

## Assessment of River Channel Stability

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**ABSTRACT:** *An optimization model is used to assess the effect of bank stability on the equilibrium hydraulic geometry of alluvial rivers. The bank-stability constraint is formulated for channels with either cohesive or noncohesive bank sediment.*

*The model is tested on published data for rivers with varying types and density of bank vegetation. The results show that the bank vegetation can exert a large influence on the stability of the banks, and hence the hydraulic geometry of the channel.*

*The bank-stability parameters can be "calibrated" using the observed channel geometry. This permits the effect of the bank vegetation on the stability of the banks and the hydraulic geometry to be indirectly quantified.*

### 1. INTRODUCTION

Currently throughout Australia, River Improvement Trusts and other organisations are involved in the development of riparian zone management plans. One of the common goals of these management plans is to promote stability of the river channels, and to minimise river bank erosion.

In order to better manage rivers it is essential that the influence that the bank stability exerts on the channel be recognised, and that the hydraulic and geotechnical processes which determine the stability of the banks be more fully understood. In the companion paper (Millar and Quick, 1996a) the optimisation model developed by the authors is presented. In this paper the model is used to investigate the influence of bank stability and bank vegetation on river channel geometry.

### 2. BANK-STABILITY CONSTRAINT

The bank-stability constraint requires that the reach averaged condition of the banks be stable. The bank-stability constraint can be formulated for banks with cohesive sediment or noncohesive sediment.

Note that stability here applies to the reach-averaged condition of the banks. Locally, such as along the

outer bend of a meander, the banks may not be stable. However the reach-average condition of the banks must be one of stability, otherwise there would be a net change in the hydraulic geometry over time, and the channel could not be considered to be in equilibrium.

### 2.1 Erosion Processes

In channels with cohesive banks there are essentially two fundamental processes of bank erosion (Thorne, 1982; Grissinger, 1982):

- mass failure, and
- fluvial entrainment of discrete grains or aggregates.

Mass failure of a river bank occurs when the driving force due to the weight of the failed soil mass, exceeds the resisting force which is produced by the cohesion and internal friction of the soil. The critical height of a bank  $H_{crit}$  which fails along a surface passing through the toe can be expressed by the following equation:

$$H_{crit} = N_s \frac{c'}{\gamma_t} \quad (1)$$

where  $\gamma_t$  = total unit weight of the soil,  $c'$  = the effective soil cohesion, and  $N_s$  = the stability number.

$N_s$  is a function of the effective friction angle  $\phi'$ , and the bank angle  $\theta$ . The value of  $N_s$  can be obtained from computed limiting stability curves. Stability curves can be determined from a geotechnical slope-stability analysis of the bank sediment using the method of slices, or similar techniques. Examples are shown in Figure 1.

Fluvial entrainment is the process whereby individual grains or aggregates on the surface of the bank are removed and entrained by the flow. The driving force is the shearing action of the fluid on the bank sediment. The resisting interparticle force for cohesive sediment is the net result of several forces of attraction and repulsion. These forces result from complex electro-chemical processes which include the clay mineralogy and content, and

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the temperature and chemistry of the pore and eroding fluids (Grissinger, 1982).

For noncohesive sediment, fluid forces exerted on the grains, as well as the down-slope gravity component must be resisted by the frictional forces for a grain to remain stable.

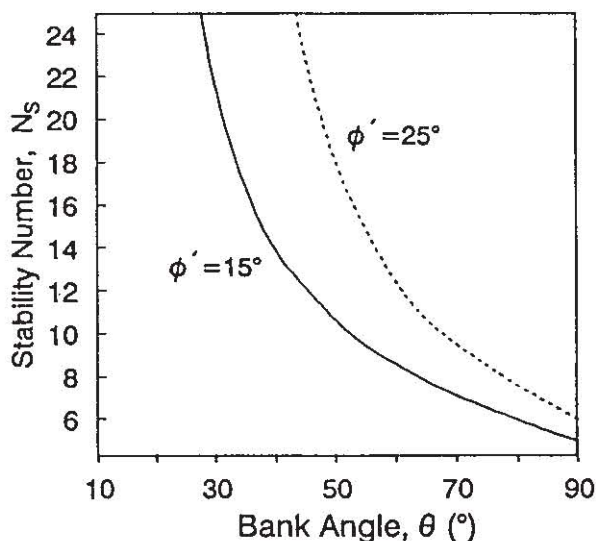


Figure 1. Limiting Stability Curves.

## 2.2 Mathematical Formulation

### 2.2.1 Cohesive Bank Sediment

For banks composed of cohesive sediment there are two separate components to the bank-stability constraint, one corresponding to the mass stability of the bank material, and the second corresponding to the stability of the bank sediment to resist fluvial entrainment. In order for a bank to be stable both constraints must be satisfied.

The bank-height constraint requires that the bank height  $H$ , be less than or equal to the critical bank height  $H_{crit}$ :

$$H \leq H_{crit} \quad (2)$$

The value for  $H_{crit}$  is calculated by Equation (1), and  $N_s$  is obtained from the limiting stability curves (see Figure 1).

The bank-shear constraint requires that the bank shear stress be less than the critical value required for fluvial entrainment of the bank sediment:

$$\tau_{bank} \leq \tau_{crit} \quad (3)$$

The value  $\tau_{crit}$  is considered to be an independent variable. The mean bank shear stress,  $\tau_{bank}$ , is a dependent variable that is calculated by the model.

### 2.2.2 Noncohesive Bank Sediment

The bank-stability constraint for noncohesive bank sediment is a modified form of the well-known USBR relation (Lane, 1955). The original form of the relation was modified allowing the effects of bank vegetation, and packing and imbrication of the bank sediment to be included.

For noncohesive sediment, the maximum bank angle that can remain stable is equal to the angle of repose,  $\phi$ . Loose, noncohesive sediment has a maximum value of  $\phi$  of about  $40^\circ$ . River banks composed of noncohesive sand and gravel with little or no cohesive material often appear much steeper than the maximum value of  $\phi$ . The effects of packing and imbrication, binding of the sediment by root systems, and small amounts of fine cohesive material can produce noncohesive banks that remain stable when bank angles exceed  $40^\circ$  or so.

The *in situ* friction angle,  $\phi_{is}$ , is introduced to account for these additional effects.  $\phi_{is}$  can take a value up to  $90^\circ$ .

The modified form of the USBR equation was developed in Millar and Quick (1993):

$$\frac{\tau_{bank}}{\gamma(s-1)D_{50bank}} \leq k \tan \phi_{is} \sqrt{1 - \frac{\sin^2 \theta}{\sin^2 \phi_{is}}} \quad (4)$$

where  $\tau_{bank}$  = mean bank shear stress,  $\gamma$  = unit weight of water,  $s$  = specific gravity of the sediment,  $D_{50bank}$  = median bank grain diameter which is assumed to be representative of the bank sediment,  $k$  = empirical constant, and  $\theta$  = bank angle.

## 3. BANK-FULL DISCHARGE

The bankfull discharge,  $Q_{bf}$ , is defined as the flow that just fills the channel to the tops of the banks.  $Q_{bf}$  is significant in terms of bank stability.

The value of  $\tau_{bank}$  generally increases with increasing discharge up to  $Q_{bf}$ . Therefore, if the banks are stable with respect to fluvial erosion at  $Q_{bf}$ , then they will be stable for all lower discharges.

When the discharge exceeds  $Q_{bf}$  and overbank flow occurs, the additional flow is usually spread across a wide floodplain. Therefore, despite the larger

discharge, the depth of flow in the main channel, and therefore  $\tau_{bank}$ , may not be significantly greater than their respective values at  $Q_{bf}$ .

Furthermore research has shown that in cases where the depth of the overbank flow is significant, complex momentum transfer effects between the main channel and the slower floodplain flow result. When this occurs the velocity of the main channel flow, sediment transport rates, and the value of  $\tau_{bank}$  can actually decrease for discharges that exceed  $Q_{bf}$  (eg Sellin, 1964; Barishnikov, 1967).

Therefore for modelling purposes the bank stability (with respect to fluvial erosion) is only assessed at  $Q_{bf}$ . If the banks are found to be stable at  $Q_{bf}$ , then they are assumed to be stable for all other discharges.

$Q_{bf}$  is also relevant for bank stability with respect to mass failure.  $Q_{bf}$  defines the 'size' of the channel. The bank height  $H$ , is by definition equal to the flow depth at  $Q_{bf}$ .

#### 4. RESULTS

Results obtained using the optimisation model for channels with both cohesive and noncohesive banks will now be presented. These results have been published previously in Millar and Quick (1993, 1994), and are discussed fully in Millar (1994).

##### 4.1 Noncohesive Banks

The model was tested on the published gravel river data collected by Andrews (1984) and Hey and Thorne (1986). The published data was used as input to the model, and the output geometry compared to the observed geometry.

The banks are characterised in terms of their vegetation density. Andrews (1983) subdivided his data set into those channels with thin and thick vegetation. Similarly, Hey and Thorne (1986) subdivided their data into four bank Vegetation Types ranging from Vegetation Type I (grass with no trees or bushes) to Vegetation Type IV (> 50% trees and bushes).

Figure 2 shows the agreement between the modelled and observed dimensions for the rivers described as having the lowest densities of bank vegetation. The value of  $\phi_{is}$  was not available, and therefore  $\phi_{is} = 40^\circ$  was assumed. The constant  $k$  in Equation (4) was adjusted to provide the best agreement between modelled and observed.

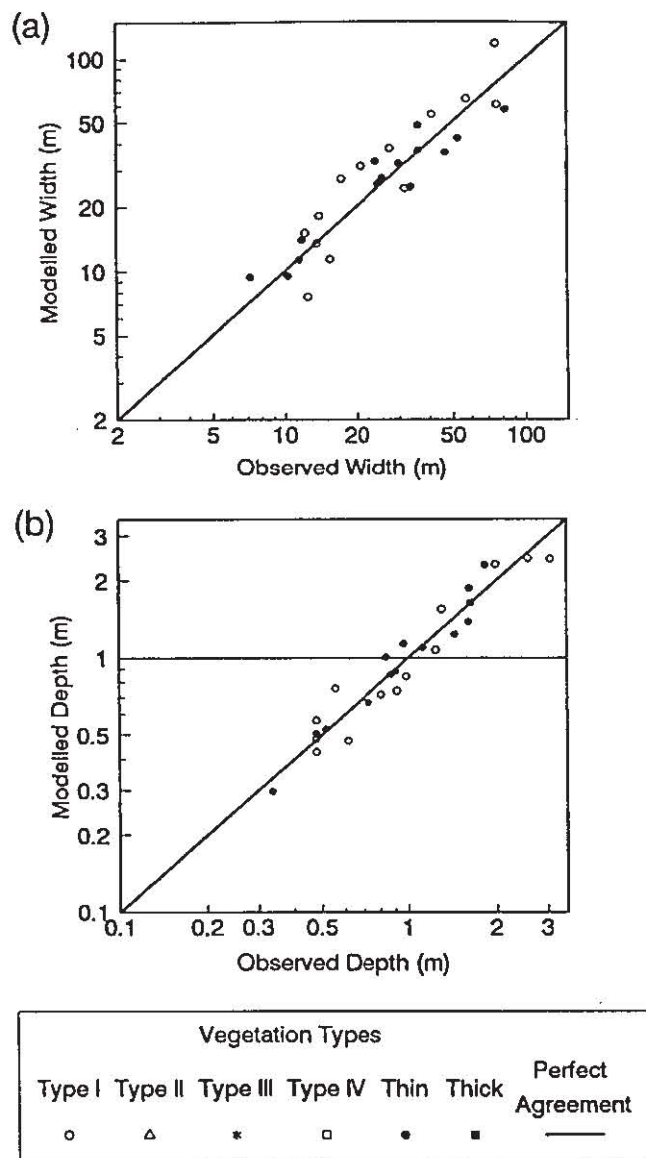


Figure 2. Analysis of channels with noncohesive bank sediment and low densities of bank vegetation. (a) Channel Width. (b) Channel Depth.

The model was then run using the full data set. The results are shown in Figure 3. A large degree of scatter is evident. Note that the scatter is asymmetric about the line of perfect agreement. The modelled channels are wider and shallower than their observed counterparts. A more detailed analysis revealed that the discrepancy between modelled and observed increased systematically with the reported bank vegetation density (Millar and Quick, 1993).

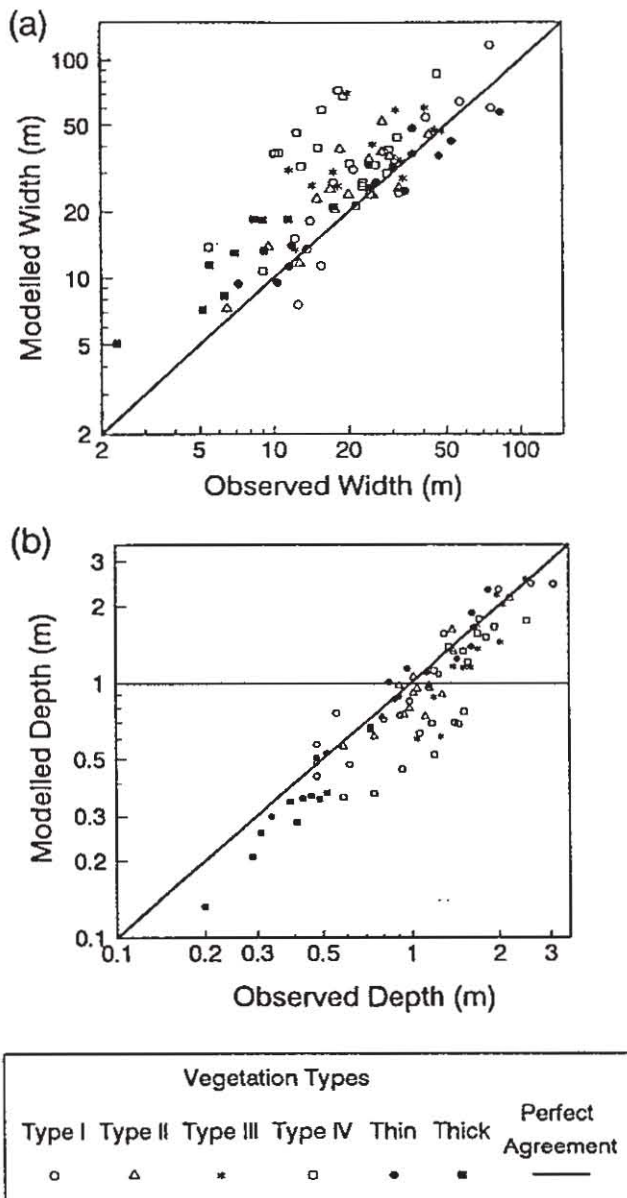


Figure 3. Analysis of channels with noncohesive bank sediment and various densities of bank vegetation. (a) Channel Width. (b) Channel Depth.

It was surmised that the bank vegetation was influencing the value of  $\phi_{is}$ . The assumption of  $\phi_{is} = 40^\circ$  was valid only for the channels with the lowest densities of bank vegetation. Therefore the modelled channel dimensions in Figure 3 should correspond to the unvegetated condition. The actual channels had a range of densities of bank vegetation, and the effect of this the bank vegetation was to increase the stability of the channel banks. This resulted in observed dimensions that were narrower and deeper than the modelled, "unvegetated" channels.

This analysis indicated that the widths and depths of the most heavily vegetated channels were in the order of 0.6 and 1.4 times their respective unvegetated dimension.

The modelled channels could be brought into agreement with their observed counterparts by adjusting the value of  $\phi_{is}$ . The "calibrated" values of  $\phi_{is}$  were shown to increase systematically with the density of the bank vegetation from a mean of  $42^\circ$  for the lowest densities, to  $60^\circ$  for channels with the densest bank vegetation (Millar and Quick, 1993).

#### 4.2 Cohesive Banks

The 14 rivers from the Charlton *et al.* (1978) data set are used to test the formulation for cohesive banks. The data included sufficient information to permit a good estimate of the bank-height constraint parameters ( $c'$ ,  $\phi'$ ,  $\gamma$ ).

The values for  $\tau_{crit}$  were not given by Charlton *et al.* (1978), and it is not possible to directly estimate the values for  $\tau_{crit}$ . The model was initially run using a value of  $\tau_{crit} = 1000 \text{ N/m}^2$ . This value is unrealistically high and forces the bank-shear constraint to be degenerate.

The term *degenerate* in optimisation terminology means that the constraint is not actively affecting the solution. For example if  $\tau_{bank}$  is equal to say  $15 \text{ N/m}^2$  for the optimal solution, and  $\tau_{crit} = 25 \text{ N/m}^2$ , then the bank-shear constraint would be degenerate because  $\tau_{bank} < \tau_{crit}$  (or  $\tau_{bank} / \tau_{crit} < 1.0$ ). Similarly if  $H < H_{crit}$  (or  $H / H_{crit} < 1.0$ ) then the bank-height constraint would be degenerate.

If either of the constraints were active, then the value of the ratio  $\tau_{bank} / \tau_{crit}$  or  $H / H_{crit}$  would be equal to 1.0 for the active constraint.

At least one of the bank-stability constraints must be active in natural rivers. For an alluvial river to adjust its boundary bank erosion must occur. Therefore changes to the reach-average geometry can only occur when the bank-stability constraint is not satisfied. As soon as it is satisfied, that is when the values of the ratios of  $H / H_{crit}$  and  $\tau_{bank} / \tau_{crit}$  are both less than or equal to 1.0, net bank erosion will cease.

A comparison between the modelled and observed channel dimensions is shown in Figure 4. The channels are subdivided into bank-height and bank-

shear constrained on the basis of the active constraint.

The modelled dimensions of the two channels denoted as bank-height constrained agree closely with the observed geometry. For these two channels the values of  $H / H_{crit}$  are both equal to 1.0, and the values of the ratio  $\tau_{bank} / \tau_{crit}$  are both less than 1.0.

The bank-shear constrained channels can be brought into agreement with their observed geometry by reducing the value of  $\tau_{crit}$ . As  $\tau_{crit}$  is reduced the modelled channels become wider and shallower. This reflects the reduction in the stability of the channel banks.

The value of  $\tau_{crit}$  for each channel was reduced until there was agreement between the modelled and observed channel widths. At agreement, the values of  $\tau_{bank} / \tau_{crit}$  are all equal to 1.0, indicating that the channels are bank-shear constrained. The values of  $H / H_{crit}$  are all less than 1.0, indicating that the bank-height constraint is degenerate.

The "calibrated" value of  $\tau_{crit}$  that results in agreement between the modelled and observed geometry provides an indirect estimate of the actual value. This is similar to the method used to estimate  $\phi_{is}$  for noncohesive channels discussed in Section 4.1.

4.2.1 Effect of Bank Vegetation.

Charlton *et al.* (1978) categorised their data set on the basis of bank vegetation into channels with grassed or treed banks. The values of  $\tau_{crit}$  obtained from the previous analysis show a strong influence from the bank vegetation. The mean and standard deviation of  $\tau_{crit}$  for channels described as having grassed banks ( $n=6$ ) are 10.4 and 2.3 N/m<sup>2</sup> respectively, compared to 29.8 and 12.7 N/m<sup>2</sup> for the treed banks ( $n=6$ ). The calibrated values of  $\tau_{crit}$  for channels with grassed banks are significantly lower compared to the channels with treed banks.

This result suggests that the effect of the bank vegetation is to increase the value of  $\tau_{crit}$  either by binding the sediment by the root masses, or conversely by affording protection of the bank and effectively reducing the value of  $\tau_{bank}$  acting on the bank sediment.

Furthermore the bank vegetation may bind the bank sediment so as to increase the stability of the banks with respect to mass failure. In this way the roots act as internal reinforcement, and have the effect of increasing the effective values of  $c'$  and  $\phi'$  above the values obtained from the analysis of small samples of the bank material.

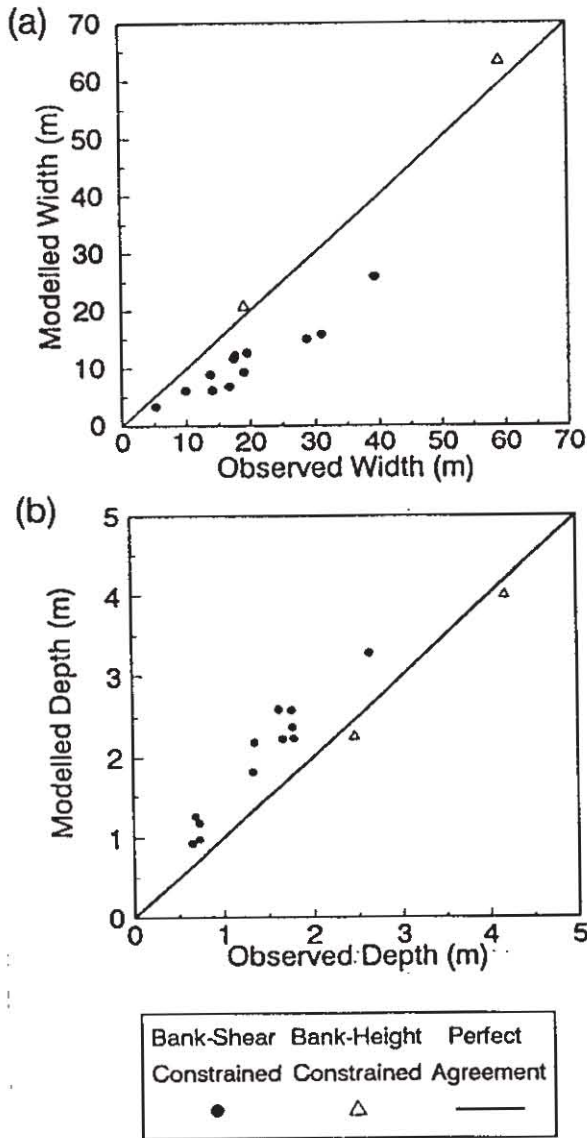


Figure 4. Analysis of channels with cohesive bank sediment. (a) Channel Width. (b) Channel Depth.

The remaining channels, which are denoted as bank-shear constrained, are narrower and deeper than their observed counterparts. For these channels the values of  $H / H_{crit}$  and  $\tau_{bank} / \tau_{crit}$  are all less than 1.0 when the value  $\tau_{crit} = 1000\text{N/m}^2$  is used.

## 5. CONCLUSIONS

The optimisation model presented in the companion paper (Millar and Quick, 1996a) has been used to assess the effect of bank stability on the equilibrium geometry of alluvial rivers. Despite deficiencies in the data sets available to test the model, it was demonstrated that the bank vegetation can exert a large influence on the stability of the banks, and hence the geometry of the channel.

The bank-stability constraints presented in this paper are simple models of relatively complex processes. The bank stability parameters, such as  $\phi_{is}$  and  $\tau_{crit}$ , represent lumped parameters that incorporate several effects.

The calibration procedure described in this paper for estimating the values of  $\phi_{is}$  for noncohesive banks, and  $\tau_{crit}$  for cohesive banks represents an indirect method for quantifying the effect of the bank vegetation on the stability of the banks, and the channel geometry.

For channels with cohesive banks it has been demonstrated that, based upon the active bank-stability constraint, two distinct channel types are identified. It is essential that in an assessment of bank and channel stability, that the active constraint be identified. Failure to do so can lead to erroneous conclusions regarding bank stability, and the influence of the bank vegetation.

The model is seen as an important adjunct to field-based investigations investigating the influence of bank vegetation on the stability of alluvial creeks and rivers. It can provide a theoretical framework for the design of field programs, and is a tool that permits the effect of bank stability to be isolated and assessed independently of other variables such as discharge and sediment load.

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