Does the Weight of Riparian Trees Destabilize Riverbanks

Article *in* Regulated Rivers Research & Management · November 2000

DOI: 10.1002/1099-1646(200011/12)16:63.0.CO;2-1

2 authors:

Bruce Abernethy
Monash University (Australia)

Ian D Rutherfurd
University of Melbourne

REGULATED RIVERS: RESEARCH & MANAGEMENT
Regul. Rivers: Res. Mgmt. **16**: 565–576 (2000)

DOES THE WEIGHT OF RIPARIAN TREES DESTABILIZE RIVERBANKS?

BRUCE ABERNETHY* AND IAN D. RUTHERFURD
Cooperative Research Centre for Catchment Hydrology, Department of Geography and Environmental Studies, The University of Melbourne, Parkville, Victoria, Australia

ABSTRACT

In contrast to the generally accepted stabilizing effects of riparian vegetation, the surcharge of trees on riverbanks has been widely implicated as a source of bank instability. Fieldwork conducted along the Latrobe River in Victoria, Australia shows that the bank-destabilizing effects of surcharge, due to silver wattle (*Acacia dealbata*), are minimal. Field observations indicate that it is unlikely that the weight of silver wattles growing on an otherwise stable bank section will directly cause mass failure. Observations of deep-seated failures and silver wattle stands on the Latrobe River indicate that where average-sized slump-blocks support an average number of average-sized silver wattles, the trees represent only 4.1% of the total saturated slump mass. Infinite slope stability analysis indicates a threshold of around 48° where banks become prone to shallow-planar slide failures as they steepen. Where bank sections are inherently unstable and prone to shallow-planar slide failure, the additional weight of the trees may contribute to overall instability. However, manipulation of other stability parameters within reasonable constraints negates the effect of surcharge so it is not possible to demonstrate conclusively a destabilizing influence of silver wattles.

KEY WORDS: bank erosion; bank stability; Gippsland; Latrobe River; mass failure; riparian vegetation; surcharge

INTRODUCTION

The additional weight, or surcharge, of trees growing on riverbanks has often been implicated in bank failure. Many landholders with river frontage believe that trees are detrimental to bank stability, while Thorne (1990, p. 139), cites the experiences of river engineers who have observed 'sections of an otherwise stable bankline dragged down by the weight of overhanging trees'. Other publications that have assessed the effect of riparian trees variously cite surcharge as an impediment to bank stability (e.g. Nolan, 1981; Hemphill and Bramley, 1989; Styczen and Morgan, 1995). The additional weight of vegetation on any slope can be resolved into forces that act downslope and forces that act normal to the slope. The downslope component tends to lower the resistance of a soil mass to sliding, while the slope-normal force tends to increase resistance to sliding (Gray and Leiser, 1982).

The considerable literature relating to the mass stability of forested hillslopes generally relegates tree surcharge to a second order effect. However, rigorous assessment of the effect of tree surcharge on riverbank stability has yet to receive the same degree of attention. Riverbanks are simply a class of slopes where the magnitude and distribution of tree surcharge are determined by bank geometry, tree weights and tree positions. A marked difference is that bank failures are generally small in comparison to hillslope failures, so the effect of the surcharge of individual trees on potentially unstable bank sections may be greater than that realized in the hillslope setting.

Catchment managers, around the world, are increasingly planting riparian vegetation to control riverbank erosion. Although, the effects of vegetation on bank erosion processes are widely recognized, data are still lacking to quantify plant behaviour in respect of bank erosion. In this light, this paper outlines a series of field observations and some simple modelling techniques with which the role of surcharge in riverbank stability has been investigated.

* Correspondence to: Sinclair Knight Merz, 590 Orronl Road, Armadale, Victoria 3143, Australia. E-mail: babernethy@skm.com.au

Received 28 July 1999
Revised 15 October 1999
Accepted 16 November 1999

REVIEW

Most assessments of the influence of tree surcharge on slope stability have investigated the effect of logging in steep terrain. Usually, the surcharge weight of trees is equated to increased soil unit weight and its effects on stability evaluated accordingly. Ellison and Coaldrake (1954) showed that creep rates on forested slopes in Queensland rain forests were higher than on grass covered slopes. However, the effects of surcharge removal were difficult to separate from all of the slope stability factors affected by logging.

Brown and Sheu (1975) agree that Ellison and Coaldrake's conclusion is true in the short term but argue that, over time, slope stability deteriorates as the roots decay and the watertable rises due to the cessation of evapotranspiration. Other post-logging studies in landslip prone areas support Brown and Sheu's conclusions. Bishop and Stevens (1964), O'Loughlin (1974) and Wu *et al*. (1979) all suggested that forest surcharge decreased the likelihood of downslope soil movement.

O'Loughlin and Ziemer (1982) assert that in many forest ecosystems the total weight of soil above a potential failure plane far exceeds the weight of the forest cover. Even a relatively dense forest represents a small surcharge stress if the total weight of the trees is considered to be distributed uniformly across the slope (Greenway, 1987). Bishop and Stevens (1964) estimated an average surcharge stress of 2.5 kPa for total sitka spruce (*Picea sitchensis*) forest cover, while Greenway (1987) reported that candlenut (*Aleurites moluccana*) exerted an average surcharge stress of 0.5 kPa.

Tree weight is not distributed uniformly over a slope, but is transmitted to the area within the root spread of individual trees. Wu *et al*. (1979) computed a surcharge stress of 5.2 kPa for individual sitka spruce trees by dividing tree weight by the area of the root mat. Gray (1978) calculated an average surcharge stress of <1 kPa when the weight of a mature douglas fir (*Pseudotsuga menziesii*) forest was spread evenly across an entire hillslope, but demonstrated that the surcharge stress immediately below a tree might be as high as 67 kPa. Gray, however, concluded that the surcharge of trees was unlikely to affect slope stability one way or the other.

The principles and techniques developed through the above hillslope work are broadly applicable to riverbanks so long as care is exercised to ensure that the bank conditions are suited to the application of any particular analysis technique. However, relatively few studies have included surcharge in bank stability analyses. Of the published works that are available, most have generally found that the weight of vegetation is detrimental only in special cases. For example, Gray (1995) maintains that levee embankment slopes in the USA are generally flat enough for the main component of the overburden weight to act perpendicular, rather than parallel, to potential failure surfaces thereby increasing stability.

Importantly, the location of trees on a bank will affect the degree to which they influence the balance of forces (Gray, 1995; Gray and Sotir, 1996). The surcharge of trees growing at the bottom of a bank prone to rotational failure mechanisms is likely to increase overall bank stability (Coppin and Richards, 1990). However, trees on actively eroding riverbanks are often restricted to the top of steep banks where they may reduce stability (Thorne, 1990).

Hubble and Hull (1996) modelled both planar and circular bank-failure mechanisms, to determine that clearing riparian forest reduced the maximum stable bank-slope on the Nepean River, NSW. The stable angle was reduced from 28° under trees, to 17° on bank sections supporting grass cover only. Hubble and Hull assumed saturated conditions throughout the bank profile and reasoned that the loss in stability was due to the loss of root cohesion and the removal of tree surcharge.

On many of the steep high banks in the Niger River delta, Abam (1993) observed that the surcharge of large trees destabilized the banks. In a later paper, Abam's (1997) stability analysis found that the surcharge of a heavy bank-top tree contributed to a deep-seated rotational failure. However, Abam's hydrological constraints of very low channel stage and saturated bank material meant that the water contained within the slump-block itself represented a large weight. Hence, the tree weight may have been incidental to the failure with the bank section only marginally stable in the conditions described.

Even given the extensive literature search underpinning the above review, the sparse results available do not resolve the issue of tree surcharge and riverbank stability. Considering both the hillslope and riverbank studies, it seems that the literature provides no clear indication on the role of surcharge in bank

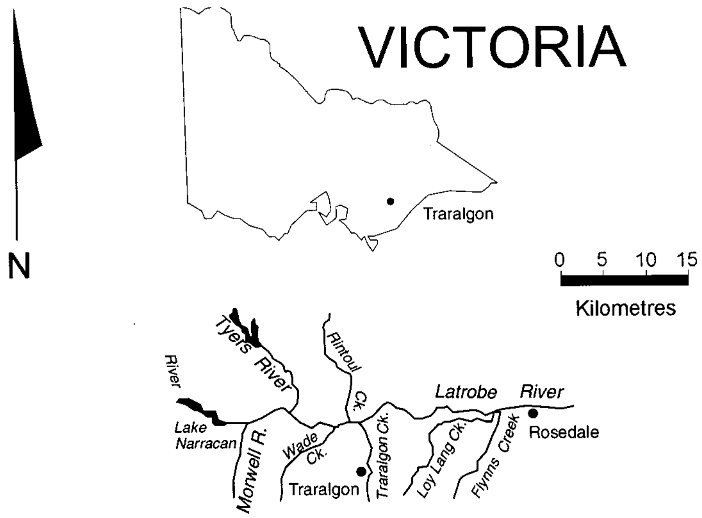

Figure 1. Field site: the Latrobe River between Tyers River and Traralgon Creek

stability. The literature, however, does suggest avenues of investigation. The authors began the study by making qualitative assessments of the extent of the destabilizing influence exerted by riparian trees. To this end, the weight of the constituent components (soil, water, vegetation) of slump-blocks that were observed within the study reach were simply compared. This part of the study worked from the premise that if trees can destabilize a bank section, their weight should represent a substantial portion of total slump-block weight.

Following the comparative analysis, Hubble and Hull's (1996) approach was adapted by performing infinite slope stability analyses of individual bank sections. This approach allowed comparison of critical failure conditions by assessing bank sections prone to shallow-planar sliding failures with and without tree surcharge. Of the various failure mechanisms that were observed, shallow-planar slides on undercut bank sections appeared to be most vulnerable to the additional forces imposed by tree surcharge.

Fieldwork was undertaken along the banks of the Latrobe River in Gippsland, Victoria, Australia (Figure 1). Landholders along the river typically nominate silver wattle (*Acacia dealbata*) as the problem species for bank stability. Silver wattle is a medium-sized tree, 20–30 m high, with a slender trunk and a well-developed crown. The species is widespread along streambanks throughout southeast Australia (Boland *et al.*, 1989) and thrives on even very steep banks that are often undercut. In many places along the lower Latrobe River, silver wattle has colonized the bank face often establishing monoculture stands (Figure 2).

Figure 2. Silver wattle, Latrobe River

COMPARATIVE ANALYSIS

The comparative analysis proceeded by firstly estimating the weight of the bank material and water contained within slump-blocks along the Latrobe River. Second, the number and weight of individual silver wattles able to grow in natural densities on the surface of the observed slump-blocks was estimated. Finally, the surcharge of the trees as a proportion of the total saturated mass of the slump-blocks was assessed.

At various points along the river, undisturbed samples of bank material were collected for which dry and saturated bulk densities were determined (Craze and Hamilton, 1991). During the course of fieldwork, the dimensions of 28 slump-blocks were also measured. In most cases, the failed bank sections were vegetated with grass only, but some were located within stands of silver wattle. The blocks were measured where they lay but, where necessary, disturbance was allowed for by inspecting the failure scar on the intact bank. For each slump, the surface area on which silver wattles could establish was specifically noted.

The volume of the above ground tree parts was estimated by visually segmenting the trunk and branches of each tree into a number of cylinders, cones, paraboloids, and neiloids and their frustums (see Telewski and Lynch, 1991). The volumes of each of the segments were estimated and summed at least twice with the mean result taken as the total volume of the above-ground parts of each tree. To estimate root volume it was assumed (after Jacobs, 1955) that the volume of wood included in the roots is about one-tenth the volume of the aerial portion of trees.

To convert tree volume to an estimate of biomass, 14 stem- and 12 root-samples were collected and wood density was determined. Parde (1980) warns that wood density for a single tree species varies with provenance, position of the sample within the tree and with climatic variations. Root biomass depends on the type and consistency of the soil, the supply of water and nutrients, population density and wind regime. To account for Parde's caution, each wood specimen was collected from different parts of different trees at different sites along the river. The mean stem density was 877 kg/m^3 and the mean root density was 1185 kg/m^3. A two-tailed t-test (unequal variances) demonstrated that there was a significant difference in the density of the two wood types (df = 17, $t = 6.839$, $p < 0.001$).

To check the accuracy of the estimates, a number of trees and branches were felled and weighed in the field. On average predictions were 93% of the weighed mass ($n = 7$). Hence, the total tree masses reported in Table I are the result of the volume of aerial portion of a number of trees and wood densities and the correction factor for the above-ground mass. By plotting tree mass against trunk diameter at breast height (DBH), an empirical relationship that allowed prediction of silver wattle biomass was developed from an easily measured independent variable (Figure 3). Parde's (1980) review of the forest biomass literature confirms the form of the regression ($y = ax^b$) and further notes the general preference for $x = \text{DBH}$.

The DBH of trees within a number of mature stands ranged from 0.07 to 0.50 m with a mean of 0.21 m ($n = 92$, $S.D. = 0.10$). The stands surveyed appeared to be in all respects typical of those along the river. Casual inspection of other silver wattle stands indicated that mature trees do not grow beyond DBH ≈ 0.5 m and that trees with DBH ≈ 0.07 m are about the smallest for which DBH can measured. From the regression derived in Figure 3, the biomass of a silver wattle with average DBH is 250 kg. Stand densities were very consistent with the mean equal to 0.5 trees/m^2. This yields an average surcharge stress of typical silver wattle stands of 1.23 kPa.

By combining average tree spacing and mass with slump-block dimensions and bulk densities, the potential surcharge of the silver wattles was estimated as a proportion of the total mass of slump-blocks along the Latrobe River (Table II). Referring to Table II, silver wattles, on average, represent 4% of the total mass of an average saturated slump-block. This small proportion represents only slightly more than half ($\sim$ 11/20) of the mass of water in the block (7.4% of total) and about one-twentieth of the soil mass (88.6% of total).

Because of the variety of slump-block shapes, sizes and failure mechanisms it is impossible to draw any general conclusion as to whether the trees are a negative or positive influence on bank stability. The analysis shows clearly, though, that the mass of trees is small in relation to the mass of other slump-block

Table I. Estimated total mass of silver wattles

DBH	Stem		Root mass[d]	Tree mass
(m)	Volume[a] (m^3)	Mass[b] (kg)	(kg)	(kg)
0.05	0.01	9[c]	1	10
0.09	0.04	41[c]	5	46
0.10	0.06	43[c]	7	50
0.17	0.13	146[c]	16	162
0.18	0.21	199	25	224
0.20	0.25	231	29	260
0.28	0.36	344	43	387
0.29	0.49	466	59	525
0.35	0.52	492	62	553
0.36	0.96	909	114	1023
0.40	0.84	788	99	888
0.45	0.77	726	91	818
0.45	1.37	1291	162	1453
0.47	1.25	1177	148	1324
0.50	2.12	2001	251	2252

[a] Estimated visually.
[b] Corrected mass (see text) assuming a mean stem-wood density of 877 kg/m^3.
[c] Weighed mass.
[d] Calculated by approximating root volume to 10% of stem volume and assuming a mean root-wood density of 1185 kg/m^3.

components. Indeed, the additional weight of water when the block saturates during and immediately following floods is more likely to contribute to any instability than is the weight of the trees.

STABILITY ANALYSIS

Observations of different combinations of bank geometry, tree location and stand density suggested that banks prone to shallow-planar slide failures were most vulnerable to the additional weight of trees. Scattered along the river are the results of shallow-planar slides where entire mature silver wattles have moved down the bank with the slump. In this section, an analysis that specifically addresses the contribution of tree surcharge in shallow-planar slide processes is presented.

An important feature of silver wattles growing on the bankface along the Latrobe River, is their propensity to develop a shallow rootplate when the material in which they are growing overlies stiff clay. In these situations, the rootplate is typically no more than about 1 m deep (measured perpendicular to the

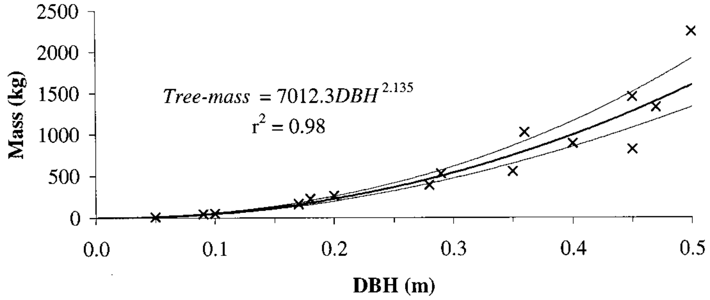

Figure 3. Relationship between DBH and silver wattle biomass on the Latrobe River (fine lines represent 95% regression confidence limits)

Table II. The trees mass of in relation to slump mass and mass of water due to saturation

Block	Component mass (kg)				Proportion (%)[e]		
	Total[a]	Soil[b]	Water[c]	Trees[d]	Soil	Water	Trees
1	1774	1523	128	123	85.9	7.2	6.9
2	2105	1714	144	248	81.4	6.8	11.8
3	3997	3254	273	470	81.4	6.8	11.8
4	8318	7236	606	476	87.0	7.3	5.7
5	13 028	11 632	974	421	89.3	7.5	3.2
6	14 734	12 879	1079	777	87.4	7.3	5.3
7	17 022	14 939	1251	832	87.8	7.3	4.9
8	17 898	15 891	1331	676	88.8	7.4	3.8
9	28 019	23 265	1949	2806	83.0	7.0	10.0
10	39 625	34 274	2871	2480	86.5	7.2	6.3
11	43 332	38 030	3186	2117	87.8	7.3	4.9
12	44 003	38 619	3235	2149	87.8	7.3	4.9
13	57 156	49 438	4141	3577	86.5	7.2	6.3
14	62 880	55 548	4653	2679	88.3	7.4	4.3
15	63 956	56 327	4718	2911	88.1	7.3	4.6
16	65 353	58 023	4860	2470	88.8	7.4	3.8
17	66 543	58 941	4937	2665	88.6	7.4	4.0
18	72 502	63 372	5308	3821	87.4	7.3	5.3
19	75 010	66 263	5550	3196	88.3	7.4	4.3
20	94 072	83 521	6996	3555	88.8	7.4	3.8
21	99 885	87 970	7369	4547	88.1	7.3	4.6
22	110 469	98 079	8215	4175	88.8	7.4	3.8
23	117 276	103 601	8678	4997	88.3	7.4	4.3
24	145 935	130 085	10 896	4954	89.1	7.5	3.4
25	254 385	226 329	18 958	9098	89.0	7.4	3.6
26	253 764	228 060	19 103	6601	89.9	7.5	2.6
27	269 134	238 948	20 015	10 170	88.8	7.4	3.8
28	310 233	275 438	23 071	11 723	88.8	7.4	3.8
Mean	84 014	74400	6232	3383	88.6	7.4	4.0

[a] Based on saturated bulk density (1876 kg/m^3), measured slump-block dimensions and tree weight.
[b] Based on field dry bulk density (1731 kg/m^3) and slump-block dimensions.
[c] Based on difference between field dry and saturated bulk density and slump-block dimensions.
[d] Based on slump-block upper surface area, stand density of 0.5 trees/m^2 and mean tree mass of 250 kg.
[e] Proportion of total saturated slump-block mass.

bankface) with very few roots penetrating deeper than this. The dense rooting pattern of the species is easily observed where fluvial scour has winnowed out the bank material from in and around the root plate of many individuals.

While fluvial action is responsible for exposing the root system of the trees, in some cases it also actively undercuts the banks on which the trees grow. To illustrate this form of bank development, examples of undercut bank profiles supporting silver wattles are reproduced in Figures 4 and 5. The depicted profiles were surveyed during a dry summer (February 1998) when the channel stage was uncharacteristically low and the undercut extent was clearly apparent. The two profiles shown on each figure represent bank sections adjacent to each other. In both cases, the upstream section has yet to fail, while the downstream section had failed before the survey.

Inspection of Figures 4 and 5 indicates that the stability of the illustrated bank profiles may be modelled by so-called ‘infinite slope’ analysis. Infinite slope analysis assumes that the ground surface, phreatic surface and basal sliding surface are all approximately parallel. Overall stability may be determined by assessing the stability of a single element (unit length by unit width) with vertical

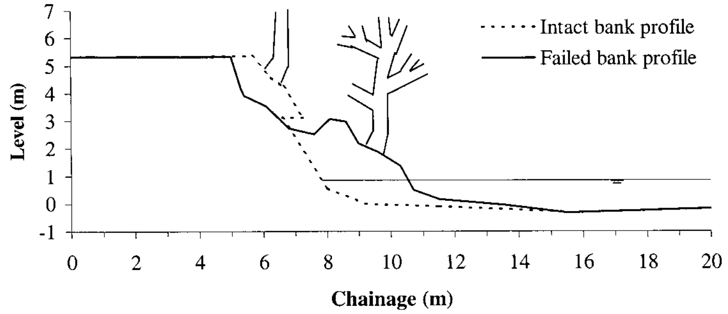

Figure 4. Left bank. Intact (upstream) bank profile: $\beta = 56°$, $H = 5.4$ m; failed (downstream) bank profile: $\beta = 39°$, $H = 5.2$ m (trees not to scale, stage as at time of survey)

boundaries, as shown in Figure 6. End effects in the sliding mass are neglected, as are lateral forces on either side of the element.

Following Wu *et al.* (1979), and assuming conditions of steady seepage, the ratio of shearing resistance (s) to force (τ), or factor of safety (F_s), of the vertical slice shown in Figure 6 may be written as:

$$F_s = \frac{s}{\tau} = \frac{(c' + c_r)L + (W'_s + W_t)\cos\beta \tan\phi'}{(W_s + W_t)\sin\beta}, \tag{1}$$

where c' = effective soil cohesion; c_r = apparent cohesion due to roots; $L = L_{AB}/\cos\beta(L_{AB} = 1)$; W'_s = unit weight of soil minus buoyancy $(\gamma_s - \gamma_w)h$, where γ = bulk unit weight, s = soil, w = water and h = vertical height of bank material above the shear surface; W_s = unit weight of soil $(\gamma_s h)$; W_t = tree surcharge stress $(P_t/\cos\beta)$, where P_t = the weight of trees per unit area of bankface; β = bank angle; and ϕ' = effective friction angle.

Although, there are fallen trees on the banks of the river that are likely to have been subject to windthrow, windthrow has been intentionally neglected from this study. Windloading produces a shear force that, were it to be considered, is added to the denominator of Equation (1) (see Wu *et al.*, 1979; Bache and MacAskill, 1984).

Ignoring wind, worst-case shallow-planar stability conditions can be assessed with Equation (1) by assuming that the failure plane lies at the bottom of the 1 m thick root plate. It is further assumed that no roots cross the failure plane ($c_r = 0$), and that the sliding mass is wholly above the river stage and fully saturated; seepage is assumed be parallel to the bank surface. Worst-case soil strength parameters were derived from triaxial compression tests of a number of undisturbed samples taken from up and down the reach shown in Figure 1 (Abernethy and Rutherfurd, 1998).

A stability chart relating slope angle to factor of safety for the undercut bank conditions found on the Latrobe River has been generated from Equation (1) and is presented in Figure 7. Curves in Figure 7

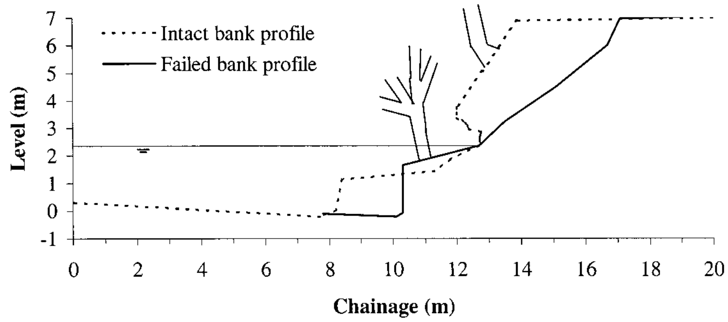

Figure 5. Right bank. Intact (upstream) bank profile: $\beta = 50°$, $H = 6.9$ m; failed (downstream) bank profile: $\beta = 46°$, $H = 7.2$ m (trees not to scale, stage as at time of survey)

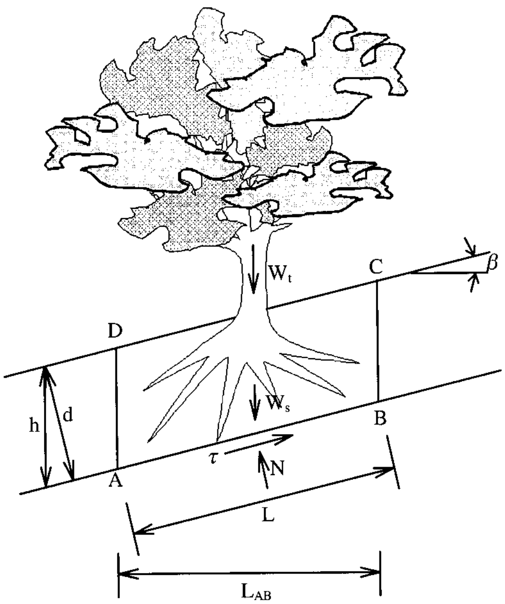

Figure 6. Infinite slope model showing forces acting on a unit length ($L_{AB} = 1$) vertical slice of sliding soil mass (note: $h = d/\cos\beta$, $L = L_{AB}/\cos\beta$)

represent stability with no trees and with the imposed surcharge of an 'average' and a 'large' tree (Table III). Tree weights are calculated with the regression equation shown in Figure 3, where average and large refer to the mean and maximum values of observed DBH. All other input parameters (variables and constants) are shown in Table IV.

Inspection of Figure 7 and Table IV reveals that although the effect of tree surcharge on the stability of undercut banks on the Latrobe River is negative the overall influence is not great. Under the conditions modelled here, bank sections with no trees are likely to fail by shallow-planar slip if they are steeper than 48°. Introducing the surcharge of an average sized silver wattle to the equation reduced the critical bank angle to 46°, while the surcharge of a large silver wattle reduced the critical bank angle still further, to 40°. However, by relaxing the assumption of no roots crossing the potential shear plane, the detrimental influence of tree surcharge can be negated.

Increasing c_r to around only 0.4 kPa at the failure surface increased the safety factor of banks supporting an average sized silver wattle to that predicted for bare banks. Similarly, the stability of banks supporting a large silver wattle was raised to that of bare banks with the addition of 2.6 kPa apparent root cohesion. Further increases in c_r resulted in a net stabilizing effect. Although the magnitude of silver wattle root reinforcement was not specifically investigated, work on other species suggests that the small

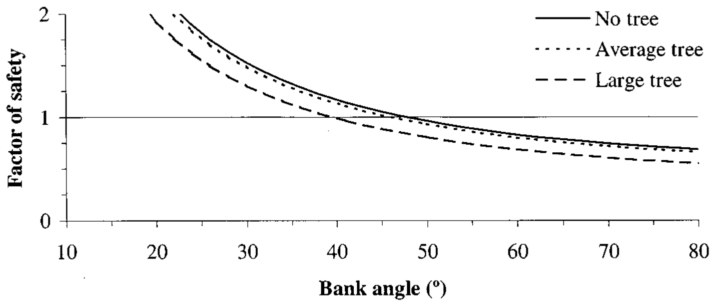

Figure 7. Stability chart for infinite slope stability analysis (see also Table IV)

Table III. Tree surcharge for infinite slope stability analysis

	Average tree	Large tree
DBH (m)	0.21	0.50
Mass[a] (kg)	250	1596
Force (kN)	2.5	15.7
Root plate area[b] (m^2)	3.1	3.1
P_t (kPa)	0.81	5.06

[a] Values derived from Figure 3.
[b] Based on observations of exposed root plates, typical trunk spacing of 2 m and assumed round root plate.

values of c_r cited above would be easily exceeded in the vicinity of potential shallow-planar shear planes (e.g. Riestenberg, 1994; Nilaweera and Nutalaya, 1999; Abernethy and Rutherfurd, in press).

Although the intact bank sections in Figures 4 and 5 were standing when they were surveyed, the stability curves of Figure 7 predict $F_s < 1$ for both profiles even under bare conditions. Maintaining $\phi' = 15.4°$, as used to derive the stability chart, but increasing c' from 12 to 12.6 kPa produces $F_s = 1$ for $\beta = 50°$, while increasing c' to 14 kPa produced $F_s = 1$ for $\beta = 56°$. These very small increases in c' are well within the natural variation that could be expected of soil strength parameters along the river.

Clearly, while surcharge can be shown to be detrimental to bank stability, its effects are minimal. The analysis, as worked here, shows that of the banks prone to shallow-planar failure, those steeper than about 48° are intrinsically unstable and are likely to fail regardless of the additional weight of trees. Any trees associated with failed bank profiles were probably incidental to the failure processes.

DISCUSSION

Within the scope of this study, the effects of tree surcharge on bank stability are minimal. Considering the field observations, it is unlikely that silver wattles growing on an otherwise stable bank section will cause any subsequent failure. However, in situations where the bank section is inherently unstable, the additional weight of trees may contribute to overall instability. Bank sections prone to shallow-planar slide failures are most likely to be affected adversely by the surcharge of mature silver wattles, yet infinite slope analysis predicts that, for the assumed conditions, banks with trees are only slightly less stable than their bare counterparts.

Where the bank is undercut by fluvial action, mature (or senescent) silver wattles often appear to have slid partway down the bank over their life span. This gradual failure over time is probably reflected in the

Table IV. Effect of tree surcharge on infinite slope stability (calculations based on Equation (1) in conjunction with Figure 6)

β	L	h	W'_s	W_s	No tree		Average tree		Large tree	
(°)	(m)	(m)	(kPa)	(kPa)	W_t (kPa)	F_s	W_t (kPa)	F_s	W_t (kPa)	F_s
10	1.02	1.02	8.77	18.77	0.00	4.49	0.82	4.36	5.14	3.86
20	1.06	1.06	9.11	19.51	0.00	2.26	0.86	2.20	5.38	1.93
30	1.15	1.15	9.88	21.16	0.00	1.53	0.94	1.48	5.84	1.30
40	1.31	1.31	11.26	24.11	0.00	1.17	1.06	1.13	6.61	0.99
50	1.56	1.56	13.41	28.71	0.00	0.96	1.26	0.93	7.87	0.80
60	2.00	2.00	17.19	36.81	0.00	0.83	1.62	0.80	10.12	0.68
70	2.92	2.92	25.09	53.74	0.00	0.74	2.37	0.71	14.79	0.60
80	5.76	5.76	49.50	106.00	0.00	0.68	4.66	0.66	29.14	0.55

Fixed data: $c' = 12$ kPa; $c_r = 0$ kPa; $\phi' = 15.4°$; $\gamma_s = 18.4$ kN/m^3; $\gamma_w = 9.8$ kN/m^3.

results for bank sections with factors of safety marginally greater than one. However, the effect of surcharge in this analysis is of the same order of magnitude as errors in the soil and root properties so it is not possible to demonstrate a conclusive destabilizing influence of silver wattles. Also, it seems likely that the forces that contribute to failure of treed bank sections include the effect of wind in the canopy transmitted to the ground through the trunk as a turning moment. Wind factors have attracted research for forestry applications (e.g. Rodgers *et al.*, 1995; Wood, 1995) but it remains for this work to be applied to riverbank stability problems.

The analyses support a conclusion that root reinforcement is more important than surcharge in controlling the incidence and type of riverbank failure. Where roots penetrate into the bank profile beyond potential shallow-planar slip surfaces, the reinforcing effect of the roots is likely to exert considerable influence over any subsequent failure process (Abernethy and Rutherfurd, 2000). While such reinforcement will prevent shallow-planar failure, it could also push potential failure planes deeper into the bank profile to produce deep-seated failure types. The majority of slumps were located on bank sections bare of any trees. Where the slumps did occur within stands of trees, the location of the failures appeared to be governed more by the distribution of roots within the bank rather than the distribution of surcharge on the bank.

It appears, then, that surcharge can only be a factor in bank stability where large, heavy trees with intensive root systems grow within the confines of potential shear planes. Silver wattle is about the right size to be implicated in promoting mass failure in this study reach of the Latrobe River. The tree is the largest species growing on the banks that can be contained entirely within typical sized slump-blocks. The weight of larger trees are borne over a more extensive root system, so their surcharge does not pose a liability to bank stability. On the other hand, the weight of smaller trees is inconsequential and they do not affect bank stability. Even though the growth habits and properties of mature silver wattle appear to encourage coherent slump-blocks, their surcharge cannot be shown to destabilize the bank to any measurable degree.

CONCLUSIONS

There is a large literature that deals with the surcharge of forest cover on hillslopes. Usually the research impetus has focussed investigations on the effects of logging on mass stability. The general conclusion of the hillslope work is that clear-felling is detrimental to slope stability mainly through decay of the root system. That the effect of surcharge is considered only secondary to other slope processes is underpinned by the demonstrated reduction in hillslope stability after the roots of felled trees begin to decay. This occurs even though the removal of the forest surcharge should assist stability.

This study demonstrates that on the Latrobe River the likely effect of surcharge is small in comparison to other destabilizing forces. Even where trees appear to be implicated in bank failure, by their direct association with failed slump-blocks or by their position on undercut banks, analysis with worst-case parameters fails to show a direct link between the additional tree weight and increased potential for failure.

That the extent to which surcharge contributes to riverbank instability has hardly been described is largely because the bank material and failure properties, and the type and density of vegetation cover conspire to complicate analyses. These complications have lead to considerable controversy over the use of trees for bank stabilization. Consequently, river managers have often excluded trees from bank stabilization schemes. However, the results of this paper tend to suggest that tree surcharge exerts only a marginal influence over riverbank stability.

ACKNOWLEDGEMENTS

During the study, the first author was receiving an Australian Postgraduate Award and a Cooperative Research Centre for Catchment Hydrology scholarship. The authors undertook this study as part of the

Australian National Riparian Zone Research Project, funded by the Land and Water Resources Research and Development Corporation. The authors thank Scott Wilkinson for his assistance with the literature search and field and laboratory work. We also thank an anonymous reviewer for many helpful suggestions.

REFERENCES

Abam TKS. 1993. Factors affecting distribution of instability of river banks in the Niger delta. *Engineering Geology* **35**: 123–133.

Abam TKS. 1997. Aspects of alluvial river bank recession: some examples from the Niger delta. *Environmental Geology* **31**: 211–220.

Abernethy B, Rutherfurd ID. 1998. Where along a river's length will vegetation most effectively stabilise stream banks? *Geomorphology* **23**: 55–75.

Abernethy B, Rutherfurd ID. in press. The distribution and strength of riparian tree roots in relation to riverbank reinforcement. *Hydrological Processes*.

Abernethy B, Rutherfurd ID. 2000. The effect of riparian tree roots on riverbank stability. *Earth Surface Processes and Landforms* **25**: 921–938.

Bache DH, MacAskill IA. 1984. *Vegetation in Civil and Landscape Engineering*. Granada Publishing: London.

Bishop DM, Stevens ME. 1964. Landslides on logged areas in Southeast Alaska, *Research Paper*, *NOR-1*. USDA Forest Service: Juneau.

Boland DJ, Booker MIH, Chippendale GM, Hall N, Hyland BPM, Johnston RD, Kleinig DA, Turner JD. 1989. *Forest Trees of Australia* (Fourth Edn). Nelson-CSIRO: Melbourne.

Brown CB, Sheu MS. 1975. Effects of deforestation on slopes. *Journal of the Geotechnical Engineering Division ASCE* **101**: 147–165.

Coppin NJ, Richards IG. 1990. *Use of Vegetation in Civil Engineering*. Construction Industry Research and Information Association/Butterworths: London.

Craze B, Hamilton GJ. 1991. Soil physical properties. In *Soils: Their Properties and Management*, Charman PEV, Murphy BW (eds). Sydney University Press: Sydney; 147–164.

Ellison L, Coaldrake JE. 1954. Soil-mantle movement in relation to forest clearing in southeastern Queensland. *Ecology* **35**: 380–388.

Gray DH. 1978. Role of woody vegetation in reinforcing soils and stabilising slopes, in *Soil Reinforcing and Stabilising Techniques in Engineering Practice: Proceedings of a Symposium Jointly Organised by the New South Wales Institute of Technology and the University of New South Wales*, *Sydney*, New South Wales Institute of Technology, School of Civil Engineering, Sydney, 253–306.

Gray DH. 1995. Influence of vegetation on the stability of slopes. In *Vegetation and Slopes: Stabilisation*, *Protection and Ecology*, *University Museum*, *Oxford*, Barker DH (ed.). Telford: London; 2–25.

Gray DH, Leiser AT. 1982. *Biotechnical Slope Protection and Erosion Control*. Van Nostrand Reinhold Company: New York.

Gray DH, Sotir RB. 1996. *Biotechnical and Soil Bioengineering Slope Stabilisation: a Practical Guide for Erosion Control*. Wiley: New York.

Greenway DR. 1987. Vegetation and slope stability. In *Slope Stability*, Anderson MG, Richards KS (eds). Wiley: Chichester; 187–230.

Hemphill RW, Bramley ME. 1989. *Protection of River and Canal Banks*, *a Guide to Selection and Design. CIRIA Water Engineering Report*. London: Butterworths.

Hubble T, Hull T. 1996. A model for bank collapse on the Nepean River, Camden Valley, NSW. *Australian Geomechanics* **29**: 80–98.

Jacobs MR. 1955. *Growth Habits of the Eucalypts*. Department of the Interior, Forestry and Timber Bureau: Canberra.

Nilaweera NS, Nutalaya P. 1999. Role of tree roots in slope stabilisation. *Bulletin of Engineering Geology and the Environment* **57**: 337–342.

Nolan MF. 1981. Vegetation on US Army Corps of Engineers project levees in the Sacramento/San Joaquin Valley, California. In *Proceedings: California Riparian Systems Conference*, *University of California-Davis*, Warner RE, Hendrix KM (eds). Berkeley: University of California Press; 538–547.

O'Loughlin CL. 1974. The effect of timber removal on the stability of forest soils. *Journal of Hydrology (New Zealand)* **13**: 121–134.

O'Loughlin CL, Ziemer RR. 1982. The importance of root strength and deterioration rates upon edaphic stability in steepland forests, in Waring RH (ed.), *Ecology of Subalpine Zones*, *Proceedings International Union of Forestry Research Organisations Workshop*, Oregon State University, Corvallis, 70–78.

Parde J. 1980. Forest biomass. *Forestry Abstracts* **41**: 343–352.

Riestenberg MM. 1994. Anchoring of thin colluvium by roots of Sugar Maple and White Ash on hillslopes in Cincinnati. *United States Geological Survey Bulletin* **2059-E**: 1–25.

Rodgers M, Casey A, McMenamin C, Hendrick E. 1995. An experimental investigation of the effects of dynamic loading on coniferous trees planted on wet mineral soils. In *Wind and Trees*, Coutts MP, Grace J (eds). Cambridge University Press: Cambridge; 204–219.

Styczen ME, Morgan RPC. 1995. Engineering properties of vegetation. In *Slope Stabilisation and Erosion Control: A Bioengineering Approach*, Morgan RPC, Rickson RJ (eds). E & FN Spon: London; 5–58.

Telewski FW, Lynch AM. 1991. Measuring growth and development of stems. In *Techniques and Approaches in Forest Tree Ecophysiology*, Lassoie JP, Hinckley TM (eds). CRC Press: Boca Raton, FL; 503–555.

Thorne CR. 1990. Effects of vegetation on riverbank erosion and stability. In *Vegetation and Erosion*, Thornes JB (ed.). Wiley: Chichester; 125–143.

Wood CJ. 1995. Understanding wind forces on trees. In *Wind and Trees*, Coutts MP, Grace J (eds). Cambridge University Press: Cambridge; 134–164.

Wu TH, Mckinnell III, Swanston DN. 1979. Strength of tree roots and landslides on Prince of Wales Island, Alaska. *Canadian Geotechnical Journal* **16**: 19–33.

