

Riverbank Reinforcement by Riparian Roots

Bruce Abernethy and Ian Rutherford¹

SUMMARY: Riparian trees strengthen riverbank material and tend to resist mass bank failure. The magnitude of root reinforcement is a function of root strength and the distribution of roots within the soil. The tensile strengths of individual roots were tested in the field and in the laboratory. Root distributions under live trees were mapped in the field. Combining the root reinforcement data with real channel geometries, stage variations, pore-water pressures and bank material strength properties, within a slope stability package, enabled us to model improvements in bank stability due to the riparian trees studied. Model results indicate that the addition of Swamp Paperbark roots to otherwise degraded bank profiles improves stability, as indicated by an increased factor of safety, by up to 132%. Similarly, the addition of River Red Gum roots increased stability by up to 175%. Quantifying the geotechnical response of river banks to root reinforcement improves our understanding of bank processes and allows for greater reliability in predicting channel adjustment to stream management options.

THE MAIN POINTS OF THIS PAPER:

- roots of woody vegetation increase the shear resistance of soils by providing an additional apparent soil cohesion;
- even low root densities provide substantial increases in shear strength compared to non-root-permeated soils; and
- the resistance of degraded bank sections to slumping can be more than doubled¹ with the addition of riparian trees.

1. INTRODUCTION

Banks of lowland rivers generally retreat by cyclical combination of toe scour followed by mass failure under gravity, followed then by basal cleanout of failed material. Each component of the cycle is affected by bank material properties including vegetation. Riparian vegetation affects the rate and distribution of bank erosion by interacting with the hydraulic, hydrological, geotechnical and morphological characteristics of the bank. Here we examine the degree to which tree roots increase the resistance of banks to deep-seated rotational slumping. Although many studies have attested to the importance of tree roots in strengthening banks, few have successfully quantified the effect.

The intermingled, lateral roots of plants tend to bind the soil together in a monolithic mass and contribute to strength by providing an additional apparent cohesion, c_r (Gray and Leiser, 1982). Roots have a negligible influence on the frictional component of soil strength. Thus, in a root permeated soil the usual Mohr-Coulomb soil-strength model can be modified to include c_r :

$$S = c' + c_r + (\sigma - u) \tan \phi' \quad (1)$$

where S is the shear strength of the soil-root composite, c' is effective cohesion, σ is normal stress, u is pore-water pressure and ϕ' is the friction angle.

Increases in c_r vary with root density, while maximum resistance to bank failure occurs when the tensile strength of roots is fully mobilised. The full reinforcement potential of shallow roots is often not realised because the roots pull out of the soil before peak tensile strength is reached (Waldron and Dakessian, 1981). Whether roots slip through the soil instead of breaking in tension depends on frictional resistance between the root surface and the bank sediments.

In this paper we estimate the potential contribution of roots to soil strength by measuring the tensile strength of the roots, and their distribution through the soil, and applying these data to a simple model of root reinforcement. Accounting for root reinforcement, bank geotechnical and hydrological properties, and bank geometry in a slope stability model then allows an assessment of the contribution of roots to bank stability under a range of natural conditions.

Most methods of assessing the mass stability of slopes (including riverbanks) adopt limit equilibrium techniques where a safety factor (F_s) is defined as the factor by which the available shear strength on the failure surface must be reduced, to bring the slope to a state of limiting equilibrium, i.e.

$$F_s = S/\tau \quad (2)$$

where τ is the shear stress acting along a failure plane. Here we use the generalised wedge method computer program (GWEDGEM) which fully satisfies force and moment equilibrium while maintaining a kinematically admissible failure mechanism (Donald and Zhao, 1995). The slip mass is divided into several wedges, the inter-surface between any two wedges not necessarily being vertical. Various multi-variable unconstrained search routines are included in GWEDGEM for the selection of critical failure mechanisms, which may be any multi-linear shape.

Because of their riparian association, and their history in bank stability work, we elected to concentrate on the bank reinforcing properties of River Red Gum (*Eucalyptus camaldulensis*) and Swamp Paperbark (*Melaleuca ericifolia*) in reinforcing banks of the Latrobe River in Gippsland, Victoria against mass failure. The two species provide quite a contrast in size and in distribution within the riparian corridor.

¹ Cooperative Research Centre for Catchment Hydrology, Department of Civil Engineering, Monash University, Clayton, Victoria, 3168. Ph: (03) 9905 5580, Fx: (03) 9905 5033, Em: bruce.abernethy@eng.monash.edu.au.

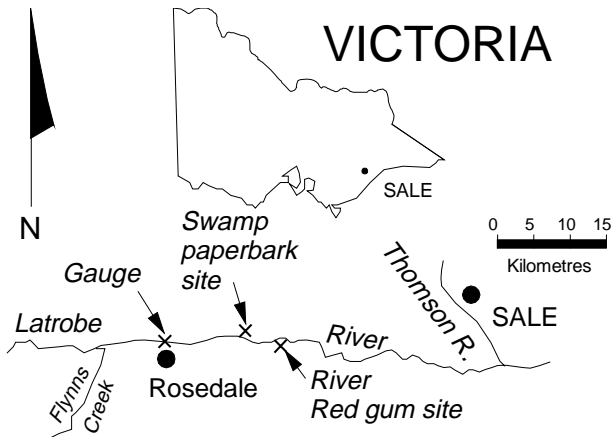


Figure 1: Latrobe River field sites.

Described below are field and laboratory work, data analysis, and modelling techniques. Cross-section data, surveyed on behalf of the Lake Wellington Rivers Authority, were kindly made available for our research. Of the 60 cross-sections surveyed, 12 occur in the vicinity of our field sites and have been used in the modelling work presented here.

2. FIELD SITES

Field work was conducted at sites on the banks of the lower Latrobe River near Rosedale (Figure 1). In this area the river is characterised by low gradients and extensive meanders on a broad floodplain. The channel is about 30 m wide and about 5 m deep. We chose sites where the river channel was well out onto the floodplain away from bordering slopes. The banks were colonised by monocultures of either Swamp Paperbark or River Red Gum. Due to their suckering habit, individual Swamp Paperbarks rarely occur so we investigated a thicket that extended up the bank face from the water line. No other woody species was present at either site so we were confident that any roots identified for study originated from the target species.

We collected ‘undisturbed’ soil samples from a range of depths down through the bank profile at the red gum site and returned them to the laboratory for analysis. The bank material at the site consisted of silty loam with little variation in particle size through the bank profile and an average saturated bulk unit weight (γ) of 18.3 kN/m³. The results of slow (drained) shear tests of saturated samples indicate that the strength parameters of these sediments are $c' = 15$ kPa and $\phi' = 16^\circ$.

3. ROOT DISTRIBUTION

Declines in root density have been observed with both lateral distance away from the tree trunk and depth below the soil surface (Gilman, 1988). Variations in root density were assessed at each of the sites by inspecting a number of vertical profile walls at various distances between the trunk and the canopy dripline. The profile walls were prepared in the manner described by Böhm (1979): rough digging of initial trenches, followed by careful forming of final, vertical, working faces. In all

cases, trench excavation continued vertically until few roots were seen to be dissected by the profile wall.

The positions of all roots dissected by the profile walls were mapped onto clear plastic sheets that were pinned in place on the profile wall. During mapping, six root-diameter size classes were differentiated by colour codes: 0-1 mm, 1-2 mm, 2-5 mm, 5-10 mm, 10-20 mm, and >20 mm. Back in the laboratory, each size class was digitised directly from the map sheets with the resultant files of coordinate pairs (per size class, per profile wall) input to a spreadsheet for further analysis.

In common with previous root morphology investigations (e.g. Böhm, 1979), root counts from each profile wall were converted to a root area ratio (RAR). The RAR is the sum of the cross-sectional area of the roots, dissected by the profile wall, A_r , expressed as a ratio of the to the wall’s total cross-sectional area, A :

$$\frac{A_r}{A} = \frac{\sum n_i a_i}{A} \quad (3)$$

where n_i = the number of roots in size class i and a_i = the mean cross-sectional area of roots in size class i . RARs were computed in increments of 10 cm down the profile walls to assess the changing root distribution with depth below the soil.

4. ROOT STRENGTH

To assess the tensile strength of individual roots, specimens, were either returned to the laboratory for testing or tested *in situ*. The strength of the soil-root bond is determined by properties of the soil not the roots. The laboratory tests provided maximum tensile strength data while the *in situ* tests gave insight into the root soil bond. The information allowed determination of the potential tensile strength of the roots and whether that strength would be fully realised during bank failure.

In the laboratory, specimens were debarked, trimmed to length (mean about 200 mm), and immediately tested with floor model 4505 Instron universal testing machine fitted with 1 kN or 5 kN reversible load cells, to assess their tensile strength. Tests were conducted at a constant strain rate of 2.5 mm/min until rupture occurred. Load and displacement were automatically logged in 0.2 second increments. For successful tests, the diameter of the root at the point of rupture was measured and the tensile stress at rupture, or root tensile strength, calculated from the peak load. Tests in which the specimen failed at or near the edges of the clamps, or within the clamps were rejected and not considered in further analyses.

Root strength was measured in the field by pulling on roots severed from their parent tree by a trench. A backhoe dug the trench close to the specimen tree trunks, with care taken not to pull the larger roots from the wall. When the initial excavation was complete, further soil was removed from the wall with hand tools.

With the root ends exposed, a purpose-built jig was positioned against the trench wall that consisted of a bearing plate, with the centre removed for access to the roots, and four legs extending back and supporting a hand operated boat winch. Both tensile load and root displacement, recorded by a stringpot and loadcell, were logged every second on a laptop computer during the tests.

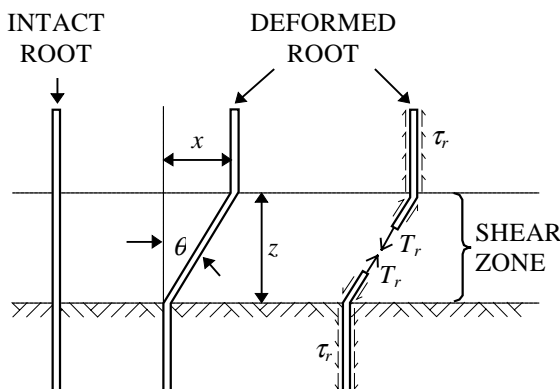
In addition to the above described, tests were also conducted under near-saturated bank conditions. To wet up the soil we dug a shallow pit (~250 mm deep) in the floodplain surface into which we pumped water over a three day period. After pumping, a trench was dug through the bottom of the pond. Testing then proceeded as per the description of the dry tests above. Throughout the testing period the bank material remained wet.

To determine whether there were any differences in root strength between species, or between laboratory and field tests or between field moisture conditions, we subjected the test results to analysis of co-variance. In all cases, differences in the strength of roots due to diameter were highly significant ($p < 0.001$) while no significant difference in the test results could be attributed to species, test method, or both species and test method combined. Regressing root tensile strength, T_r (MPa), against diameter, d (mm), yields:

$$T_r = 49.391d^{-0.773} \quad R^2 = 0.41. \quad (4)$$

5. ROOT REINFORCEMENT

A simple model of a fibre-reinforced soil subject to direct shear is shown in Figure 2 (Wu, *et al.*, 1979). During shear, the flexible, elastic root is stretched as it deforms across a planar shear zone of finite extent, z . As the soil deforms, tensile stress accumulates in the roots and mobilises the soil-root interface shear strength τ_r . The model assumes that there is sufficient τ_r to prevent pullout of the root.



z = Thickness of shear zone x = Deflection of root
 θ = Angle of shear distortion T_r = Root tensile strength
 τ_r = Skin friction along root

Figure 2: Root reinforcement model with a flexible elastic root perpendicular to shear zone at start.

The tensile force developed in the root as it elongates can be resolved into components tangential and normal to the shear plane. The resulting reactions produce a change in the shear strength of the soil, by direct resistance and by changing the confining stress in the shear zone as follows:

$$c_r = T_r \frac{A_r}{A} (\cos \theta \tan \phi + \sin \theta) \quad (5)$$

where T_r = maximum tensile stress developed in the roots (Equation (4)), A_r/A = the root area ratio (Equation (3)) and θ = angle of shear distortion (Figure 2).

It is extremely unlikely that all roots crossing a potential shear zone will do so at right angles. However, according to Gray and Ohashi (1983) the perpendicular model provides an average estimate of all possible orientations. The shear distortion angle, θ , remains an indeterminate variable but can be set to a range on the basis of the shear zone thickness and the amount of root displacement during *in situ* testing: $43^\circ < \theta < 66^\circ$. Considering $\phi = 16^\circ$, the bracketed term in Equation (5) is reasonably insensitive to changes within the range of θ and remains close to 1 (cf. Wu, *et al.*, 1979). Now, accounting for Equations (3) and (4), Equation (5) may be approximated by:

$$c_r \approx \frac{\sum n_i a_i t_i}{A} \quad (6)$$

where t_i is the tensile strength of roots in size class i .

Using the RAR and root strength values obtained above, Equation (6) may be used to calculate c_r at discrete points away from the tree and with depth below the soil surface. Fitting a simple linear regression through the log-transformed data for each species yields the following expressions of root reinforcement:

$$c_r = e^{4.920 - 0.099C - 1.333D} \quad R^2 = 0.70 \quad (7)$$

for River Red Gum and:

$$c_r = e^{4.769 - 0.540C - 1.891D} \quad R^2 = 0.63 \quad (8)$$

for Swamp Paperbark, where C is distance from the tree trunk and D is the depth below the soil surface. The regressions show that the reinforcement of both species drops off very quickly with both depth and spread.

6. BANK STABILITY ANALYSIS

6.1 Model process

Our model simulations proceed on the premise that failure usually occurs when bank material strength is minimised and weight is maximised. There is much anecdotal and published evidence to suggest that such conditions are associated with periods of prolonged rainfall and drawdown of river stage on the falling limb of a flood hydrograph (e.g. Darby and Thorne, 1996). At such times banks may be further weakened by positive pore-water pressures.

Although GWEDGEM can handle up to 15 individual soil layers with differing geotechnical properties, we

input the geotechnical parameters, $c' = 15$ kPa, $\phi' = 16^\circ$ and $\gamma = 18.3$ kN/m³, as uniformly distributed throughout the bank profile. The free water weight in the channel is automatically transferred to a hydrostatic pressure acting on the bank, while pore-water pressures are calculated (see Bishop, 1954) by assuming a drawdown of 2.6 m (from Rosedale gauge record) and adopting a conservative groundwater configuration whereby the water-table is coincident with the soil surface (Freeze and Cherry, 1979).

Where permanently saturated material occurs c_r is set to zero; any point in a bank profile below the level of the summer base flow (0.8 m on Rosedale gauge) is not reinforced in our model. To reflect the root distribution under the Swamp Paperbark stand, C is set to zero between the low flow level and the edge of the thicket so that root density varies only with depth. Beyond the stand c_r remains a function of both depth and distance from the trees.

With the bank geometry, stage height, pore-water pressures and root reinforcement parameters set, the next step is to run the model to determine the default three-wedge failure mechanism of the bank section of interest. After the user specifies the coordinates of the lowest and highest points of the profile, the bank-toe and the bank-crest, the model generates three trial failure mechanisms - shallow, medium and deep. Each three wedge mechanism is then optimised by GWEDGEM as the program automatically searches for, and reports, the failure mechanism with the lowest safety factor. After all have been optimised the one with the lowest F_s is used for finer subdivision and further calculation. Any fixed user input failure plane can also be assessed without optimisation.

Depicted in Figure 3a is the left bank of one of the surveyed cross-sections with a default three-wedge failure plane; $F_s = 1.82$. Although three-wedges usually give values of F_s within 5% of conventional stability analyses (Donald and Zhao, 1995), including more

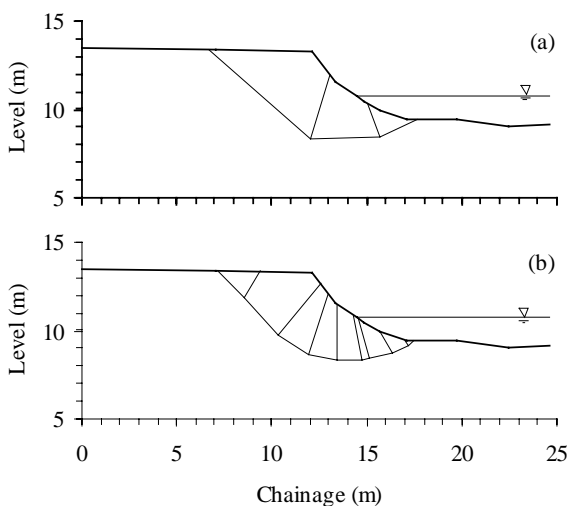


Figure 3: Stability analysis: (a) three-wedge analysis, $F_s = 1.82$; (b) nine-wedge analysis, $F_s = 1.75$.

wedges (up to nine) in the analysis improves the prediction and produces more realistic failure surfaces. The result of finer subdivision of the default three wedge failure is shown in Figure 3b. As in the case of the three wedge analysis the bank is predicted to be very stable with a safety factor of 1.75.

Adding root reinforcement to the analysis presented in Figure 3 improves bank stability. For the sake of demonstration we have assumed a typical position for a River Red Gum - trunk centred at 1 m to the floodplain side of the bank crest - and for the Swamp Paperbark - thicket from low-water line up to and over bank crest, onto the floodplain by 1 m. Although not shown, adding root reinforcement forces the predicted failure planes deeper into the profile and results in higher safety factors. Comparing the optimised results: bare bank, $F_s = 1.75$; bank reinforced by Swamp Paperbark roots, $F_s = 2.06$ (18% improvement in stability over non-reinforced soil); and bank reinforced by River Red Gum roots, $F_s = 2.11$ (21% improvement). Reinforcing the original bare failure plane (no optimisation) with Swamp Paperbark improves bare bank stability by 29% and with River Red Gum by 57%.

6.2 Model application

We applied the above process to the 12 surveyed cross-sections. Cross-section dimensions do not vary greatly through the reach with the mean width and depth equal to 29.8 m and 4.4 m respectively. There is, however, quite a range in bank geometry: $\beta = 23.45 - 55.47^\circ$, mean 41.5° ; and $H = 2.9 - 5.5$ m, mean 4.0 m. Similarly there are a range of safety factors with F_s , under bare conditions, ranging from 1.23 to 2.40 the mean being 1.70.

In all cases adding root reinforcement, from either species, improves the stability of the bank profile. When the failure plane is optimised for Swamp Paperbark reinforcement, stability is improved by 8 - 97%, mean = 29%. Swamp Paperbark roots improve the stability of the original failure plane (fixed) by 12 - 132%, mean = 47%. Similar, but slightly better, improvements to stability are predicted when the model is run with River Red Gum root reinforcement. Improvements to stability with optimised failure planes are 10 - 110%, mean = 37%, while predictions with the failure plane fixed at that predicted under bare conditions indicates an improvement in stability of 15 - 175% with a mean of 67%.

So far we have ignored the effect of surcharge on stability. A 10 tonne mass, estimated for the mature River Red Gum, borne evenly over the area of the root ball yields a surcharge of 4.13 kPa. This load can be included in analysis by applying a normal surface pressure to the bank profile centred on the point 1 m away from the bank crest. In the case of a tree surcharge applied with no root reinforcement, only 1% difference

Table 1: Effect of scour on bank stability.

	Prior to scour		2 m of Lat. scour		1.3 m of Bed scour	
	Opt.	Fix.	Opt.	Fix.	Opt.	Fix.
	Bare	1.23	--	1.00	--	1.00
Paperbark	1.49	2.27	1.39	2.13	1.48	1.55
Red Gum	1.49	2.24	1.46	2.11	1.43	1.54

(no surcharge $F_s = 1.75$, with surcharge $F_s = 1.74$) could be detected in the factor of safety. Retaining the surcharge load but adding root reinforcement to the analysis produces a result that is 2% different from the analysis of root reinforcement alone (no surcharge $F_s = 2.11$, with surcharge $F_s = 2.16$). The surcharge of the smaller Swamp Paperbark, even when considering whole stands, would be much less than the above example. The small difference detected here between stability with and without tree surcharge indicates that surcharge may be ignored as a major factor in riverbank stability.

While the improvements in safety factor, above, indicate the great potential of root reinforcement for increasing bank stability, the strength of the bank material alone was enough to ensure that all surveyed profiles were stable. In the following analysis we investigate the reinforcing effects of the roots when the bank profile has undergone fluvial erosion and the bank geometry is brought to the critical condition ($F_s = 1$).

Of the results presented in Table 1 the bare left bank of section 9 (9L) has the lowest predicted safety factor and is hence the bank profile that is closest to its critical state for the given conditions. The profile was surveyed on an outside bank of a right hand meander bend. The critical failure plane predicted by the model has a safety factor of 1.23.

Simulating lateral toe scour by simply moving the point representing the bank toe to the left causes the bank profile to steepen. Critical bank stability conditions are produced when 2 m of bank is removed from the toe; the safety factor of the non-reinforced bank is reduced to unity. Lateral scour at the toe, as described, increases the bank angle from 53° to 70° while the height remains the same at 5 m.

As expected, the roots of both species improve stability. The safety factors of the new bank geometry with root reinforcement are presented in Table 1. For comparison, the safety factors predicted for the pre-scour geometry are also shown. Although bank stability has been reduced to critical under bare conditions, the reinforced bank is still very stable.

Over-steepening is not the only process responsible for reducing bank stability on the Latrobe River. Fluvial

Table 2: Effect of River Red Gum position on stability.

Simulation (Figure 4)	Tree position (from crest)	Safety factor
bare	--	1.00
a	15 m left	1.26
b	10 m left	1.43
c	5 m left	1.61
d	1 m left	1.43
e	At crest	1.48
f	1 m right	1.48
g	2 m right	1.51

entrainment of bed material can also work to destabilise a bank by increasing its height. To simulate bed scour we have lowered the level of the bed adjacent to the bank. Bed scour of 1.3 m produces critical stability conditions in the bank; height and angle are increased to 6.32 m and 58.7° .

As can be seen in Table 1, the smaller Swamp Paperbark is predicted to increase the safety factor more than the River Red Gum. With the bank heightened, the Swamp Paperbark stand produces a greater value of c_r around the lower portions of the bank which pushes the failure plane deeper than simulations of River Red Gum reinforcement. That the species can be established low on the bank, such that high root densities reinforce potential failure planes near to the toe, bears out the local river management authority's faith in the species as a bank stabilising agent.

While it was convenient, and realistic, to model a typical River Red Gum growing 1 m away from the bank crests, River Red Gums are found all over the floodplain, sometimes even growing on the bankface. The analyses shown in Figure 4 and Table 2 show the effect, on bank stability, of moving the tree to various points on the bank and floodplain. To ease interpretation only the failure planes are shown; wedge boundaries are not depicted. The profile geometry adopted for this analysis is that used above (Profile 9L with 1.3 m of bed scour) where $F_s = 1$ under bare conditions.

All potential failure surfaces illustrated in Figure 4 are deeper than the critical failure surface under bare conditions. In general the safety factor declines as the tree is moved further from the toe. The exception to this is where the tree is positioned at about where the failure plane intersects the floodplain surface. The factor of safety returned by the model for the tree in position c is markedly higher than the other simulations and the failure surface is forced well out onto the floodplain.

7. DISCUSSION

In the usual sense of bank stabilisation and protection works, project costs are directly related to the safety margin required of the bank. Hemphill and Bramley

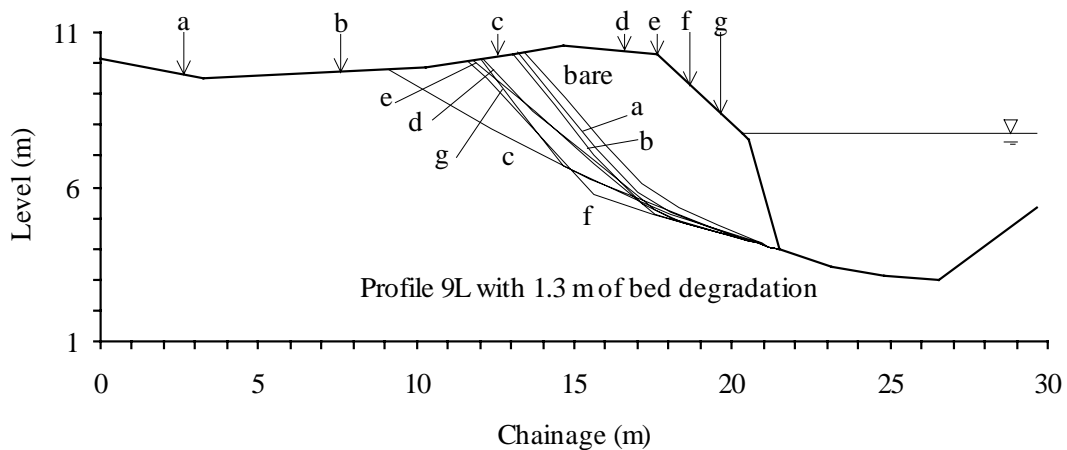


Figure 4: The effect of River Red Gum position on critical failure plane position.

(1989) maintain that a value of F_s marginally above unity (say 1.05 to 1.10) might be acceptable where the potential loss from bank failure is small. In situations where extensive damage to property may result, Hemphill and Bramley argue that an F_s as high as 1.40 or more may be necessary for an adequate level of protection.

The modelling framework reported here provides a quick and accurate method of establishing the safety factor of a given bank section under a range of botanical, geotechnical and hydrological treatments. Moreover, our model accounts for many of the weaknesses of previous attempts to characterise the effects of vegetation on riverbank stability (see Darby and Thorne, 1996).

The shape of the failures predicted by the model appear to broadly conform with those observed in the field. In the reach surveyed for the analysis, large rotational failures, such as that predicted for the bare condition above, are restricted to locations where the banks retain a grass-cover only. Bank sections supporting trees were stable in all observed instances. However, the prediction of stability involves many uncertainties and the computed safety factor represents only an estimate based on the best choice of input parameters. Much of the uncertainty arises from the heterogeneity of bank materials and poor estimates of pore-water pressures.

8. CONCLUSIONS

The results presented herein indicate that high levels of protection can be achieved through root reinforcement of the bank substrate. The effects of surcharge on bank stability are minimal and should be regarded as secondary at best.

The addition of roots to the bank profiles improved stability even under worst-case hydrological and geotechnical parameters. The reinforcement was apparent over a range of bank geometries and varied with tree position in relation to the bank. Positioning trees close to potential failure plane locations, either low

on the bank or on the floodplain realises the greatest reinforcement.

Even when its bare counterpart is on the verge of failure a root permeated bank, as modelled here, returns a value for F_s that allows a great deal of confidence over its stability.

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