Stability of Sitka spruce on mole-drained and ploughed surface water gley soil

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Abstract

A study compared the effects of two site preparation methods, double mouldboard ploughing and mole-drainage on the stability of Sitka spruce trees subjected to repeated and monotonic forced loads. The trees were planted on a low-permeability surface water gley soil in two experimental plots in the north-west of Ireland. The soil is highly productive with average Sitka spruce productivity in excess of 18 m^3 ha^{-1} yr^{-1}. However, the major constraint on production is windthrow, which is dependent on a number of factors, including soil preparation. Repeated loading tests were carried out on 6-metre tall truncated tree stems in both cultivation treatments using a specifically constructed tree rocker. During a repeated load test in the double mouldboard plot, pore water pressure increased under the root plate and fractured the soil causing a washout of fines. Once this fracturing occurred, the sway of the tree stem and, as a result, the overturning moment increased substantially, making the tree very unstable. When a repeated load test was carried out in the mole-drained plot, there was little build-up of pore water pressure even though the loading was greater than that applied to the tree stem in the mouldboard plot. Monotonic tests, which consisted of pulling six trees over in each plot, were used to calculate the trees' maximum overturning moments. In the double mouldboard ploughed plot, the repeated loading test clearly showed that soil failure can be initiated at much lower overturning moments than the maximum moment applied during monotonic pulling tests. Both the repeated and monotonic loading tests indicated that the trees planted in the mole-drained plot were substantially more stable than those planted in the double mouldboard plot.

Keywords: Windthrow, dynamic tests, Sitka spruce, mole-drainage, double mouldboard ploughing, pore water pressure, overturning moment.

Introduction

Windthrow is defined as the overturning of trees and their root plates during windy conditions. In Ireland, it was estimated that windthrow caused direct financial losses of €14 m during the period 1987-1997 (Hendrick, 1998). Windthrow can also lead to increased soil erosion, run-off and adverse visual impact. Windthrow is common worldwide, particularly in Ireland, the United Kingdom, Northern Europe, North America and New Zealand.

The occurrence of windthrow depends on tree species, root system configuration, harvesting methods (Flesch and Wilson 1999; Mitchell 2000), as well as a number of

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other factors, including soil type, soil drainage, soil strength, climate, elevation, aspect and location. In poorly drained wet soils, liquefaction and failure of the soil occurs (Rodgers et al. 1995) under the root plate during windthrow, and roots are pulled out of the ground. The level of windthrow can be reduced by lowering the water table using effective drainage, which also facilitates deep rooting (Mason and Quine 1995) resulting in increased resistance to roots being pulled out (Stokes et al. 1996).

In the past, the preferred method of drainage used in water surface gleys was double mouldboard (DMB) ploughing (Hendrick 1989). The furrow provided the drainage channel and the tree seedlings were planted in the plough ribbon. Although successful in terms of lowering the water table beside the furrow, the method fostered asymmetric root plates, by confining the root development to the overturned plough ribbon and the inter-furrow surface soil (Hendrick 1989). The result of such confinement is to make the trees vulnerable to damage when the wind blows from a direction at right angles to the direction of ploughing (Hamilton 1980).

Mechanical (or excavator) mounding is now the favoured method of site preparation where the trees are planted in small mounds of soil excavated from drains at approximately 12 m spacing. This method incorporates both cultivation and drain excavation in one operation. The mounds are typically 45 x 45 cm in area and 15 cm in height. Owing to the fact that it is only relatively recently that this technique has become widespread, little is known about the stability of trees established on mounds. The ability of the drains at 12 m centres to lower the water-table to a sufficient depth in impervious soils depends on the permeability of the soil (Mulqueen 1998). Wills et al. (2001) found that the mechanical mounding system only lowered the water-table for a distance of 3 m from the drain.

Mole drainage, which is suitable for many Irish soils but rarely used in forestry, comprises 75 mm diameter drains installed using a mole plough, about 450 mm below the ground surface at 1.0 - 2.0 m centres; the correct drain spacing depends on the permeability of the soil (Mulqueen et al. 1999), and the planting and thinning strategies. The plough consists of a frame with a mounted vertical narrow shaft, which carries at its bottom a cylindrical mole with an inclined leading edge that faces upwards (Mulqueen 1998). As the plough is pulled, the soil above the level of the mole is lifted and cracked. A cylindrical expander, which follows the mole, partially remoulds the soil to produce a self supporting tunnel drain. The soil cracking is of critical importance in increasing the permeability of the subsoil to the same order of magnitude as that of the topsoil (Rodgers et al. 2003). The cracks allow the rapid percolation of excess water to the mole drain thereby lowering the water table in the soil. Wills et al. (2001) found that mole drainage lowered the water-table uniformly across a suitable site, and may therefore be more effective in surface water gleys than mechanical mounding. The trees are normally planted beside the slot formed by the plough shaft.

A number of monotonic and dynamic testing studies have been carried out to examine the mechanisms of windthrow in coniferous forests. Monotonic testing is the more common form of testing due to its simplicity (Coutts 1986, Blackburn et al.

1988). However, since wind loading is dynamic, a more realistic insight into windthrow mechanisms is provided by dynamic forced loading tests.

Monotonic testing normally involves pulling trees over using a winching system. Displacements of the tree and pulling forces are measured during the test. Using these measured data, the applied overturning moments can be readily calculated. Monotonic analyses are useful when comparing the relative stability of trees planted in different soil types or drainage conditions (Hendrick 1989). Coutts (1986) conducted a series of monotonic tests on Sitka spruce trees planted on a peaty gley (wet mineral soils of low permeability that have developed under conditions of permanent or intermittent water logging). From these tests, he identified four major components of resistance to overturning: soil resistance, the windward roots acting in tension, the weight of the root plate, and the resistance to bending at a hinge on the root plate. Hendrick (1989) conducted a series of destructive monotonic tests on the truncated stems of Sitka spruce planted on two differently drained plots: on one plot, mole-drainage was used and on the other, spaced furrow ploughing. He found that the mean maximum overturning moment for the trees on the mole-drained plot was significantly higher than that for the trees on the furrow ploughed plot. This study also indicated that the root plates for the mole-drained trees were deeper and more radially symmetric that those for the furrow ploughed trees; the asymmetrical root systems of the furrow ploughed trees being caused by the truncating effect of the furrow. Blackburn et al. (1988) noted from a series of monotonic tests on Sitka spruce trees planted on a peaty gley that the load/displacement ratio of the tree system was reduced by a factor of 2-3 after soil failure had taken place. This reduction indicates that once the soil under the root plate of a tree has failed, increased displacements will occur for the same pre-failure wind load with a consequent increase in the overturning moment and likelihood of windthrow.

Rodgers et al. (1995) conducted repeated forced loading tests on 6 m high truncated stems of Sitka spruce trees planted on a peaty gley. Spaced furrow ploughing had been used to drain the soil and provide elevated planting positions. The repeated loading was carried out using a mechanical rocker, which was mounted on top of the truncated stem. Various responses of the test trees were monitored during the repeated loading tests, and included: the horizontal displacement of the stem, the strain along the stem at various heights, the pore water pressure at a depth of 400 mm below the surface of the root plate, and the vertical movement of the root plate. Results from this forced rocking experiment on a test tree showed that when the maximum overturning moment in a load cycle exceeded 7 kNm, there was a build-up in the soil pore water pressure. This build-up continued to increase to about 17 kPa, when hydraulic fracture of the soil occurred; the pore water pressure increase was accompanied by increases in the maximum cyclic displacements and overturning moments. Liquefaction of the soil was observed in the root plate and fines were pumped out through fractures in the soil surface. For another test tree, once the hydraulic fracturing took place, the movement of the tree stem changed from an oscillating motion in a single vertical plane to a loop motion in plan indicating that the natural frequency of the tree system had changed. When a reduced loading was later applied to the tree, its movement reverted to its oscillating motion with larger displacements, indicating that once soil failure has occurred, a tree can be swayed by less external energy after failure than before. It was considered that possible failure of the tree had been initiated when there was a substantial increase in the pore water pressure build-up. The overturning moment required to initiate failure using the tree rocker on the spaced furrow ploughed plot was considerably lower than the maximum overturning moment found from monotonic pulling tests conducted on intact neighbouring trees. A complete tree was also instrumented on the same site and its response to windy conditions was remotely monitored. In a storm, pore water pressures under the root-plate of 9 kPa and overturning moments of 7 kNm were measured, indicating that the tree rocker experiments produced realistic data on the dynamic behaviour of trees and their root plates during storms.

This paper compares the performances of 27-year-old Sitka spruce planted on a low-permeability surface water gley soil in two experimental plots when they were subjected to both monotonic and repeated forced loading tests; one plot had been cultivated using double mouldboard ploughing and the other was mole-drained. The objective of the study was to establish if mole-drainage was likely to increase the stability of Sitka spruce and reduce the losses caused by windthrow.

Site and soil characteristics

The testing was conducted in the northwest of Ireland at Ballyfarnon Forest, Co Sligo, which was planted with Sitka spruce in 1971. The forest lies, for the most part, on the slopes of one of a number of drumlins, the dominant topographical feature in the area. The parent material of these drumlins consists of a very sticky glacial till derived mainly from middle limestone (calp), upper Carboniferous limestone, Ordovician and Silurian shale, Coal measure shale, and Millstone shale (An Foras Talúntais 1980). The soil is highly productive with an average Sitka spruce yield in excess of 18 m^3 ha^{-1} yr^{-1} (Hendrick 1999). However, the major constraint on production is windthrow, which is dependent on a number of factors, including soil preparation. The area in which the forest is located has an average annual rainfall of approximately 1300 mm and experiences a mean annual wind speed of 4-5 m s^{-1}. The maximum gust speed likely to be exceeded once in fifty years is about 48 m s^{-1}. Some windthrow had occurred within the forest but none was observed within the test plots. The top mean height of the forest at the time of testing was approximately 16.5 m.

The topsoil at the site is 100-200 mm thick and is underlain by a silty sandy clay or surface water gley subsoil with a very low permeability. The top layers of undrained soils at the site are frequently saturated, mainly in late autumn through early spring. As a result, the roots of Sitka spruce trees in uncultivated soil are very shallow, since they can only survive in unsaturated conditions. The constituents of the subsoil, excluding gravel, were silt (27.2 %), sand (29.6 %) and clay (40.7 %). The average natural moisture content (w_n) of the undrained subsoil was 31.5 %. Its liquid limit and plasticity indices were 52.8 %, and 24.9 %, respectively. The average undrained shear strength of the soil, from fall cone tests, was 135 kPa. The hydraulic conductivity (K) of this soil type is approximately 7 x 10-10 m/s (Mulqueen 1998). From these details, the soil from the test site can be classified as a firm to stiff, silty sandy clay of intermediate to high plasticity (B.S. 5930: 1981), with a very low permeability.

A multi-point mercury manometer tensiometer was installed in the mole-drained plot and in an undrained test plot at a distance of 0.35 m from the trees to monitor the hydraulic potential of the soil at various depths. Figure 1 presents the results from both plots following dry and wet periods. The depths of the water table below ground surface occur where the hydraulic potential crosses the gravitational potential line. For the dry period, the water table depths were 0.6 m in the undrained plot and 0.8 m in the mole-drained plot; for the wet period, the water table depths were 0.2 m for the undrained plot and 0.4 m for the drained plot. These depths clearly show that the mole-drains were effective in lowering the water table.

Methods

Monotonic testing was carried out using a winching system that comprised a wire rope, a winch and a load cell. The load cell operated in tension only and was designed to measure tensile forces up to 10 kN. The system is illustrated in Figure 2. The trees were truncated at a height of 6 m. One end of the wire rope was attached to the top of the truncated stem and the other end to the winch. The load cell was then connected between the winch and an anchor tree.

The tree rocking device consisted of two disks with eccentric masses, which were rotated in opposite directions by a hydraulic motor through gears, chains and sprockets. A vertical elevation of the rocker is illustrated in Figure 3 and its operating principle is shown in Figure 4. A hydraulic pump, which was driven by a petrol engine, activated the motor. The tree rocker was mounted and clamped on the

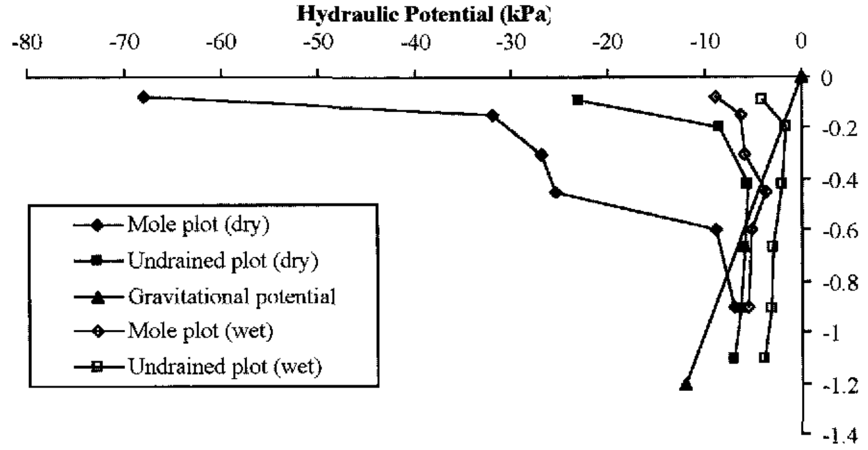

Figure 1: Variation in hydraulic potential between mole-drained and undrained plots at Ballyfarnon during dry and wet periods.

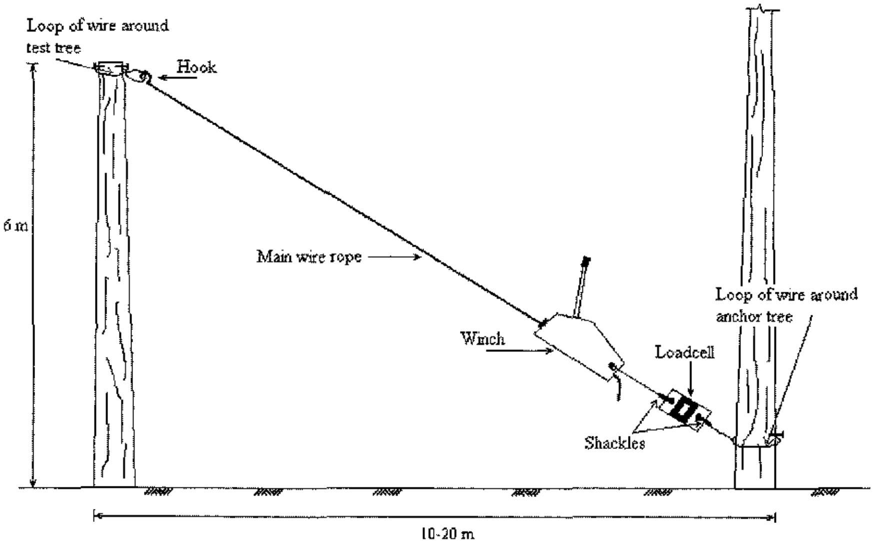

Figure 2: Destructive monotonic tree pulling arrangement.

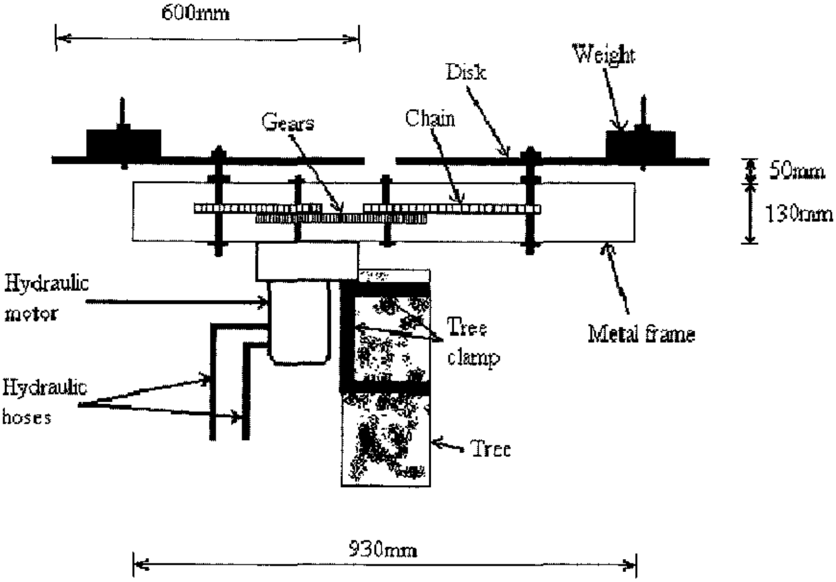

Figure 3: Elevation of tree rocker.

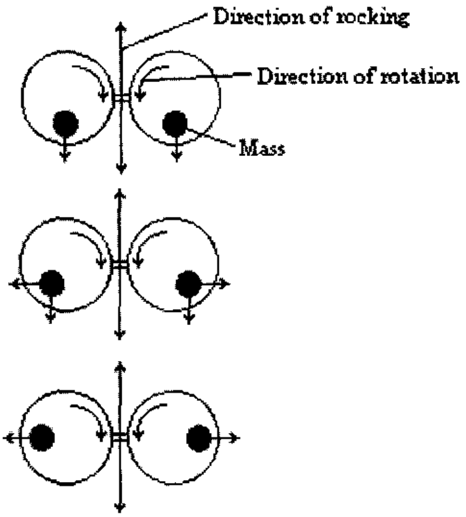

Figure 4: Plan view of rocker disks showing principle of operation (mass was varied to increase/decrease moment).

truncated stems of the test trees 6 m above ground surface. Using the rocking device, it was possible to rock the tree in a selected vertical plane.

Each of the trees subjected to dynamic testing was instrumented with eight transducers to monitor various responses of the tree and the soil beneath the tree during the forced loading experiments. Three saturated pore water pressure transducers (Figure 5) were inserted to a depth of 400 mm below the ground surface at locations close to the stem of the test tree and the major structural roots. The pressure transducers were calibrated in the laboratory using GDS pressure controllers.

Three strain gauges were mounted on the tree stem at heights of 1.3 m, 2.3 m and 3.3 m above ground surface. The strain gauges were formed by attaching a displacement transducer with a spindle displacement of 5 mm to the stem of the test tree and pressing the spindle of the transducer against a plate that had also been fixed to the test stem, as illustrated in Figure 6.

The horizontal displacement of the stem at 6 m height was measured using the arrangement illustrated in Figure 7; a similar arrangement was used for the horizontal displacement at 3 m height. As the tree rocked, the spindle of the displacement transducer was either compressed or extended in response. Knowing the dimensions of the lever arm it was possible to calculate the actual horizontal displacement of the tree stem. The transducer used to measure the horizontal displacement at the 6 m height had a spindle displacement of 100 mm and that used at the 3 m height had a spindle displacement of 50 mm; all displacement transducers were calibrated in the

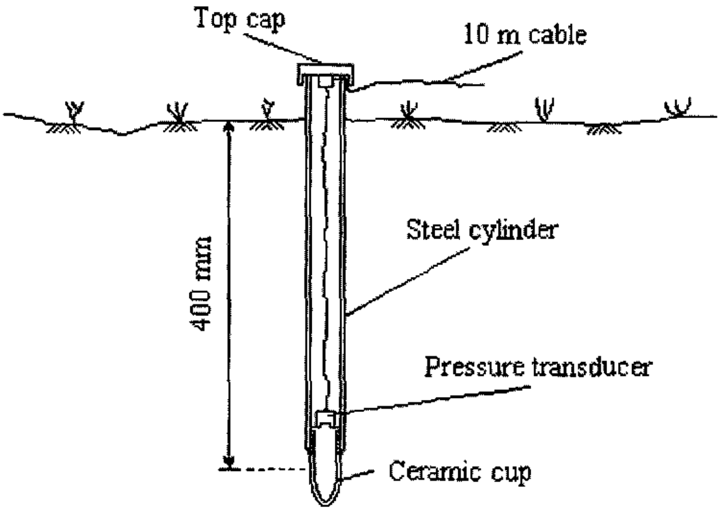

Figure 5: Pore water pressure measurement.

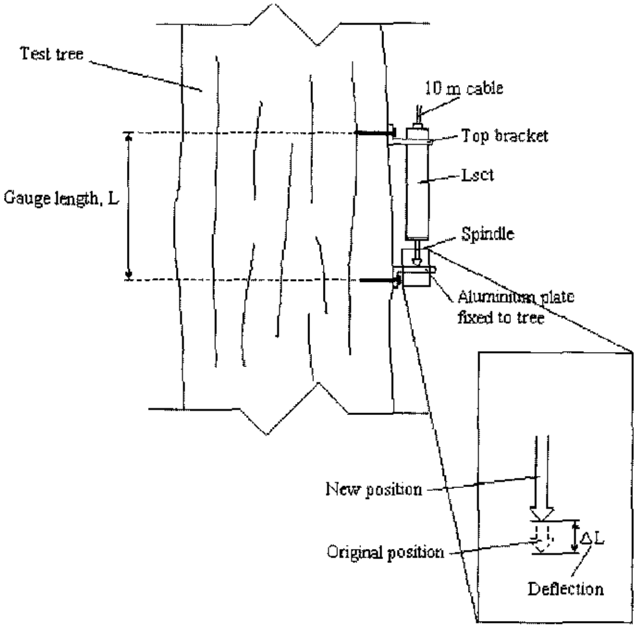

Figure 6: Stem strain gauge arrangement.

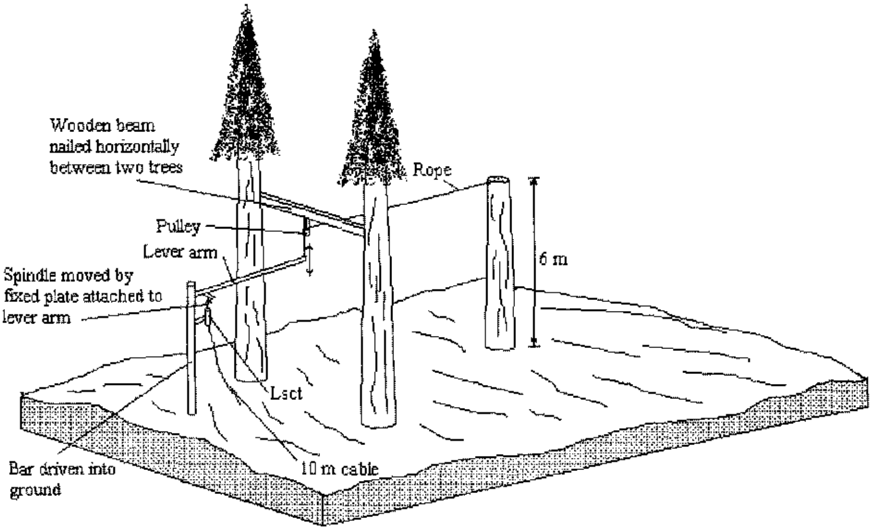

Figure 7: Horizontal stem displacement measure arrangement.

laboratory using a micrometer. The readings from the eight transducers were sampled on a Macintosh II computer using a National Instruments™ NB-MIO-16H-9 analogue-to-digital board and LabVIEW™, a software development package. This arrangement enabled results to be plotted and checked in the field when a test was in progress.

In the double mouldboard ploughed plot and mole-drained plot, the direction in which the trees were monotonically pulled or dynamically loaded was chosen at right angles to the direction of the drainage channel.

In the monotonic tests, the trees were winched over at rates varying from 0.01 to 0.02 m/s. The tensile loads in the rope were recorded every 100 mm of displacement. Pulling continued until the maximum overturning moment had been exceeded. Six trees in each of the two plots with diameters of about 220 mm at breast height (dbh) - 1.3 m above ground surface - were tested in this fashion (Table 1). Overturning moments were calculated using the following equation (Figure 8):

$$\text{Overturning moment (kNm)} = F.(\text{Cos}\theta \times L + \text{Sin}\theta \times e) \quad [1]$$

where:

F = the tensile force in the wire rope (kN),
θ = the angle of the wire rope relative to the horizontal (°),
L = the lever arm (m), and
e = the eccentricity of the displaced stem (m).

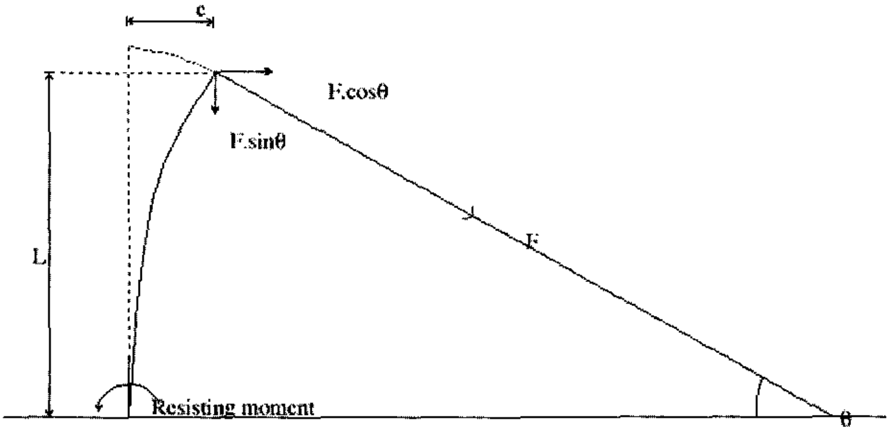

Figure 8: The components of force, overturning moment and displacement for tree pulling tests.

The repeated forced loading tests were carried out on a tree with a dbh of 220 mm in each of the experimental plots. The pore water pressure transducers were installed two days prior to testing to allow water pressures in the soil and transducers to equilibrate. A non-destructive monotonic test was conducted on the test tree before dynamic testing commenced. The tree was pulled over by a small total amount so that no damage was caused to the root plate. During the test, readings from the three strain gauges and the load cell were recorded at selected displacement intervals. The overturning moments were calculated and plotted against the strain gauge readings, yielding near linear relationships (Figure 9).

The linear relationships were used to estimate the overturning moments from the strain gauge values measured during dynamic testing. The stiffness of the test trees was calculated prior to the dynamic tests and at intervals during the test when rocking was stopped to facilitate changing the masses on the disks. The stiffness was defined using the following equation:

$$\text{Stiffness (kN/m)} = \frac{\text{Applied force}}{\text{Horizontal deflection at 6 m}} \qquad [2]$$

Rocking was initiated with small masses on the disks and a slow rotation rate. Readings from the eight transducers were monitored at selected intervals and when no further changes in their responses were observed, the rotation rate was increased. When a high rate of rotation was attained and no further changes in the responses were observed, testing was suspended for a stiffness test and to increase the masses on the disks. This procedure was followed until the test was terminated. The actual repeated loading test times for the trees in the double mouldboard ploughed and mole-drained plots were 415 and 400 minutes, respectively. The total time taken to complete each dynamic test was about 6 days. After completion of the repeated

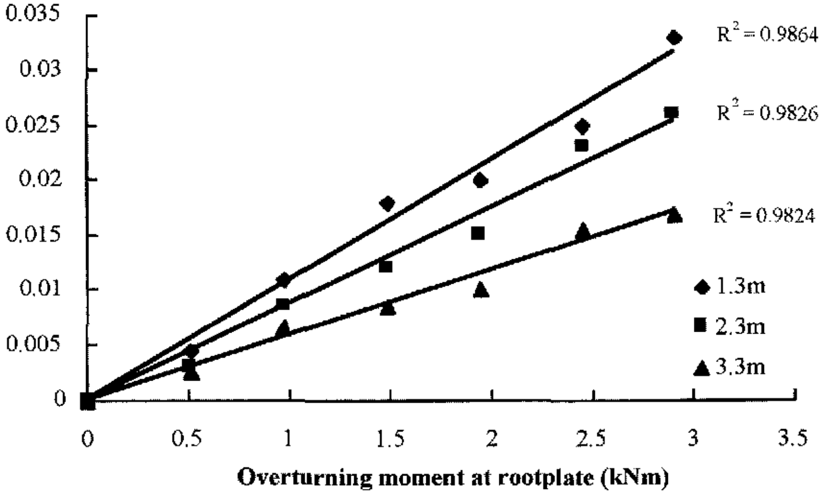

Figure 9: Calibrations to calculate overturning moment from bending strain for repeated loading test in the double mouldboard plot.

loading test, the tree was pulled over and its maximum overturning moment calculated.

Results and discussion

The results from the monotonic tests are presented in Table 1. The average value of the maximum overturning moments for the trees in the mole-drained plot was significantly ($p \leq 0.05$) greater than the average value in the double mouldboard plot.

Overturning moments obtained from the monotonic loading tests are plotted against displacement in Figure 10 for tress of the same dbh in the mole-drained and double mouldboard plots.

Table 2 shows that the dynamically loaded test tree in the mole-drained plot was 1.5-2.3 times as stiff as the test tree in the double mouldboard plot before, during and after the repeated loading tests.

For the double mouldboard test tree, there was little increase in pore water pressure (Figure 11) as the disk loading and rotation rate of the rocker were intermittently increased to 36.29 kg/disk and 42 revolutions per minute (rpm), respectively, during the initial testing time of 350 minutes. However, once the rotation rate was increased to 50 rpm at 350 minutes, the pore water pressure increased rapidly from a value of 0 kPa to a maximum value of 5.5 kPa at 370 minutes. As 1 kPa of water pressure corresponds to a 100 mm water head, water would have risen to a maximum height of 150 mm above the ground surface in a standpipe piezometer if installed at the level of the transducer tip - 400 mm below ground surface. At approximately 370 minutes, the soil fractured due to the increased pore water pressure and liquefied soil began to appear at the ground surface. At hydraulic fracture and soil liquefaction – indicated by a decrease in pore water

***Table 1:** Summary of destructive tree pulling tests in Sitka spruce at Ballyfarnon.*

Treatment	***Tree***	***dbh*** ***cm***	***Maximum overturning moment*** ***kNm***	***Mean*** ***kNm***
Mole-drained				
	1	*22.5*	*29.23*	*32.23 ± 5.06*
	2	*22.7*	*27.21*	
	3	*22.1*	*33.14*	
	4	*22.2*	*27.97*	
	5	*22.0*	*35.66*	
	6	*22.1*	*40.16*	
Double mouldboard ploughing				
	1	*22.6*	*23.18*	*20.35 ± 3.47*
	2	*22.0*	*23.96*	
	3	*22.0*	*15.46*	
	4	*22.0*	*18.18*	
	5	*22.0*	*22.87*	
	6	*22.1*	*18.46*	

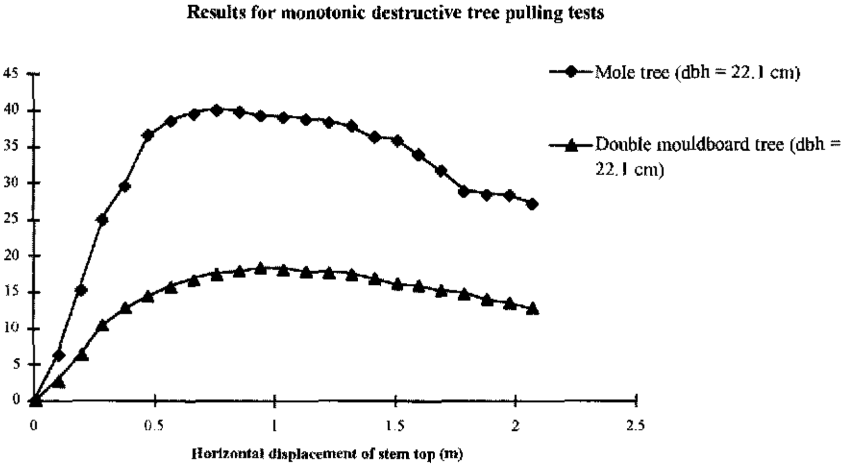

Figure 10: Overturning moments of trees in mole-drained and undrained plots as a function of horizontal stem displacement.

***Table 2**: Summary of results of non-destructive swaying of Sitka spruce stems in mole drained and double mouldboard ploughed treatments at Ballyfarnon.*

Treatment	***Time min***	***Stiffness kN/m***
Mole-drained		
	0	*12.76*
	31	*12.54*
	72	*11.93*
	158	*10.46*
	401	*9.29*
Double mouldboard ploughing		
	0	*8.68*
	30	*8.65*
	190	*7.83*
	326	*5.91*
	415	*4.08*

pressure - the maximum cyclic horizontal displacement of the stem top increased to about 500 mm. The overturning moment increased from about 10 to 17 kNm during the same period even though neither the masses on the disks nor their speed of rotation were increased. This increase in overturning moment was due to the increased displacement of the rocker. When the overturning moment and displacements had reached their highest values – at about 375 minutes- the motion of the tree changed from oscillating in a single vertical plane to an erratic looping action in plan indicating that the natural frequency of the tree system had changed. The rotation rate of the tree was reduced to 29 rpm. This generated an overturning moment of about 11 kNm and a horizontal sway of 200 mm, which was about the same as that for 42 rpm phase prior to liquefaction, indicating that the tree had less stiffness once the soil fractured. The tree was then monotonically tested to failure and had a maximum overturning moment of 22.9 kNm. The dynamic data suggest that failure of the tree was initiated at an overturning moment of about 10 kNm, which is substantially lower than the maximum overturning moment obtained from the monotonic destructive test carried out on the tree after dynamic testing was complete.

Figure 12 illustrates the maximum cyclic pore water pressure behaviour and maximum cyclic overturning moments for the tree tested in the mole-drained plot. Despite a higher loading regime than used on the tree in the double mouldboard plot, only a small increase in the pore water pressure was recorded at about zero pore water pressure. The maximum overturning moment of 15 kNm was in excess of the 10 kNm value that initiated failure in the test tree in the double mouldboard plot. No hydraulic fracturing or soil liquefaction was observed. The maximum cyclic

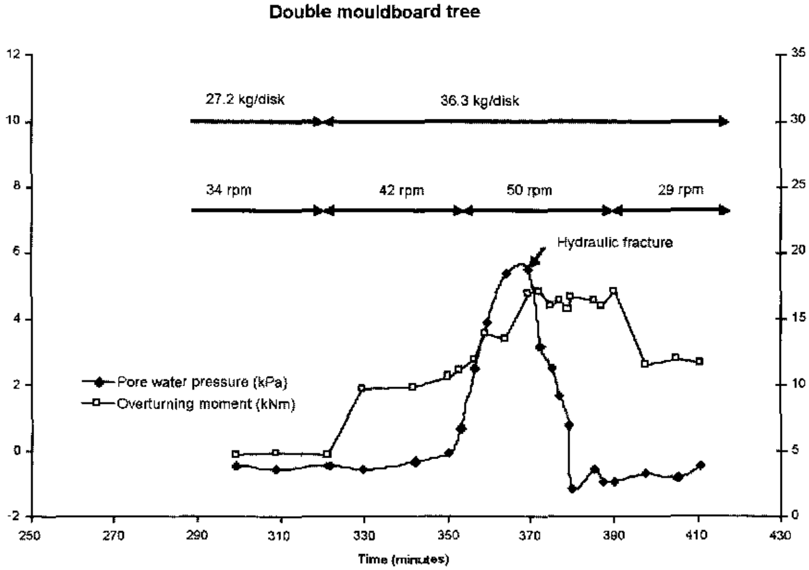

Figure 11: Pore water pressure and overturning moments for the tree tested in the double mouldboard plot.

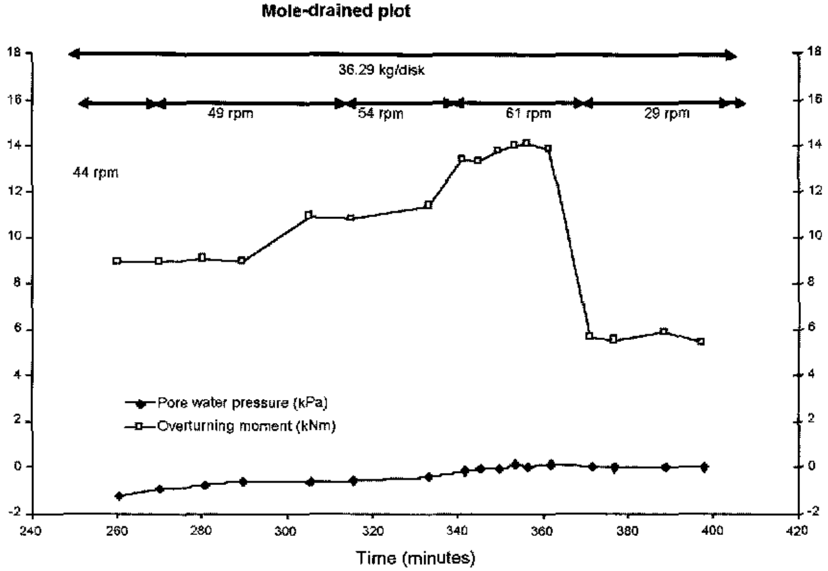

Figure 12: Pore water pressure and overturning moments for the tree tested in the mole-drained plot.

horizontal displacement of 300 mm at the stem top was also less than the maximum cyclic horizontal displacement of 500 mm of the stem top in the double mouldboard plot. Under the high loading regime a looping action in plan was induced, though it was considerably less pronounced than was the case for the tree tested in the double mouldboard plot. This looping action indicates that some fatiguing had occurred within the rooting system. This is confirmed by the measured values of stiffness in Table 2, which show a decrease throughout the course of the test. The rotation rate of the disks was then reduced to 29 rpm giving a horizontal sway of 50 mm, which was substantially less than the 200 mm for the double mouldboard tree at the same loading and rotation rate after liquefaction had occurred. Figure 12 shows that there was very little change in pore water behaviour before and after the looping took place. The tree was then pulled over with a maximum overturning moment of 33 kNm. It is worth noting that the maximum overturning moments obtained in the pulling tests for the two trees that were subjected to repeated loading are close to the average values obtained for the trees that were only monotonically loaded. This demonstrates that a monotonic pulling test gives limited information on the actual mechanism by which windthrow occurs.

Conclusions

1. The dynamic forced rocking test caused high pore water pressures, hydraulic fracture and liquefaction of the soil in the double mouldboard plot. The tree tested in the mole-drained plot, despite being subjected to a more severe loading regime, showed only a small increase in pore water pressure in the soil, smaller sway and no failure of the soil was observed.
2. Mole drainage, at a depth of 0.45 m below ground surface, should be used on surface water gley soils for planting Sitka spruce trees, where slope and field conditions allow. This drainage encourages roots to grow to the depth of the drain resulting in an increase in root plate weight and a reduction in pore-water pressure build-up in the soil in windy conditions.
3. Monotonic pulling tests, which are widely used, do not simulate the conditions experienced by trees during windy conditions. The repeated forced loading tests clearly show that soil failure can be initiated at much lower overturning moments than the maximum overturning moment applied during monotonic pulling tests.
4. The study shows that the stability of slender structures founded on slow draining soils can be substantially improved by proper soil drainage.

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