Vegetation for slope stability

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Executive Summary

Shallow slip failures on embankment and cutting slopes are more likely in certain geologies, particularly over-consolidated clays. The reinstatement of these shallow failures can be costly and the potential for slips may be reduced not only by the use of vegetation planted to provide reinforcement, through the plant root system, but also by a reduction in moisture content and pore water pressure. However, there is a potential conflict between the engineering requirements of earthwork materials to maintain stability and the moisture requirements to promote and sustain plant growth. For this reason careful selection of plant species is necessary and more information on successful planting regimes will reduce the requirement for replacement planting. The use of vegetation and bioengineered approaches also has the advantage of offering improved ecological and aesthetic benefits, in addition to improvements in slope stability.

This report reviews the potential for vegetation as a preventative measure in high risk areas as well as investigating associated aspects such as the use of vegetation on reinforced steepened slopes in road widening and the use of live willow poles in reducing the risk of shallow failures.

The project has involved a literature review to establish tree, shrub and herbaceous species that have the potential to grow in a highway environment, growing trials under controlled conditions, and the monitoring of a vegetated embankment trial. Studies on the highway network have included a survey of the use of vegetation reinforced steepened slopes and on the use of live willow poles to enhance stability of a clay slope on the A249. The implications of the findings are discussed.

1 Introduction

Shallow slip failures on embankments and cuttings are more likely in certain geologies, particularly over-consolidated clays, as identified during the survey of slope condition on motorway earthworks and reported by Perry (1989). The reinstatement of these shallow failures can be costly and the potential for slips may be reduced not only by the use of vegetation planted to provide reinforcement, through the plant root system, but also by a reduction in moisture content and pore water pressure. However, there is a potential conflict between the engineering requirements of earthwork materials to maintain stability and the moisture requirements to promote and sustain plant growth. For this reason careful selection of plant species is necessary and more information on planting regimes will reduce any requirement for replacement planting. The use of vegetation and bioengineered approaches also has the advantage of offering improved ecological and aesthetic benefits, in addition to the improvements in slope stability.

In 1995, the Highways Agency (HA) commissioned TRL to undertake a research project into slope stability and the establishment of vegetation. The aim of the project was to review the potential for vegetation as a preventative measure in high risk areas as well as investigating associated aspects such as vegetation reinforced steepened slopes in road widening and the use of live willow poles in reducing the risk of shallow failures. Bioengineering techniques of this type may reduce the need for the costly maintenance of shallow slip failures on highway embankments and cuttings using traditional methods such as those reported by Johnson (1985).

2 Background

Five principal phases of the investigation were undertaken as follows:

- Phase 1 Identify plant species to be used in controlled trials to determine their growth in over-consolidated clay soils.
- Phase 2 Undertake short-term, screening growth trials of plant species identified in Phase 1. Investigate the long-term growth of the most promising species under controlled growing conditions.
- Phase 3 Construct a typical highway embankment and monitor a field growing trial of the plant species used in Phases 1 and 2.
- Phase 4 Investigate the use of vegetation reinforcement of steepened slopes.
- Phase 5 Assess and develop the use of live willow poles to enhance stability in slopes formed in over-consolidated clays.

Phases 1 and 2 (establishment of vegetation) were undertaken at the Macaulay Land Use Research Institute (MLURI) and the findings of a literature review and the controlled growing trials are summarised in Section 3 of this report. Phase 3 (the field trial) was undertaken at TRL and is described in Section 4, which also presents new data on the longer term growth of the vegetation. The findings from Phases 4 (vegetation reinforced steepened slopes) and 5 (willow pole reinforcement) are summarised in Sections 5 and 6 respectively.

3 Establishment of vegetation

3.1 Introduction

A literature survey was undertaken to identify plant species that were potentially suitable for establishment on earthwork slopes adjacent to highways: the results of the survey were reported by Marriott (1996). The survey considered factors such as salt tolerance of plants, their resistance to wind and pollution, and the levels of maintenance required. Based on the findings of this survey, 25 species (comprising herbaceous species, shrubs and trees) were selected for preliminary screening trials in two clays (Gault clay and Reading Beds clay) which were associated with a high occurrence of slope failures (Perry, 1989). The aims of the trials were to determine plant survival in these soils during the initial establishment phase, and to identify a short-list of species for inclusion in subsequent longer term trials.

The short-term screening trials were conducted over a period of four months in controlled environment rooms. Two different temperature regimes were used to simulate the warmer conditions of south facing slopes and the cooler conditions of north facing slopes. Many of the species established and grew well in at least one of the clays, and the five most successful species were selected for longer term trials. The longer term trials, which lasted about three years, provided information on plant growth under different climatic/edaphic conditions, and enabled relations between root growth and various physical parameters of the soils to be examined. The trials allowed the suitability of the selected species for improving slope stability to be assessed, and provided an opportunity to examine the long-term management requirements of the various species. The results of the trials were also used as the basis of an economic assessment, which considered the cost of purchasing, planting and maintaining suitable species in standardised motorway situations. Details of the growth trials and economic assessment have been reported by Marriott *et al.* (2001).

This section of the report provides a brief summary of the findings of the literature survey, discusses the results of the screening trials, and outlines the recommendations arising from this part of the project.

3.2 Literature survey

The literature survey showed that both hydrological and mechanical mechanisms contributed to the beneficial influence of vegetation on slope stability. Vegetation modifies the moisture content of the soil, influencing soil strength, and the presence of roots in the soil increases soil strength and, therefore, its stability. The survey discussed the plant groups relevant to slope stabilisation, the form and function of the root systems, and the processes by which vegetation may enhance stability. The various species which could potentially be used for slope stabilisation were identified and discussed.

3.2.1 Plant groups

Grasses, herbs, trees and shrubs all have characteristics relevant to improving slope stability.

Grasses have a wide range of tolerances and quickly establish through vegetative spread to give good ground cover. They tend to be relatively shallow rooting, with some 60-80% of the roots lying in the top 50mm of soil, and so are more suited to surface protection rather than improving slope stability.

Herbs are broad-leaved, non-woody plants, some species of which are deeper rooting than grasses, and therefore might be more suitable for providing stability. However, it should be noted that many species die back in winter.

Shrubs and trees are woody perennials which can exhibit rooting habits varying from deep tap roots to shallow branched roots. Those having a deeper rooting habit have a potential role in stabilising shallow failures on slopes. Although shrubs and trees may take longer to fully establish and mature than grasses and herbaceous plants, a demonstration trial conducted by the Construction Industry Research and Information Association (CIRIA) showed that 15 months after establishment there were at least as many roots down to 0.35m depth under broom/gorse and willow treatments as under a grass and forb mix (CIRIA, 1996).

3.2.2 Form and function of root systems

The structure of the root system of plants is very diverse, varying from very fine fibrous systems through branched systems to those with a dominant vertical tap root. Tap roots are perennial structures associated with storage, particularly where the above-ground parts die back substantially in winter, whereas fine fibrous roots are subject to annual cycles of decay and renewal. Grasses generally have a finely branched fibrous root system, while those of herbs range from tap rooted and modified tap rooted to fibrous systems. Trees and shrubs have both tap rooted and branched systems.

The spatial distribution of the root system is usually influenced by both the genetic character of the plant and the localised soil conditions, and may vary over time. Most roots are usually found in the upper 0.5m of the soil under herbaceous vegetation, and up to 3m deep under trees and shrubs. In well drained soils, roots have to go deeper and forage over a greater soil volume than those in moister soils, while the presence of a high ground water level or a compacted layer will encourage the development of a laterally spreading system.

The ability of roots to take up water from the soil is strongly influenced by:

- the amount of water within the soil;
- the matric potential of the soil;
- the length of roots in the soil;
- the specific activity of the roots (i.e. water uptake per unit length of root); and
- the placement of roots within the soil (e.g. the volume of soil explored by roots and the density of roots within a given volume of soil).

Finely branched and tap root systems might have the same weight of roots but differ in the quantity and spatial pattern of water extraction from the soil profile. It is important to distinguish between long-lived roots such as tap roots, which function primarily as transporting roots during most of their lifespan, and the shorter-lived roots that serve primarily absorptive functions (Klepper and Rickman, 1990).

Elongation of roots is greatly affected by factors such as soil strength and oxygen diffusion rate. The effect of soil compaction (a fundamental aspect of earthworks) is to reduce soil porosity (and hence the movement of oxygen to root surfaces) and increase soil strength, both of which can limit root growth. For example, studies have shown that plant roots are often unable to penetrate further than 100-150mm in compacted soils and the few roots that penetrate to greater depths grow through cracks or fissures. Plant roots often grow laterally until they encounter a vertical channel, which they follow until encountering another impeding layer. Thus it is important that species used for highway slopes are suitable for use in compacted soils. It has been shown, for example, that the diameter of roots is important in determining the capability of roots to penetrate compacted layers. Materechera *et al.* (1992) found that roots with larger diameters tend to thicken more in compacted soil and have greater penetration than those with smaller diameters. Thicker roots are presumably less prone to buckling and more able to develop the higher pressures necessary to penetrate harder soils.

3.2.3 Functions of vegetation in slope stability

Vegetation can improve the stability of slopes through:

- soil moisture depletion;
- root reinforcement;
- buttressing and arching;
- surface cover shading the soil.

Soil moisture depletion.

Vegetation cover can reduce soil moisture content through:

i foliar interception and direct absorption and evaporation of rainwater, which reduces the amount infiltrating into the soil; and

ii extracting soil moisture via the transpiration stream, thus reducing pore water pressure and counteracting the reduction in soil strength that wetting causes.

Transpiration is greater when plants are growing rapidly in summer, under non-limiting moisture conditions. Many plants that live in damp habitats are characterised by high transpiration rates, and so have a high capacity to remove water from the soil. Such plants are potentially useful for reducing high pore water pressure, but their tolerance of drier soils may be limited.

Soil water depletion is strongly influenced by root depth and distribution. Many cereals and grasses are capable of rooting to considerable depth in good agricultural soils. For example barley sown in spring can achieve root depths of greater than 1m by the middle of summer and be removing water at this depth. Perhaps not surprisingly, species having an extensive and deeply penetrating root system have been shown to extract more water from the soil than those with shallower root systems (Burch and Johns, 1978).

The ability of many trees to reduce soil moisture to considerable depth is well known. Biddle (1985) showed that mature poplar depleted soil moisture in clay soils to depths of up to 3.5m in summer. It was more effective at depleting soil moisture than the surrounding grass, which had a transient drying effect to depths of only 0.5m. In this study poplar and oak were the most successful species in depleting soil moisture, but eucalypt species can also consume great amounts of water (Rhizopoulou and Davies, 1993).

As plant metabolic activity and transpiration are lower over the winter, this reduces the impact vegetation has on soil/water relationships during the period when rainfall is at a maximum. This led Coppin and Richards (1990) to argue that the ability of trees to reduce soil water and affect soil strength would be less than the effect their roots had on soil reinforcement, especially at the times critical for slope stability, i.e. in the spring when soil moisture is high and before transpiration rates begin to increase.

Root reinforcement.

The shear strength of a soil is increased as root fibres grow and extend across potential failure planes. For example, under wet conditions in Swiss pastures containing a range of grasses, Tobias (1995) found a 9-55% increase in shear strength in the root layer compared with the rootless soil.

The range of root factors that have been identified as important for reinforcement purposes include density, tensile strength, length/diameter ratio and orientation of roots in relation to the failure plane. Roots increase cohesion in proportion to their density and those less than 15-20mm in diameter are considered to contribute most to increasing shear strength. The roots of shrubs and trees can have very high tensile strengths, but there may be large differences within a single species depending on size, age and condition of the root and season of the year. The roots of herbaceous species can also have high strength, particularly perennial roots.

Buttressing and arching.

Trees and root columns can act as buttress piles or arch abutments to counteract downslope shear movements. Significant soil arching and buttressing is achieved by deep root systems such as tap roots on larger trees. Roots having diameters greater than 20mm are generally regarded as soil anchors in studies of slope strength. As shown in Figure 3.1, Coppin and Richards (1990) described the processes diagrammatically and showed a vertical cylinder of soil anchored by roots to bedrock, a mass of soil upslope from the tree buttressed by the soil cylinder and a zone of arching between the buttressed zones. They stated that the size of the arching effect was dependent on the spacing, diameter and embedment of the trees, the thickness and inclination of the yielding stratum and the shear strength properties of the slope.

Surface cover shading the soil.

A vegetative cover will shade the soil surface and reduce the incidence of shrinkage cracking and deep penetration of rainwater. For example, Anderson *et al.* (1982) found extensive, deep cracks on sparsely vegetated areas of clay embankments on the M4 motorway, whereas there were few cracks where the vegetation was dense. Open cracks in the middle of the slope allowed winter rainfall to enter and raise pore water pressures, leading to shallow seated failures.

3.2.4 Other considerations

In addition to stabilising the soil, species planted on highway slopes must show a degree of salt tolerance and resistance to wind as well as some resistance to pollution from exhaust fumes. Dunball (1979) identified alders,

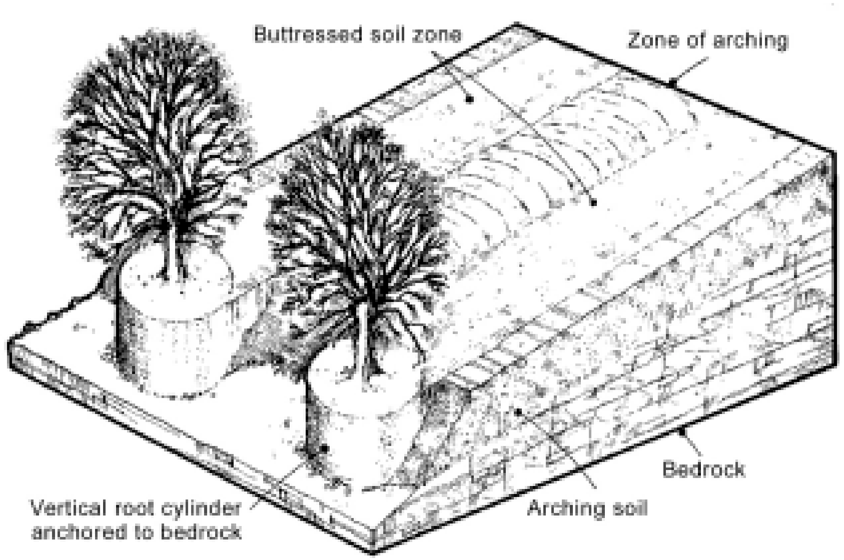

Figure 3.1 Schematic of soil buttressing and arching (Coppin and Richards, 1990)

shrubby willows, birch, pines and larch as particularly suitable species for use adjacent to highways.

Highway slopes are often elevated above the natural ground level and the exposed conditions mean that young trees are at risk of scorch by the sun or buffeting by the prevailing winds (Dunball, 1979). Grace and Russell (1979) suggested that the windiness of road verges would be of little consequence if the air was clean. It is, however, polluted to some degree by gases, droplets and other particulate matter. Surface damage to leaves when they rub in the wind or are abraded by particles may increase water loss and the uptake of pollutants.

Another important consideration is the level of maintenance required, since motorway slopes cover a large area and often have access problems. Suitable species should have relatively low maintenance requirements in terms of the need for herbicide treatments to reduce competition with neighbouring plants, fertilisation to sustain growth, and cutting/trimming to restrict top growth. Leaf litter can be a problem, causing blocked drains, and therefore evergreen species and deciduous species with non-persistent litter are more desirable.

Dimitri and Siebert (1979) tested 114 willow species, 5 poplars and 5 other plant species for salt tolerance. They found that willows and poplars were more resistant to salt (applied either to shoots or the soil) than other tree species. Thompson *et al.* (1979) investigated salt tolerance under conditions designed to simulate the central reserves and verges of motorways, and identified a range of suitable species. After one winter there was considerable damage to some species when salt had been applied to the soil, and some indication that the effects of salt applied as spray were similar, but of a much reduced magnitude. Although spray damage at distances up to 40m has been reported in American and European literature, Colwill *et al.* (1982) found that sodium concentrations 2m from the hard shoulder were less than half those at the centre of the corresponding central reserve, even in the areas with the highest application rates of salt. At distances greater than 5m from the hard shoulder the concentrations of salt in the soil were below those where effects on plants are noticeable. Their report compiled a list comparing the salt tolerance of a range of 80 shrub and tree species. In addition southern England was identified as an area where the salt hazard was generally negligible to low, and it should therefore be possible to consider even salt-sensitive species for stabilising clay embankments in this area.

Arnal (1979) compared the growth of a range of 14 shrub species under two levels of lead pollution from traffic and found on average a 20% reduction in the heights and weights of leaf dry matter between moderate and high levels of pollution. Small and hairy leaves and tall plants may be expected to trap pollutants more successfully than large and smooth leaves and prostrate plants (Grace and Russell, 1979).

3.2.5 Screening trials for selected species

While all the plant groups discussed in the foregoing can play a role in stabilising slopes, the literature survey showed that shrubs and trees are potentially the most important in stabilising shallow slope failures. For example species such as shrubby willows, birch, pines and larch were identified in Supplementary Report SR513[1] as being generally suitable for motorway conditions (although no consideration was given to their suitability for clay soils). Other species, for example some of the hardier eucalyptus, with their rapid growth rate and ability to tolerate defoliation, may also be useful.

The survey identified a range of requirements for vegetation on highway slopes, and collated a list of potential species. Subsequently 25 species, shown in Table 3.1, were

[1] *The proceedings of a symposium on the impact of road traffic on plants, organised by the British Ecological Society and TRL, September 1978.*

Table 3.1 Species selected for screening trials in Gault Clay and Reading Beds (cohesive)

	Evergreen/semi-evergreen		*Deciduous*	
	N_2 fixers	*non-N_2 fixers*	*N_2 fixers*	*non-N_2 fixers*
Trees				
		Eucalyptus niphophylla	Alnus glutinosa	Acer campestre
		Pinus nigra	Robinea pseudoacacia	Betula pubescens
				Crataegus monogyna
				Fraxinus excelsior
				Salix aurita
				Salix caprea
				Salix cinerea
				Populus TT32 (P. tacamahaca x trichocarpa)
Shrubs				
	Cytisus scoparius	Cotoneaster simonsii		Amelanchier canadensis
	Hippophae rhamnoides	Vinca minor		Cornus alba
	Lupinus arboreus			Corylus avellana
	Ulex europaeus			Rosa rugosa
				Sambucus nigra
Herbaceous species				
	Medicago sativa			Achillea millefolium

selected for testing in screening trials to determine their ability to grow in two over-consolidated clay fills, Gault Clay and Reading Beds, with and without added topsoil. Both evergreen and deciduous trees and shrubs were included, along with two herbaceous species. The trials were conducted under two temperature and light regimes to simulate the warmer conditions of south facing slopes in spring/summer and the cooler conditions of north facing slopes in autumn/winter. Plant survival percentages were recorded at monthly intervals over a four month growing period; many of the species established and grew well in at least one of the clays, and the five most successful species were selected for longer term growth trials.

3.3 Long-term growth trials

The five species selected for longer term trials were:

1 *Betula pubescens*	a deciduous tree.
2 *Cytisus scoparius*	a nitrogen-fixing evergreen/ semi-evergreen shrub.
3 *Hippophae rhamnoides*	a nitrogen-fixing evergreen/ semi-evergreen shrub.
4 *Lupinus arboreus*	a nitrogen-fixing evergreen/ semi-evergreen shrub.
5 *Salix caprea*	a deciduous tree.

Plants of these species were grown in compacted Gault and Reading Beds over two winter periods, i.e. spring 1997 to summer 1999. The plants were subjected to different temperature/light regimes to simulate the environmental conditions of north and south facing slopes. The colder conditions of a north facing slope were simulated by a covered enclosure (i.e. covered roof and open sides) while a large enclosed glasshouse was used to simulate the warmer conditions on a south facing slope. The mean daily temperatures in the glasshouse were generally 2 to 5ºC higher than those in the covered enclosure, and the difference between maximum and minimum temperature was greater, especially in the summer months. The glasshouse environment was also lighter than the covered enclosure, with mean light intensities of 1200 mmol/sec and 800 mmol/sec respectively. In each of the environments plants were grown under high and low water regimes.

The plants were grown in large containers with a soil depth of about one metre. Seasonal patterns of root and shoot growth and soil moisture were measured. To determine the effect on the physical properties of a soil of growing different plant species, a number of unplanted clay samples were used as control specimens. At intervals during the trial a range of physical properties, including bulk density, shear strength, plastic/liquid limits, soil water retention, and specific surface area, were measured for both the planted and unplanted clays.

3.3.1 Root and shoot growth

The principal functions required of vegetation to increase slope stability are soil reinforcement and soil water removal. These depend on the vegetation having roots that develop at depth in the soil, a vigorous root development throughout the soil and a large transpiration surface of shoot material above ground. A large shoot canopy will also shade the clay surface, thus reducing the extent of surface desiccation and cracking. In addition, the canopy will intercept and increase the evaporation of rainfall, which will reduce infiltration into the clay

All five species in the growth trial showed useful qualities for increasing slope stability. They survived and grew over three seasons. The highest rate of failure during establishment was for *Betula*, although it grew well once it had established. Three species (*Cytisus*, *Lupinus* and *Salix*) showed rapid root growth in the first year after planting, reaching a depth of 0.5m by autumn in Reading Beds clay. *Salix* plants had the greatest root masses in the third year after establishment. By this time, all species had at least 23% of the root mass at depths of 0.3 to 0.4m in at least one treatment combination; in general, the proportion of roots at this depth was greater in the low moisture treatment. All species apart from *Betula* had roots at depths greater than 0.7m in the third year after establishment when growing in deeper containers.

Bud burst in spring, when regrowth recommences after winter and moisture demand starts to increase, was generally at least four weeks earlier for the semi-evergreen/evergreen species (*Cytisus*, *Hippophae* and *Lupinus*) than the deciduous trees (*Betula* and *Salix*). This suggests that these species could be beneficial in removing soil moisture in the spring, when many shallow slope failures occur (Coppin and Richards, 1990). Measurements of the water supplied in the high moisture regime during a growing season suggested that all species had a high water demand, although the amount supplied to *Salix* was generally the greatest. The changes in plant height, individual shoot length and total shoot mass of the different species showed that a considerable canopy developed. Therefore, there are potential benefits from all species in terms of surface shading and the interception of rainfall.

In general, root and shoot growth of *Salix* exceeded that of the other four species in the growth trials. However, *Betula*, *Cytisus*, *Hippophae* and *Lupinus* all grew well in at least some of the treatment combinations, and therefore all five species merited consideration for future planting schemes.

3.3.2 Physical effects of vegetation

Vegetation can increase slope stability through both mechanical and hydrological effects. The mechanical effects result from the reinforcement of the soil by roots, and anchorage and buttressing by tap-roots. The resulting increase in strength and competence of the soil increases stability. The presence of vegetation also modifies the transfer of water in the atmosphere-soil-plant system. By modifying the moisture content of the soil, the strength is generally improved.

Measurements of the change in cohesive shear strength and porosity confirm that improvements to both the strength and moisture content of Gault and Reading Beds clays occurred as a result of planting different species. There was a general increase in the undrained shear strength of clays planted with the five species compared with that of the unplanted clay. In addition, there was a positive relation between root mass and shear strength under the different experimental conditions used in the growth trial. This suggests that the stability of Gault and Reading Beds slopes would increase under a range of climatic conditions where any of the trial species was actively growing.

There was some evidence that the permeability of the planted clays was greater than that of unplanted clays. This could improve slope stability, since excess water would drain away more easily and a reduction in moisture content would increase strength. In some of the laboratory situations, the planted clays had a higher saturated moisture content than the unplanted clays. This could have an adverse effect on slope stability, but under field conditions this is likely to be offset by the increased interception of rainfall and transpiration by the vegetation.

3.4 Economic assessment

The results of the long-term trials suggested that all five species were potentially useful for stabilising slopes. However, it was necessary to estimate the cost for the establishment and management of different species so that the most cost-effective solution could be identified, and also to allow comparison with the cost of other stabilisation measures.

Recommendations were drawn up for six different planting options: five single planting regimes using each of the species used in the growth trials, and a mixed planting regime that included all five species (in a ratio of one tree (*Salix* or *Betula*) to three shrubs (*Cytisus*, *Hippophae* or *Lupinus*). These recommendations, details of which are given in Table 3.2, were used as the basis for discussions with horticultural and landscape contractors to estimate the cost of implementing the different options. The economic assessment for each option was based on a five year management plan (after which time it was assumed that the vegetation would be well established) and took into account the costs of ground preparation prior to planting, purchase of the plants, and planting and maintenance of the vegetation. The assessment also considered the likely replacement rates of plants based on contractors' experience in the field rather than data obtained from growth trials. In determining the costs it was assumed that access to the motorway verge was straightforward, that the slope angle of the verge was between 1:2 and 1:2.5, and that the ground was newly made-up and therefore not difficult to work. The figures did not include the cost of any motorway traffic management or rabbit fencing.

Because vegetation may be used over a relatively small area of slope (for example when repairing an existing slip) or applied on a much larger scale (for example when used as a slip prevention measure), the costs were calculated for

Table 3.2 Recommendations for implementing six species planting options for embankment slopes of clay

Salix caprea	*Hippophae rhamnoides*	*Cytisus scoparius*	*Lupinus arboreus*	*Betula pubescens*	*Mixed species (all 5 in table)*
Planting stock					
1-year-old rooted cuttings, pruned to 200 mm above ground level at planting.	2-year-old plants, with roots undercut, cut back by half at planting.	1-year-old pot-grown seedling plants. No pruning at planting.	1-year-old seedling plants, pruned to 200 mm above ground level at planting.	2-year-old undercut stock. No pruning at planting.	As for 5 species shown in previous columns.
Planting distance					
1 metre centres	600 mm centres	600 mm centres	600 mm centres	1 metre centres	*S. caprea* and *B. pubescens* at 3 metre centres spread across the area to be planted. The remaining 3 species at 600 mm centres
Fertiliser at planting (per plant)					
Controlled release-90 g	Controlled release-50 g	Controlled release-50 g	Controlled release-50 g	Controlled release-90 g	Controlled release-70 g
Weed control in year of planting					
Ground to be kept free of weeds by hand-weeding, glyphosate or paraquat-based herbicide.					
Maintenance pruning					
Every 2-3 years cut back to 200mm above ground level.	None	None	Annually in spring to 200mm, remove prunings.	None	As for 5 species in previous columns.
Maintenance fertiliser					
Controlled release fertiliser at 90 g/m^2 in years of pruning.	None	None	After pruning controlled release fertiliser -50 g/m^2.	Controlled release fertiliser at 90 g/m^2 every second year after planting.	Controlled release fertiliser at 50 g/m^2 every second year after planting.

two separate cases. In the first case the costs of establishing the six options were determined for an area measuring 10m x 10m, and in the second for an area 4km long x 10m wide.

The data from the economic assessment are shown in Tables 3.3 to 3.6. It can be seen that Options 1, 5 and 6 offer the most cost-effective solutions. For small areas the most cost-effective solution is Option 1 using *Salix caprea*, with Option 5 *Betula pubescens* and Option 6 *Mixed species* being the second and third most cost-effective, respectively. For larger areas the most cost-effective option is Option 5, with Option 1 and Option 6 being the next least expensive choices. The difference in cost-effectiveness at the two different scales may be explained by variations in the management techniques employed. Horticultural contractors differ somewhat in their treatment of the establishment and maintenance of trees and shrubs; however, at both scales there is reasonable consistency between the least and most expensive options.

Options 2, 3 and 4 are clearly more expensive. These species are planted at a greater density and also have more expensive requirements. For example, *Cytisus scoparius* (Option 3) and *Lupinus arboreus* (Option 4) may require shrub shelters rather than tree guards as well as more labour intensive planting methods. There are also differences in fertiliser and pruning regimes between the options. Lastly, Options 3 and 4 are also less desirable because of the the higher supply cost of the plants, as these particular species are generally only available in a container pot. The differences in supply cost are shown in Table 3.5, which also shows that costs are reduced when plants are bought in larger quantities. In Table 3.6 the cost of planting a 10m x 10m area is compared with the cost of planting a similar sized area within a larger planting scheme, and considerable economies of scale are shown, with Options 1, 5 and 6 providing the greatest savings.

3.5 Recommendations

The most cost-effective species to plant and maintain, in a motorway situation are *Salix caprea* and *Betula pubescens*, although the latter species had the poorest survival rate in growth trials on Gault and Reading Beds clays. A mixed species option of the type suggested is also likely to provide value for money and has the advantage that the risks associated with such an option are likely to be less than that with a single species. As might be expected in this type of operation there are also considerable cost-savings to be gained from purchasing and planting at larger scales.

In addition to the engineering functions of vegetation in terms of protecting and stabilising the surface of the soil and increasing soil strength at depth, there are benefits of enhancing the quality of the landscape. Mixed planting schemes, with different species planted in small blocks of a single species or finely interspersed, could be particularly desirable for landscaping purposes. As well as increasing biodiversity, they also bring added benefits through complementary growth patterns and resource use, and potentially create a system that has greater ecological viability.

Table 3.3 Typical costs of planting, establishment and maintenance of small areas (10 m x 10 m).

Option	*1*	*2*	*3*	*4*	*5*	*6*
Planting and establishement Year 1						
Cost given in £/10 m x 10 m						
Ground cultivation				Not advised		
Plants	47	130	520	694	36	429
Stake + tree guards	137	327	327	327	137	103
Planting	121	289	347	289	121	100
Fertiliser (tablet form)	16	38	38	38	16	12
Herbicide (2 applications)	200	200	200	200	200	200
Establishment Year 2						
Replacement of plants	262	275	330	460	305	320
Herbicide (2 applications)	200	200	200	200	200	200
Management Year 3						
Replacement of plants – average	220	220	220	220	220	220
Herbicide (2 applications)	200	200	200	200	200	200
Management Year 4 & 5						
Routine management and replacement (for 2 years)	440	440	440	440	440	440
Herbicide (for 2 years)	400	400	400	400	400	400
Total cost per 10 m x 10 m	2243	2719	3222	3468	2275	2624

Option 1 Salix caprea
Option 2 Hippophae rhamnoides
Option 3 Cytisus scoparius
Option 4 Lupinus arboreus
Option 5 Betula pubescens
Option 6 Mixed planting with all five species.

Table 3.4 Typical costs of planting, establishment and maintenance of large areas (4 km x 10m).

Option	*1*	*2*	*3*	*4*	*5*	*6*
Planting and establishment Year 1						
Cost given in £/4 km x 10 m						
Ground cultivation				Not advised		
Plants	16400	42772	116756	144500	14800	32032
Stake	6000	17340	17340	17340	6000	5460
Planting and pruning	9200	26588	31212	34680	8000	9464
Fertiliser	2400	3468	3468	3468	2400	1092
Herbicide	2000	5780	5780	5780	2000	1820
Labour where not included	29600	85544	92480	92480	29600	28028
Tree guards/shrub shelters	17200	49708	113288	113288	17200	29484
Establishment Year 2						
Replacement of plants	6900	19507	30345	31428	6750	9669
Routine maintenance	3000	8670	8670	8670	3000	2730
Fertiliser				9248		
Herbicide (2 applications)	3600	10404	10404	10404	3600	3276
Pruning				4624		346
Management Year 3						
Replacement of plants	3200	12138	17340	15172	3700	4436
Routine maintenance	3000	8670	8670	8670	3000	2730
Fertiliser	4400			12716	4400	4004
Herbicide (2 applications)	4000	11560	11560	11560	4000	3640
Pruning	3400					3400
Management Year 4 & 5						
Replacement of plants	3200	12138	17340	15172	3700	4436
Routine maintenance (2 years)	6000	17340	17340	17340	6000	5460
Herbicide (4 applications)	8000	23120	23120	23120	8000	7280
Total costs per 4 km x 10 m	131500	354747	525113	579660	126150	158787

Option 1 Salix caprea
Option 2 Hippophae rhamnoides
Option 3 Cytisus scoparius
Option 4 Lupinus arboreus
Option 5 Betula pubescens
Option 6 Mixed planting with all five species

Table 3.5 Wholesale supply cost of species options (excl. VAT)

Option	*1*	*2*	*3*	*4*	*5*
	Salix caprea	*Hippophae rhamnoides*	*Cytisus scoparius*	*Lupinus arboreus*	*Betula pubescens*
Per plant (single plants)	£0.59	£0.88	£2.20 *	£5.25*	£0.88
Per plant (100 plants)	£0.47	£0.45	£1.80*	£2.40*	£0.37
Per plant (10,000 plants)	£0.29	£0.43	£1.26*	£1.23*	£0.36

** Plants supplied in container pot (Lupinus arboreus and Cytisus scoparius are difficult to obtain except in this form)*

Table 3.6 Economies of scale for vegetation options

Option	*1*	*2*	*3*	*4*	*5*	*6*
	Salix caprea	*Hippophae rhamnoides*	*Cytisus scoparius*	*Lupinus arboreus*	*Betula pubescens*	*Mixed species*
Total cost (£) of 10 m x 10 m at small scales	2243	2719	3222	3468	2275	2624
Total cost (£) of 10 m x 10 m at larger scales	329	887	1313	1449	315	397
Percentage savings	85	67	59	58	86	85

4 Vegetated embankment trial

4.1 Introduction

The observation trial was established to augment both the vegetation trials being monitored on the M20 (CIRIA, 1996) and the laboratory growing trials at the MLURI, as described in Section 3. A trial embankment was constructed at TRL, and selected species of trees, shrubs and perennial plants were planted in individual panels on the north and south facing side slopes. Instrumentation was installed to monitor any changes in pore water pressure resulting from the vegetation. This Section briefly describes the construction of the embankment and presents data on the longer term growth of the vegetation and its effect on pore water pressures.

4.2 Embankment construction

Full details of the method of construction are presented by Snowdon *et al.* (1998) and only a brief summary of the work is provided below. A Reading Beds clay (PL = 25%, LL = 64%) was selected for the core of the trial embankment and this was obtained, at its natural moisture content, from Starr Quarry (near Twyford, Berkshire).

The embankment was about 42m long (including an access ramp for compaction plant) and accommodated four growing panels per embankment side (each approximately 6m wide). Investigation of the ground conditions of the site revealed a 0.9m layer of general fill material covering a 0.1m layer of sandy organic material. A firm sand layer continued to a depth of 1.8m, and thereafter a silty clay continued to a depth of about 10m to the local Bagshot Beds.

Construction took place in October 1996. Owing to operational constraints, the major axis of the embankment was oriented at a bearing of 055°, which resulted in the growing panels being offset from the north/south facing direction. The dimensions of the completed embankment core were approximately 34m in length, 9.5m in width, including a 1.75m berm at the top, 2.1m in overall height, and slope ratio of 1:1.94, as shown in Figure 4.1. Graded topsoil (screened to 10mm) was then placed over the embankment core, raked level and gently tamped with a JCB back-actor bucket, as shown in Figure 4.2. The slope surface was not harrowed prior to top soiling because the finished clay surface was considered sufficiently rough for the top soil to adhere. The thickness of the compacted topsoil was typically 150mm. General views of the construction works are shown in Figure 4.3, and a view of the completed embankment is shown in Figure 4.4.

In October 1996 the top soil was fertilised using ‘Growmore’ hand spread at approximately 100g/m^2 and seeded with the ‘MOT’ road verge amenity grass mixture to Table 6/5, supplied by British Seed Houses, to the requirements of SHW Clause 618.7 (MCHW 1) at a rate of 20g/m^2 and raked into the top soil. A chemical analysis was made of the Reading Beds cohesive fill and is presented in Table 4.1. Deer fencing incorporating an anti-rabbit netting, partially buried for the lower 300mm, was erected around the completed embankment.

4.3 Instrumentation

The study was based on long-term observations of the establishment and growth of selected vegetation, although some instrumentation was installed to monitor the effects of the vegetation on the moisture régime within the embankment. For this purpose eight clusters of four Thies Clima tensiometers were installed to monitor pore water pressures within the embankment core. They were installed in the centre of each panel, to nominal depths of 0.25, 0.5, 0.75 and 1.0m. The porous ceramic tip of each tensiometer was encased in sand, at the bottom of the hole, with the annulus between the tube and soil backfilled with bentonite pellets and clay. Their locations are shown in Figure 4.1.

4.4 Plant selection and planting scheme

The plant species selected for the trials were based upon a combination of the more successful species identified in Phase 1 of the MLURI trials (Marriott, 1996) and those planted in the M20 Longham Wood trial on Gault Clay (CIRIA, 1996). All of the trees and shrubs were planted in mid February 1997, and the perennial plants were planted in late February 1997.

4.4.1 Trees

The trees were planted in panels S1 and N1 (Figure 4.1), approximately 8m wide by 4.4m. The species selected were:

- Goat willow (*Salix caprea*)
- Common white birch (*Betula pubescens*)
- Common ash (*Fraxinus excelsior*)
- Black locust (*Robinia pseudoacacia*)
- Common alder (*Alnus glutinosa*)
- Common osier (*Salix viminalis*)

They were supplied as bare rooted stock and were planted randomly at approximately 1m centres. A total of 90 plants (15 of each species) were planted. None of the plants supplied were undercut, i.e. had their main tap root cut off. Following planting the trees were pruned to a height of 0.3m.

4.4.2 Shrubs

The shrubs were planted in panels S2 and N2, each approximately 6m wide by 4.4m. The selected species were:

- Sea buckthorn (*Hippophae rhamnoides*)
- Common broom (*Cytisus scoparius*)
- Tree lupin (*Lupinus arboreus*)
- Alder buckthorn (*Rhamnus frangula*)
- Common elder (*Sambucus nigra*)
- European gorse (*Ulex europeaus*)
- Lesser periwinkle (*Vinca minor*)

A total of 105 plants (15 of each species) were supplied as container grown and planted randomly at approximately 0.75m centres. The shrubs were also pruned to a height of 0.3m immediately after planting.

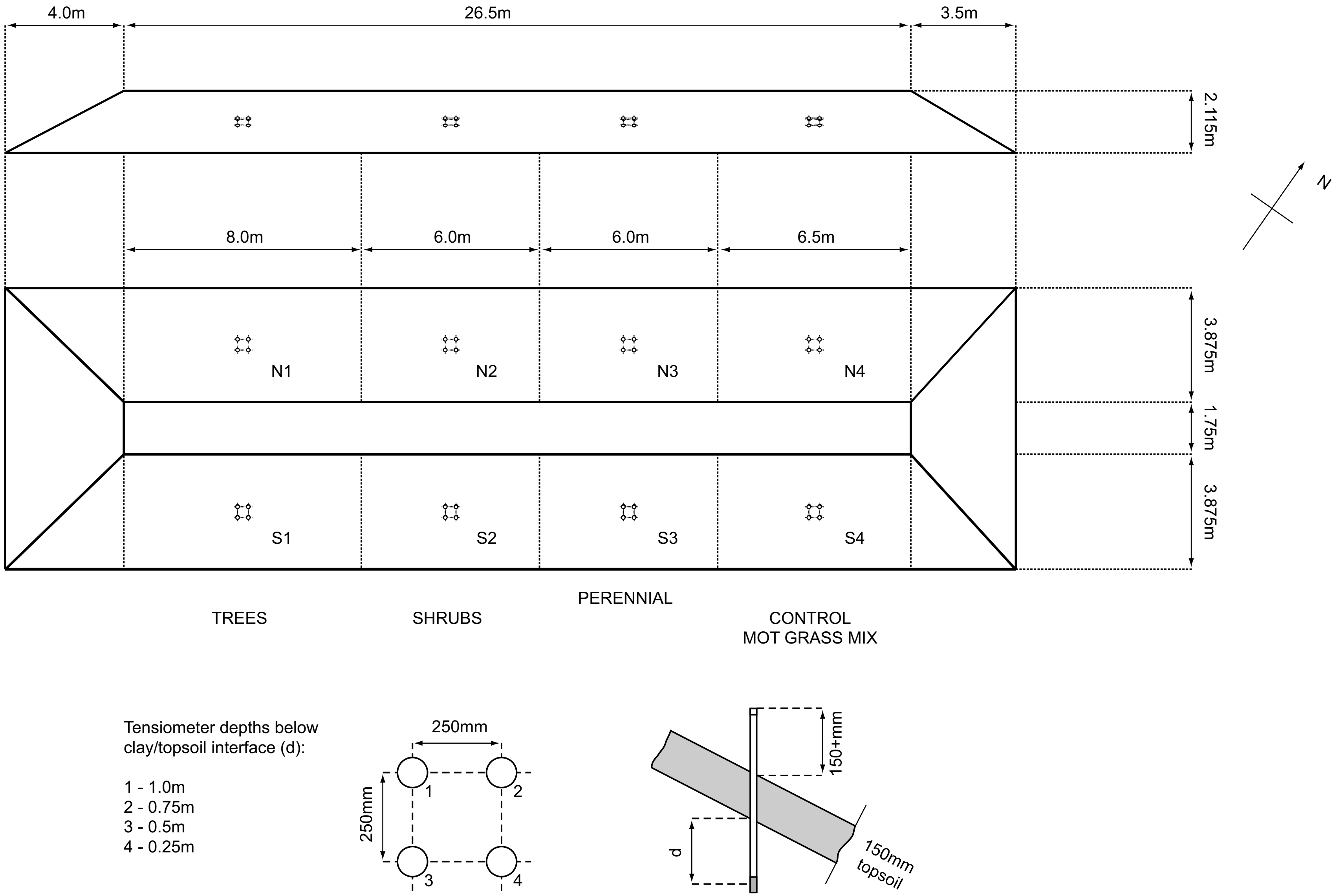

Figure 4.1 Embankment core side elevation and plan view

Figure 4.2 Placing and tamping the top soil

Figure 4.3a Delivery of the Reading Beds cohesive fill

Figure 4.3b The HAMM vibratory tamping roller compacting the fill

Figure 4.4 View of the completed embankment, October 1996

Table 4.1 Chemical analysis of the Reading Beds cohesive fill

% loss on ignition	5.41
pH (H_2O)	8.38
pH ($CaCl_2$)	7.62
% C	0.14
% N	0.04
P_2O_5 (mg/100g)	56.90
Ca (meq/100g)	17.17
Na (meq/100g)	0.19
K (meq/100g)	0.97
Mg (meq/100g)	8.18

4.4.3 Perennial species

The perennial species were planted in panels S3 and N3, each approximately 6m wide by 4.4m. The selected species were:

- Yarrow (*Achillea millefolium*)
- Lucerne (*Medicago sativa*)
- Ribwort plantain (*Plantago lanceolata*)
- Kidney vetch (*Anthyllis vulneraria*)
- Birdsfoot trefoil (*Lotus corniculatus*)
- Black knapweed (*Centaurea nigra*)
- Ox-eye daisy (*Leucanthemum vulgare*)

A total of 336 plants (48 of each species) were supplied as either container grown or as plugs and planted randomly at approximately 0.4m centres.

4.4.4 Grass

All of the panels had previously been seeded with a ‘MOT’ road verge amenity grass seed mixture in October 1996. The control panels S4 and N4, each approximately 6.5m wide by 4.4m, did not have any other planting.

4.5 Monitoring regime

4.5.1 State of vegetation

Observations of vegetation growth were made during visits for reading the tensiometers. Full surveys on the state of the vegetation were made during September 1997, May 1998, November 1998, July 1999 and June 2000. Survival rates and the condition and height of growth were recorded. Figure 4.5 shows the north and south facing slopes of the embankment in September 1997, prior to grass cutting, and views of the slopes at later stages of the trial are given in Figure 4.6.

4.5.2 Pore water pressures

Readings commenced in March 1997 and the tensiometers were generally monitored on a fortnightly basis. This increased to weekly during the summer, when the instruments required more frequent visits to prevent them drying out; the instruments were refilled with water after each reading. Figure 4.7 shows the tensiometer transducer with the handheld read-out unit in use.

4.5.3 Maintenance

Owing to lack of rainfall following planting, it was necessary to carry out minimal hand watering of the trees and shrubs in mid-April 1997. Hand weeding of large weeds was carried out occasionally during visits and routine monitoring.

The grass was cut using a strimmer to 75mm, on the non-planted panels S4 and N4 only, in May 1997.

Figure 4.5a View of the South facing slope, September 1997

Figure 4.5b View of the North facing slope, September 1997

Figure 4.6a General view of embankment looking East, September 1999

Figure 4.6b General view of embankment looking East, October 2000

Figure 4.7 Monitoring the tensiometers, April 1997

Subsequently, the grass was cut to 75mm on all panels in late October 1997 and again in mid July 1999. Hand trimming was required around the trees and shrubs to prevent damage from the strimmer.

It was noted that there was significant vole activity, primarily within the top soil, during autumn 1997. Some damage to the bark and cambium of some plants was noted. Treatment to remove the rodents was put in hand, but no replacement planting was undertaken.

4.6 Results

4.6.1Climatic conditions

Climatic data, comprising rainfall, sunshine, and maximum and minimum temperatures for the duration of the growing trial were obtained from a meteorological station located less than a mile from the site of the trial embankment. The data are shown in Figure 4.8, which compares the monthly values during the growth trials with the monthly averages for the period 1961 to 1990. The rainfall and sunshine data are summarised in Table 4.2.

Rainfall

Over the period of the growing trial (i.e. February 1997 to June 2000), the site received about 13 per cent more rainfall than average but, as might be expected, Figure 4.8(a) and Table 4.2 show that from month to month there was considerable variation from the average values for the site. For example, the winter following construction of the embankment (during which time the trees, shrubs and perennials were planted) was relatively dry, having less than 60 per cent of the average winter rainfall. The spring of 1997 was even dryer, with the site receiving only about one third of the average rainfall (as discussed in Section 4.5.3, the lack of rain during this period necessitated some hand watering of the vegetation). The summer of 1997 was 50 per cent wetter than average, but overall the year was relatively dry, receiving only 87 per cent of the average annual rainfall.

For the remainder of the study period the weather was slightly wetter than average, but again there was a good deal of variation in the data. Spring 1999 was relatively dry but the site received more than twice the average rainfall for the season during the spring of 2000. The summers of 1998 and 2000 were dryer than average but the summer of 1999 was wetter by some 30 per cent, while the autumns of 1998 and 1999 were both wetter than average.

Sunshine

Figure 4.8(b) shows the total monthly hours of sunshine during the trial and compares them with the average monthly values for the site over the period 1961 to 1990; the data are summarised in Table 4.2. Over the course of the study, the site received about 5 per cent more sunshine than average. The data show less variability from the average than the rainfall data, but it can be seen that the autumn and winter periods were generally sunnier than average throughout the duration of the trial, while three out of the 4 spring seasons were marginally less sunny than average (the exception being the first spring after planting when hand watering was required).

Temperature

The meteorological data obtained for the site provided details of the daily maximum and minimum temperatures. For each month, the mean values of the maximum and

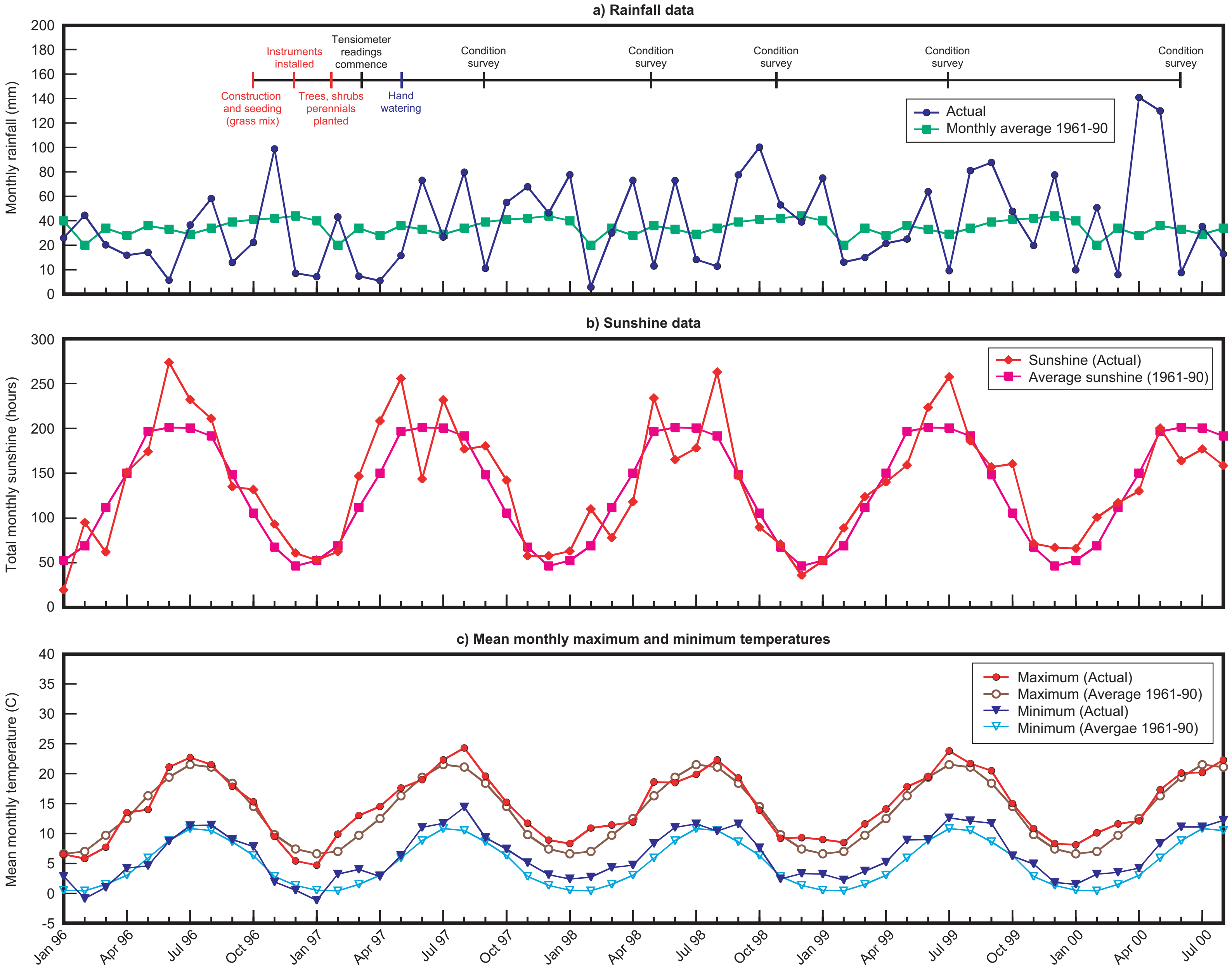

Figure 4.8 Comparison of climatic data during growth trial with monthly averages for period 1961-1990

Table 4.2 Comparison of climatic data obtained during growth trial with data for previous 30 years

	Seasonal rainfall and sunshine data during growth trial expressed as a percentage of the average values for the period 1961-1990[1]	
Season	*Rainfall (%)*	*Sunshine (%)*
Winter 1996	110.3	94.3
Spring 1996	67.3	84.5
Summer 1996	93.7	120.9
Autumn 1996	102.7	112.0
Year average	93.5	102.9
Winter 1997	57.6	104.8
Spring 1997	36.2	133.3
Summer 1997	153.5	93.1
Autumn 1997	101.0	118.4
Year average	87.1	112.4
Winter 1998	103.5	137.6
Spring 1998	105.1	93.8
Summer 1998	92.3	102.2
Autumn 1998	159.6	95.6
Year average	115.1	107.3
Winter 1999	109.8	105.3
Spring 1999	73.7	92.3
Summer 1999	130.8	112.5
Autumn 1999	118.2	121.1
Year average	108.1	107.8
Winter 2000	114.6	139.3
Spring 2000	206.7	97.6
Summer 2000	67.8	84.2
Year average[2]	129.7	107.0

Winter: Dec, Jan, Feb
Spring: Mar, Apr, May
Summer: Jun, Jul, Aug
Autumn: Sep, Oct, Nov

[1] Data obtained from Beaufort Park, Bracknell
[2] Values for Autumn 2000 not included

minimum temperatures were calculated and these are shown graphically in Figure 4.8(c). For comparison, the figure also shows the average values for the period from 1961 to 1990 of the monthly mean temperatures. The data indicate that, since the planting of the trees, shrubs, and perennials in February 1997, the mean monthly minimum temperature has very rarely dropped below the average value. Similarly, the mean monthly maximum temperature during the course of the trial was generally higher than average, although there were a few exceptions, such as June and July 1998 and July 2000.

Summary

A certain amount of caution has to be exercised when considering mean monthly values as they tend to mask the more extreme temperature events, particularly those of short duration. Nonetheless, the data obtained suggest that, for the duration of the growing trial, the climatic conditions were slightly warmer, wetter and sunnier than the average. Although these conditions are generally considered conducive to the growth of vegetation, it is difficult to assess the effect of individual seasons on the growth potential; for example the particularly dry spring following planting may well have had a detrimental effect on plant growth.

4.6.2 Vegetation

As discussed in Section 4.5.1, several surveys of the condition of the vegetation were undertaken during the course of the study. The survival rates for the tree and shrub species are shown in Figures 4.9 and 4.10 respectively, and the data are summarised in Table 4.3[2]. The condition of the perennials and grasses are summarised in Table 4.4.

Table 4.3 Summary of survival rates for tress and shrubs

	Survival rate (per cent)	
Condition survey	*Trees*	*Shrubs*
Survival rates for trees and shrubs		
Sept 1997	87	67
May 1998	74	63
July 1999	80	35
June 2000	77	31

	Survival rate (per cent)			
	Trees		*Shrubs*	
Condition survey	*North*	*South*	*North*	*South*
Effect of slope orientation on survival rate				
Sept 1997	95	79	64	70
May 1998	78	69	56	70
July 1999	88	73	31	39
June 2000	86	69	29	34

Table 4.4 Survival rates for perennials and grasses

	Survival 1997		*Survival 2000*	
Species	*North*	*South*	*North*	*South*
Perennials Yarrow *(Achillea millefolium)*	P	A	P	G
Lucerne *(Medicago sativa)*	P	P	N	N
Ribwort plantain *(Plantago lanceolata)*	P	N	G	A
Kidney vetch *(Anthyllis vulneraria)*	N	N	A	A
Birdsfoot trefoil *(Lotus corniculatus)*	N	N	N	N
Black knapweed *(Centaurea nigra)*	G	A	N	N
Ox-eye daisy *(Leucanthemum vulgare)*	G	G	N	P
Grasses	Formed a dense mat up to 0.5 m high			

Survival index
G = good
A = average
P = poor
N = nil

[2] The survival rates should be viewed in the context of the fairly limited numbers of plants used in the study. Thus the failure of a relatively small number of plants can have a marked influence on overall survival rates.

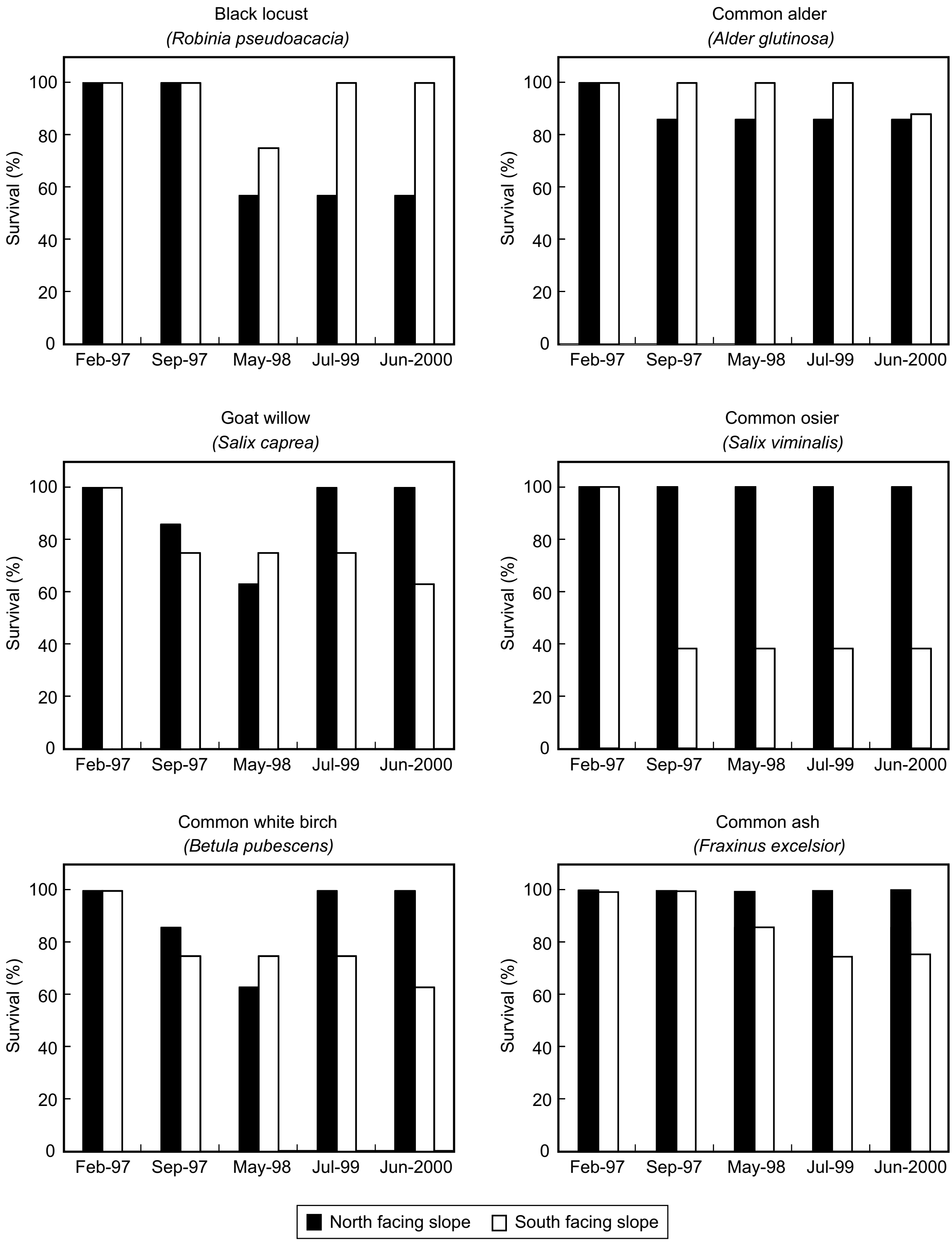

Figure 4.9 Tree survival rates

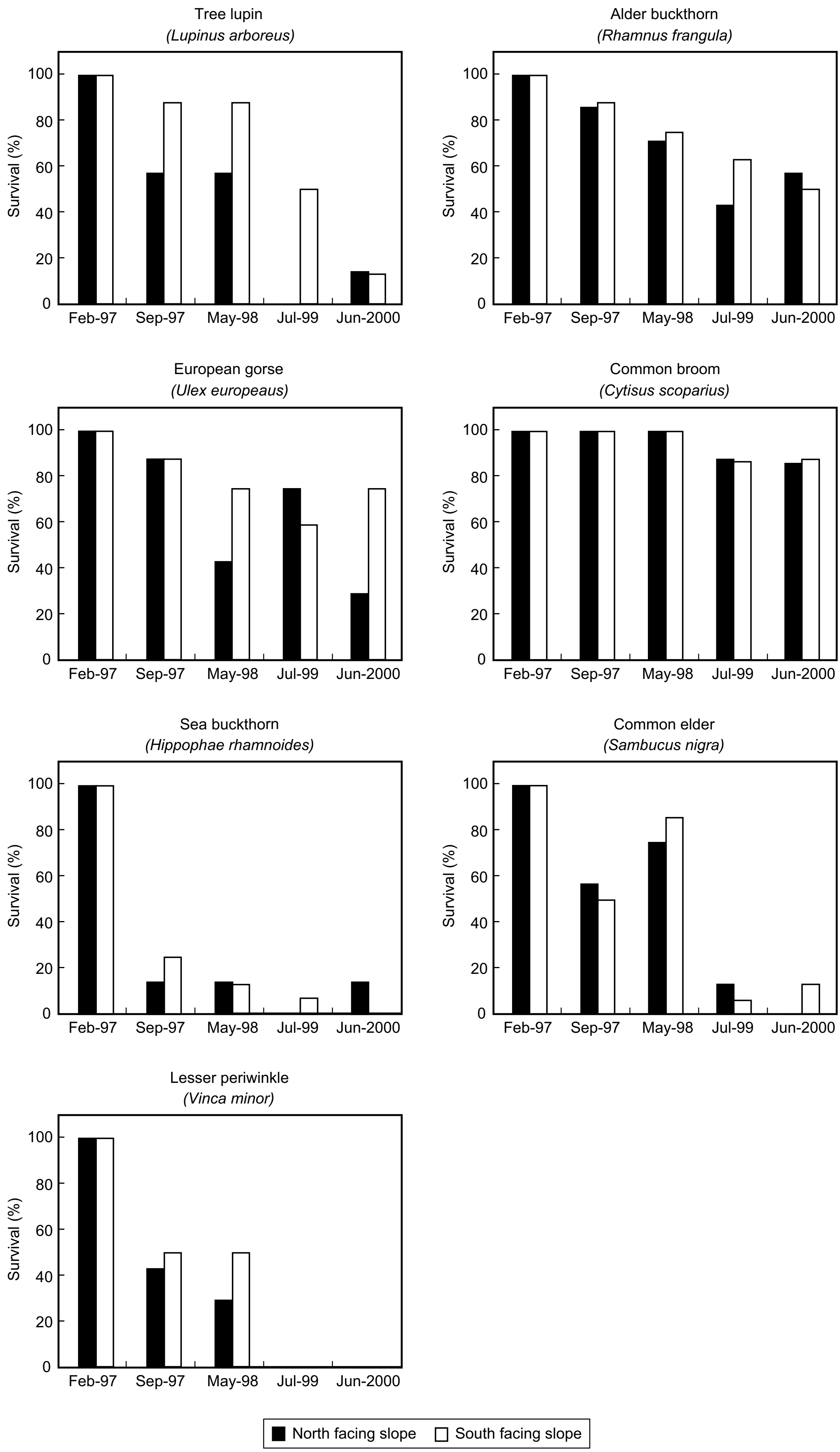

Figure 4.10 Shrub survival rates

Trees

From Table 4.3(a) it can be seen that the trees were more successful in establishing themselves than the shrubs. By June 2000, some 3 years and 4 months after planting, 77 per cent of trees had survived compared to 31 per cent of the shrubs. The trees showed a decline in numbers in the early stages of the trial but have since recovered slightly; the shrubs, on the other hand, have declined continuously since planting. The effect of slope orientation on the survival rate of the vegetation is shown in Table 4.3(b). For the trees, the survival rate was greater on the north facing slope, whereas the shrubs showed slightly higher survival rates on the southern slope (although in June 2000 the survival rate of shrubs on the southern slope was still only about half that of the trees on the same slope).

Figure 4.9 shows the survival rates for each of the six tree species. In June 2000, four species showed a 100 per cent survival rate on the northern slope but lower survival rates on the southern slope; these included *Salix caprea* (Goat willow) and *Betula pubescens* (Common white birch), the two trees selected for long-term growing trials by the MLURI. *Salix viminalis* (Common osier) declined to 38 per cent on the southern slope by September 1997 and never recovered. This tree may have been adversely affected by the combination of a very dry spring after planting and the southern aspect. *Alder glutinosa* (Common alder) survived reasonably well throughout the trial, exhibiting a survival rate of over 80 per cent on both the north and south facing slopes in June 2000. *Robina pseudoacacia* (Black locust) differed from the other species in that all of these plants on the southern slope survived while plant numbers on the northern slope declined to less than 60 per cent by May 1998 and never recovered.

It is interesting to note that several tree species showed an initial decline in numbers up to May 1998, but recovered during the trial (for example, the Goat willow and Common white birch on the northern slope, and the Black locust on the southern slope). This trend was due to both the recovery of individual plants that had initially shown signs of deterioration, and to the growth of new plants. The data show that an apparent early decline in plant numbers need not represent an irrevocable failure of the vegetation.

Shrubs

Although the shrubs as a whole had fairly low survival rates, Figure 4.10 shows that the *Cytisus scoparius* (Common broom) survived relatively well on both the north and south slopes. Again this was one of the shrub species selected for the long term growing trials at MLURI. Four of the shrub species performed particularly poorly, declining to less than 20 per cent or dying out altogether by June 2000; these included *Lupinus arboreus* (Tree lupin) and *Hippophae rhamnoides* (Sea buckthorn), the two remaining species selected for the MLURI growing trials.

Perennials

Table 4.4 shows that the perennials did not perform well and exhibited low survival rates by as early as September 1997; again the high failure rate could be due to the dry spring of 1997. By June 2000 only *Plantago lanceolata* (Ribwort plantain) and *Achillea millefolium* (Yarrow) showed good survival rates on at least one of the slopes, but again it should be noted that these had appeared to be deteriorating to a greater extent in the earlier survey.

Mean heights of trees

The mean heights of the various tree species in June 2000 are shown in Figure 4.11[3]. Because the various species grow at different rates there is little to be gained from comparing the mean heights of different species as a means of assessing their relative success. However, the effect of slope orientation on the growth of individual species can be examined. Table 4.5 compares the mean heights of each tree species on the north and south slopes of the embankment in June 2000. Although there were marked differences in the mean heights of some species, the data do not fit well with the patterns of survival rates described above. For example the mean height of Black locust on the north slope was some 20 per cent higher than

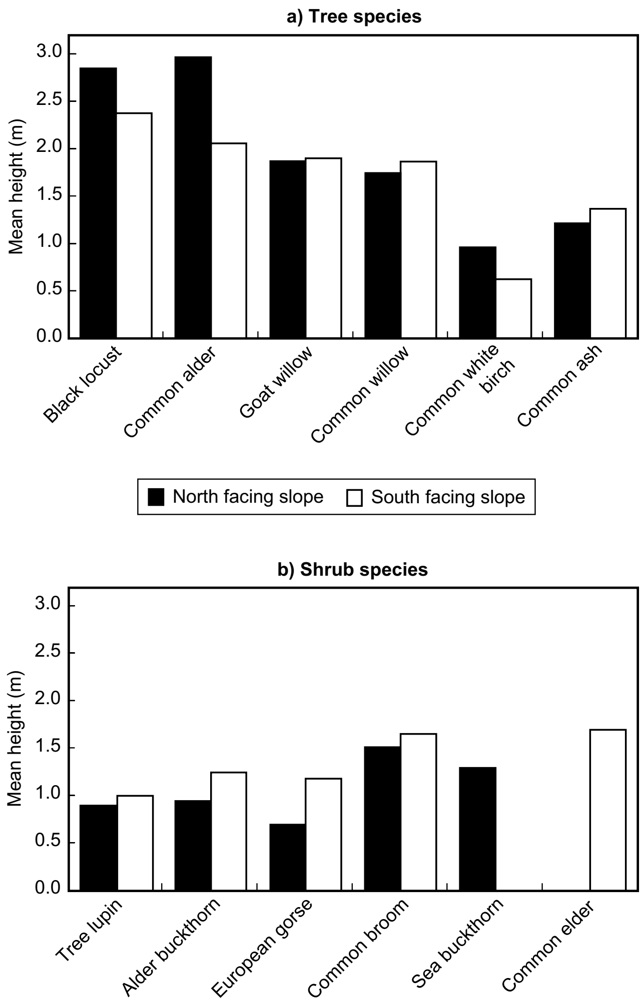

Figure 4.11 Mean heights of trees and shrubs, June 2000

[3] *As stated in Section 4.4.1, when first planted all of the tree species were pruned to the same height of 0.3m.*

Table 4.5 Mean height of tree species (June 2000)

Tree species	Mean plant height (m) North slope (N)	South slope (S)	N/S
Black locust *(Robinia pseudoacacia)*	2.85	2.37	1.20
Common alder *(Alder glitinosa)*	2.97	2.06	1.44
Goat willow *(Salix caprea)*	1.87	1.90	0.98
Common osier *(Salix viminalis)*	1.74	1.87	0.93
Common white birch *(Betula pubescens)*	0.96	0.63	1.52
Common ash *(Fraxinus excelsior)*	1.21	1.37	0.88

on the south slope, yet less than 60 per cent of the trees planted on the north slope survived whilst there was a 100 per cent survival rate on the south slope. The mean height of Common alder was 44 per cent higher on the north slope, but survival rates were about the same for both the north and south slopes. The Common white birch did exhibit some correlation between mean height and survival rate but the Common ash did not. Thus, for this particular site, the growth rates of plants on the north and south slopes (as expressed through the mean heights) did not provide a good measure of the relative success of individual species within these environments.

4.6.3 Pore water pressures

Tensiometer readings were taken from March 1997 (one month after planting) up to January 2001. The data are shown for four depths within the embankment in Figures 4.12 and 4.13 for the north and south facing panels respectively. As all of the pore pressures were negative, the relations are presented in terms of suction against time.

Although there were variations in the measured suctions at different depths and under the various planting schemes, the data clearly show seasonal trends in pore pressures within the embankment. Suction increased during the summer months, when temperatures are higher and the transpiration rates of plants are at a maximum, and generally attained a peak value during the late summer/ early autumn. Thereafter suction decreased (sometimes quite rapidly) with the onset of the late autumn and winter periods when greater levels of rainfall infiltrated the embankment and the vegetation became dormant. Similar trends were reported by Crabb *et al.* (1987) for a Gault Clay embankment near Cambridge.

It is possible to discern the effects of the climatic characteristics of particular seasons on the suction within the embankment. In 1998, 1999, and 2000, the suctions generally followed the pattern described above, i.e. they began to increase during May or June, reached a maximum between the end of July and early September before declining again by about the end of October. However, in the first spring after planting (1997) the data, although more variable, showed a distinct increase in suction from as early as April, with some of the instruments then beginning to detect falling suctions during the summer months. This was probably not related to the effects of the vegetation (which had insufficient time to become established) but was more likely due to the exceptionally dry spring in that year, which was followed by an exceptionally wet summer (see Table 4.2). Similarly, the rapid decrease in suction at all levels within the embankment during the autumn of 1998 can probably be attributed to the fact that rainfall was almost 60 per cent greater than the average over this period.

The data show that, once established, vegetation can have a marked effect on the pore pressures within an embankment. For example on the northern slope the tensiometers located under the trees and shrubs generally recorded higher suctions than those located under the grassed control panel during the last three summers of the study. However, during the first summer after planting, when the root systems of the vegetation would have been less extensive, the differences between the planted and control sections were less marked. On the southern slope, the suctions beneath the trees and shrubs were again greater than under the control section, but the difference was less apparent than for the northern slope. This was probably due to a combination of lower survival rates amongst trees on this slope (and the generally poor survival rate amongst shrubs) and greater drying out of the surface soils due to the southerly aspect.

The suctions under the different planting schemes for each of the four depths within the embankment are shown in Figures 4.14 to 4.17. At a depth of one metre (Figure 4.17) it might be anticipated that trees and shrubs would generate greater suctions than perennials and grasses because of their greater root penetration, and also because they are more able to intercept rainfall and remove moisture through transpiration. This was indeed the case for both the north and south facing slopes during the summers of 1999 and 2000 but the pattern was less clearly defined in 1997 and 1998. During the first two summers the measured suctions under the shrubs were greater than under the trees on both the north and south panels. The suctions under the trees were similar to, and in some cases lower than, the perennials and grasses. Data from the tensiometers at shallower depths (see Figures 4.14 to 4.16) show that the trees were generating suctions at this stage and thus the low suction values at a depth of one metre may reflect the time taken for the tree root systems to penetrate to depth. Interestingly, the tensiometer data for each depth within the embankment suggest that the shrubs were able to generate suctions at least as soon as the trees but, once established, greater suctions were measured under the latter.

The suctions measured under the perennials and grasses at a depth of one metre during the summers of 1997 and 1998 were similar to those under the shrubs and trees but by 1999 and 2000 the suctions under the former were relatively low during the summer periods. Several factors may account for this pattern; the construction process can create suctions within an embankment fill which reduce over time as water infiltrates the soil. The exceptionally dry spring of 1997 would have helped to maintain or enhance these suctions at depth. However, the summer of 1999 and the spring of 2000 were very wet, leading to a wetting up of the fill, particularly under the grasses and perennials which were less able to remove water from depth. In addition, Table 4.4 shows that the perennials were deteriorating throughout the

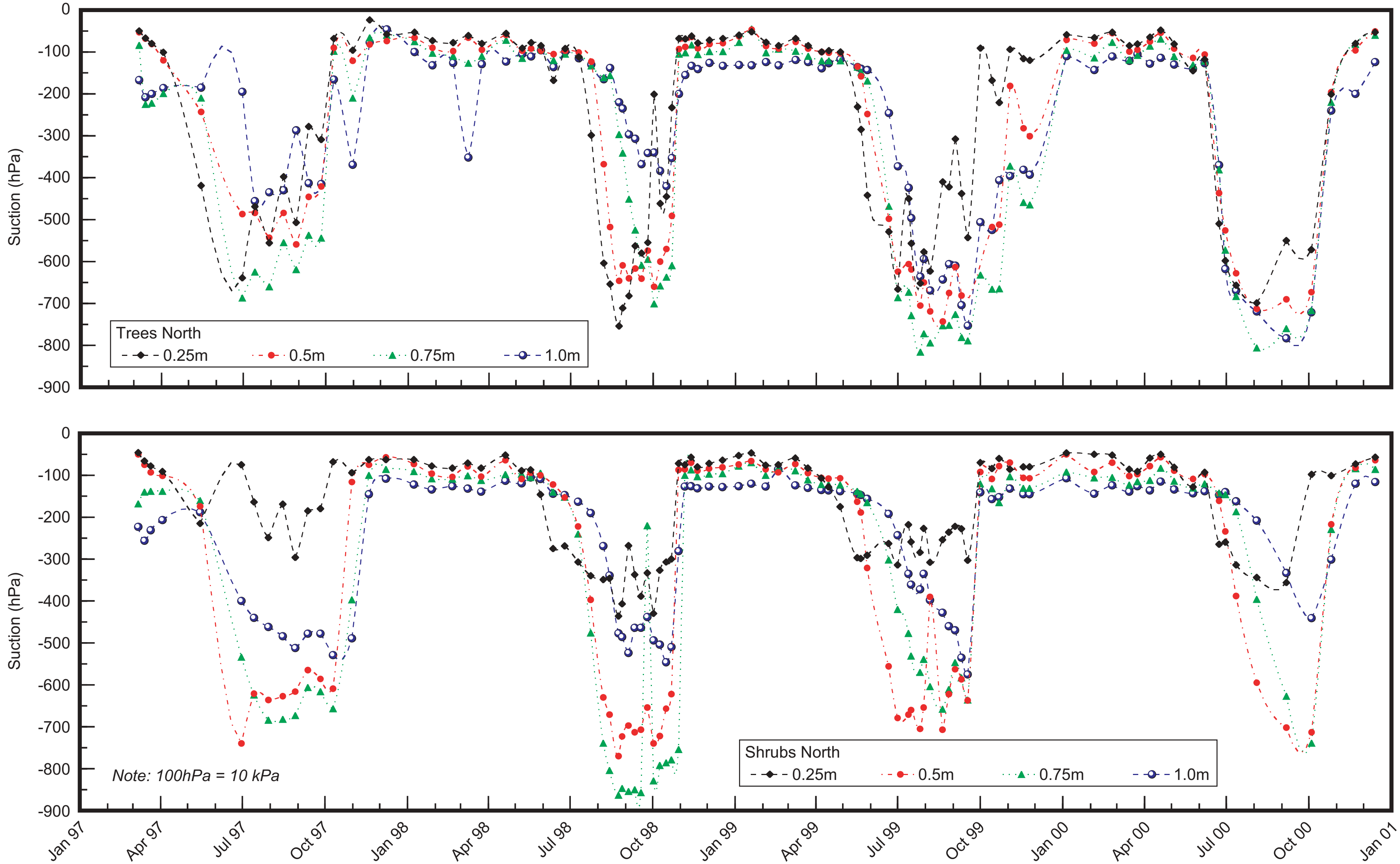

Figure 4.12a Tensiometer data for trees and shrubs on North slope

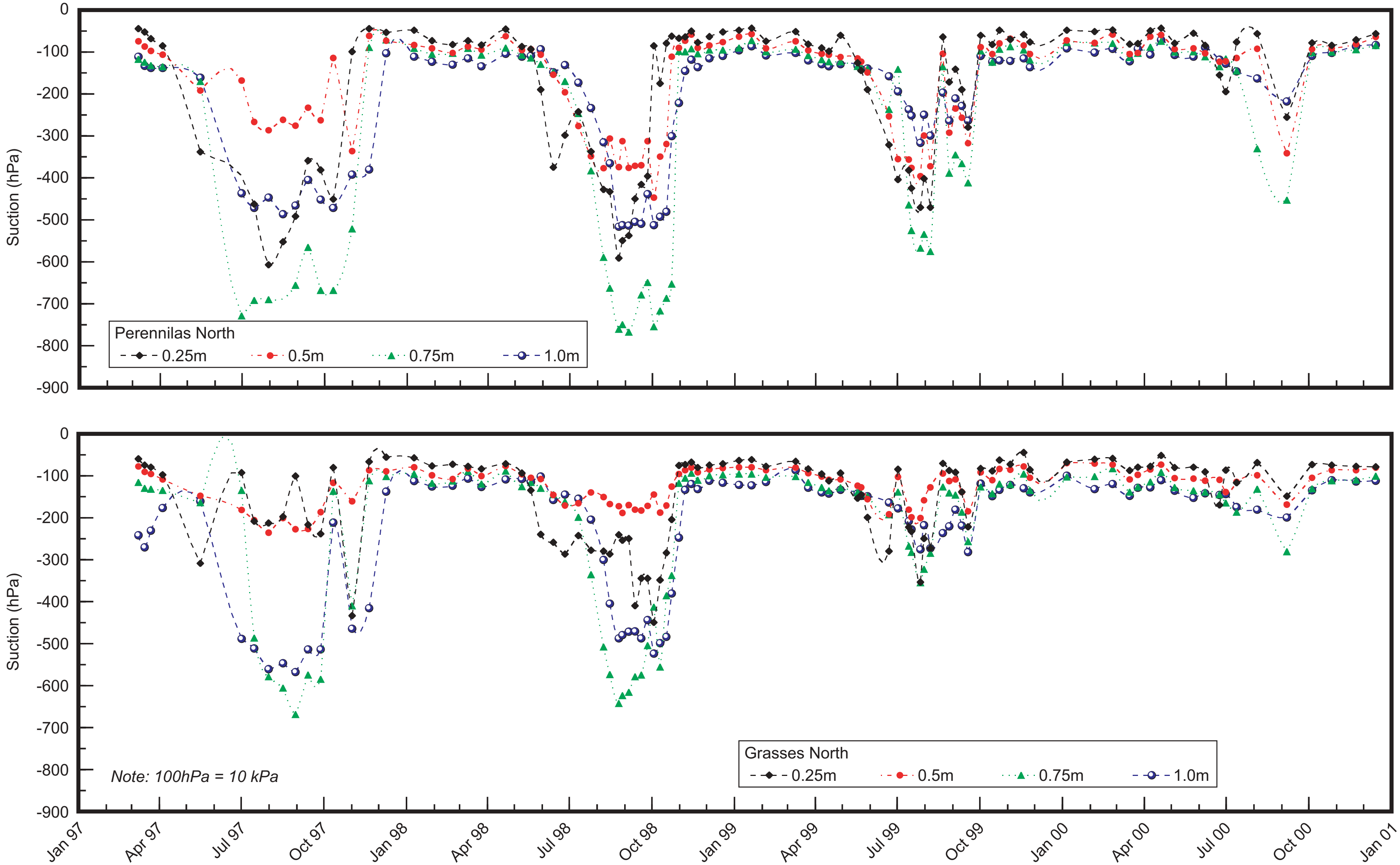

Figure 4.12b Tensiometer data for perennials and grasses on the North slopes

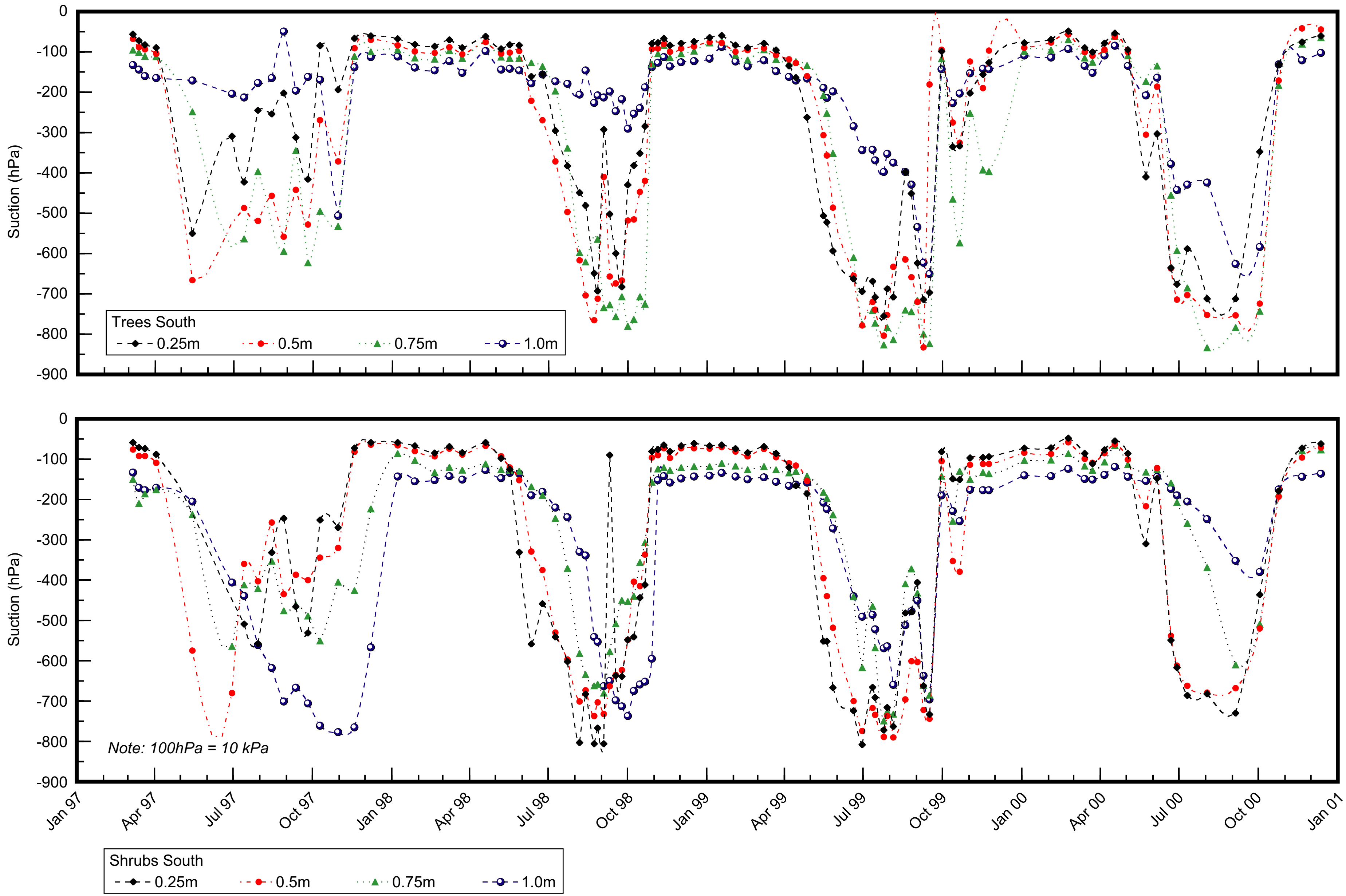

Figure 4.13a Tensiometer data for trees and shrubs on South slope

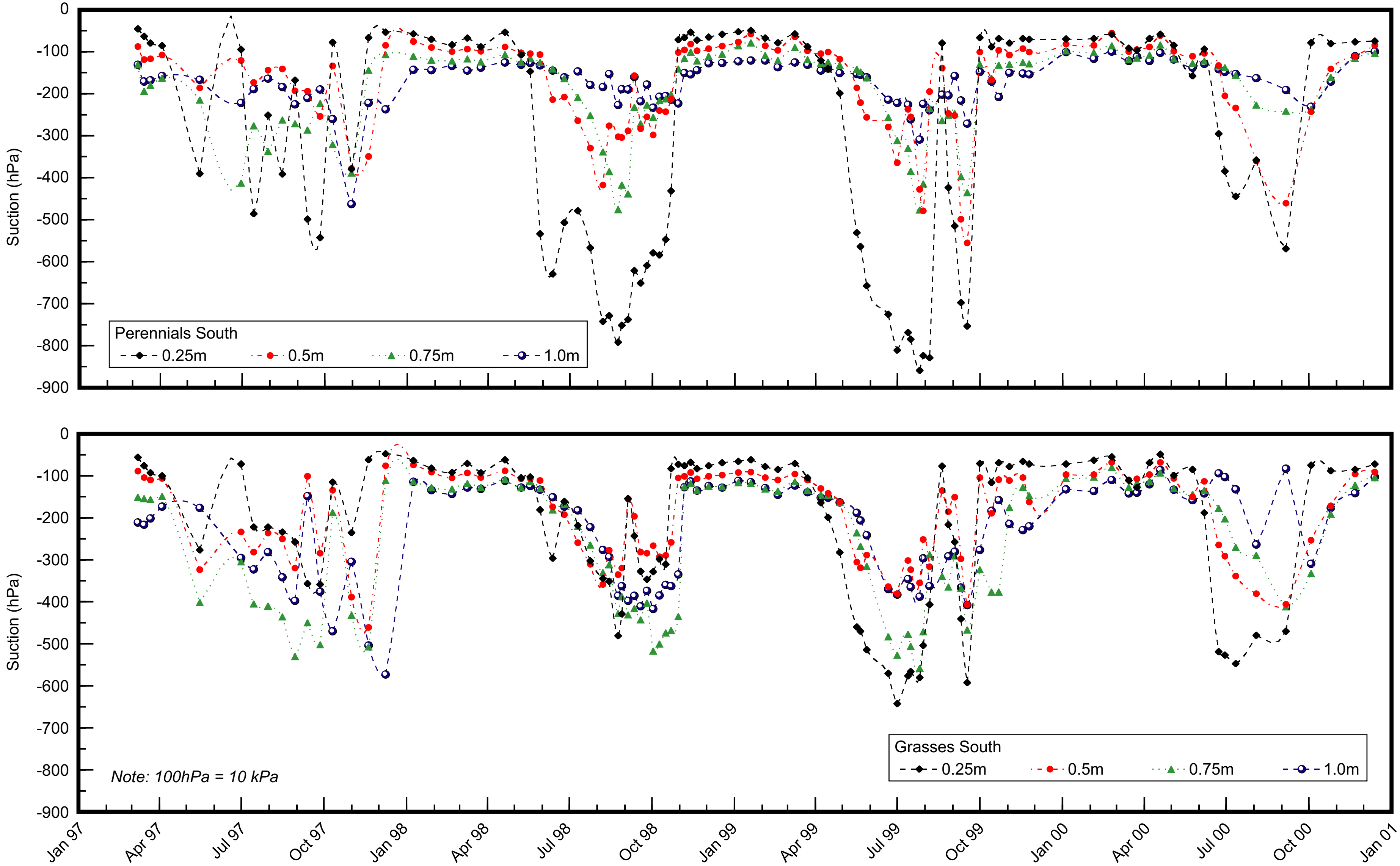

Figure 4.13b tensiometer data for perennials and grasses on South slope

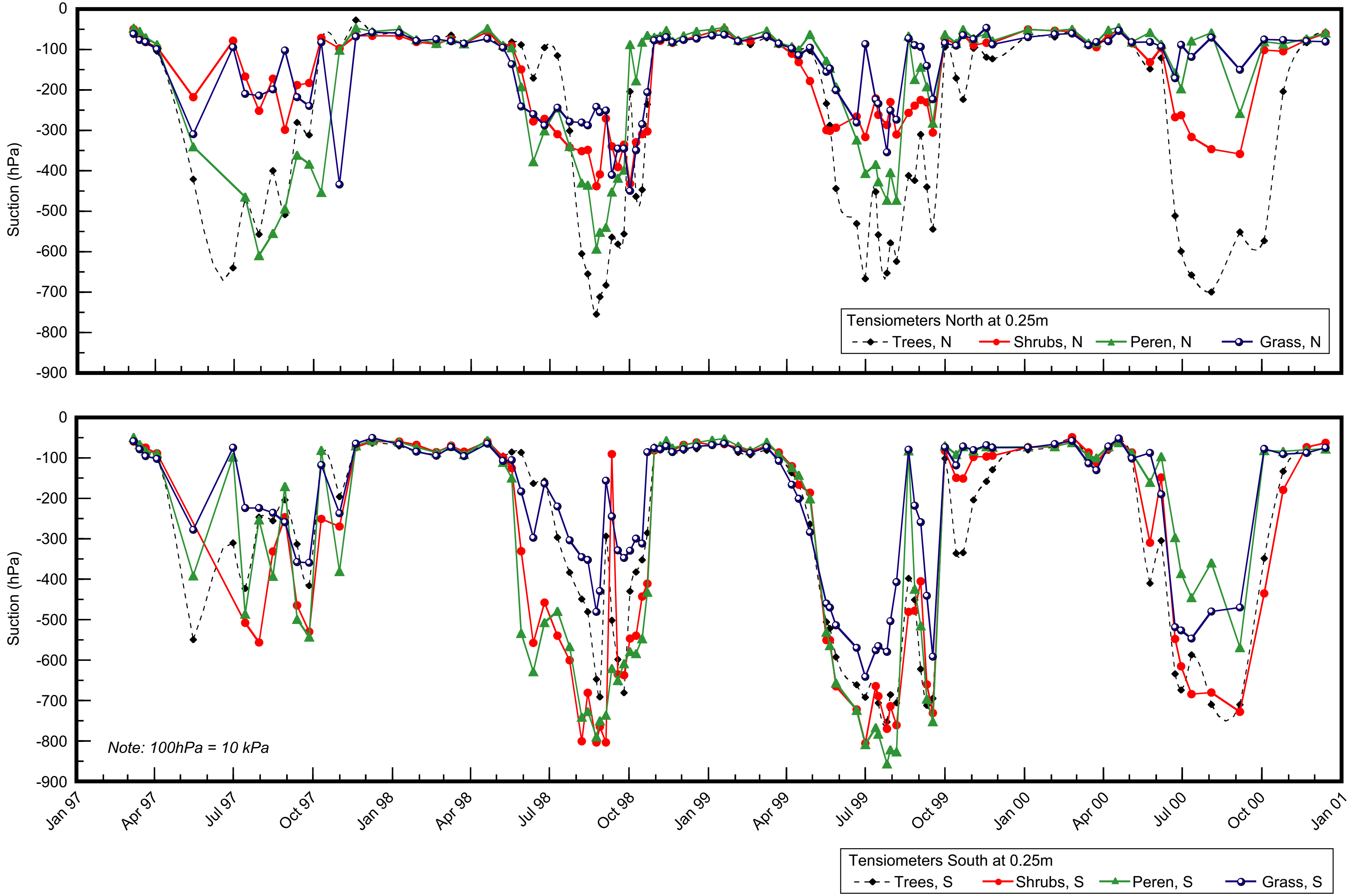

Figure 4.14 Tensiometer data for North and South slopes at 0.25m

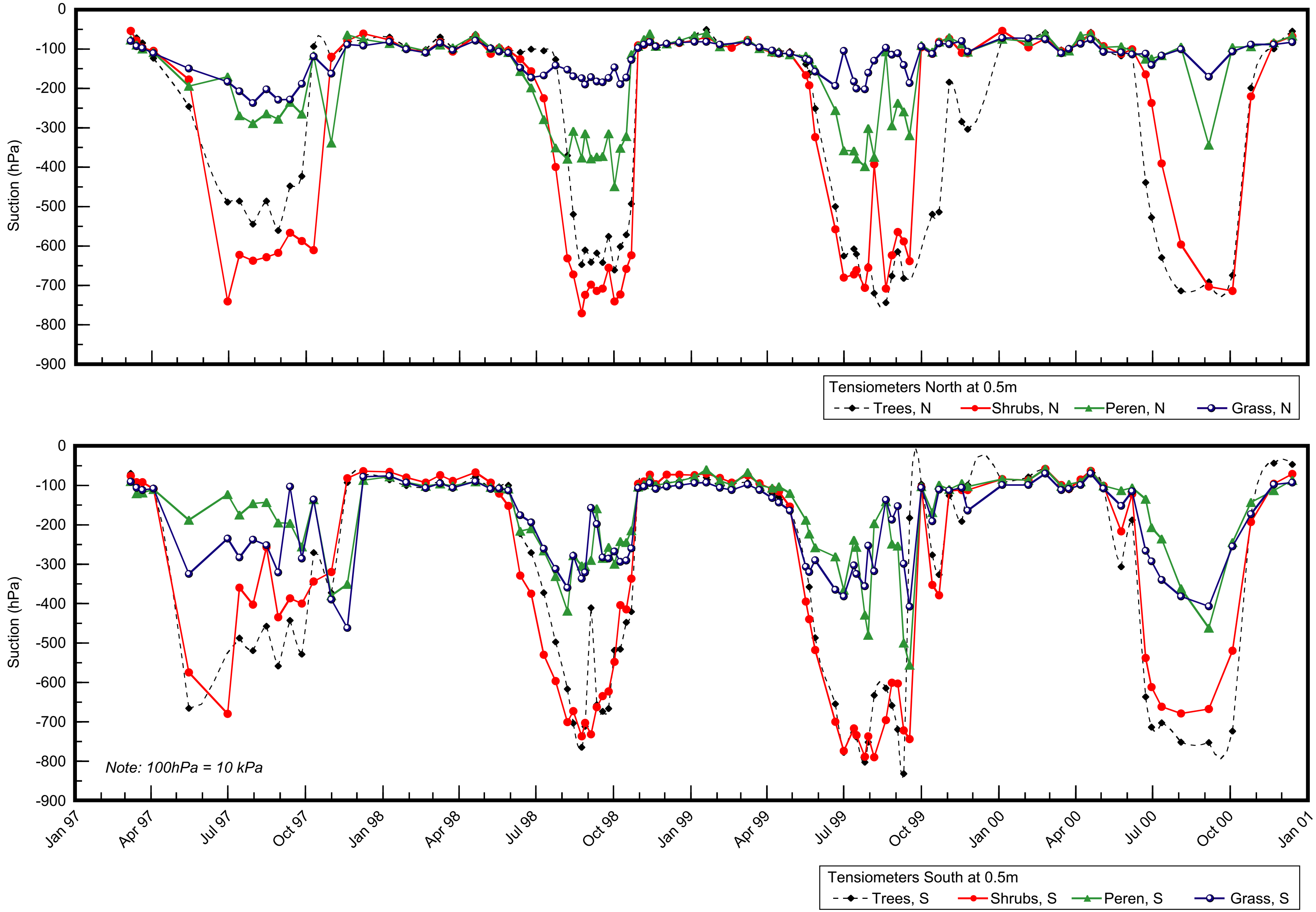

Figure 4.15 Tensiometer data for North and South slopes at 0.5m

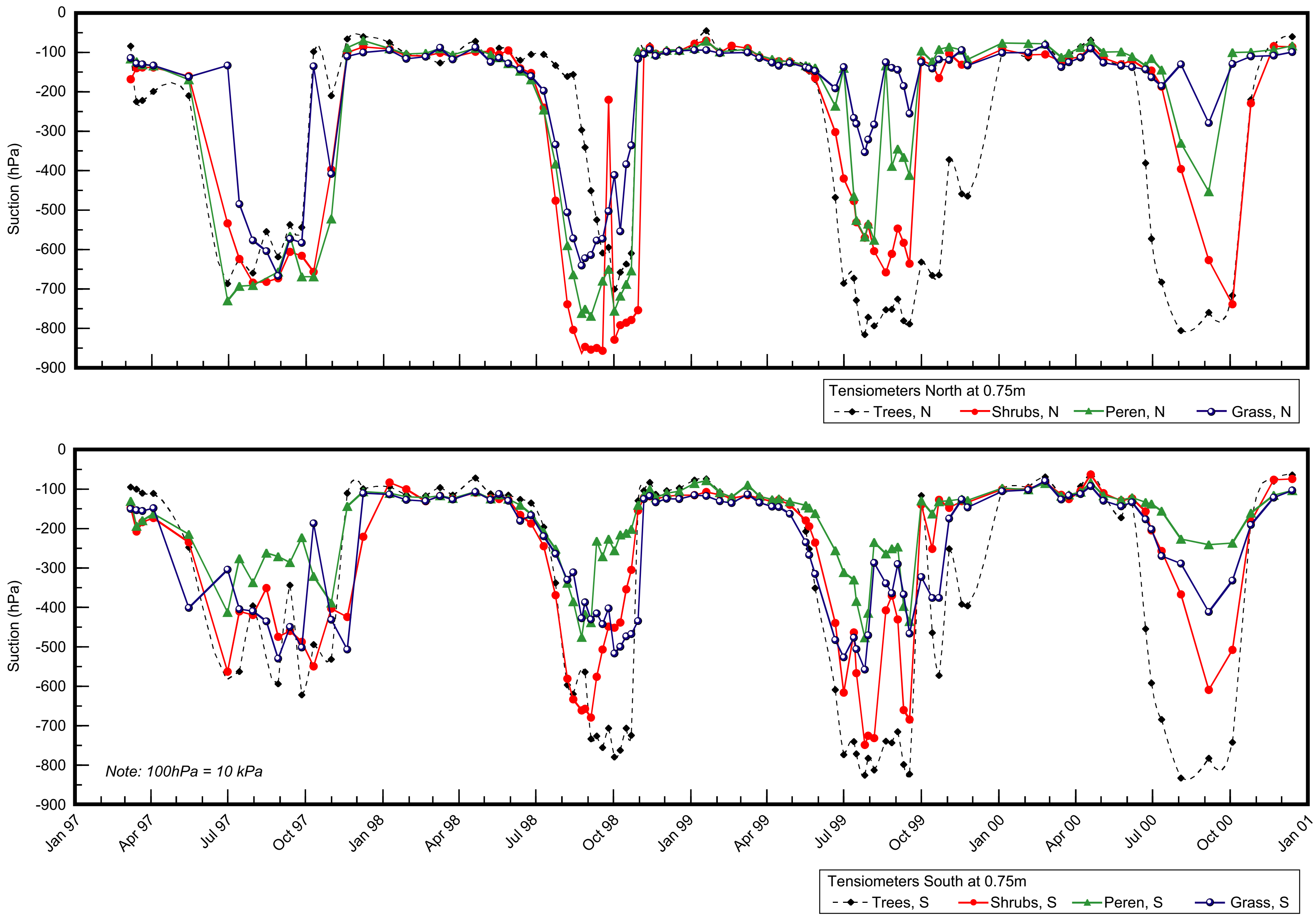

Figure 4.16 Tensiometer data for North and South slopes at 0.75m

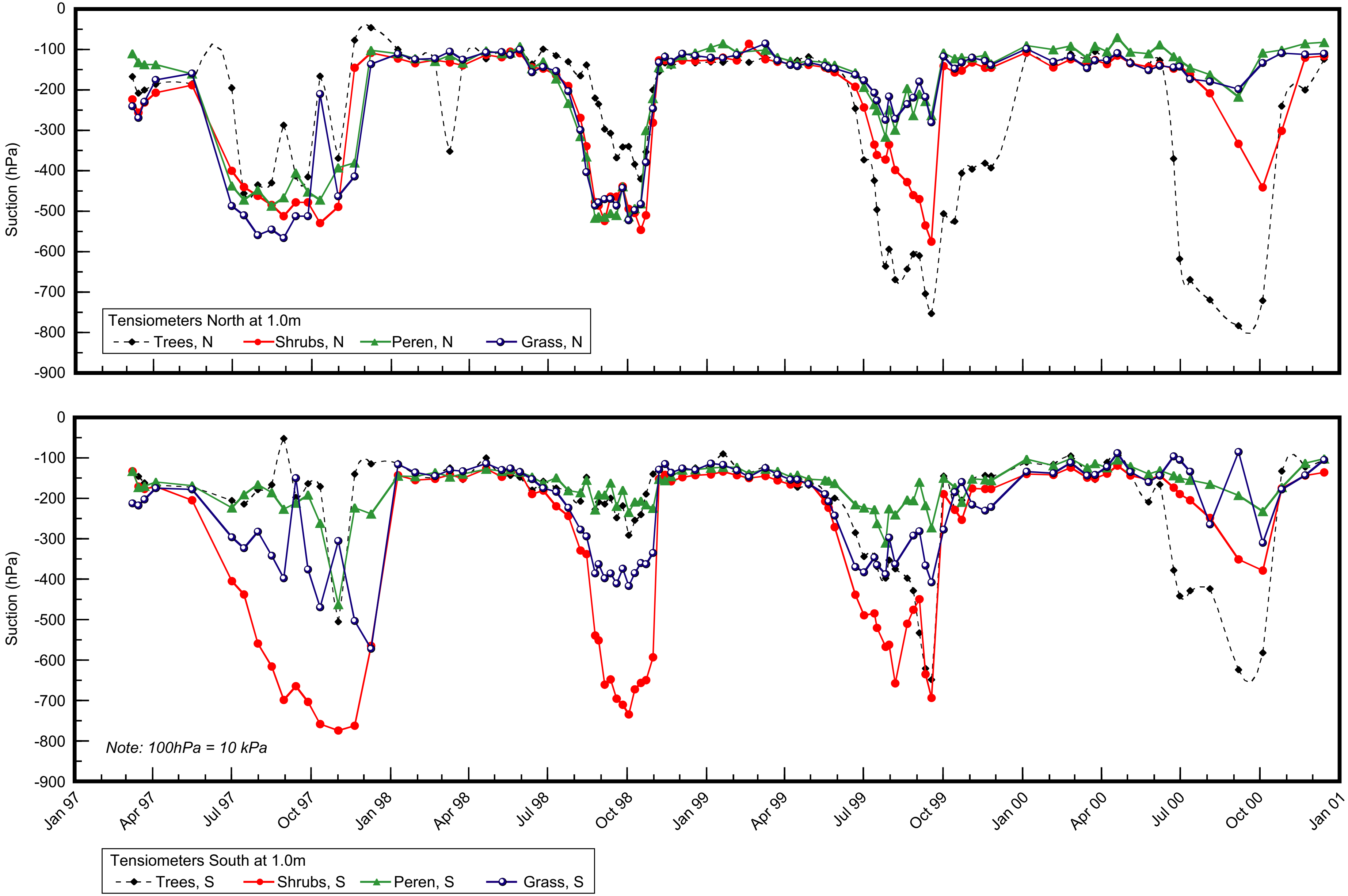

Figure 4.17 Tensiometer data for North and South slopes at 1.0m

course of the study, which would have further reduced their soil moisture depletion capabilities. In contrast the trees, which showed good survival rates, would gradually have established deeper and more extensive root systems and were therefore able to generate suctions at depth, even after the very wet spring of 2000.

The tensiometer data for a shallower depth of 0.5m showed that suctions beneath the trees and shrubs were of a similar magnitude and almost always greater than under the perennials and grasses throughout the trial. The effect of slope orientation in the tensiometer data can also begin to be discerned at this depth; the suctions under the perennials and grasses on the south slope were larger than under the same species on the north slope during the summer of 2000. This is considered to reflect the warmer, sunnier conditions of a southerly aspect. The same effects were slightly more pronounced at depths of 0.25m.

Although the results of this growing trial have shown that vegetation can reduce pore water pressures within a slope, the data show that suctions are low from about the middle of autumn to the end of spring, during the period when plant metabolic activity and transpiration rates are low. Although bud burst occurs in spring and the moisture demand of the vegetation increases, the tensiometers did not, in most cases, register marked increases in suction until June. Rainfall tends to be at a maximum between late autumn and spring and, as reported by Coppin and Richards (1990), many shallow slope failures occur in spring. Thus the data obtained in this study confirm the view of Coppins and Richards that, during the most critical period for slope stability, the reinforcing action of vegetation is probably more important than its soil moisture depletion potential.

4.7 Recommendations

The construction of the trial embankment provided a typical highway earthworks slope which enabled a long-term study of the growth of vegetation, and its effects on the stabilisation of shallow slopes constructed using over-consolidated clay fill. To date, the results have shown that vegetation can play an effective role in reducing pore water pressures within the embankment fill, thereby enhancing slope stability. The suctions generated under panels planted with trees and shrubs were generally higher and generated to greater depths than those planted with perennials or grasses. In terms of survival rates, the trees performed better than the shrubs and perennials on both the north and south facing slopes and thus may also be preferred for aesthetic reasons as well as their soil moisture depletion capacities.

The trial also showed that the suctions generated by the vegetation varied seasonally, with low suctions being measured under all vegetation types during the period from late autumn to late spring, when earthworks slopes are more vulnerable to failure. (Again this suggests that the planting of trees and shrubs would be preferable to perennials or grasses because the former started to remove water from the embankment marginally earlier in the spring than the latter.) Nonetheless, it is likely that during the wetter seasons the stabilising effect of vegetation will be due to the reinforcement action of the roots rather than soil moisture depletion and thus factors such as the rate and extent of root growth (as well as moisture demand) will influence the selection of plant species.

The five species selected by MLURI (see Section 3) were also evaluated during the embankment trial. The two trees (*Salix caprea and Betula pubescens*) survived well, particularly on the northern slope, but of the three shrub species only *Cytisus scoparius* (Common broom) flourished under these particular site conditions.

5 Use of vegetation reinforced steepened slopes in highway schemes

5.1 Introduction

Over recent years, the requirement for motorway widening has led to an application of vegetation reinforced steepened slopes. This has allowed the steepening of existing earthworks slopes, up to 70°, to accommodate extra carriageway lanes within the existing motorway land corridors. Whilst the use of these types of construction is significantly cheaper than hard structures, eg. concrete faced, evidence of their early life performance shows a wide range of success and failure in the establishment of vegetation.

Data collected from a survey, and subsequent site visits, have been analysed to identify any structural and aesthetic problems with these techniques, and to compliment the data obtained from the TRL trial embankment.

5.2 Survey of slopes

The survey was based on the use of vegetated reinforced slopes incorporated in HA schemes and the data were obtained through the Agency’s Technical Services Division (Environmental Branch) at Bristol. Selected site visits were then made and discussions held with consultants, contractors and manufacturers.

The response illustrated a wide range of success with vegetation establishment and short-term growth on the slopes; the oldest slope reported was less than 10 years old, and the majority had been vegetated for less than 3 years. Slope angles varied between 22° and 80° with the slopes facing to all points of the compass. Whilst a few schemes included shrubs, grass was the primary vegetation used. The grass was placed, mainly by hydroseeding, and success varied from good (95% cover) to virtually no grass and only weeds. The survey highlighted the variability in the causes of success or failure of the vegetation: virtually every slope performed differently. However, the primary causes of failure were attributed to a lack of water and a southerly facing slope. The survey also identified concerns about long-term maintenance issues, mainly to do with access on the steeper slopes.

5.3 Types of construction

In relation to their requirements for vegetation, reinforced slopes fall into two basic types. Firstly, those constructed with biodegradable wrap-around facings which rely on the successful establishment of vegetation to provide some degree of reinforcement within the facing soil to prevent wash out and erosion. Secondly, systems which employ either permanent geosynthetic reinforcements and only require vegetation to provide ultra-violet radiation protection, or those with an open steel mesh and man-made geotextile backing. But all systems also require vegetation for an aesthetic appearance. Examples of typical facing constructions of proprietary systems are shown in Figure 5.1.

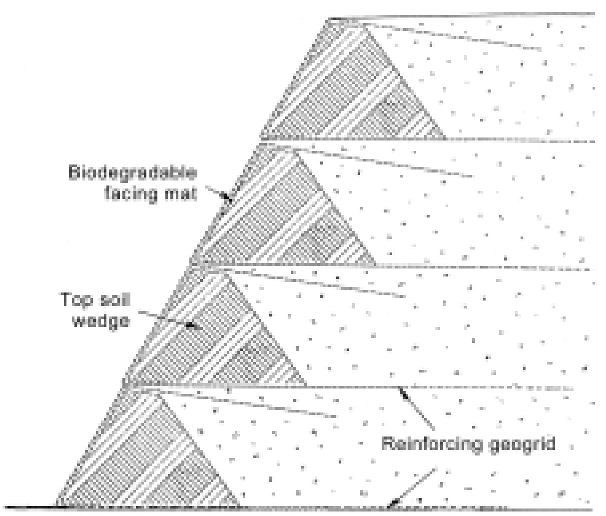

Figure 5.1a Construction using wrap-around reinforcing geogrid with biodegradable mat backing

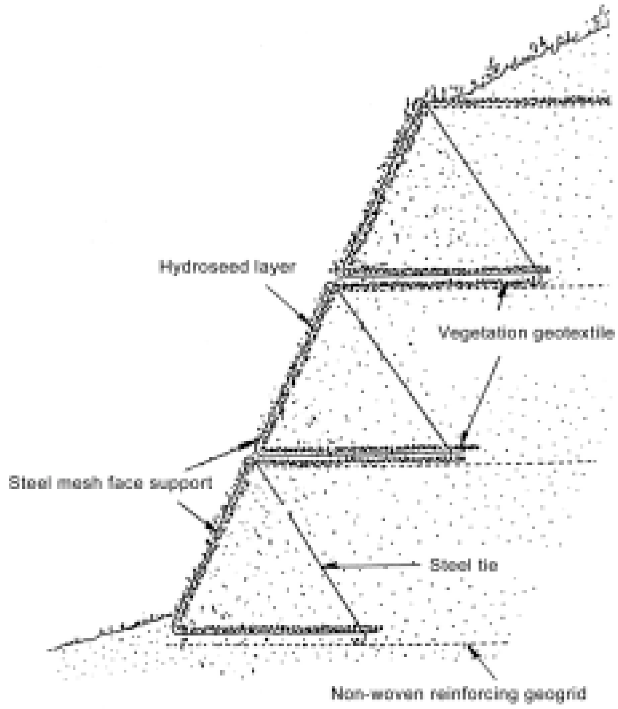

Figure 5.1b Construction using steel mesh face support with a synthetic backing

5.4 Reasons for vegetation

The side slopes of cuttings and embankments are generally shallower than 1 in 2, about 27°, and are covered with approximately 150 to 300mm of top soil (HA 44, DMRB 4.1.1). It has long been recognised that vegetation can play an important role in the prevention of shallow slip failures on such slopes: it can provide tensile reinforcement to the soil through its root structure, lower the *in situ* moisture content, reduce the pore water pressure in the soil mass and prevent rainfall erosion of the soil surface.

With steeper reinforced slopes, where the slope face is often at an angle of between 60° and 69°, the successful establishment of vegetation can be difficult in what can be a hostile micro-climate. The lack of available moisture is the primary problem in establishing and maintaining growth: this can be contrasted with the use of vegetation to remove excess moisture in flatter slopes to prevent shallow slips. Containment of the top soil on steep slopes is often reliant upon some form of geotextile. If this geotextile is biodegradable (biomat), e.g. woven jute, the vegetation will need to take over the role of the geotextile in preventing face erosion. Successful establishment of root structures will then be essential in the relatively short-term (i.e. about three years) for the vegetation to become effective in engineering terms.

If non-biodegradable geotextile is used as reinforcement, the vegetation is only required to provide long-term ultra-violet protection and an aesthetic finish. In such cases, it is unlikely there would be any form of structural failure in the long-term if the vegetation died. This should also apply to systems incorporating steel mesh for facing reinforcement, or as a sacrificial formwork.

5.5 Discussion

Vegetation is used on earthwork slopes to enhance stability against shallow failures by a combination of root reinforcement and removing moisture from the soil through transpiration, thus reducing pore water pressures. During establishment, the vegetation relies on a supply of moisture within the top soil which is mainly the consequence of rainfall onto the face of the slope. However, for steeper reinforced slopes, significant run-off of the rainfall will restrict moisture accumulation in the soil. Furthermore the effects of desiccation within the top soil often reach between 0.3 and 0.5m on a south facing slope during the summer months. In addition to creating a major problem for plant establishment and prolonged plant growth, drying out of the soil through desiccation can also produce a gap between the surface of the top soil and the back of the facing material: this is particularly likely with systems that use relatively stiff facing materials. This effect can lead to problems with effective hydroseeding, particularly on south facing walls; the seeds adhere to the outside of the facing but are isolated from any water supply, thus inhibiting germination. It has been observed that hydroseeded walls with facings incorporating fabrics made of natural materials are more successful than those with finer woven manmade materials. This is thought to be associated with the much higher water holding capabilities of natural materials (Rickson, 1988). In some instances the combination of the finer, and somewhat stiffer, manmade materials and the hydroseed mixture have resulted in a virtually impermeable barrier, thus creating a surface that enhances rainfall run-off and prevents any moisture penetration through the face.

Systems using only biodegradable facing materials rely totally upon the successful establishment of vegetation to prevent face erosion when the containment role of the facing material has degraded. Whilst no structural failures of these systems have been recorded to date, progressive erosion of the soil in the face could lead to failure in the longer term.

For reinforced slopes using non-biodegradable geogrids, the vegetation will only be required to cover the facing material to provide a greening effect and to act as a screen against ultra-violet radiation. Clauses 9.2.5.3 and 9.3.4.1.3 of BS 8006 (BSI, 1995) refer to the role of vegetation in reinforced soils and the requirement for UV protection. Geogrids used for reinforced earth structures, which contain carbon black to assist in UV protection, are subject to restrictions regarding UV exposure and SHW Clause 609.3 (MCHW 1) states that temporary exposure shall not exceed 5 hours. However it is debatable to what extent any reduction in the tensile strength of the geogrids would affect their ability to contain soil within the wall face and long-term exposure to low levels of UV is probably unlikely to reduce the strength to the extent that facing failure occurs. Figure 5.2 shows an eight year old south facing reinforced 80° slope, constructed with a geogrid facing, which currently exhibits no sign of structural distress, although the previously established vegetated cover has died back (Duffin, 1989).

The use of plant species and planting schemes designed specifically for long-term UV protection and aesthetic use could be considered. Rather than trying to grow vegetation on the entire surface of the facing, climbing and rambling broad leaved species (preferably evergreen such as ivy) could be planted in pockets or on small benches along the horizontal interfaces between the layers of the reinforcing geogrid. This approach, combined with planting at the top of the slope to produce a curtain effect over the slope face, could prove a more reliable long-term solution. A trial reinforced noise bund, which after twenty years has been covered with self-seeded ivy, is shown in Figure 5.3 to illustrate this effect. In contrast, Figure 5.4 shows a two year old south facing wall which has been hydroseeded twice, where the only vegetation growth occurs at the interface between the reinforced layers, thus indicating the presence of some available moisture.

European structures often employ vegetation planted at these interfaces (Schiechtl and Stern, 1996). An illustration using woody vegetation on a gabion wall is also given in HA 56 (DMRB 10.1.2). On the Frejus Torino highway, willow cuttings were placed between the reinforced layers of a 20m high wall to ensure a stable vegetation cover in drought conditions (Fantini and Roberti, 1996). Ruegger (1986) describes a reinforced soil trial wall in which a combination of hydroseeding and bush layers were successfully used on a south-west facing slope. A similar approach, of using top planting, may also be applicable for visually softening hard faced (concrete) structures.

Timing of construction events can significantly affect the establishment of vegetation. The cutting back of existing earthworks slopes and subsequent construction of the steeper reinforced slopes generally takes place early in the construction to allow the carriageway widening. This can often be in conflict with the planting period for general earthworks, which tend to be planned for the first planting season after the road has been opened to traffic (Sangwine, 1996). Access for hydroseeding and planting can often be made available towards the end of the construction period, which may be many months after forming the slope, and may occur at a time that is outside the hydroseeding periods and not ideally suitable for planting. Hydroseeded seeds, although mulched, only have a limited period of protection and are vulnerable to surface drying (Coppin and Stiles, 1995). Incorporating the grass seeds, or seeds of other plant species, within the top soil at the time of placement may help to overcome this problem. Figure 5.5 shows an unplanned demonstration of this technique which occurred on a length of north facing wall on the M25 which had been totally covered in poppies and daisies: the seeds were unknowingly included within the imported top soil. It is also probable that the abundance of vigorous weeds seen on some walls resulted from seeds contained in the top soil in addition to some self-colonization (see Figure 5.6). In Norway a south-west facing 13m high reinforced wall, with a 60° slope, incorporating a 0.5m thickness of pre-seeded top soil was successfully vegetated (Vaslestad, 1996). The use of pre-seeded mulch mats or a turf lining behind a wrap around geotextile facing may also be considered as akin to pre-seeding.

Other factors such as the orientation of the slope face can influence the success or failure of vegetation on steepened slopes. A south facing slope would suffer more from desiccation effects than a north facing slope. Figure 5.7 shows the difference in vegetation growth between similar walls, and treatments, with southerly and northerly aspects. Effects of local hostile micro-climate should be considered, especially as these slopes are often located much closer to the carriageway than other earthworks. Persistent winds generated by high sided heavy goods vehicles, exhaust contaminants and de-icing salt spray during the winter will often prove detrimental to the vegetation (Colwill *et al.*, 1982). The use of indigenous plant species, particularly those growing within the local micro-climate, may be more suitable and provide better integration with the local environment. Drought resistant plants may have a better chance of propagating on south facing slopes. Barker (1990) gives a short list of plant species applicable for use in most regions of Britain and Meier (1997) has collated lists of plants used in Europe for a range of engineering applications: this includes plants for *front greening* of walls and salt tolerant plants. Contaminants within the top soil can significantly inhibit plant establishment and top soils should therefore be tested and conform to BS3882 (BSI, 1994). Greater top soil depths, possibly incorporating moisture retaining polymers or even industrial spillage absorbents made from calcined clays, in combination with slow release fertilisers, may be

Figure 5.2a General view of 8 year old 80° reinforced wall

Figure 5.2b Detailed view of geotextile on 8 year old 80° reinforced wall

Figure 5.3a Geotextile noise bund after construction in 1979

Figure 5.3b Self seeded ivy covering 20 year old noise bund

Figure 5.4 South facing wall demonstrating growth only at layer interfaces

Figure 5.5a Poppies growing from imported top soil containing seeds

required to counteract the effects of desiccation on the more vulnerable south facing slopes. In some cases, the as-dug materials used for general fill may provide a combination of granular and cohesive materials (which retain a degree of moisture) which can be used in the place of imported top soil.

Systems have been developed in Europe that employ pre-fabricated facing blocks varying in length from 2 to 6m (Rimoldi and Jaecklin, 1996). These use either steel gabions with a layer of pre-seeded top soil and compacted fill, or a triangular section using a steel mesh former and geotextile containing a turf face and fill, which can be constructed off-site and brought to site as required. Rigid box-like panels of soil, containing pre-seeded top soil, have also been designed for attaching to the heads of soil nails to provide vegetated cover to reinforced slopes (Shirley, 1995).

Long-term maintenance requirements should be considered for steepened slopes. Access to the steep facing for grass cutting and plant maintenance, particularly on high walls, may require incorporation of some form of wide benching for vehicle access and to allow personnel to work in safety. Damage to a geotextile during grass mowing must be avoided, as well as damage to the mowing equipment striking the steel mesh used in some systems. The use of ground cover plant species could reduce grass cutting requirements. The design of slopes which use a wall to steepen its lower part (eg. the first two metres), whilst the upper part is shallower so that vegetation is easier to maintain may be worth considering. This could be achieved within the same land-take as that required for a steepened slope.

Figure 5.5b Growth of poppies and daisies from imported top soil

Figure 5.6 Vigorous weeds from self-colonisation

a Good growth on a north facing wall

Repair techniques need to be developed both for existing and future construction forms employing biodegradable facings and those with geotextiles or steel mesh. Techniques should address both vegetation failure and structural repair to the facing following impact and any fire damage resulting from vehicular accidents, or vandalism. The use of individual plants, possibly including small diameter live willow poles inserted through the facing and at the layer interfaces, re-hydroseeding timed for best growing season including some form of additional mulching layer to increase the probability of establishing growth, should be considered. The use of soil panels anchored to the face to provide an increased depth of top soil may offer a practical alternative approach. Whatever method is adopted, it is essential that long-term monitoring is carried out, both to ascertain the level of success and to gather data for future reference on the suitability of vegetative techniques for steepened earthworks.

For future schemes the following points should be considered:

1 provision of an adequate depth of top soil to reduce the effects of desiccation, particularly on southerly facing slopes;

2 inclusion of water retaining polymers and slow release fertilisers;

3 incorporation of seeds within the top soil;

4 use of a reinforcing geogrid for the facing, possibly backed with an open textured biodegradable fabric;

5 the planting of rambling and climbing evergreens at the top of the wall and at reinforcing layer interfaces; and the use of salt resistant plants at the bottom of the wall;

b Similar construction and location, but south facing

Figure 5.7 The effect of slope orientation on vegetation growth

6 inclusion of some form of mini-benching (perhaps only 0.1m wide would be sufficient) at the layer interfaces to provide a catchment area to retain rainfall run-off;
7 incorporation of a hard, steeper lower face to the wall whilst reducing the upper vegetated slope angle;
8 timing planting in relation to construction activities and plant welfare requirements;
9 ease of maintenance operations including safety, access and timing;
10 repair techniques for the wall facing and replacement of vegetation in case of vehicular damage or fire.

5.6 Conclusions

Vegetation can play an important role in preventing shallow slip failures in embankment and cutting slopes by removing excess moisture and providing tensile reinforcement through the roots. However with steepened slopes the lack of available moisture is a major problem in establishing and successfully maintaining the required level of vegetation for reinforcement when a biodegradable facing material has ceased to function.

The survey illustrated highly variable success rates with vegetated reinforced slopes. In general, lack of sufficient moisture coupled with a southerly orientation of the slope face were the primary causes for failure of the vegetation. A combination of the lack of available water and desiccation within the top soil creates a hostile micro-climate.

It is recommended that biodegradable materials should not be the sole facing for these steep slopes as the total reliance on the successful establishment of vegetation to replace their role in erosion prevention cannot be guaranteed, either in the short or long-term. Some degree of permanent reinforcement should be incorporated with the biodegradable material. Systems which use a reinforcing geotextile may only require vegetation to provide an aesthetic facing and a long-term barrier to ultra-violet degradation. Planting in both new and existing slopes at the reinforcing layer interfaces should not present any major problems.

Long-term maintenance requirements need to be considered during the design stage. Repair techniques, both to replace failed vegetation and for any structural damage caused to the slope facing, need to be developed for existing slopes.

6 Use of live willow poles in highway schemes

6.1 Introduction

In addition to the use of vegetation reinforcement to steepen existing slopes for motorway widening purposes, the stability of shallow slopes can be improved by vegetation. Shallow slope failures on embankments and cuttings have been identified as a source of maintenance problems for a number of years with an ongoing commitment for costly remedial works. The potential for such slips can often be reduced by the appropriate use of vegetation planted to provide reinforcement as well as a reduction in moisture content and pore water pressure. One of the more innovative approaches in bioengineering is to employ live willow poles to stabilise slopes. The poles provide an immediate reinforcing action and grow to provide the longer term benefits associated with established trees.

Live willow poles were incorporated in a new cutting slope on the A249 Iwade improvement scheme to enhance the existing level of stability in the cut slope. Their performance is discussed and recommendations are made for future works of this type.

6.2 Willow pole installation at Iwade

Five hundred live willow poles were installed to augment the buttressing action of a series of counterfort drains along an 80m length of south-east facing slope: the arrangement is shown in Figure 6.1. The 1 in 3 slope was cut in the Woolwich Beds Clay overlying Woolwich Beds Sands with discontinuous sub-horizontal shear surfaces.

Following installation of the poles during the late spring of 1996, two visits were made in the spring of 1997 to monitor the condition of the poles and root growth. The percentage of live poles was somewhat lower than anticipated: after an initial growth response of 95%, significant die-back of the poles occurred to give a survival rate of about 15%. The reasons for the low success rate and methods to optimise success in future plantings were investigated using the following approaches:

- site observations;
- exhumation of some of the poles;
- review of the viability of the technique.

6.3 Site observations at Iwade

The survival rate of live poles at this site was lower than expected and this was attributed to a number of factors specific to the site (Barker, 1997). One of the main factors was considered to be the lack of moisture in the poles and soils. This may have been due to the use of less than fresh willow poles or initially sound material drying out whilst on site. It is also arguable that in the period before the installation of the poles, the combination of a long dry spell and the construction of the counterfort drains and the crest drain drastically reduced the supply of water to the slope. The soils showed little evidence of excess water but the poles thrived in areas where the slope was wettest.

Problems were encountered with the pole installation methods and handling of the live poles. A significant number of installation operations were carried out in two stages. The poles were partially installed and left exposed for some time (possibly some days) before they were fully embedded in the slope. This may have adversely affected the survival rates of these poles, given the strong breezes and hot weather at the time.

Figure 6.1 Installed willow poles at A249 Iwade improvement scheme

6.4 Exhumation of poles at Iwade

Exhumation of willow poles at Iwade was undertaken in January 2000 with the objective of assessing the below ground condition of a number of live and dead poles: this work has been described by Steele *et al.* (2000). Five dead poles were exhumed from the cutting and these showed varying degrees of decay and little or no evidence of any root structure. Their condition was however thought to be sufficiently good for them to be providing a beneficial effect as dowels improving the stability of the upper layer of the slope. Furthermore there was no evidence to suggest that the poles were forming a pathway for moisture ingress to the slope. It is thought that a period of up to five years may pass before remedial action for the dead poles is required.

The potential of the willow pole technique was clearly shown by the exhumation of a live willow pole. This showed an extensively developed root system across the full buried length of the pole and a taproot which extended well beyond the 1.5m depth of the excavation (see Figure 6.2).

6.5 Review of the viability of the technique

A literature review (Hiller and MacNeil, 2001) was undertaken with the objective of using previous experience, together with the data gained from the Iwade scheme, to make recommendations on the installation process and to assess the merits of the live willow pole technique. They confirmed that to ensure the success of the technique, particular attention needs to be given to the following:

Selection of species appropriate to the local condition

There are numerous species available (see Meikle, 1984) and hardwood species (*Salix alba*, *Salix fragilis* and other *Salix* species) sourced from an approved supplier or location are appropriate for the application. Fast growing varieties are normally used to provide rapid slope stabilisation. The disbenefit is that more frequent maintenance (trimming and coppicing) may be required for vigorous varieties.

Pole length and diameter

To ensure an immediate reinforcement of the slope by dowelling action, the poles must extend to a depth greater than the depth of the potential failure surface. Root growth needs to develop at the greatest depth of penetration. Poles are usually installed with a diameter of 40 to 100mm as these provide sufficient tensile strength. It is also generally acknowledged that the greater the biomass, the better will be the success rate of establishing unrooted cuttings.

Harvesting, handling and transportation of the poles

Willow for live poles should be freshly harvested after autumn leaf-fall and prepared for direct transportation to site, or taken to an approved cold store. Ideally replanting is best within about 3 weeks of harvesting. During transportation and storage on site, poles should be kept moist by storing them in either a water tank or wrapped in damp hesian. In particular, live poles should be protected from intense sunlight and strong winds which may cause drying out.

Installation procedure

Vertical installation of live poles is generally more practical than an installation normal to the slope surface although both are acceptable. In weak soils the poles may be driven to refusal directly, but more usually pre-drilling

Figure 6.2 Development of the root system on a live willow pole exhumed at the Iwade improvement scheme

of holes is required. To enable shoot development and growth, a length of live pole of about 0.3 to 0.5m should be proud of the ground. For rapid cover, Coppin and Richards (1990) suggested that staggered rows with 1.5m spacing between poles may be used, although such close spacing will require thinning at an early stage. Spacing needs to take into account the required improvement in slope stability.

Protection and maintenance

Treeguards are usually required to protect against rabbit or other pest festation and in some cases deer attack. Access for trimming and coppicing needs to be available.

The various risks in using live willow pole planting and the actions to minimise them are summarised in Table 6.1.

As highlighted by the successful development of clusters of live willow poles at Iwade, the reasons for the successful localised growth or failure of individual poles are complex and difficult to quantify. For example, Bache

Table 6.1 Minimising risks in using live willow pole planting

Risk	*Actions to minimise*
Application of the live willow pole technique at inappropriate sites.	Characterisation via records archive or site investigation.
Difficult climatic conditions throughout the service life of the stabilised slope.	Selection of most appropriate species.
Disease.	At each site, use a minimum of two species with differing disease susceptibilities.
Competition with local vegetation.	Removal of problematic species prior to commencing the installation. Use of a maintenance program at appropriate intervals.
Poor development in shaded areas.	Selection of open slopes with no shading vegetation.
Uneven slopes, producing localised pooling of runoff water and resulting in decay at the soil surface interface of the pole.	Trim profile of uneven slopes prior to installation.

and MacAskill (1984) list some of the factors which potentially affect root development; nutrient availability, oxygen supply, moisture content, temperature, toxin levels in the soil, the system of soil pores into which roots can grow, and the shear strength and compressibility of the soil. These factors will also have differing impacts on different willow species, and the willow poles themselves will also have natural variations in their vigour. Variations in the method and timeliness of installation are also likely to have a significant effect.

6.6 Recommendations

The use of live willow poles to stabilise slopes is potentially a versatile and cost effective alternative to more traditional engineering methods. Bioengineered approaches also offer ecological and aesthetic benefits. To give the maximum success rate in planting, care is required in the selection of species, harvesting and handling, and in the installation procedure.

Site selection is the principal factor in the successful application of the technique and care should be taken to ensure that proposed sites can sustain the development of the live willow poles. To this end, proposed sites should have clearly defined stability problems, encompassing a soil type predominantly of clay, the presence of excess quantities of water, and a supportive local climate. It may well be the case that the technique is not suitable for application on every over-consolidated clay slope in the UK which is experiencing shallow depth stability problems, but indications are that it will be beneficial to many.

Following the mixed success in planting live willow poles to stabilise a cutting slope on the A249 at Iwade, further trials on the highway network are recommended to provide the civil engineering industry with confidence in the technique.

7 Summary

This project investigates the potential for vegetation as a preventive and remedial measure to stabilise slopes, particularly those in over-consolidated clays, which are at risk of shallow failure. Bioengineering approaches have the advantage of offering improved ecological and aesthetic benefits, in addition to the improvements in slope stability. The use of vegetation may reduce the need for the costly maintenance of shallow slip failures on highway embankment and cutting slopes using traditional methods. This report also covers associated aspects such as the use of vegetation on reinforced steepened slopes in road widening and the use of live willow poles in reducing the risk of shallow failures. The main findings are now summarised:

i In addition to the engineering functions of vegetation in terms of protecting and stabilising the surface of the soil and increasing soil strength at depth, there are benefits of enhancing landscape quality. Careful selection of species for use in a highway situation is of paramount importance. Five species are identified within the report, which are considered cost-effective to both plant and maintain. Mixed planting schemes, with different species planted in small blocks of a single species or finely interspersed, could be aesthetically desirable as well as minimising the risks associated with failure if only one species is used. Generally there are considerable cost-savings to be gained from bulk purchasing and planting.

ii The trial embankment constructed to typical highway specifications provided valuable data on the long-term growth of vegetation, and its effect on the stabilisation of clay slopes against shallow failure. Survival of trees was better than shrubs and perennials on both north and south facing slopes. Suctions generated under areas planted with trees and shrubs were generally higher and to a greater depth than those under perennials or grasses. Suctions generated by the vegetation varied seasonally with low suctions being measured between late autumn and late spring, when earthwork slopes are most vulnerable to failure. Soil moisture depletion at this critical time cannot therefore be relied on and the slope stabilising effect will thus depend more on the reinforcing action of the roots.

iii With reinforced steep slopes the lack of available moisture can be a major problem in both establishing and successfully maintaining the level of vegetation required to ensure stability when the biodegradable facing material has ceased to function in this role. A survey showed highly variable success rates with vegetated steep slopes and it is therefore recommended that biodegradable materials should not be the sole facing and that some degree of permanent reinforcement should be incorporated. Systems which use a reinforcing geotextile may only require vegetation to provide an aesthetic facing and a long-term barrier to ultra-violet degradation.

iv The use of live willow poles to stabilise slopes is potentially a versatile and cost effective approach. Site selection is the key to successful application and sites should generally be predominantly of clay, with the presence of excess quantities of water, and a supportive climate. Following the mixed success in planting live willow poles to stabilise a cutting slope on the A249 (Iwade improvement scheme), further trials utilising lessons learnt, are currently underway on the motorway and trunk network.

The use of vegetation and bioengineering approaches to stabilise slopes is a cost-effective technique with the potential for being used more extensively on the highway network. The following recommendations for further research are made to progress more confidence in its widespread usage.

i The trial embankment at TRL is a unique facility and the opportunity exists to extend the growing trial by a further period of monitoring to provide invaluable longer-term data. At the end of the monitoring, an invasive assessment of both shallow and deep root architectures is recommended. This would include an investigation of the spatial distribution of the root system together with measurements of root shear strength.

ii Continued monitoring of the live willow pole trials is currently progressing under a separate contract with the Highways Agency. However, measurements of the seasonal variation of moisture content with depth, using a neutron probe, would enhance the scope of this monitoring. This is important because the growth of live willow poles is primarily dependent on the availability of sufficient water.

iii The survival rate of the live willow poles at Iwade was lower than anticipated and remediation will be required shortly. This offers a unique opportunity to gain a better insight into root architecture, and to further develop a unified approach to using large cuttings of pioneer plants, whereby initial growth is replaced over the long-term by inter-planted tree, shrub and hedge species. Data would also be obtained on the use of more drought tolerant willow and poplar species as replacements for dead poles.

iv Soils are central to the sustainability of ecosystems, and perform essential functions such as nutrient cycling to support plant growth and biodiversity. A number of microbiological parameters have been proposed as indicators of soil health and quality, particularly in relation to soil erosion, waste cycling, and pollution. Further information is required on the use of mycorrhizal fungi to improve soil health by assisting nutrient transfer from soils to plants and protecting against drought stress. This could significantly improve survival, vigour and make plants more self reliant in difficult growing conditions.

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Abstract

The reinstatement of shallow slope failures can be costly and the potential for slips may be reduced by the use of vegetation planted to provide reinforcement, through the plant root system, and a reduction in moisture content and pore water pressure. This report summarises experiences on the establishment of vegetation for slope stability. This study includes a literature review to establish tree, shrub and herbaceous species that have the potential to grow in a highway environment, growing trials under controlled conditions, and the monitoring of a vegetated embankment trial. Studies on the highway network have included a survey of the use of vegetation reinforced steepened slopes and on the use of live willow poles to enhance stability of a clay slope on the A249.

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