Equilibrium scour in rivers with sandbeds

A Rooseboom[1]* and A le Grange[2]
[1]*Department of Civil Engineering, University of Stellenbosch, Private Bag X5018, Stellenbosch 7599, South Africa*
[2]*BKS Inc, PO Box 3173, Pretoria 0001, South Africa*

Abstract

Severe floods caused extensive scour along sand-bedded rivers in Natal during 1984 and 1987. Recorded information on the extent of scour as well as peak flood discharges was analysed in an attempt to develop criteria which could be used to predict scour depths in future.

Contrary to expectations, all the indications are that laminar rather than turbulent boundary layer conditions prevail when equilibrium scour depths are approached.

By deforming their beds through the formations of dunes and other bed formations, the sediment transporting capacity of rivers is decreased. This means that rivers have a built-in mechanism through which excessive scour is prevented when extreme floods occur.

Introduction

Severe floods caused extensive damage to river systems in south-eastern Africa during 1984 and 1987 (Kovács et al., 1985; Van Bladeren and Burger, 1989). The floods which occurred in the Komati, Mkuze, Black Mfolozi and White Mfolozi Rivers during 1984 together with the 1987 flood in the Mhlatuze River were the largest on record at the gauging stations on these rivers. Their respective estimated return periods ranged from at least 20 years to more than 200 years.

Extensive bed and bank erosion occurred and a large number of bridges were either destroyed or severely damaged.

Shortly after the floods had occurred, the South African Department of Water Affairs performed topographical surveys of specific reaches (Fig. 1) along these rivers. Maximum flood levels that had been reached were recorded at the same time. It was thus possible to calculate the peak discharges that had occurred and compare these values with the depths and widths to which the sandbed river channels had been eroded, in an attempt to establish criteria which could be used in future to predict equilibrium scour depths.

Theoretical background

It might be expected that when extremely large floods with high sediment carrying capacities occur in rivers with erodible bed and bank materials, scour will continue to take place until the erosive capacity of the stream approaches the minimum value required to transport the available material.

A number of criteria have been developed which depict the critical stage where a stream's transporting capacity becomes sufficient to transport the available material. Classical examples of such criteria are represented by the Hjülstrom (1935), Shields (1936) and Liu (1957) diagrams. Whilst these diagrams were developed primarily on an intuitive basis, rigorous theoretical analysis of flow transporting capacity and sediment transportability (Rooseboom, 1974; 1992) leads to the type of relationships represented in the Liu diagram. The success of this (applied power) approach is attributed to the fact that both flow transporting capacity and sediment transportability can be expressed in directly comparable scalar terms. This approach has been developed further in order to quantify the influence that bed roughness has on sediment transporting capacity.

It can be argued that whenever alternative modes of flow exist, that mode which requires the least amount of unit power will be followed. Accordingly fluid flowing over movable material would not transport such material unless this would result in a decrease in the amount of unit power which is being applied. Alternatively, if two modes of yielding exist, yielding will take place according to that mode which offers the least resistance.

Where flow takes place over movable material and the relatively large amount of unit power required to maintain motion along the bed becomes greater than that which would be required in the process of deformation of the bed, the stream should begin to transport the bed material rather than persist in its existing mode of flow. The applied power required per unit volume to suspend a particle with density ρ_s and settling velocity V_{ss}, in a fluid with density ρ, equals $(\rho_s - \rho)\, g\, V_{ss}$.

In rough turbulent flow the unit stream power applied in maintaining motion along a smooth bed consisting of particles with diameter d is proportional to:

$$\frac{\rho g s D \sqrt{gDs}}{d}$$

(representing the applied unit stream power $\tau dv/dy$ along the bed)

with:

- ρ = fluid density
- g = acceleration due to gravity
- s = energy slope
- D = flow depth
- d = particle diameter (proportional to the absolute bed roughness for a smooth bed)
- τ = shear stress
- dv/dy = velocity gradient

In terms of the concept of minimum applied power, the stream will begin to entrain particles when the power required to suspend the particles becomes less than the power required to maintain the status quo.

At that stage:

$$(\rho_s-\rho)\, g\, V_{ss} \propto \rho g s D \frac{\sqrt{gDs}}{d} \qquad (1)$$

*To whom all correspondence should be addressed.

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