ECO- AND GROUND BIO-ENGINEERING: THE USE OF VEGETATION TO IMPROVE SLOPE STABILITY
Eco- and Ground Bio-Engineering: The Use of Vegetation to Improve Slope Stability

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ALEXIA STOKES
IOANNIS SPANOS
JOANNE E. NORRIS

and

ERIK CAMMERAAT

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Cover photo:
The Finite Element Method was used to calculate the strength of tree root anchorage, with a digitized Maritime pine (*Pinus pinaster* Ait.) root system shown here as an example (data from F. Danjon, INRA). This numerical method was not only used on real root systems, but also applied to simulated schematic root patterns. These theoretical investigations provided information concerning various aspects of tree anchorage mechanics, with regard to both root morphology and soil characteristics. It was shown for instance that the soil type significantly modifies the mode of failure of the root/soil plate. It was also demonstrated that, for a given total root biomass, heart-root systems are the most resistant pattern in clay-like soil and tap-root anchorage efficiency is higher in sandy-like soil.

*Printed on acid-free paper*
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Preface

In an era where climate change, natural catastrophes and land degradation are major issues, the conservation of soil and vegetation in mountainous or sloping regions has become an international priority. How to avoid substrate mass movement through landslides and erosion using sustainable and ecologically sound techniques is rapidly becoming a scientific domain where knowledge from many different fields is required. These proceedings bring together papers from geotechnical and civil engineers, biologists, ecologists and foresters, who discuss current problems in slope stability research, and how to address those problems using ground bio- and eco-engineering techniques. A selection of papers were previously published in Special Editions of Plant and Soil (2005), volume 278, 1–179, and in the Journal of Geotechnical and Geological Engineering (2006), volume 24, 427–498.

Ground bioengineering methods integrate civil engineering techniques with natural materials to obtain fast, effective and economic methods of protecting, restoring and maintaining the environment whereas eco-engineering has been defined as a long-term ecological strategy to manage a site with regard to natural or man-made hazards. Studies on slope instability, erosion, soil hydrology, mountain ecology, land use and restoration and how to mitigate these problems using vegetation are presented by both scientists and practitioners. Papers encompass many aspects of this multidisciplinary subject, including the mechanisms and modelling of root reinforcement and the development of decision support systems, areas where significant advances have been made in recent years.

Alexia Stokes
Ioannis Spanos
Joanne Norris
Erik Cammeraat
Mechanisms and modelling of root reinforcement on slopes
The influence of cellulose content on tensile strength in tree roots

Marie Genet¹,⁸, Alexia Stokes¹, Franck Salin², Slobodan B. Mickovski¹,³, Thierry Fourcaud¹,⁴, Jean-François Dumail⁵ & Rens van Beek⁶,⁷

¹Laboratoire de Rhéologie du Bois de Bordeaux, (Mixed Unit: INRA/CNRS/Université Bordeaux I) Domaine de l’Hermitage, 69, rte d’Arcachon, 33612, Cestas Cedex, France. ²INRA, Equipe de Génétique et Amélioration des Arbres Forestiers, UMR BIOGECO, 69, rte d’Arcachon, 33612, Cestas Cedex, France. ³Civil Engineering Division, School of Engineering and Physical Sciences, University of Dundee, DD1 4HR, Dundee, UK. ⁴AMAP-CIRAD AMIS, TA 40/PS2 Cedex 5, 34398, Montpellier, France. ⁵XYLOMECA, 41, rue Michel de Montaigne, 24700, Moulin Neuf, France. ⁶Institute for Biodiversity and Ecosystem Dynamics – Physical Geography, University of Amsterdam, Nieuwe Achtergracht 166, NL 1018 WV, Amsterdam, The Netherlands. ⁷Department of Physical Geography, Utrecht University Heidelberglaan, 110, P.O. BOX 80.115, NL-3508, TC, Utrecht, The Netherlands. ⁸Corresponding author*

Key words: biomechanics, Castanea sativa Mill., Pinus pinaster Ait., root reinforcement, slope stability, soil fixation

Abstract

Root tensile strength is an important factor to consider when choosing suitable species for reinforcing soil on unstable slopes. Tensile strength has been found to increase with decreasing root diameter, however, it is not known how this phenomenon occurs. We carried out tensile tests on roots 0.2–12.0 mm in diameter of three conifer and two broadleaf species, in order to determine the relationship between tensile strength and diameter. Two species, Pinus pinaster Ait. and Castanea sativa Mill., were then chosen for a quantitative analysis of root cellulose content. Cellulose is responsible for tensile strength in wood due to its microfibrillar structure. Results showed that in all species, a significant power relationship existed between tensile strength and root diameter, with a sharp increase of tensile strength in roots with a diameter < 0.9 mm. In roots > 1.0 mm, Fagus sylvatica L. was the most resistant to failure, followed by Picea abies L. and C. sativa., P pinaster and Pinus nigra Arnold roots were the least resistant in tension for the same diameter class. Extremely high values of strength (132–201 MPa) were found in P abies, C. sativa and P. pinaster, for the smallest roots (0.4 mm in diameter). The power relationship between tensile strength and root diameter cannot only be explained by a scaling effect typical of that found in fracture mechanics. Therefore, this relationship could be due to changes in cellulose content as the percentage of cellulose was also observed to increase with decreasing root diameter and increasing tensile strength in both P pinaster and C. sativa.

Introduction

The use of vegetation by civil engineers when dealing with unstable slopes has become increasingly popular over the last 20 years (Bischetti et al., 2005; Coppin and Richards, 1990; Gray and Sotir, 1996; Greenway, 1987; Norris, 2005; Roering et al., 2003; Schiechtl, 1980). In particular, trees and woody shrubs have been studied with regards to the soil reinforcing properties that their root systems convey to slopes subject to erosion or slippage problems (Schmidt et al., 2001; Wu, 2007). If the root system characteristics, which govern soil stabilisation, could be better identified, screening of suitable species for use on unstable slopes would be more efficient. Vegetation has been recognised as a factor useful for increasing the shear resistance of soil on an unstable slope (Anderson and Richards, 1987; Coppin and Richards, 1990; Operstein and Frydman, 2000). The major factors which influence the shear resistance of root-permeated soil are the quantity and directional

* E-mail: genet@lrbb3.pierroton.inra.fr, stokes@liama.ia.ac.cn

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distribution of roots as well as their tensile strength, soil shear strength and soil–root interaction. Strength is the maximum force per unit area required to cause a material to break (Niklas, 1992). Tensile strength is considered one of the most important factors governing soil stabilisation and fixation, and has therefore been studied in great detail (Burroughs and Thomas, 1977; Hathaway and Penny, 1975; Nilaweera and Nutralaya, 1999; Operstein and Frydman, 2000; Phillips and Watson, 1994; Schiechtl, 1980). Not only is root tensile strength important when considering soil reinforcement, but can also affect plant anchorage. In herbaceous species, plants must withstand grazing pressure, whereby uprooting occurs in tension, therefore a higher root tensile strength will enable the plant to remain anchored in the soil (Ennos and Fitter, 1992). In trees, most anchorage is provided by the large structural roots (Stokes, 2002); however, the roots held in tension provide around 60% of the resistance to overturning during a storm (Coutts, 1983). Therefore, a greater root tensile strength will also be beneficial for tree anchorage.

Wide variations in root tensile strength have been reported in the literature, and appear to depend on species and site factors such as the local environment, season, root diameter and orientation (Gray and Sotir, 1996). Root resistance to failure in tension can be influenced by the mode of planting e.g. naturally regenerated Scots pine (Pinus sylvestris L.) had stronger roots than those of planted pines (Lindström and Rune, 1999). The time of year has also been found to affect tensile strength, roots being stronger in winter than in summer, due to the decrease in water content (Turmanina, 1965). Tensile strength usually decreases with increasing root size (Burroughs and Thomas, 1977; O’Loughlin and Watson, 1979; Operstein and Frydman, 2000; Turmanina, 1965; Wu, 1976) and this phenomenon has been attributed to differences in root structure, with smaller roots possessing more cellulose per dry mass than larger roots (Commandeur and Pyles, 1991; Hathaway and Penny, 1975; Turmanina, 1965).

The structure of cellulose has been found to be optimal for resisting failure in tension (Sjostrom, 1993). Cellulose is made up of polymer chains consisting of glucose units which are linked together by highly resistant hydrogen bonds (Delmer and Amor, 1995). These cellulose chains are then grouped together in a hemicellulose matrix and the entire structure is termed a microfibril. Each layer of the wood cell wall is made up of many microfibrils arranged in a helical structure.

In order to determine the relationship between tensile strength for a range of species and root size, mechanical tests were carried out on small roots from three conifer and two broadleaf species. To relate the root strength to the cellulose content, two species were then chosen for subsequent dosing of percentage cellulose in those roots tested mechanically. Results are discussed with regards to the structure of cellulose.

### Materials and methods

#### Plant material

Roots with a diameter between 0.2 and 12.0 mm were collected from five tree species (Table 1). Trees were situated throughout different parts of France (Table 1). Roots of Maritime pine, Austrian pine and Sweet chestnut were collected in France, while roots of European Beech, Norway spruce and Sweet chestnut were collected in Isère.

<table>
<thead>
<tr>
<th>Species common name and Latin name</th>
<th>Location where collected in France</th>
<th>Number of trees</th>
<th>Min.–Max. Height (m)</th>
<th>Min.–Max. DBH (m)</th>
<th>Total number of roots sampled</th>
<th>Number of roots successfully tested</th>
</tr>
</thead>
<tbody>
<tr>
<td>Austrian pine (Pinus nigra Arnold)</td>
<td>Gironde</td>
<td>2</td>
<td>15.3–17.6</td>
<td>0.3–0.49</td>
<td>85</td>
<td>30</td>
</tr>
<tr>
<td>Maritime pine (Pinus pinaster Ait.)</td>
<td>Gironde</td>
<td>2</td>
<td>33.0–36.2</td>
<td>0.28–0.4</td>
<td>81</td>
<td>34</td>
</tr>
<tr>
<td>Norway spruce (Picea abies L.)</td>
<td>Isère</td>
<td>3</td>
<td>10.7–14.6</td>
<td>0.19–0.26</td>
<td>91</td>
<td>27</td>
</tr>
<tr>
<td>European Beech (Fagus sylvatica L.)</td>
<td>Isère</td>
<td>2</td>
<td>15.7–17.8</td>
<td>0.18–0.27</td>
<td>35</td>
<td>11</td>
</tr>
<tr>
<td>Sweet chestnut (Castanea sativa Mill.)</td>
<td>Gironde</td>
<td>2</td>
<td>NA</td>
<td>NA</td>
<td>202</td>
<td>53</td>
</tr>
</tbody>
</table>

NA—not available as trees were coppiced.
chestnut were collected from a sandy podzol soil in Gironde, located in SW France (Cucchi et al., 2004). Trees were growing at an altitude of 58 m in a flat region, where mean annual precipitation is 990 mm. Norway spruce and Sweet chestnut roots were sampled in the Forêt domaniale de Vaujany, Isère, in the French Alps. This forest, which is located at an altitude of 1350–1600 m, has a slope gradient of 38–42°. The soil is a crystalline soil and mean annual precipitation is 1353 mm (Stokes et al., 2005). Species were chosen in such a way as to cover a broad range of roots to test from both conifer and broadleaf trees. Roots were collected from two or three trees for each species (Table 1).

Live roots were manually excavated to a depth of about 0.6–0.7 m below the soil surface. Care was taken to avoid any damage to roots during the excavation process. Samples were collected randomly from the root system in order to have representative samples of different types of roots. Once the roots had been removed from the tree, they were put into separate bags and taken to the laboratory where they were stored at 4 °C. Mechanical testing was carried out as soon as possible, always within 1 week from sampling, to ensure that root material was still fresh.

Root tensile tests

Tensile testing was carried out on 494 root samples, using a Universal Testing machine (ADAMEL Lhomargy, France). The length of each sample was at least 15 times its central diameter. A load cell with a maximal capacity of 1.0 kN was used to measure the force required to cause failure in tension of each root. Crosshead speed was kept constant at 2.0 mm min⁻¹ and both force and speed were measured constantly via a PC during each test. In order to avoid slippage of roots out of the clamps (Nilaweera and Nutalaya, 1999), thin slices of cork were inserted between the jaws and the root. The cork helped to improve the grip between the jaws and the root. Tests were considered successful only when specimens failed approximately in the middle of the root so that root rupture was due to the force applied in tension and not due to any existing damage (Table 1).

Tensile strength was calculated as the maximal force required to cause failure in the root, divided by the root cross-sectional area at the point of breakage. The diameter of each root was measured with an electronic slide gauge with 1/50 mm accuracy.

Cellulose content

Two contrasting species were chosen for consequent measurements of cellulose content: Maritime pine and Sweet chestnut. The method used to measure total cellulose content was based on that developed by Leavitt and Danzer (1993) and consisted of removing as many non-cellulosic compounds as possible from the root material. Initially, bark was removed from each root using a scalpel. The roots were then dried at 60 °C for 24 h and weighed using a balance with a precision >0.001 mg. Each root was then ground into a fine powder with a vibration mill (Retsch MM 300). This powder was poured into a Teflon sachet (no. 11803, pore size 1.2 μm), and each bag was carefully marked with the identification code of the corresponding root. Teflon sachets were used because they have a good compatibility with strong acids and solvents and are resistant to heat with inflammable temperatures around 200 °C (Lambrot and Porté, 2000).

The first compounds removed from the ground root tissue were lipids (waxes, oils and resins). Each sample was placed into a soxhlet extractor (50-mm i.d., 200-mL capacity to siphon top) equipped with a flask containing a 700-mL mixture of toluene 99%–ethanol 96% (2–1; v/v) heated until boiling point. After 24 h of extraction using this method, the toluene ethanol was replaced with 700 mL of ethanol heated to the same temperature. After 24 h, the samples were removed from the soxhlet and immersed in distilled water heated to 100 °C for 6 h. This process removes hydrosoluble molecules from the sample.

The final step consisted of eliminating lignin compounds from the samples. Each sample was placed in a beaker containing 700 mL of distilled water, 7.0 g of sodium chlorite (NaClO₂), and 1.0 mL of acetic acid (C₂H₄O₂). The samples and solution was shaken using a magnetic agitater and heated to 60–70 °C during 12 h. This procedure was repeated three times, with the solution concentrated by 100% each time. The samples were then removed and rinsed in distilled water, dried at ambient temperature during 12 h and weighed. The percentage of cellulose was evaluated by calculating the relative difference in the initial and final weight of each sample.

Statistical analyses

Linear and power regressions were carried out initially to evaluate the correlation between the different
variables. A Kolmogorov–Smirnov test was used to test the normality of the data before proceeding with analyses of variance. Data were log-transformed, before analysis, to reflect the power relationship in linear regressions. To evaluate the influence of species, diameter of roots and cellulose content on tensile strength of roots, analysis of covariance (ANCOVA) and analysis of variance (ANOVA) were used. ANCOVA was used to detect differences in cellulose content of roots between species with regards to root diameter. In order to evaluate the influence of species on tensile strength only, roots were then classed into two groups according to diameter (<0.9 mm and >1.0 mm) and a Student’s \( t \)-test was carried out to detect differences in tensile strength between the two groups. These data were then analysed with ANOVA and pair wise Tukey’s Studentized Range (HSD) test in order to determine differences between species. Data were analysed with Minitab version 13 or XLstat-Pro version 7.5 software.

Results

Root tensile tests

Only 33% of the tensile tests were successful (Table 1). Failure often occurred near the jaws, or roots slipped out of the clamps. Mean root tensile strength was significantly different between species (\( F_{4,152} = 15.16, p < 0.001, \) ANCOVA) with regards to root diameter (\( F_{1,155} = 113.01, p < 0.001, \) ANCOVA). Mean root strength was 28.4 ± 2.0 MPa when all species and diameters were considered together (means are ± standard error). A power regression between tensile strength and diameter was significant for all species (Table 2, Figure 1). Tensile strength was also significantly different between root size classes (\( t = 5.49, p < 0.001 \)). For roots <0.9 mm, mean tensile strength for each species was greater than for roots >1.0 mm but variability was high (Figure 1). However, when root size classes were analysed individually, no significant differences were found between species for roots <0.9 mm (ANOVA). Nevertheless, extremely high values of strength (132–201 MPa) were found in Norway spruce, Maritime pine and Sweet chestnut, for this size class of roots (Figure 1). For roots >1.0 mm, the tensile strength of roots was significantly different between species (\( F = 10.17, p < 0.001, \) ANOVA/HSD). Within this root size class, European beech was found to be the most resistant to failure in tension, followed by Norway spruce and Sweet chestnut. Maritime pine and Austrian pine roots were the least resistant in tension for the same diameter class.

Table 2. Parameters of the root tensile strength and diameter power law regressions for each tree species tested

<table>
<thead>
<tr>
<th>Species</th>
<th>Regression Equation</th>
<th>( R^2 )</th>
<th>( p )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Austrian pine</td>
<td>( y = 18.40x^{-0.52} )</td>
<td>0.23</td>
<td>0.010</td>
</tr>
<tr>
<td>Maritime pine</td>
<td>( y = 23.40x^{-0.87} )</td>
<td>0.51</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Norway spruce</td>
<td>( y = 37.86x^{-0.51} )</td>
<td>0.43</td>
<td>0.005</td>
</tr>
<tr>
<td>European Beech</td>
<td>( y = 63.51x^{-0.61} )</td>
<td>0.56</td>
<td>0.006</td>
</tr>
<tr>
<td>Sweet chestnut</td>
<td>( y = 31.92x^{-0.73} )</td>
<td>0.51</td>
<td>&lt;0.001</td>
</tr>
</tbody>
</table>

Figure 1. Tensile strength increased significantly with decreasing diameter when roots of Sweet chestnut, European beech, Maritime pine, Austrian pine and Norway spruce were considered together (\( y = 28.97x^{-0.32}, R^2 = 0.30, p < 0.001 \)).
Maritime pine and Sweet chestnut roots were chosen for subsequent dosing of cellulose content, as a higher number of samples were available across the entire diameter range. The mean cellulose content was 60.0 ± 2.2% in Sweet chestnut roots and 69.9 ± 2.3% in Maritime pine roots. Cellulose content of roots was significantly different according to diameter ($F_{1,68} = 49.8$, $p < 0.001$, ANCOVA) but was not different between the two species ($F_{1,68} = 0.32$, $p = 0.58$, ANCOVA). As with tensile strength, a significant linear relationship existed between cellulose content and root diameter for both Sweet chestnut (Figure 2) and Maritime pine ($y = -13.49 + 81.87$, $R^2 = 0.34$, $p < 0.001$). Root tensile strength was also significantly related to cellulose content; however, variability was high in both Sweet chestnut (Figure 3) and Maritime pine ($y = 0.95x - 24.48$, $R^2 = 0.17$, $p = 0.026$).

Figure 2. Tensile strength (white squares, Table 2) and cellulose content (black squares, $y = -9.44x + 77.59$, $R^2 = 0.43$, $p < 0.001$) decreased significantly with increasing root diameter in roots of Sweet chestnut.

Figure 3. Tensile strength was significantly and positively related to percentage cellulose in roots of Sweet chestnut ($y = 0.56x - 9.45$, $R^2 = 0.34$, $p < 0.001$).
Discussion

Results from the tensile testing of roots were comparable to those of other authors on woody species, in that a power equation existed between diameter and tensile strength (Burroughs and Thomas, 1977; Gray and Sotir, 1996; Nilaweera and Nutalaya, 1999; O’Loughlin and Watson, 1979; Operstein and Frydman, 2000; Turmanina, 1965; Wu, 1976). The smallest roots were the most resistant in tension, and strength increased sharply with a decrease in root diameter <0.9 mm. Tensile strength differed between the species tested, for roots >1.0 mm, with beech being the most resistant, followed by Norway spruce, Sweet chestnut, Maritime and Austrian pine. Values for roots >1.0 mm are similar to those reported in previous studies for Maritime pine and Norway spruce (Bischetti et al., 2005; Turmanina, 1965). For roots <0.9 mm, no significant differences in tensile strength between species were observed, probably due to the low number of samples available. A comparison with other studies is not possible since, to our knowledge, no other studies exist concerning the tensile strength of such small roots for any of the species tested. The strength values of 132–201 MPa observed in Norway spruce, Maritime pine and Sweet chestnut were surprising, as such high values have rarely been documented in the literature. These results may be due to the fact that such small tree roots are rarely tested. To our knowledge, only Operstein and Frydman (2000) and Bischetti et al. (2005) have carried out tensile tests on small diameter roots. In the species tested by Operstein and Friedman (2000), only woody shrubs were measured and values were always lower than 80 MPa. However, Bischetti et al. (2005) also found extremely high values in roots 0.2–0.5 mm in diameter. These authors observed tensile strength values up to 750 MPa in several tree species, including beech and Norway spruce located in the Prealps. Therefore, strength values tend to lie within the range typical of that usually reported for tree roots (Schiechtl, 1980; Stokes, 2002; Ziemer, 1981) with the only exceptions being for very small diameter roots. It would be of extreme interest to carry out more testing of such small diameter roots, and to determine why tensile strength values may be so high in certain roots.

Not only is root tensile strength an important parameter to consider when determining the influence of vegetation on slope reinforcement (Greenwood et al., 2001), but is also an important factor with regards to tree anchorage (Coutts, 1983). It would therefore be interesting to relate root tensile strength to tree resistance to overturning. Winching tests were carried out on Norway spruce and European beech by Stokes et al. (2005) on the same trees where root samples were collected for our study. Trees were winched sideways and the force necessary to cause failure was measured. The critical turning moment $TM_{crit}$ was then calculated (Cucchi et al., 2004). Results showed that European beech was significantly more resistant to overturning than Norway spruce. As the tensile strength of beech roots >1.0 mm was higher than that of Norway spruce roots, it may be assumed that this mechanical property plays an important role in tree resistance to overturning. It would be of extreme interest to study in detail the correlation between $TM_{crit}$ and root tensile strength in order to evaluate the importance of this parameter on tree anchorage.

A power relationship, $\sigma_n \approx d^{-a}$, with $\alpha \geq 0.5$, existed between root tensile strength $\sigma_n$ and diameter $d$. This type of relation is well known in fracture mechanics as a size effect between small and large samples (Bazant and Kazemi, 1990). The size effect is transitional between two asymptotic behaviors. There is no size effect for small dimensions of structures. For bigger dimensions a power relationship exists between the nominal strength $\sigma_n$ and a characteristic dimension of the structure, e.g. the root diameter $d$, $\sigma_n \approx d^{-a}$ which is the size effect exhibited by Linear Elastic Fracture Mechanics (Bazant and Kazemi, 1990). Therefore the exponent $\alpha$ cannot be greater than 0.5. However, our results show that this exponent exceeded systematically this maximum theoretical value. This was also the case in previous studies on root tensile strength (Bischetti et al., 2005; Gray and Sotir, 1996; Operstein and Frydman, 2000). These differences between theoretical and experimental equations could be due to experimental error, but the estimated exponent value always overestimated the maximum theoretical exponent value. Another possible explanation for our results is that the wood material is different according to root size. This assumption was confirmed by the observed change in cellulose content between the samples.

The quantity of cellulose was found to differ significantly between roots of different sizes as well as between Sweet chestnut and Maritime pine. When both species were considered together, the mean cellulose content of roots was 65%. The mean percentage
cellulose in roots was therefore in the same range as other values found in the literature, e.g. Hathaway and Penny (1975) found that mean cellulose percentage in roots of six *Populus* and *Salix* species was 72%. Cellulose quantity and tensile strength of roots were significantly correlated but variability was high. In our study, cellulose content was measured using the method developed by Leavitt and Danzer (1993). In this method, hemicelluloses, which are polysaccharides linked to the cellulose present in the cell walls, were not separated from the crystalline cellulose. The quantity obtained at the end of the experiment represents therefore both cellulose and hemicelluloses. The amount of hemicelluloses of the dry weight of wood is usually around 20%. Hathaway and Penny (1975) separated hemicelluloses and crystalline cellulose. These authors found that hemicelluloses represent 17% of the dry weight of wood in roots studied. However, the hemicellulose content and composition differs between species (Sjostrom, 1993). The changes in these proportions may therefore be able to explain the high variability observed in our results. A further experiment whereby only crystalline cellulose was measured would help determine the influence of cellulose content on wood tensile strength (Akerholm et al., 2004; Andersson et al., 2003). Other chemical and anatomical parameters, which can influence tensile strength of roots, should explain the high variability observed. Lignin can also affect strength properties, especially at high moisture contents (Hathaway and Penny, 1975). The microfibril angle in root wood may also influence mechanical properties (Kerstens et al., 2001). When these microfibrils are aligned at an angle almost parallel to the cell axis, as in young wood, the combined effect of these cellulose chains is a high resistance in tension, but a low bending strength (Archer, 1986; Sjostrom, 1993). Thus, future work should concentrate on the influence of microfibril angle and lignin/cellulose ratio on tensile strength of roots.

Although cellulose content and tensile strength increases with decreasing root diameter, no measurements of annual growth rings were made in the roots studied, therefore the age of each root remains unknown. It can be imagined that cellulose content is higher in young roots, which are more resistant in tension, but this assumption should be verified through measurements of root age.

Differences in cellulose content have been proposed as the major determinant governing root tensile strength (Commandeur and Pyles, 1991; Turmanina, 1965). Nevertheless, the shape and size of a root system is influenced by its immediate environment as well being inherent to a particular species (Köstler et al., 1968). For example, trees growing on slopes may develop a specific type of root system architecture, as the mechanical function of the uphill portion of the root system is different to that downhill (Chiatante et al., 2003; Köstler et al., 1968; Shrestha et al., 2000). Root system morphology can also be modified by soil type. Nutrient supply, fertility and soil acidity all influence root growth (Fitter and Stickland, 1991; Gersani and Sachs, 1992; Gruber, 1994). Soil physical properties such as soil bulk density and strength are also important factors affecting both shoot and root growth (Campbell and Hawkins, 2003; Goodman and Ennos, 1999). In our study, samples were collected from two different habitats. As root morphology is affected by local environment and since root chemical composition also varies with root morphology, it may be possible that the local environment also influenced root cellulose content. More studies on the differences in root tensile strength of species from the same site are therefore necessary. It would also be of interest to compare the tensile strength of roots from trees growing on different types of slope or in different soil conditions, as well as testing cellulose content and tensile strength in roots around a tree, and to compare up- and down-hill roots growing on a slope (Schiechtl, 1980). Not only can cellulose content be assumed to differ between roots in a root system, but the role of this chemical compound in the overall anchorage of a root system needs to be determined, especially in young trees or woody shrubs. It has generally been assumed that root architecture is the principal component in resisting uprooting of a plant (Ennos, 2000; Dupuy et al., 2005a,b; Hamza et al., 2006; Stokes et al., 2000). However, a highly branched root system will probably not have the same percentage cellulose as a root system with fewer but thicker branches. The role each parameter plays in resisting uprooting therefore needs to be investigated.

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References


Novel biomechanical analysis of plant roots

O. Hamza¹,², A.G. Bengough², M.F. Bransby¹, M.C.R. Davies¹, C. Halpin³ & P.D. Hallett²,⁴
¹Division of Civil Engineering, University of Dundee, Dundee, DD1 4HN, Scotland. ²Scottish Crop Research Institute, Invergowrie, Dundee, DD2 5DA, Scotland. ³College of Life Sciences, University of Dundee at SCRI, Invergowrie, Dundee, DD2 5DA, Scotland. ⁴Corresponding author

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Abstract

The mechanical behaviour of individual roots and their interaction with soil controls plant anchorage and slope stabilisation, and this is controlled by plant genotype. Tensile tests were performed on roots of tobacco (Nicotiana tabacum ‘Samsun’) plants with lignin biosynthesis pathways affected by down-regulating cinnamyl-alcohol dehydrogenase (CAD) enzyme production. Altering this pathway resulted in root stiffness <50% of the unmodified control, although failure stress was not different. Like most biological tissues, the roots had non-linear mechanical behaviour, were irregular in shape, and heterogeneous. Particle image velocimetry (PIV), applied for the first time to the tensile testing of materials, identified the localised strain fields that developed in roots under tension. PIV uses a cross correlation technique to measure localised displacements on the surface of the root between sequential digital images taken at successive strain intervals during tensile loading. Further analysis of root sections showed that non-linear mechanical behaviour is affected by cellular rupture, with a clear step-wise rupture from cortex to stele in some younger roots. This will affect slip planes that develop under pull-out at the root–soil interface. By assessing localised axial and radial strain along a root section with PIV, we have been able to determine the true stress that controls ultimate failure and the true stress–strain behaviour along the root length. The techniques used have clear potential to enhance our understanding of mechanical interactions at the root–soil interface.

Abbreviations: CAD, cinnamyl-alcohol dehydrogenase; PIV, particle image velocimetry

Introduction

Plant root systems have evolved into complex engineered structures capable of mechanically supporting a large shoot mass above ground by forming a biological anchor in soil (Niklas, 1998). The anchorage of plants is essential to understand for preventing windthrow of trees (Crook and Ennos, 1998) and reducing crop lodging in agriculture (Goodman et al., 2001). Soil stabilisation by roots has implications for the physical stability of agricultural soils (Czarnes et al., 2000), riverbank erosion, and reducing landslide risk on slopes (Sidle and Wu, 1999). The major properties of roots that control their effectiveness in either anchorage or soil stabilisation are the architecture of the root system (Stokes et al., 1996) and the biomechanics of the root tissue (Watson et al., 1999).

Root biomechanical behaviour is strongly influenced by environmental conditions and the tissue cellular structure. Niklas (1998) demonstrated that the mechanical stimulation of shoots, similar to the types of stresses induced by wind gusts or foraging, caused the biomass allocation to roots, root tensile strength and root stiffness to increase. This adaptive response allows plants to function in a wider range of environments, with more resilient species having the greatest competitive advantage (Wahl and Ryser, 2000). Considerable differences in root biomechanical behaviour have been found between species in a range of studies (Crook and

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Ennos, 1994; Easson et al., 1995; Ennos, 1991; Ennos et al., 1993a,b). Crop cultivars also show differences in root biomechanical behaviour, which probably leads to differences in lodging resistance (Berry et al., 2003). Little work, however, has attempted to relate species or cultivar differences in root biomechanical behaviour to the structure of the tissue.

Modern genetic approaches can be used to change tissue structure by altering biosynthesis pathways. Hepworth and Vincent (1998) found that the genetic modification of lignin biosynthesis pathways in tobacco could reduce the tensile modulus of xylem tissue by one third. This provides an ideal model system for a more in-depth understanding of plant tissue effects on biomechanics, but it is not known if these effects would also be found in root tissue. In addition to the great value that these plants could have as a tool to improve our fundamental understanding of root biomechanics, unexpected side effects of plant modification in agricultural crops may also alter root biomechanics. Saxena and Stotzky (2001) reported higher lignin levels in Bt-maize, which is modified to express a natural insecticide. This could potentially affect lodging resistance and hence crop yields, although it is not known if the differences in lignin would affect root biomechanics, or would be expressed under field conditions.

The study of root biomechanics is complicated by the heterogeneous structure and mechanical behaviour of roots (Niklas, 1999) and soil (Bridle and Davies, 1997). As roots taper along their length, branch, bend and have defects caused by the soil environment (e.g., indentations due to stones; McCully, 1999), the stress distribution is highly spatially dependent. Many studies on root biomechanics take the diameter of the root at the point of rupture to evaluate an engineering stress (Easson et al., 1995), which provides a good estimate but does not determine the true stress distribution before ultimate failure occurs as the radial strain is unknown. Tensile tests of root biomechanics typically measure a highly nonlinear mechanical response (Ekanayake and Phillips, 1999), but the impact of radial strain verses elastic-plastic behaviour on the shape of the stress–strain relationship is impossible to discern. Many pioneering modelling studies of root biomechanics and anchorage have understandably simplified the problem by using linear elastic assumptions and simple root structures (e.g., Ennos et al., 1993a; Niklas, 1999; Stokes et al., 1996).

This paper presents data from tensile tests on individual plant roots with an aim to present new approaches that could advance our understanding of root biomechanics. In the first study we tested tobacco plants (*Nicotiana tabacum* ‘Samsun’) with modified lignin biosynthesis pathways to examine how genetics and cellular structure influenced root biomechanics. Altered lignin biosynthesis was hypothesised to lower the stiffness and failure stress. These tests were confounded by localised strain fields caused by the irregular shape of roots. An imaging approach was subsequently adapted from geotechnical engineering to quantify strain locally from the movement of pixels in successive digital images taken during mechanical testing. The development of this methodology and its implications for root mechanical testing will be discussed. Finally, future research opportunities using model plant systems and the novel testing procedures presented in this paper will be suggested.

## Materials and methods

### Root mechanical testing

A mechanical test frame was used to evaluate the mechanics of individual plant roots under tension (Model 5544, INSTRON, 100 Royall St., Canton, MA 02021-1089, USA). The cross-head displacement and force transmitted to the load cell were recorded using INSTRON Merlin software. The cross-head displacement rate was set to 0.05 mm s$^{-1}$, with displacement accurate to 1 $\mu$m. The load cells were accurate to 1% at 1/250 maximum load and had a range of 5, 50 N or 2 kN depending on the strength of the root tested.

Gripping the plant roots in the test frame was problematic, with slippage and surface damage potentially affecting mechanical behaviour. This was minimised by using a screw-thread clamp with rubber-faced grips to secure the older portion of the root at one end. High strength, low modulus roots such as young maize could also be clamped with the same type of grip at the younger end of the root. More mature roots were wrapped around a spindle at the younger end and affixed with rubber tape. A microscope fitted with a graticule was used to measure the diameter of the root where it failed. Other gripping approaches were evaluated including the use of super glue, medical adhesives and fast-setting araldite. These either failed to grip the root adequately or damaged the root tissue by desiccation and heat stresses.
Plants that differ in lignin structure and composition were produced by suppressing specific genes in tobacco (*Nicotiana tabacum* L. cv. Samsun; Halpin et al., 1994). Earlier research by Hepworth and Vincent (1998) suggested that altered lignin crosslink density changed the mechanical behaviour of shoot material. The plants used in the current study provided a model system to quantify the influence of genetics and cellular structure on biomechanical behaviour. Several lines were tested, although here we only report the findings of the unmodified wildtype, WT line and a modified line, cinnamyl-alcohol dehydrogenase (CAD), which has altered lignin structure but displays a normal phenotype including similar sized lateral roots and only slight alterations to the shape of vessels (Chabannes et al., 2001). CAD plants have been modified to down-regulate CAD, an enzyme important to lignin biosynthesis. The plants were grown in a glasshouse under natural light in 400-mm diameter × 400-mm depth pots filled with potting compost. Six plants of each line were grown. The shoots were supported with canes to reduce mechanical stresses on the root system. However, several plants were rejected because the bending of the shoot may have caused lateral loading. At 10 weeks the plants reached flowering stage and roots were harvested by washing away the potting compost. The largest adventitious roots that emerged at the highest point on the main root were selected for mechanical testing using a grip and spindle, described previously, to hold the root. There were two roots from each of four different CAD plants (*n* = 8) and two roots from each of two different WT plants tested (*n* = 4). Lateral sections of roots were imaged using a Leica SP2 confocal microscope. Intact roots of the WT line were stained with 0.1% Safranin O, which stains nuclei, chromosomes, lignified and cutinised cell walls red. Images were produced that are a 3D reconstruction using 20 slices of 0.5-μm thickness. The purpose was to investigate the potential of using confocal microscopy to investigate the strain of individual cells *in situ* caused by mechanical loading.

**Determining localised strain with image analysis**

Particle image velocimetry (PIV) was extended to evaluate localised strain fields in mechanically tested roots. The theory is presented in White et al. (2003) and algorithms supplied by this group were used. PIV uses a cross-correlation technique to detect the movement of pixels between sequential digital images (Adrian, 1991). It was developed first for fluid mechanics and was modified to assess deformation in soil element tests by White et al. (2003).

PIV measures the movement of patches of natural texture in an image. In soil this is provided by different colour grains and pores, but roots have little texture so it was applied artificially by dabbing graphite powder on the root surface. During mechanical testing at least ten successive digital images were taken using a Nikon D100 camera fitted with a Nikkor 60 mm f2.8 lens. The images were 6 megapixels in size and covered the length of the root and the end of the grips. During the PIV procedure, a grid of patches was placed over the root in the initial image in the sequence. In the next image, a search patch beginning at the same location as an initial patch moved around progressively to detect the new location of the patch from the peak of the autocorrelation function. The distance between patches was used to determine the localised strain fields at different stages of imposed mechanical strain.

There are several advantages of PIV over other approaches. Strain gauges placed onto roots only measure at one location, can be difficult to adhere, and may influence mechanical behaviour. Previous imaging approaches that rely on the movement of artificial targets placed on the material’s surface provide a much lower resolution than PIV (White et al., 2003). We evaluated PIV first using the roots of maize (*Zea mays*) seedlings and later applied the approach to tobacco roots.

**Results and discussion**

**Lignin-modified tobacco roots**

Altered lignin biosynthesis through the genetic modification of tobacco resulted in a significantly lower modulus (*P* < 0.001), but similar maximum stress for roots of approximately the same size (Figure 1). Hepworth and Vincent (1998) found that the modulus of woody xylem tissue from the shoot of the same tobacco lines was about 10-times higher, with a 1/3 reduction in the CAD plants. The reduction between WT and CAD appears to be greater in the roots. The plants where CAD enzyme production, hence lignin monomers biosynthesis, was down-regulated appeared similar to the unmodified controls in terms of plant height, mass and root diameter (*P* > 0.05). Chabannes et al. (2001a,b) also found the plants to be phenotypically
similar and reported similar lignin contents of 22% (Klason method) for both CAD and WT plants. A difference was found in lignin composition, however, with a lower ratio of syringyl (S) to guaiacyl (G) monolignal units in CAD plants. Interfascicular fibres are generally higher in S units, so this result could indicate that lignification of these structures is lower in CAD plants (Chabbanes et al., 2001b). Zhong et al. (1997) noted that elasticity reduced markedly in an interfascicular fibre mutant of *Arabidopsis*, but also reported a large reduction in strength that was not found for the tobacco plants tested here.

The genetic modification of plants to alter lignin biosynthesis pathways is being explored to improve the efficiency of paper pulping (Baucher et al., 2003). If the approach is employed to modify tree stock used for forestry, our early research on tobacco suggests that root anchorage may be influenced. Lower root stiffness may increase damage caused by wind, pull-out from soil, and ultimately the occurrence of blow-down. However, roots tend to become stiffer when repaired from mechanical damage (Niklas, 1998), so these problems may be self-correcting under mechanical damage from wind in the field. Hepworth and Vincent (1999) found that flexural stimulation increased the shoot stiffness of the same tobacco lines that we studied. In a field study, Pilate et al. (2002) found CAD modified poplar trees grew just as well as natural lines, although the biomechanics of the roots were not evaluated.

The testing approach may also need to be improved. Grip slippage and damage was problematic, particularly after the yield stress was exceeded. This would affect the maximum stress more than the modulus, as the modulus was evaluated from the linear part of the stress–strain relationship below the yield stress. Ultimate failure generally occurred near to the bottom grip, where the root was younger and smallest in diameter.

**Determining localised strain with image analysis**

PIV, applied for the first time to the tensile testing of biological materials, successfully measured the movement of patches placed over the surface of roots (Figure 2). The surface texture produced by graphite powder allowed for the new location of patches in successive images to be detected from the peak of the autocorrelation function. Patch movement could be used to evaluate displacement trajectories along the length of the root. These data could then be converted to radial and axial strain components.

By assessing localised axial and radial strain along a root section with PIV, the true stress that controls ultimate failure and the true stress–strain behaviour along the root length could be determined (Ashby and Jones, 1996). Figure 3 shows an image of a root at the point of cortex failure. This produces a localised zone of intensified stress and strain, where more damage occurs and
ultimately leads to the failure of the stele. After cortex failure, the true strain in this localised area was almost 40%, whereas the engineering strain (i.e. strain applied to the entire root) was less than 5%. The reduction in root cross-sectional area caused by cortex failure almost doubled the true stress at this point of localised failure. About half-way along the length of the root it is slightly wider, so this location has a lower true stress.

**PIV and tobacco roots**

PIV analysis of the tobacco root tests found a similar modulus to the values evaluated from the engineering stress–strain relationship from the loading frame. For the WT tobacco, the modulus was 358 ± 98 MPa (average ± s.e.) from the images, whereas it was 222 ± 40 MPa from the engineering stress–strain relationship ($P = 0.21$). In the CAD tobacco, the modulus was 105 ± 26 MPa from the images, compared to 108 ± 24 MPa from the engineering stress–strain relationship ($P = 0.94$). The coefficient of variation was relatively
Figure 4. True stress–strain relationship for WT tobacco. Average (Δ) and local (other lines) values at various locations along the root are shown.

large (20 to 25%), which although is inherent in many biological materials, may also be due partly to experimental difficulties during testing such as grip slippage. The PIV analysis presented here looked at the average deformation along the entire root. More accurate and meaningful results could be obtained by looking at patches that are closer together, particularly near to the zones where failure ultimately occurs.

As radial strain during tensile testing reduces the area over which an applied force acts, the true tensile stress will be higher than calculated from pre-loading specimen geometries. PIV was used to convert from engineering stress–strain to true stress–strain using radial strain over the average of the root and at specific locations (Figure 4). The average true stress for a given strain was higher than the engineering stress (data not shown), as would be expected due to radial contraction of the root diameter. In the particular example, the localised stress fields determined were heterogeneously distributed along the root length. They were generally higher than the average value calculated for the entire root length because the impact of grip slippage was removed. In addition to PIV identifying localised true stress and strain fields by measuring radial and axial strain it can also be used to determine the Poisson ratio.

Future research areas

Two novel approaches have been presented that could improve our understanding of root biomechanics considerably. PIV allows for localised measurements of stress and strain that develop during mechanical loading. Model plants with controlled biosynthesis pathways provide geometrically similar plants that vary considerably in biomechanical behaviour. The role of specific genes in lignin biosynthesis is well characterised for these plant lines (Halpin, 2004) and could be used to start to unravel how plant genomics links to biomechanics.

The potential applications of PIV extend beyond mechanical tests on individual plant roots. Figure 5 shows a confocal microscope image that identifies the cellular structure of a WT tobacco root. It should be possible to mechanically test intact roots in the confocal microscope to image deformation of the tissue structure. Voytk-Harbin et al. (2003) proposed a mechanical-loading imaging technique using confocal microscopy to quantify load-induced changes to the scaffold of cells in biological materials. This approach offers considerable potential to gain greater understanding of the biophysical mechanisms that control the mechanical behaviour of roots.

The genes that shape root biomechanical behaviour could also be identified using the wide range of modified plants that are currently available. In addition to the tobacco plants used in this study, there is a wider range

Figure 5. Confocal microscope images of WT tobacco root, 240-μm across.
of modified tobacco plants (Halpin, 2004) and poplar trees (Halpin and Boerjan, 2003) available that could help elucidate root biomechanics at the molecular level. Further advances could be achieved with Arabidopsis (Zhong et al., 1997), although the practicality of testing such small roots may pose a problem. Studies with Arabidopsis mutants have already studied the importance of root hairs to anchorage (Bailey et al., 2002).

Conclusions

As with many biological materials, roots are heterogeneous, irregularly shaped, and have a highly nonlinear mechanical behaviour. This is further confounded by genetic differences, which can have profound effects on mechanical behaviour. In model tobacco plants, suppressing a lignin biosynthesis pathway reduced stiffness by almost 2/3. The irregular shape and heterogeneous structure of roots complicates analysis using conventional mechanical testing approaches. PIV was shown to be a useful approach to help overcome this problem. It showed that localised areas of intensified stress and strain occur in the root, which will likely receive greater damage and ultimately be the locations where failure occurs. PIV also detected that cortex failure in younger roots causes a large concentration of stress during mechanical testing.

Understanding plant root biomechanics is integral to describing root anchorage and soil stabilisation by roots. New approaches from geotechnical engineering, specifically PIV and the behaviour of inclusions in soil, should help us explore this multifarious problem. Future root biomechanics research will explore how the stress–strain relationship is affected by damage at the cellular level. We are also investigating the biomechanics of Bt-Maize, a commercially grown GM crop that is reported to have lower lignin levels. This biomechanical research should ultimately increase our understanding of how plant roots stabilise slopes and anchor plants in the ground.

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Root reinforcement: analyses and experiments

Tien H. Wu*
Ohio State University, 2070 Neil Avenue, Columbus, OH, 43210, USA.

Abstract

Simple and complex analytical models of root reinforcement and the associated requirements and limitations are reviewed. Simple models include the limiting equilibrium solution and the cable and pile solutions. The complex model is the finite element method (FEM). The simple models were used to analyze published data from laboratory and in situ shear tests and pullout tests on soils reinforced with synthetic materials and root systems. The models can be used for approximations when the model requirements are met. The FEM was used to simulate experiments and provided more detailed information. These results provide insight on the failure mechanisms. This forms the basis for suggestions on models to be used in stability analysis of slopes.

Introduction

The literature on the influence of vegetation on slope stability is rich, covering a broad spectrum of theoretical, experimental, and empirical studies. Comprehensive reviews are given in Coppin and Richards (1990), Gray and Sotir (1996), Morgan and Rickson (1995), and Schiechtl and Stern (1996). More specifically, the role of vegetation roots as a soil reinforcement has been the subject of many studies. Because of the wide variety of site conditions and vegetation types, the results from different studies do not always appear to be consistent. Therefore, it may be difficult to choose parameters for use in stability analysis. The overall objective of this paper is to address the question of how to evaluate the role of root reinforcement on slope stability. The first part reviews available analytical models of root reinforcement. Models may be simple or complex. Simple models are easy to use and require less data. Complex models, namely the finite element method (FEM), can provide more detailed information but require more data. In the second part, simple models are used to analyze data from a variety of laboratory and in situ tests. This provides a means for evaluating the failure mechanisms. The FEM is used to supplement the results from simple models. This provides insight on the failure mechanisms. Finally, suggestions are given on the use of simple models in stability analysis.

Models of root reinforcement

Bending stiffness of roots

The experiments of Shewbridge and Sitar (1989) on sand reinforced with fibers and rods clearly demonstrate the important influence of the bending stiffness on the thickness of the shear zone and the deformation of the reinforcement. A thin shear zone leads to larger extension in the reinforcement than a thick shear zone. On the other hand, flexible reinforcements require more extension to reach the failure strain than stiff reinforcements. Selection of an appropriate model requires consideration of the deformation of the reinforcement.

Simple models

For a reinforcement that is embedded at an angle of 90° to the failure surface (Figure 1a), limit equilibrium requires that

\[ s_r = \frac{[T_y + T_z \tan \phi]}{A} \]

(1a)
Figure 1. Simple Models. (a) Limit equilibrium, (b) flexible reinforcement, (c) cable model.

where $s_r =$ shear strength contributed by reinforcement, $T =$ tensile force in reinforcement, $\alpha =$ inclination of $T$, $A =$ area of the section under consideration, $\varphi =$ angle of internal friction of the soil. When written in terms of the stress, $\sigma_r$, Eq. (1a) becomes

$$s_r = \frac{\sigma_r A_r (\cos \alpha + \sin \alpha \tan \varphi)}{A}$$  

(1b)

where $A_r =$ area of the reinforcement. A modified version of Eq. (1) can be used when the reinforcement is not perpendicular to the failure surface (Gray and Ohashi, 1983). For $48^\circ < \alpha < 72^\circ$, the quantity $(\cos \alpha + \sin \alpha \tan \varphi)$ is approximately 1.2 and Eq. (1b) may be simplified to (Wu et al., 1979)

$$s_r \approx 1.2 \sigma_r A_r / A.$$  

(2)

For fibers and bars the limiting value of $\sigma_r$ or $T$ is the ultimate tension ($T_u$), which is the tensile strength or the friction between the soil and reinforcement. In the case of roots, the failure modes are tension failure in the main root, progressive tension failure in branch roots, and slip between root and soil. When pullout tests are used to measure the $T_u$, all three modes are possible. The deformation required to produce failure depends on the root properties and ranges between 0.05 and 0.15 m. This topic is considered further in a subsequent section.

The simplest application of Eq. (2) is to assume that the reinforcement deforms with the soil, or it has no influence on the shear deformation. Then $\alpha$ is determined by the shear strain in the soil (Figure 1b). Tension in the reinforcement is developed by extension in the shear zone and can be estimated from the tensile strain (Wadron, 1977). If the extension is insufficient to develop the ultimate tension, then $\sigma_r$ would be less than the ultimate tension but Eqs. (1) and (2) remain valid provided the right value of $T$ or $\sigma_r$ is used.

The thickness of the shear zone in laboratory shear tests ranges between 5 and 50 mm for flexible fibers and depends strongly on the boundary conditions of the test (Gray, 1991; Shewbridge and Sitar, 1991). With increasing bending stiffness the thickness of the shear zone increases and the reinforcement no longer deforms with the soil (Abe and Ziemer, 1991; Jewell and Wroth, 1987). Experiments with reinforced soil walls show similar results (Jaber et al., 1987; Plumelle and Schlosser, 1991). To consider the deformation and bending resistance of the reinforcement, one can use the equation for a tie (Figure 1c), which is (Oden, 1967)

$$EI \frac{d^4u}{dz^4} - T_z \frac{d^2u}{dz^2} = q$$  

(3)

where $E =$ Youngs modulus and moment of inertia of the reinforcement, $q =$ soil reaction, $u =$ displacement, $L =$ length of tie = deformed portion of reinforcement. For the limiting case, $q = q_y =$ soil reaction or bearing pressure at yielding. For $\eta L < 1.5$, with $\eta = [T_z/El]^{1/2}$, the tie may be represented as a beam or a laterally loaded pile. For elastic soil support, the beam solution is well known (e.g., Hetenyi, 1946). For the limiting case when the soil support is $q_y$, the solution for a laterally loaded pile has been summarized by Broms (1964a,b) and Jewell and Pedley (1992). The solution can be expressed in dimensionless numbers

$$N_c = \frac{T_y}{cd^2}, \ N_\phi = \frac{T_y}{\gamma K_p d}$$  

(4)

where $\gamma =$ unit weight, $d =$ pile diameter, $K_p =$ coefficient of passive earth pressure. $N_c$ and $N_\phi$ are functions of $M_y =$ moment at yielding of the pile or beam, $d$, $c$, $\varphi$, and $\gamma$ and are given in Broms (1964a,b).

Eq. (3) can be simplified to a flexible cable if $\eta L > 2.5$. The cable solution is given by (Oden, 1967)

$$T_z(0) = T(L)$$  

(5a)

$$T_z(0) = q_y L$$  

(5b)

$$u(0) = q_y L^2 / 2T_z(0)$$  

(5c)
The tension $T$ in this case is also limited by the ultimate tension. For a root perpendicular to the slip surface, the beam or pile solution may be used for small $u$, which means $\alpha \rightarrow 90^\circ$, or $T_z \rightarrow 0$. This represents the condition the initial failure at yielding in the root. If the root is ductile and does not fracture, $u$ continues to increase, $T$ increases and the limit is the cable solution.

**Finite element method (FEM)**

The FEM makes it possible to solve for the stresses and displacements in the 3-dimensional problem of a reinforcement buried in soil. It has been applied to a single root (El-Khouly, 1995; Frydman and Operstein, 2001) and to the root systems of trees (Dupuy et al., 2005). The ABAQUS software package was used for our FEM studies (El-Khouly, 1995). The root is represented by beam elements and the interface between soil and reinforcement by slide-line contact elements. The reinforcement is linear-elastic up to the yield point and the interface shear has an angle of friction $\delta$. The soil is elastic-plastic and can be represented by either the Drucker-Prager model (Drucker et al., 1957) or the Cap model (DiMaggio and Sandler, 1971).

**Evaluation of tests on reinforced soil**

The simple models were used to analyze data from published laboratory and in situ tests to improve the understanding of failure mechanisms. Finite element analysis was used to provide more detailed information. We distinguish between tests on soils reinforced with fibers or bars from those on soils containing an entire root system of a plant. The difference is that, with the former group, the initial geometry of the reinforcement is simple and known, while with the latter, it is complex and usually not well known.

**Direct shear tests**

Several experimental studies that represent different reinforcement properties and measurements are reviewed to illustrate the influence of the properties and test conditions on $s_r$. The results are summarized in Table 1.

**Tests on fibers, rods, and root members**

Consider first the laboratory direct shear tests by Gray and Ohashi (1983). Eq. (2) was used to calculate $s_r$, with $T_\mu$ calculated from friction between soil and reinforcement. The normal stress $\sigma$ on the reinforcement was taken to be 1.5 times the vertical stress, $\sigma_z$, based on calculations with the FEM model. The calculated $s_r$'s are about 1.5 times the measured values. This suggests that friction was not fully developed, although pullout was noted by the authors in some cases.

In the direct shear tests by Jewell and Wroth (1987), the rods were provided with a rough surface and the ultimate tension was equal to the friction. The displacements within the soil and the force in the reinforcement

<table>
<thead>
<tr>
<th>Author</th>
<th>Test</th>
<th>Spec.</th>
<th>D (cm)</th>
<th>Model</th>
<th>$s_r$, kPa Calc.</th>
<th>$s_r$, kPa Meas.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gray</td>
<td>direct shear</td>
<td>6 reed</td>
<td>0.18</td>
<td>Eq. (2)</td>
<td>1.5 kN</td>
<td>0.6 kN</td>
</tr>
<tr>
<td>Ohashi</td>
<td>direct shear</td>
<td>6 copper</td>
<td>0.18</td>
<td>Eq. (2)</td>
<td>0.72</td>
<td>0.3</td>
</tr>
<tr>
<td>Jewell, Wroth</td>
<td>direct shear</td>
<td>polymer coil S9Y</td>
<td>Eq. (2)</td>
<td>0.46 $\sigma_y$</td>
<td>0.6$\sigma_y$</td>
<td></td>
</tr>
<tr>
<td>Shewbridge</td>
<td>shear</td>
<td>14 wood</td>
<td>0.32</td>
<td>Eq. (2)</td>
<td>3.7 kPa</td>
<td>1.8 kPa</td>
</tr>
<tr>
<td></td>
<td></td>
<td>14 para. chord</td>
<td>0.32</td>
<td>Eq. (2)</td>
<td>4.3</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>14 wood</td>
<td>0.32</td>
<td>cable</td>
<td>2.7</td>
<td>1.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>14 para. chord</td>
<td>0.32</td>
<td>cable</td>
<td>2.5</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>14 wood</td>
<td></td>
<td>FEM</td>
<td>1.6</td>
<td>1.2</td>
</tr>
<tr>
<td>Shewbridge</td>
<td>in situ shear</td>
<td>Hopea ordata</td>
<td>0.5–0.8</td>
<td>Cable eq.</td>
<td>1.2–2.9 kPa</td>
<td>3 kPa</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Pile eq.</td>
<td>0.08</td>
<td></td>
</tr>
<tr>
<td>Nilaweera</td>
<td>in situ shear</td>
<td>Pinus radiata</td>
<td>cable and pile</td>
<td>1.7–20.8 kN</td>
<td>18.2 ult.</td>
<td>23.2–24.2 peak</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Friedman</td>
<td>direct shear</td>
<td>alfalfa</td>
<td></td>
<td>Eq. (2)</td>
<td>$\mu = 1.0* $</td>
<td>$\mu = 0.26$</td>
</tr>
</tbody>
</table>

$\mu = s_r/A_r$. 

<table>
<thead>
<tr>
<th>Author</th>
<th>Test</th>
<th>Spec.</th>
<th>D (cm)</th>
<th>Model</th>
<th>$s_r$, kPa Calc.</th>
<th>$s_r$, kPa Meas.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wu, Watson</td>
<td>in situ shear</td>
<td>Pinus radiata</td>
<td>cable and pile</td>
<td>21.5</td>
<td>18.2 ult.</td>
<td>23.2–24.2 peak</td>
</tr>
</tbody>
</table>

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were measured. In this case the calculated value is close to the measured one and agrees with the authors’ observation that friction was fully developed.

In the tests by Shewbridge and Sitar (1989), the deformations of the soil and the reinforcements were observed. The latter was used by the authors to calculate the tensile force in the reinforcement and $s_r$. In this study, the friction was used to calculate $T_u$ and Eq. (2) to calculate $s_r$. Eq. (2) overestimates $s_r$. This indicates that friction was not fully developed, although Shewbridge and Sitar (1989) observed slip in the case of wooden dowels. Since the deformed shapes of the reinforcements were observed, it was possible to estimate $\alpha$, $L$, and $u(0)$ for the cable solutions. The cable solution requires the bearing pressure $q_y$ exerted by the soil on the reinforcement. The upper and lower limits were given by Jewell and Pedley (1992). The range between the limits is large. Palmeira and Milligan (1989) gave a modified upper limit based on experimental results. Using their relation $q_y/\sigma_z = 35$, where $\sigma_z$ = overburden pressure. Broms (1964b) recommended a ratio $q_y/\sigma_z$ that is 3 times Rankine’s passive pressure. This gives $q_y/\sigma_z \approx 10$ and is the lower limit used here. For wooden dowels, the estimated values of $\alpha$ and $L$ are 30° and 5 cm, respectively. Similar estimates were made for parachute chords. The calculated ranges of $s_r$ are given in Table 1 and are higher than the measured values. The results of FEM simulation are shown in Figure 2. The load displacement curve for 14 wooden dowels shows that the calculated $s_r$ is slightly larger than but close to the measured value. Figure 3 shows the calculated octahedral shear stress $q$. Good agreement between simulated

![Figure 2. FEM simulation of Shewbridge and Sitar's test, load-displacement curve.](image)

![Figure 3. FEM simulation of Shewbridge and Sitar's test, stress distribution (a) on failure plane, (b) on longitudinal section.](image)