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Effect of Purity of Water on Riverbank Erosion Under Variable Operating Conditions

Sanchayan Mukherjee
Assistant Professor, Kalyani Government Engineering College, Email ID : sanchayan02@yahoo.com

Abstract — In this paper the behavior of a particle on a riverbank is analyzed for pure water and two 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 and gravitational pull. It is influenced by the arrangement of other particles surrounding it. The cohesive force has 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. There are remarkable differences between the results obtained for pure and saline water.

Keyword — Cohesive Force, Escape Velocity, Riverbank, Truncated Pyramid Model.

1. Introduction

Erosion means soil removal from the earth's surface. Erosion is essentially a smoothening or leveling process with soil and rock particles being carried, rolled or washed down by the force of gravity. It is also instrumental in the formation of alluvial soil and sedimentary rocks. It is caused by water, wind, temperature changes and biological activities.

River bank erosion is a perennial problem in this country especially in districts like Malda, Murshidabad, Nadia, Sagardwip etc. of West-Bengal, causing loss of lands and livelihood. Structural and non-structural interventions are needed to prevent potential loss of lands and livelihoods.

River bank erosion occurs under natural conditions. It is a part of an on-going cycle of sediment erosion and deposition within the stream system. However, large-scale changes to streams and their catchments lead to instability of the streams. As a result they seek for a new balanced system.

Increased run-off from cleared catchments imposes considerable erosive stress on streams. Where local soils do not have the necessary strength to resist water erosion, the removal of protective vegetation can lead to extensive erosion.

Many streams in the Sundarbans drained into wetland areas before entering the sea. These wetland areas are drained for agriculture and rivers often get straightened and de-snagged. As a result, the water velocity tends to increase along the length of the stream. This kind of treatment heightens the potential for erosion unless structures are introduced into the stream to slow down the flow of water.

Dharamdial and Khanbilvardi (1988) have developed a conceptual model to predict bank migration in a single river or a system of streams. The model is based on dividing the river into stream links. The methodology for estimating the volume of bank materials that would be entrained in the river flow, as well as the sediment sources and deposition of materials detached by river flow, has been described and incorporated into the model. The model considers the mechanics of the riverbank erosion processes and can serve as a tool in conservation and land management [1]. In another significant work, Darby and Thorne (1996) have tried to predict the stability of riverbanks with respect to mass failure [2]. Likos and Lu (2002) have made a theoretical analysis for modeling the constitutive relationships among water content and capillary cohesion in unsaturated granular soils. A rigorous series of equations has been developed by them to describe the inter-particle forces due to negative pore-water pressure for idealized spherical particles in simple cubic and tetrahedral packing geometries [3]. Duan (2005) has derived an analytical method to predict the rate of bank erosion, which she applied to a two-dimensional, depth-average model to simulate alluvial channel migration process. This approach suggests that the rate of basal bank erosion depends on the longitudinal gradient of sediment transport, the strength of the secondary flow and the sediment eroded from the bank [4]. Soulie et al. (2006) have proposed a model where the macroscopic mechanical behavior of wet polydisperse granular media has been investigated. Capillary bonding between two grains of unequal diameters has been described by a realistic force law implemented in a molecular-dynamics algorithm together with a protocol for the distribution of water in the bulk. Experiments have been performed in similar conditions. [5]. Mukherjee and Mazumdar (2010) have proposed a new model named the ''Truncated Pyramid Model'' for the arrangement of particles. They have suggested a general equation for the impending acceleration, as well as the escape velocity. They have shown that this escape velocity is largely dependent on the inter-particle distance for a particular volume of water entrapped between adjacent particles [6],[7].

2. TRUNCATED PYRAMID MODEL AND GENERAL EQUATIONS FOR IMPENDING ACCELERATION AND ESCAPE VELOCITY

An analytical model called the Truncated Pyramid Model (Mukherjee and Mazumdar, 2010) has been used in the present paper to calculate the escape velocity of a particle on a riverbank. As described in the model, each soil particle, spherical in shape and materially homogeneous, rests on a pair of particles in a pyramidal structure. 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 23 is the fourth particle in the third row and it rests on particles 33 and 34. The radii of the particles increase by a small amount as one proceeds along positive x and y directions. Impending acceleration of a particle in dynamic equilibrium, can be found out in x and y directions. The general equations of impending acceleration as given by Mukherjee and Mazumdar (2010) can be written for x and y direction as follows:

$$\ddot{x}_{ij} = \left(3\sigma/4R_{ij}^3\rho_s\right)\left[F_{1x}+F_{2x}+F_3-F_{4x}-F_{5x}-F_6\right] \quad (1)$$

Here

F_{1x} = Part of x-component of force between particles ij and i+1,j+1

$$= \sqrt{R_{ij}R_{i+1,j+1}}\left\{c_{i+1,j+1}+\exp\left[a_{i+1,j+1}\left(D/R_{i+1,j+1}\right)+b_{i+1,j+1}\right]\right\}$$
$$\left\{1-2R_{ij}R_{i+1,j}/\left[\left(R_{ij}+R_{i+1,j+1}\right)\left(R_{i+1,j}+R_{i+1,j+1}\right)\right]\right\} \quad (2a)$$

F_{2x} = Part of x-component of force between particles i-1,j and ij

$$= \sqrt{R_{i-1,j}R_{ij}}\left\{c_{ij}+\exp\left[a_{ij}\left(D/R_{ij}\right)+b_{ij}\right]\right\}$$
$$\left\{1-2R_{i-1,j}R_{i,j+1}/\left[\left(R_{i-1,j}+R_{ij}\right)\left(R_{ij}+R_{i,j+1}\right)\right]\right\} \quad (2b)$$

F_3 = Part of force between particles ij and i,j+1

$$= \sqrt{R_{ij}R_{i,j+1}}\left\{c_{i,j+1}+\exp\left[a_{i,j+1}\left(D/R_{i,j+1}\right)+b_{i,j+1}\right]\right\} \quad (2c)$$

F_{4x} = Part of x-component of force between particles ij and i+1,j

$$= \sqrt{R_{ij}R_{i+1,j}}\left\{c_{i+1,j}+\exp\left[a_{i+1,j}\left(D/R_{i+1,j}\right)+b_{i+1,j}\right]\right\}$$
$$\left\{1-2R_{ij}R_{i+1,j+1}/\left[\left(R_{ij}+R_{i+1,j}\right)\left(R_{i+1,j}+R_{i+1,j+1}\right)\right]\right\} \quad (2d)$$

F_{5x} = Part of x-component of force between particles i-1,j-1 and ij

$$= \sqrt{R_{i-1,j-1}R_{ij}}\left\{c_{ij}+\exp\left[a_{ij}\left(D/R_{ij}\right)+b_{ij}\right]\right\}$$
$$\left\{1-2R_{i-1,j-1}R_{i,j-1}/\left[\left(R_{i-1,j-1}+R_{ij}\right)\left(R_{i,j-1}+R_{ij}\right)\right]\right\} \quad (2e)$$

F_6 = Part of force between particles ij and i,j-1

$$= \sqrt{R_{i,j-1}R_{ij}}\left\{c_{ij}+\exp\left[a_{ij}\left(D/R_{ij}\right)+b_{ij}\right]\right\} \quad (2f)$$

Parts F_3 and F_6 do not have any corresponding y-component and, hence, do not contain x in the subscripts.

$$\ddot{y}_{ij} = \left[1-\left(\rho/\rho_s\right)\right]g + \left(3\sigma/4R_{ij}^3\rho_s\right)\left[F_{1y}+F_{2y}-F_{3y}-F_{4y}\right] \quad (3)$$

Here

F_{1y} = Part of y-component of force between particles ij and i+1,j

$$= \sqrt{R_{ij}R_{i+1,j}}\left\{c_{i+1,j}+\exp\left[a_{i+1,j}\left(D/R_{i+1,j}\right)+b_{i+1,j}\right]\right\}$$
$$\left\{2\sqrt{R_{ij}R_{i+1,j}R_{i+1,j+1}\left(R_{ij}+R_{i+1,j}+R_{i+1,j+1}\right)}/\left[\left(R_{ij}+R_{i+1,j}\right)\left(R_{i+1,j}+R_{i+1,j+1}\right)\right]\right\} \quad (4a)$$

F_{2y} = Part of y-component of force between particles ij and i+1,j+1

$$= \sqrt{R_{ij}R_{i+1,j+1}}\left\{c_{i+1,j+1}+\exp\left[a_{i+1,j+1}\left(D/R_{i+1,j+1}\right)+b_{i+1,j+1}\right]\right\}$$
$$\left\{2\sqrt{R_{ij}R_{i+1,j}R_{i+1,j+1}\left(R_{ij}+R_{i+1,j}+R_{i+1,j+1}\right)}/\left[\left(R_{ij}+R_{i+1,j+1}\right)\left(R_{i+1,j}+R_{i+1,j+1}\right)\right]\right\} \quad (4b)$$

F_{3y} = Part of y-component of force between particles i-1,j-1 and ij

$$= \sqrt{R_{i-1,j-1}R_{ij}}\left\{c_{ij}+\exp\left[a_{ij}\left(D/R_{ij}\right)+b_{ij}\right]\right\}$$
$$\left\{2\sqrt{R_{i-1,j-1}R_{i,j-1}R_{ij}\left(R_{i-1,j-1}+R_{i,j-1}+R_{ij}\right)}/\left[\left(R_{i-1,j-1}+R_{ij}\right)\left(R_{i,j-1}+R_{ij}\right)\right]\right\} \quad (4c)$$

F_{4y} = Part of y-component of force between particles i-1,j and ij

$$= \sqrt{R_{i-1,j}R_{ij}}\left\{c_{ij}+\exp\left[a_{ij}\left(D/R_{ij}\right)+b_{ij}\right]\right\}$$
$$\left\{2\sqrt{R_{i-1,j}R_{ij}R_{i,j+1}\left(R_{i-1,j}+R_{ij}+R_{i,j+1}\right)}/\left[\left(R_{i-1,j}+R_{ij}\right)\left(R_{ij}+R_{i,j+1}\right)\right]\right\} \quad (4d)$$

Here

$$a_{ij} = -1.1\left(\forall/R^3\right)^{-0.53} \quad (5a)$$

$$b_{ij} = \left(-0.148\ln\left(\forall/R^3\right)-0.96\right)\phi^2 - 0.0082\ln\left(\forall/R^3\right)+0.48 \quad (5b)$$

$$c_{ij} = 0.0018\ln\left(\forall/R^3\right)+0.078 \quad (5c)$$

Where the coefficients a_{ij}, b_{ij} and c_{ij} are functions of the volume $\forall$ of the liquid bridge, the surface tension σ, the contact angle ϕ and R, i.e., the greater value between R_{ij} and radius of its neighbouring particle (Soulie et al., 2006).

ρ, ρ_s = densities of water and sediment particles, respectively, and g = acceleration due to gravity.

The resultant impending acceleration (in m/s^2),

$$f_{ij} = \sqrt{\ddot{x}_{ij}^{\;2} + \ddot{y}_{ij}^{\;2}} \qquad (6)$$

The direction of the resultant acceleration is given by $\tan^{-1}\left(\ddot{y}_{ij}/\ddot{x}_{ij}\right)$

A particle is said to be entrained when it is displaced by a distance equal to its diameter. From the momentum law, the escape velocity (in m/s) of the particle ij would be

$$V_{sij} = \sqrt{R_{ij}\, f_{ij} \times CF} \qquad (7)$$

where R_{ij} is expressed in mm, and CF is the conversion factor of value 0.002.

3. Calculation of escape velocity of a sediment particle on the riverbank

In the present work calculations have been made to study the variations of the escape velocity with gradual increase in volume of the water bridge between particles for different inter-particle distances. For the present set of analyses it is assumed that the radius of particle 11 is 0.396 mm and the radii of particles increase by 0.004 mm in x and y directions as envisaged in the Truncated Pyramid Model. Only the particle sitting at the leftmost position of a row (i.e. j = 1) has been considered. Separate calculations have been made for pure and saline water (Type I and II) with properties as follows:

- Pure water:

Surface Tension, σ =0.073 N/m;

Density of material of particle, ρ_s=2650 kg/m^3;

Density of water, ρ =1000 kg/m^3;

Volume of liquid bridge, V =15 nl and 25 nl (two different cases);

Angle of contact, $\theta = 0$.

- Type I saline water:

Surface Tension, σ =0.065 N/m;

Density of material of particle, ρ_s=2650 kg/m^3;

Density of water, ρ =1010 kg/m^3;

Volume of liquid bridge, V =15 nl and 25 nl;

Angle of contact, $\theta = 25°$.

- Type II saline water:

Surface Tension, σ =0.0681 N/m;

Density of material of particle, ρ_s=2650 kg/m^3;

Density of water, ρ =1025 kg/m^3;

Volume of liquid bridge, V =15 nl and 25 nl;

Angle of contact, $\theta = 25°$.

It can be noted that according to Bakker et al. (2003)[8] contact angle varies in the range from 15° to 50° depending on the nature of the solid surface, and according to Morgan (1963)[9] contact angle can be considered as 25° for impure water.

4. Results and discussions

Based on the given equations and properties of water the escape velocity of the particle 11, 21 and 31 are calculated for different operating conditions as depicted in the graphical presentations.

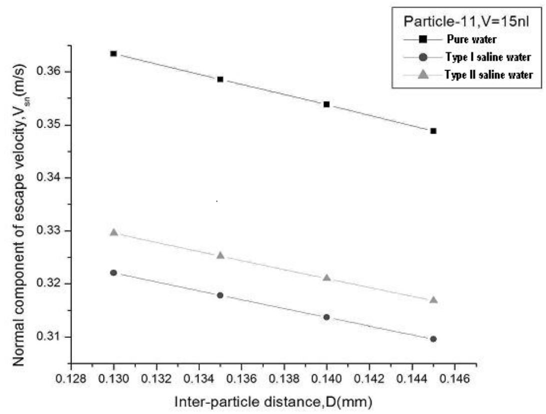

Fig.1. Component of escape velocity normal to the riverbank with the inter-particle distance for particle 11 and volume of the liquid bridge 15 nl

Figure 1 shows the variation of the component of escape velocity normal to the riverbank with the inter-particle distance for particle 11 and volume of the liquid bridge 15 nl.

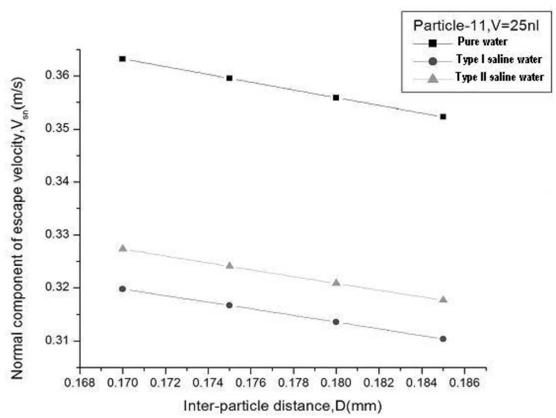

Fig.2. Component of escape velocity normal to the riverbank with the inter-particle distance for particle 11 and volume of the liquid bridge 25 nl

Figure 2 shows the variation of the component of escape velocity normal to the riverbank with the inter-particle distance for particle 11 and volume of the liquid bridge 25 nl.

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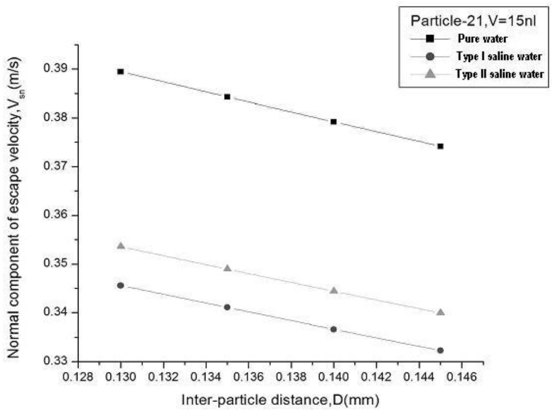

Fig.3. Component of escape velocity normal to the riverbank with the inter-particle distance for particle 21 and volume of the liquid bridge 15 nl

Figure 3 shows the variation of the component of escape velocity normal to the riverbank with the inter-particle distance for particle 21 and volume of the liquid bridge 15 nl.

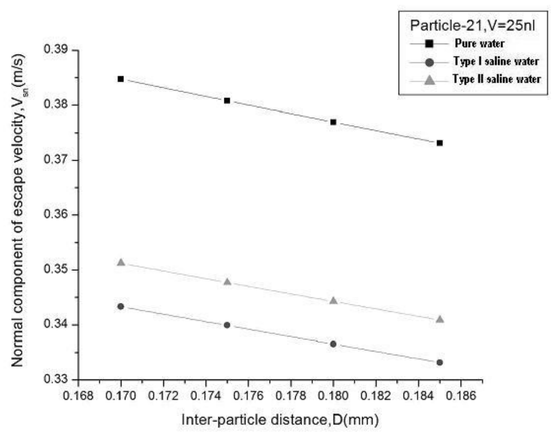

Fig.4. Component of escape velocity normal to the riverbank with the inter-particle distance for particle 21 and volume of the liquid bridge 25 nl

Figure 4 shows the variation of the component of escape velocity normal to the riverbank with the inter-particle distance for particle 21 and volume of the liquid bridge 25 nl.

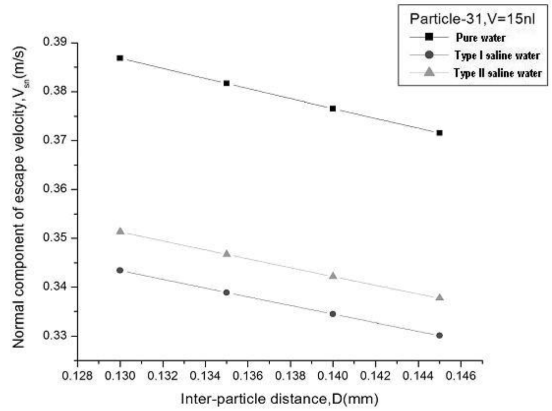

Fig.5. Component of escape velocity normal to the riverbank with the inter-particle distance for particle 31 and volume of the liquid bridge 15 nl

Figure 5 shows the variation of the component of escape velocity normal to the riverbank with the inter-particle distance for particle 31 and volume of the liquid bridge 15 nl.

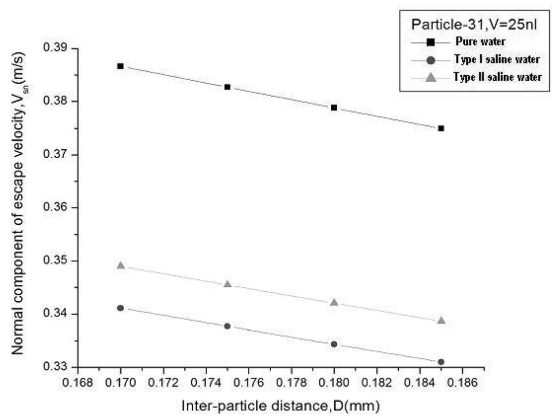

Fig.6. Component of escape velocity normal to the riverbank with the inter-particle distance for particle 31 and volume of the liquid bridge 25 nl.

Figure 6 shows the variation of the component of escape velocity normal to the riverbank with the inter-particle distance for particle 31 and volume of the liquid bridge 25 nl.

From Fig. 1- 6 it is clear that for same values of the escape velocity the inter-particle distance is more in case of greater values of the volume of the liquid bridge. In other words, as the volume of the liquid bridge increases a particle requires more velocity to escape for a particular inter-particle distance. This is because the entrapped water increases the force between the particles up to a certain limit. Also, as the salinity (or impurity) of the water increases the escape velocity becomes smaller. This result falls exactly in line with findings of Soulie et al. (2006) where they have shown that the force between the particles is less for impure water than for pure water.

5. Conclusion

From the results obtained in the previous section following conclusion can be drawn:

- For the same value of the particle diameter and the volume of the liquid bridge the escape velocity decreases as the inter-particle distance increases. This is because of weakening of cohesive force between the particles.
- For the same value of the particle diameter and the inter-particle distance the escape velocity increases as the volume of the liquid bridge increases.
- As water deviates more and more from purity the escape velocity decreases for the same value of the particle diameter, the inter-particle distance and the volume of the liquid bridge. So, the saline water reduces the escape velocity compared to the pure water. So, riverbanks having saline water content are more vulnerable.

6. Acknowledgment

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7. Reference

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Author's Profile

Sanchayan Mukherjee

Ph.D. (Engineering) from Jadavpur University, Kolkata; M.E. (Distinction with CGPA 10.0 out of 10.0) (B.I.T.S., Pilani); B.M.E. (1st Class Hons.) (Jadavpur University).

Professional Experience: 11 Years as Lecturer, Senior Lecturer and Assistant Professor of Mechanical Engineering in Kalyani Government Engineering College. 4 Years as Design Engineer in M/S Development Consultants Limited, Kolkata, India, and M/S Voltas Limited, Jamshedpur, India

Publications: Books: 5
Edited Conference Proceedings: 1
International journals: 7
National Journals: 7
International Seminar/Conference: 4
National Seminar/Conference: 19

Editorial Board Member of

International Journal of Soft Computing and Engineering (India)

International Journal of Water Resources and Environmental Engineering (Academic Journals)

Reviewer of

Journal of Hydro-environment Research (Elsevier) (2*);
Journal of Hydraulic Engineering (ASCE) (2*);
Journal of Applied Mathematical Modelling (Elsevier) (1*);
Engineering Applications of Computational Fluid Mechanics (Hong Kong Polytech. Univ.) (2*);
KSCE Journal of Civil Engineering (Springer) (3*);
Journal of the Institution of Engineers (India) (Springer) (5*);
Journal of the Association of Engineers (India) (2*);
* Number of papers reviewed

Book Reviewed: 1 (Pub: Tata McGraw-Hill)
Ph.D. Viva Voce Conducted (As External Examiner): 1
Ph.D. Thesis Examined: 2

M.E. Thesis Examined & Viva Voce Conducted (As External Examiner): 6
M**.E. Project Supervised:** 3
Membership of Professional Societies: Life Fellow – The Association of Engineers (India), Corporate Member – The Institution of Engineers (India), Life Member – Forum of Scientists, Engineers & Technologists (FOSET), Life Member – Institute of Science, Education & Culture (ISEC), Life Member – Bangiya Bijnan Parishad (founded by Prof. S. N. Bose) and Member – Indian Society of Heating Refrigerating & Air-conditioning Engineers (ISHRAE).

Awards/Achievements:
Ranked 13th in Madhyamik Pariksha 1990; Winner of Polar Science Scholarship 1991 and interviewed by the *Calcutta Skyline*; Received the *Best Research Paper Award* in the Technology (Engineering) Session in the 17th West Bengal State Science & Technology Congress held in Kolkata, March 4 – 5, 2010, Kolkata; Interviewed by the *All India Radio* in July 2011; Two of the authored books cited by *wikipedia* for defining Simple Machine and Perpetual Motion Machine of the Third Kind; One of the authored books is available in the National Library (Call No.: E 621 M 896 s).