYRAMID MODEL AND FORCES ACTING ON A PARTICLE

The Truncated Pyramid Model has been conceived based on the fact that a particle tends to be in a stable position and that each particle will lie on top of two particles with a small-volume water bridge between them. According to the model, each particle, spherical in shape and materially homogeneous, rests on two particles in the form of a truncated pyramid with a small volume water bridge between them. A small, gradual increase in the size of the particles is assumed as heavier and bulkier particles will be placed at the bottom and away from the river. The geometry of the arrangement of particles, their dimensions and parameters, like the inter-particle distance and volume of Water Bridge, will determine the geometry of the bank itself. Suffices i and j indicate the spatial location of a particle in two-dimensional frame. Here i is the row number and j is the column number. For example, particle 24 is the fourth particle in the second row and it rests on particles 34 and 35. Radius of a particle at a location ij is denoted as R_{ij} . Radius of the next particle in the same row is $R_{i+1,j}$ and so on.

Some assumptions have been made to analyze the forces acting on the particles on the riverbank in the Truncated Pyramid Model:

1. Particles are spherical and materially homogeneous.
2. The size of particles increase slightly row wise and column wise.
3. Angles are expressed in terms of approximate trigonometric relations. Since the model itself defines geometry of the arrangement, the angles can be determined in terms of the radii of the three adjacent particles.
4. Effect of vegetation on the riverbed is neglected.

III. FORCE ANALYSIS

Fig. 1 depicts net forces acting on a particle on a riverbank. The pre-dominant forces are capillary cohesion, viscous force, gravitational force due to submerged weight of the particle and force due to pore pressure.

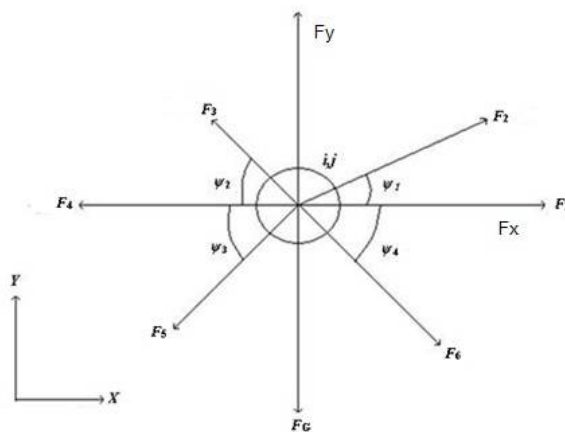


Fig. 1 Free-Body Diagram Showing Net Forces on a Particle

Here,

- F_1 = Force between particle ij and particle $ij+1$
- F_2 = Force between particle $i-1,j$ and particle ij
- F_3 = Force between particle $i-1,j-1$ and particle ij
- F_4 = Force between particle $ij-1$ and particle ij
- F_5 = Force between particle ij and particle $i+1,j$
- F_6 = Force between particle ij and particle $i+1,j+1$

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ψ_1 = Angle subtended by particle $i-1,j$ with x -axis
 ψ_2 = Angle subtended by particle $i-1,j-1$ with x -axis
 ψ_3 = Angle subtended by particle $i+1,j$ with x -axis
 ψ_4 = Angle subtended by particle $i+1,j+1$ with x -axis

F = Cohesive force + Viscous force = $F_c + F_v$
 F_c = Capillary force + Pore pressure force = $F_{cap} + F_{pore}$

Capillary cohesive force expression given by Soulie et al. [8] :

$$F_c = \pi\sigma\sqrt{R_1R_2} \left[c + \exp\left(a\frac{D}{R} + b\right) \right] \quad (1)$$

Where the coefficients a , b and c are functions of the volume ∇ of the liquid bridge, the surface tension σ , the contact angle ϕ and R , i.e., the greater value among R_1 and R_2 .

Also

$$a = -1.1 \left(\frac{\nabla}{R^3} \right)^{-0.53} \quad (2a)$$

$$b = \left(-0.148 \ln\left(\frac{\nabla}{R^3}\right) - 0.96 \right) \phi^2 - 0.0082 \ln\left(\frac{\nabla}{R^3}\right) + 0.48 \quad (2b)$$

$$c = 0.0018 \ln\left(\frac{\nabla}{R^3}\right) + 0.078 \quad (2c)$$

Zhang & Li [9] stated that the dynamic normal viscous force induced by the discrete liquid bridge in a pendular state can be reduced in two ways. Firstly, the viscosity influences the shape of the gas-liquid interface, which is called the non-lubrication region. Secondly, the viscosity governs the bridge strength of the inner region, which is called the lubrication region. As the gap between the particles is within the limit of small width, the effect of interfacial shape can be ignored and the lubrication theory can be used.

The dynamic normal and tangential viscous force vector F_{vn} and F_{vt} in the liquid bridge between cohesive soil particles can be calculated by

$$F_{vn} = 6\pi\eta R^* v_n (R^*/D) \quad (3a)$$

$$F_{vt} = 6\pi\eta R^* v_t [(9/15)\ln(R^*/D) + 0.9588] \quad (3b)$$

Where,

v_n = Normal component of escape velocity due to normal viscous force,

v_t = Tangential component of escape velocity due to tangential viscous force,

η = Coefficient of dynamic viscosity, and

$R^* = R_{ij}R_{i,j-1}/(R_{ij}+R_{i,j-1})$

The resultant capillary force between the particles is the sum of all the above forces:

$$F_{pore} = u_a \pi R^{*2} - (u_a - u_w) \pi r^2 - T_s (2\pi r_2) \quad (4)$$

Where the term u_a and u_w are the air pressure and water pressure at the interface, respectively, $(u_a - u_w)$ is matric suction. The radius r , rotated about its axis parallel to the cross section, defines the convex curvature of the meniscus in the third dimension. T_s is the surface tension at the interface. u_a being set to a reference value of zero and pore-water pressure being negative, F_{pore} is a negative number, indicating that the macroscopic effect of capillarity in unsaturated soil is to compress the granular soil matrix, creating what has been often referred to as an "effective cohesion" in otherwise cohesionless soils [10].

Assuming equal separation distances between the central particle and six neighboring particles and same liquid bridge volumes, acceleration expressions are given as:

Along x -direction:

$$\ddot{x} = d v_x / dt = \left[3 / (4\pi R_{ij}^3 \rho_s) \right] [F_1 + F_{2x} - F_{3x} - F_4 - F_{5x} + F_6] \quad (5)$$

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Along y-direction:

$$\ddot{y} = d v_y / dt = [1 - (\rho / \rho_s)] g - [3 / (4 \pi R_{ij}^3 \rho_s)] [F_{2y} + F_{3y} - F_{5y} - F_{6y}] \quad (6)$$

Where,

v_x = Particle escape velocity along x-direction, v_y = Particle escape velocity along y-direction, ρ_s = Density of material of the soil particle and ρ = Density of water.

Resultant particle separation speed v is found out by the following way:

$$v = (v_x^2 + v_y^2)^{0.5} \quad (7)$$

The values of the input parameters considered for calculation are as follows:

Density of soil particle $\rho_s = 2650 \text{ kg/m}^3$;

Density of pure water $\rho = 1000 \text{ kg/m}^3$;

Density of saline water: 1025 kg/m^3 ;

Coefficient of dynamic viscosity $\eta = 0.00009 \text{ Pa-s}$;

Surface Tension for water with Type I salinity = 0.065 N/m ;

Surface Tension for water with Type II salinity = 0.0681 N/m ;

Contact angle for saline water = 25° (Bakker et al. [11] suggested the range of the contact angle from 15° to 50° depending on the nature of the solid surface, and according to Morgan [12] contact angle can be considered as 25° for impure water);

Radius of soil particle $R_{ij} = 0.0004 \text{ m}$;

Liquid bridge volume $\forall = 10\text{-}30 \text{ nl}$.

IV. RESULTS AND DISCUSSION

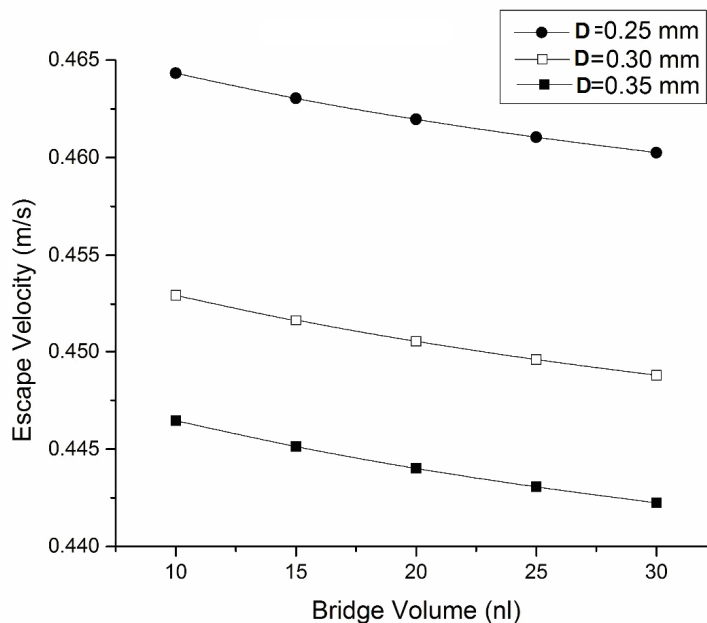


Fig. 2. Escape Velocity vs. Liquid Bridge Volume at Type I Salinity for different inter-particle distances

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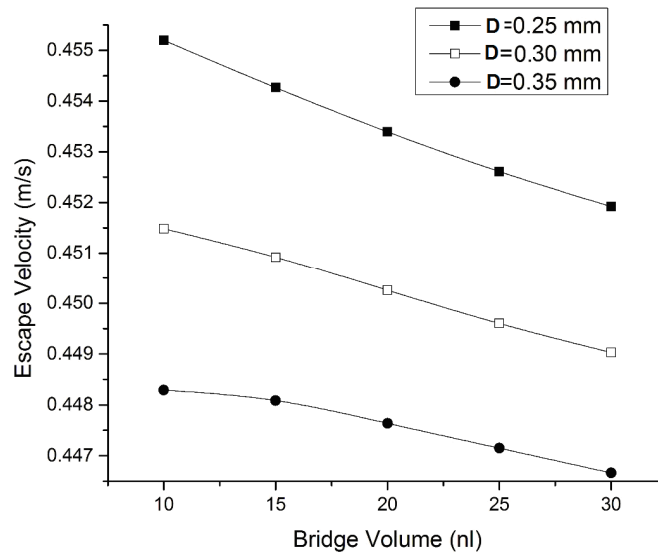


Fig. 3. Escape Velocity vs. Liquid Bridge Volume at Type II Salinity for different inter-particle distances

Fig. 2 and 3 show the combined effect of capillary cohesion and viscous force without pore pressure. The nature of the graphs shows that as the salinity of the water changes the escape velocity of the particle also changes. In case of Type I saline water soil particles require more velocity to escape from the bank.

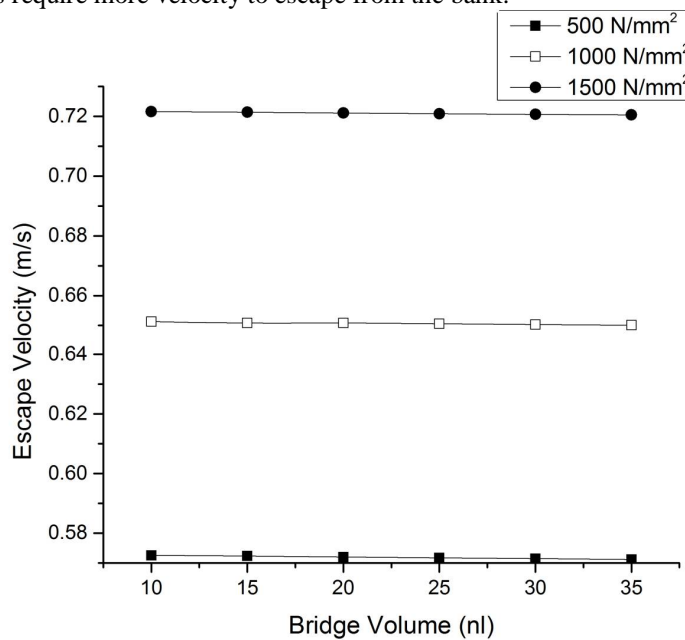


Fig. 4. Escape Velocity vs. Liquid Bridge Volume at Type I Salinity for different pore pressures

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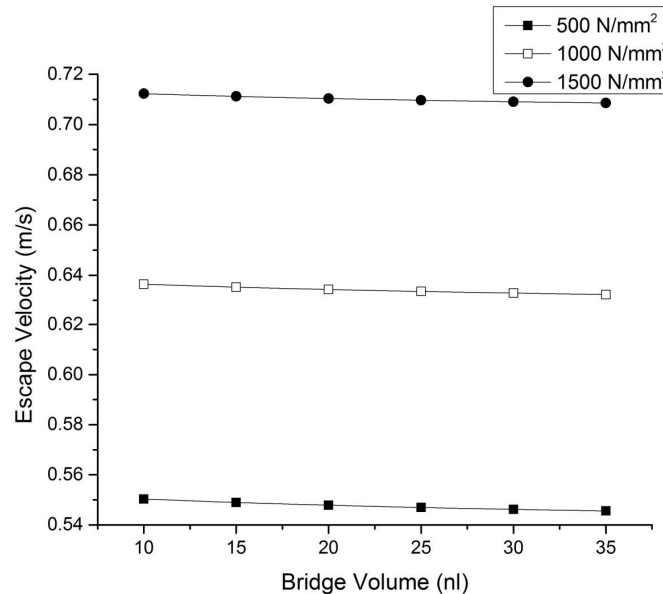


Fig. 5. Escape Velocity vs. Liquid Bridge Volume at Type II Salinity for different pore pressures

Fig. 4 and 5 depict that as the salinity of water changes the escape velocity of a particle also changes. Again, in case of Type I saline water a particle requires more velocity to escape.

V. CONCLUSION

Following conclusions can be drawn from the present analysis:

- 1) The escape velocity increases with increase in pore water pressure within the domain of the analysis. It also depends highly on the salinity of water. This is because a rise in pore pressure would induce more water in the inter-particle distance and that would increase the force between the adjacent particles up to a certain limit till it becomes saturated.
- 2) The escape velocity decreases with increase in inter-particle distance. The salinity of water also influences the escape velocity to a significant extent. Increase in inter-particle distance weakens the force between the neighboring particles and, thus, it results in a drop in the escape velocity.
- 3) The escape velocity decreases with increase in liquid bridge volume for the same inter-particle distance and pore pressure. Keeping the inter-particle distance induction of more and more water would have a negative influence on the force acting between the adjacent particles resulting in a decline in the escape velocity.

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