International Conference « Wind Effects on Trees »
September 16-18, 2003, University of Karlsruhe, Germany

Root anchorage of Maritime pine (*Pinus pinaster* Ait.) growing in different soil conditions.

Cucchi, V.[1], Stokes, A.[1], Meredieu, C.[1], Berthier, S.[1-2], Najar, M.[3], Bert, D.[1]
[1]INRA URF – UMR LRBB, 69, route d'Arcachon 33 612 Cestas Gazinet, France.
cucchi@pierroton.inra.fr
[2]Forestry Commission Research Agency, Scotland, U.K.
[3]AFOCEL Sud-Ouest, France.

Abstract

Static winching tests were carried out in order to determine the mechanical resistance of Maritime pine to overturning. The selected stands were chosen over a wide range of ages and tree sizes, and grouped into two sets based on their typical soil conditions; wet Lande, characterised by the presence of a hardened iron pan horizon with a shallow ground-water table in winter, and dry Lande, where the iron pan can be absent or broken up and a deeper ground-water table. The iron pan horizon limits the vertical growth of tree roots.
The critical turning moment at the base of the stem was found to be positively related to [H x DBH^2] ($r^2 = 0.96$), stem weight ($r^2 = 0.95$), cube of diameter at breast height [DBH^3] ($r^2 = 0.94$) and certain root characteristics e.g. soil-root plate depth and volume.
Linear regression analyses between critical bending moment and [H x DBH^2], with regards to soil conditions, showed no significant differences between uprooting resistance for the trees growing on wet Lande compared to the dry Lande. However, allometric characteristics showed that trees on wet Lande have significantly a greater relative crown length and basal swept than those growing on dry Lande.
Modulus of rupture (MOR) calculated on trees broken during winching was 46% lower than the values obtained on green wood found in the literature. MOR does not differ significantly between dry Lande and wet Lande, but the results were highly variable.
These data on the mechanical behaviour of Maritime pine anchorage for conditions in Southwest France will allow the development of allometric relations in models which will be used to adapt ForestGALES: a wind risk assessment model developed by the Forestry Commission. ForestGALES predicts the return times of high winds able to overturn or break the average tree of a stand. The adapted model will constitute an expert system to estimate wind risks according to the dendrometric evolution of the stand.

Introduction

Monospecific stands of Maritime pine (*Pinus pinaster* Ait.) cover about 800.000 ha in the Aquitaine region, Southwest France, and are thus of great economic importance. This cultivation produces 16% of the national pulp and wood, even though it only covers 7% of forested land in France. In December 1999, the most violent hurricanes known since the establishment of this cultivated forest occurred. Wind devastated the northernmost part of the range and caused estimated losses of 26.1 million m^3 of wood, i.e. 19% of standing volume and 3.5 years of harvest (IFN, communication from the updated 4th Gironde and Landes inventory).
This study aims to characterise the resistance of root anchorage for Maritime pine growing in the two main soil conditions found in the Landes region. Anchorage strength of trees has been characterised by several authors using a static tree-pulling method (Fraser 1962,

Somerville 1979, Coutts 1986, Smith et al 1987, Fredericksen et al 1993, Papesch et al 1997, Ray and Nicoll 1998, Moore 2000, Peltola et al 2000, Meunier et al 2002). This method allows comparisons between species due to their different mechanical behaviour (Savill 1983, Peltola et al 2000). This behaviour could be explained by stem characteristics e.g. taper (Meunier et al 2002) or root system architecture and anchorage strength (Stokes 1999). From these static tests, the critical turning moment is calculated for each tree. Numerous authors have found a linear relationship between the critical turning moment and a variable of tree size e.g. stem weight (Fraser 1962, Somerville 1979, Papesch et al 1997, Gardiner et al 2000, Meunier et al 2002).

Soil type and conditions play an important role in tree anchorage (Fraser 1962, Stone and Kalisz 1991, Ray and Nicoll 1998), and yet have received relatively little attention in the past. In the Landes region, soil is a sandy podzol, and sites are classified into two types: in « wet Lande », vertical growth of tree roots is limited by a shallow ground-water table or by a hardened iron pan horizon at a depth of 0.5 – 1.0 m (Jolivet et al 1997, Trichet et al 1997). This horizon, formed by winter water logging, is fairly regular, and results in the formation of poorly anchored, shallow root-systems. In « dry Lande », the iron pan horizon is absent or broken up because of a deeper ground-water table. Consequently, tree root systems are able to penetrate deeper in the soil, thereby improving anchorage. Most damage resulting from the 1999 storm was due to the uprooting of trees, rather than from stem breakage.

By carrying out winching tests on a wide range of Maritime pine trees, this study investigated the following three points:

- which is the most effective relationship for predicting the critical turning moment for Maritime pine?
- using this relationship, do differences exist concerning the mechanical resistance of anchorage according to Lande type?
- can the allometric comparison of trees between the two Lande types can be linked to the critical turning moment?

Material and Methods

The « Landes de Gascogne » region is located in the Southwest of France. This region is flat. Mean annual precipitation is 930 mm, occurring mainly in the winter and spring months (Porté et al 2000). Prevailing winds are from the west to northwest with a mean wind-speed of 3.3 $m.s^{-1}$ (Stokes 1999).

In order to determine the mechanical behaviour of Maritime pine at different ages and in different soil conditions, the experiments were carried out at several sites in this region. Six stands were sampled and classified according to the predominant understorey species (*Molinia caerulea* for wet Lande, *Calluna sp.* for dry Lande) : four in wet Lande and two in dry Lande. These stands were chosen with tree age and size varying from stand to stand (Table 1).

In each stand, trees were selected to represent all the Diameter at Breast Height classes (DBH) in the stand. As it was difficult to take into account the flexuosity of Maritime pine stems, with regards to tree mechanical behaviour, only straight and leaning trees were chosen for this study. When leaning trees were selected, it was ensured that they leaned in the direction of the prevailing wind (SE). Trees were also single-stemmed with no apparent stem defects.

The winching system was similar to that used by Coutts 1986, Papesch et al 1997, Stokes 1999, Moore 2000, Peltola et al 2000, Meunier et al 2002. A motorised winch (Tirefor type Hit-Trac 16) was used with a 16 kN maximal strength capacity. For the larger trees a pulley was also used which doubled the winch capacity, and occasionally a 320 kN maximal strength capacity hand winch was utilised. The winch was attached to the base of an anchoring tree at the longest possible distance to the winched tree, in order to obtain a small angle θ between ground level and the cable. The nominal height of the cable attachment was 10 – 50% of the tree height, varying from tree to tree. This height was usually lower than a third – half of tree height (Moore 2000, Peltola et al 2000) and always lower than 80% height in order to maintain a uniform stress profile in the outer fibres (Wood 1995).

Table 1: Characteristics of each stand used in the study

Study site	Lande	Stand establishment	Tree age (years)	Number of tree/ha	Mean DBH (cm)	Mean height (m)
Eperville	Wet	Sown in bands	31	94	35.3	20.8
D. France	Wet	Planted	15	1133	17.6	11.3
Callen	Dry	Natural regeneration	50	127	38.7	25.2
Cameleyre	Wet	Sown in bands	49	383	39.7	23.2
Coyole	Dry	Natural regeneration	47	260	36.2	21.4
Luë	Wet	Sown in bands	29	427	25.8	18.8

Table 3: Number and characteristics of winched trees. Means are ± standard error

Study site	Winched	Uprooted	Broken	Date of winching	Mean DBH	Mean height
Eperville	6	5	1	6-8/03/02	38.4 ± 6.0	20.9 ± 1.3
D. France	11	9	2	29/03-9/04/02	18.1 ± 2.9	11.3 ± 1.2
Callen	14	10	4	12-18/04/02	41.0 ± 8.0	25.3 ± 1.4
Cameleyre	6	6	0	20-23/01/03	34.1 ± 7.2	21.4 ± 1.6
Coyole	7	6	1	23-28/01/03	26.7 ± 3.8	19.6 ± 2.1
Luë	11	10	1	10-12/03/03	26.1 ± 2.6	18.8 ± 1.5

Table 2: Measurements on the tested trees

On standing trees	Total height, of the first living branch	cm
	Girth at 1.30m, and at the stem base	mm
	Stem lean from the vertical at 0m and 1.50 m; Azimuth of lean	cm, °
On winched trees	Tree total length, to the first living branch, and to the cable point attachment	cm
	Stem girth every 1 m intervals	mm
	Distance from the stump to each whorl which must have at least one living branch	cm
	Basal diameter of each living branch	mm
	Crown area (see Fig. 1)	cm^2
	Total mass of all living branches (= crown biomass)*	kg
	Dimensions and mass of a one meter long section of trunk (= green wood density)*	$kg.m^{-3}$
On broken trees	Height between the stem base and the failure	cm
	Length of the broken part of the stem	cm
On soil-root plate of uprooted trees	Length of the four radii	cm
	Depth	cm
	Diameter of lateral roots on the windward edge	mm

* Measurements on at least 30% of the total number winched trees

The attachment height also had to be low enough in the stem to induce root failure instead of stem breakage. The tension applied to the winched tree was measured by a load cell attached between the winch and the anchoring tree, and recorded every second using a data logger type Almemo 2290-8 V5. Three different load cells used for experiments (Scaime type K25H – 50 kN, K25H – 20 kN and M11 – 50 kN) depending on the size of the tree, and which measured loads of up to 20 or 50 kN. In order to determine deflection angle α of the tree during the winching test, two inclinometers were tied to the tree, one at the cable attachment point, and the other at the base of the stem. The latter allowed soil-root plate rotation to be taken into account. Measurements of angle were recorded every second with a second identical data logger, synchronised and simultaneously activated with the load cell data logger. The distance between the test tree and anchoring point, as well as the cable height were measured. The compass direction of winching was also noted. Measurements on trees were taken before and after winching the tree sideways until failure (Table 2).

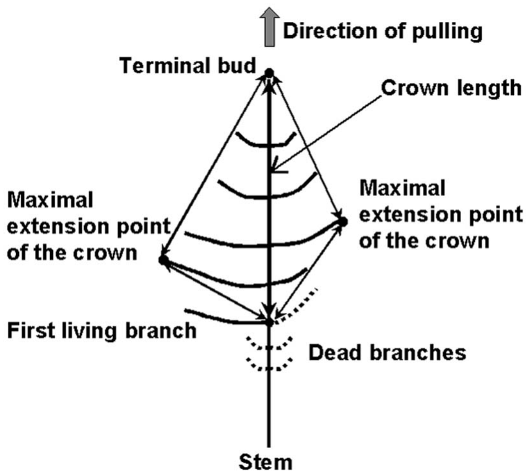

Fig. 1: Measurements of crown dimensions on winched trees. The crown area was calculated with trigonometric relationships using crown length and lengths of the quadrilateral's sides.

56 trees were pulled sideways until failure (Table 3), 35 in wet Lande and 21 in dry Lande. Tree winching was carried out during the winter and spring months, when the soil moisture was greatest. After each tree was winched over, several samples of soil between 150 and 200 cm^3 were removed from around and underneath the soil-root plate, in order to measure soil humidity. Each sample was immediately weighed, and then over dried at 105°c until a constant mass was reached. Dry mass was then measured and %weight loss calculated.

The force needed to cause failure of a tree was extracted from the recorded load data, associated with deflection values at the rupture time. The critical bending moment applied at the stem base was calculated according to Young 1972:

$$TM_{crit,applied} = F_x \times H_{cable} + F_y \times \sin\alpha \times H_{cable}$$

where F_x is the horizontal component and F_y the vertical component of the maximal applied force F (N), H_{cable} is the cable attachment height (= the lever arm, m) and α the deflection angle of the lever arm when the force is maximal. This angle is obtained from the values given by the inclinometers. F_x and F_y are deducted from the value of F (N) and the cable angle θ, which was derived from the distance between the tree winched and the anchoring tree distance, and the cable attachment height:

$$F_x = F \times \cos\theta \text{ and } F_y = F \times \sin\theta$$

The total critical turning moment $TM_{crit,total}$ at the stem base adds the critical bending moment applied by the winch to the critical turning moment $TM_{crit,weight}$ due to the force resulting from the overhanging weight of the leaning tree during winching. The weight of the winch and cable were neglected. Crown mass was measured or estimated by a relationship with DBH calibrated for each stand. Stem mass was estimated with the sum mass of one meter stem sections. Stem section mass was deduced from the green wood density measured for the tree or calculated for the stand. The stem section was assumed to be a truncated cone form. The Modulus of Rupture of the trees which failed in the stem was calculated (Petty and Worrell 1981) with the same hypothesis of stress in the outer fibres as Morgan and Cannell 1994. As the moment was applied at the height of failure, the cable attachment height is reduced by subtracting this height to compensate for the critical turning moment.

Using REG and GLM procedures of SAS software (SAS Institute, Inc., Cary, NC, USA), we performed Pearson correlations between $TM_{crit,total}$ and the characteristics of trees. The best relationship with $TM_{crit,total}$ was found by Stepwise Regression and differences between regressions according to soil type were tested by analysis of covariance. We also carried out analyses of variance in order to investigate differences in allometry and MOR between trees according to soil conditions.

Results

Only nine of the 56 trees failed in the stem. Failure occurred at ground level for four trees, at 4 - 10% of the height of the lever arm for four others (mean failure height = 7.2% ± 2.6) and at 28% for one tree. Four failures, in dry Lande, showed numerous lengthwise splits with no movement of the soil-root plate. Three stem failures in wet Lande showed breaks with movement of the soil-root plate also occurring. Only two failures, one in each type of Lande, showed a clean horizontal break indicating a defect in the wood.

Table 4: Significant Pearson correlation coefficients at 0.05 level between tree characteristics, soil moisture and $TM_{crit,total}$ (56 winched trees)

Variables	P value	R^2
DBH (cm)	0.001	+ 0.90
DBH^3 (cm^3)	0.001	+ 0.94
Tree height (cm)	0.001	+ 0.73
Stem taper [H/DBH]	0.001	- 0.51
[H x DBH^2] (cm^3)	0.001	+ 0.96
Depth of the soil-root plate	0.001	+ 0.65
Volume of the soil-root plate	0.001	+ 0.83
Vertical asymmetry of the soil-root plate gravity centre	0.073	+ 0.39
Horizontal asymmetry of the soil-root plate gravity centre	0.230	+ 0.25
Total cross area of the lateral roots measured (m^2)	0.010	+ 0.42
Stem weight (kg)	0.001	+ 0.95
Crown weight (kg)	0.001	+ 0.92
Basal sweep (degrees)	0.060	- 0.26
Soil moisture	0.750	< 0.01

These correlations are linked to tree size. If variables are standardised, then no relation is significant.
Using stepwise regression the variable [H x DBH^2] was found to be the best variable to explain the variability of $TM_{crit,total}$.

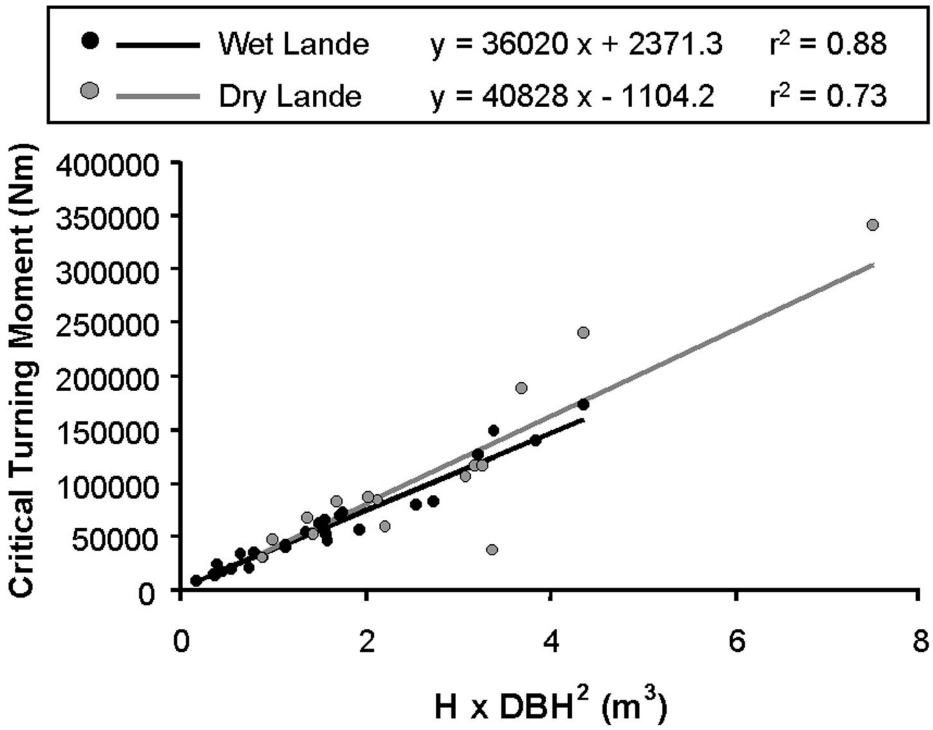

Fig. 2: Regressions between Critical Turning Moment and [H x DBH^2]. Lines show weighted regressions performed by SAS software for the two soil conditions (n = 45 uprooted trees).

Linear regression between $TM_{crit,total}$ and [H x DBH^2] allowed a comparison of the mechanical behaviour of root anchorage of Maritime pine according to soil conditions (Fig. 2). The two regression intercepts were not forced through zero in order to not influence the slope values for the covariance analyses. Regressions were weighted in order to assume the homogeneity of the residuals at 0.01 level (Levene test and t test) and compare the two slopes according to soil conditions. The value of each point was weighted by the [H x DBH^2] classes. Covariance analysis showed no effect of soil condition on TMcrit,total ($p = 0.69$ for slopes comparison and $p = 0.74$ for intercepts).

Some characteristics of the soil-root plates were related to $TM_{crit,total}$ residuals in order to explain the residual variability of anchorage resistance. No significant correlations with soil-root plate dimensions, total cross-area of the lateral roots or root number were found. Moreover, variability of $TM_{crit,total}$ was not related to the presence of a tap root.

Allometric differences according to soil conditions were tested by variance analysis (Table 5). The relative crown length was longer in wet Lande compared to dry Lande, hence the repartition of aerial weight between the stem and crown was different. Tested trees in wet Lande showed a higher basal sweep. Initial lean of the trees was not significantly correlated to DBH. Soil moisture depended both on soil conditions and on dates of winching tests (“date” effect highly significant, $p < 0.001$). These values showed low soil humidity, apart from Eperville (15.7 ± 5.0%).

Table 5: Allometric characteristics of trees according to soil type. Variables showing a significant relationship to tree size were used as relative (*). The “+” assigned to horizontal and vertical asymmetries of soil-root plates corresponds to a centre of gravity offset to the south and east respectively. Values indicate the percentage of offset respectively relative to the soil-root plate width and height. Means with the same letter do not differ significantly at the 0.05 level as indicated by Analysis of Variance and Bonferroni groups.

Lande	Wet		Dry	
Variable	Mean	SD	Mean	SD
Relative length of crown (%)	44.4 a	± 12.6	30.3 b	± 4.2
Basal sweep (°)	7.4 a	± 4.2	4.7 b	± 3.6
Basal rotation at critical point of uprooting (°)	5.4 a	± 5.4	1.7 a	± 1.4
Vertical asymmetry of soil-root plate	+ 7.7 a	± 7.7	+ 4.5 a	± 9.6
Horizontal asymmetry of soil-root plate	+ 0.8 a	± 6.5	- 1.7 a	± 5.9
Stem weight*/Total tree weight ratio	0.82 a	± 0.06	0.86 a	± 0.03
Crown weight*/ Total tree weight ratio	0.18 a	± 0.06	0.14 a	± 0.03
Rooting depth*/DBH ratio	2.52 a	± 0.63	2.74 a	± 0.73
Soil-root plate volume*/Stem volume ratio	2.68 a	± 0.89	1.99 a	± 0.88
Total area of lateral root cross-sections*/Soil-root plate area ratio	0.31a	± 0.26	0.31a	± 0.23
Soil moisture (%)	10.4 a	± 4.6	6.5 b	± 2.0

Modulus of Rupture calculated on trees which failed in stem during winching did not differ significantly between wet and dry Lande ($p = 0.072$; homogeneity of variance respected at 0.05 level, Levene test $p = 0.11$). Mean MOR of the nine broken trees was 18.99 ± 6.17 MPa, with 13.17 MPa as minimum and 34.20 MPa as maximum. MOR on standing trees represented 53% of the theoretical MOR (clear green wood = 36 MPa).

Discussion

The use of winching to carry out bending tests on trees is a useful technique to compare the strength of root anchorage, even though this method does not accurately simulate wind loading, due to the lack of dynamic sway (Oliver and Mayhead 1974). Furthermore, O'Sullivan and Ritchie 1993 did not find any differences in anchorage strength between cyclic and static loading, nor did Coutts 1983 find differences in the type of damaged roots between winched or windblown trees.

As found by Fraser 1962, Somerville 1979, Papesch et al 1997, Gardiner et al 2000, Meunier et al 2002, $TM_{crit,total}$ was correlated to tree size, and particularly to stem weight or stem volume. For Maritime pine trees the stem volume expression [H x DBH^2] was the best predictive variable, as also found by Moore and Quine 2000 for *Pinus radiata*. Using [H x DBH^2], limits errors due to stem weight estimation and also allows the use of typical variables which can be measured directly in the field.
Fraser 1962 found that the drainage for *Picea sitchensis* and *Pseudotsuga taxifolia* increased $TM_{crit,total}$. The author linked the rooting depth to the mechanical resistance of anchorage. The vertical root growth of Maritime pine is also affected by the drainage and the presence of an iron pan horizon (Danjon et al 1999). In this study, for Maritime pine trees with same dimensions in height and DBH, the $TM_{crit,total}$ was not modified according to the type of Lande. No differences in rooting depth between the two Landes were observed. In dry Lande, as in wet Lande, the iron pan horizon could be present locally, therefore resulting in highly variable rooting depths. Furthermore, in dry Lande, we observed only quite shallow rooting depths (1.5 m max. for a 56 year old tree) similar to that found in wet Lande. For these silvicultural conditions, the presence of tap root was not related to the anchorage resistance for the oldest trees. Moreover, for the anchorage strength, the size of the tap root was small compared to tree size.
Nevertheless, even if we did not observe a difference in anchorage resistance between the two types of Landes, the number of trees which failed in the stem and the different failure types showed that some trees growing in dry Lande were better anchored than trees growing on wet Lande. As the MOR was not different between the two Landes and the size of the broken trees did not differ compared to the uprooted trees, the trees which failed in the stem with lengthwise splits may have possessed better anchored root systems.

The curves of tree mechanical behaviour show a critical loading point reached at the beginning of the winching test, when the stem lean was small, particularly in the oldest trees. As this critical loading point, the turning moment due to tree weight represents a mean of $8.6 \pm 5\%$ of the $TM_{crit,total}$ as also shown by Papesch et al 1997 for *Pinus radiata*. We can assume that this $TM_{crit,total}$ is explained by the strength of the lateral roots on the windward side of the tree. Mickovski and Ennos 2002 showed that in Scots pines growing on clay soil the tap and sinker roots represented the major components of anchorage. Even if Scots pine can be considered a species similar to Maritime pine, the rooting depth is limited in the Landes, therefore the lateral roots could play a major role in anchorage strength. We did not observe any correlation between $TM_{crit,total}$ residuals and the total area of lateral root cross-sections, however more accurate characteristics of these roots (e.g. I and T beam taper or architectural characteristics) would be more useful in highlighting the strength of these roots.

The relation $TM_{crit,total}$ versus [H x DBH^2] could be used in mechanistic models predicting wind risk (Gardiner et al 2000). ForestGALES© is one of these mechanistic models already implemented as a software. In order to use ForestGALES© as a forest management tool, we plan to include Maritime pine as a new species, along with various silvicultural conditions, in much the same way as Ruel et al (2000) working with *Abies balsamea*.

Acknowledgements

This research was supported by GIP ECOFOR (contract n° 2002.09). The authors thank E. Borg, B. Issenhuth, H. Lataillade, H. Bignalet , N. Cheval, (INRA, UE Hermitage, France), M. Chassagne (UMR LRBB, Bordeaux, France), J.Y. Fraysse (Afocel Sud-Ouest, France) for their helpful assistance with fieldwork; A. Denis and R. Lastennet (CDGA, Bordeaux, France) for their aid with soil measurements and T. Fourcaud (UMR LRBB, Bordeaux, France) for his comments and critique of this study.

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