Modulus of elasticity and tensile strength of Douglas-fir roots

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The modulus of elasticity and the tensile strength were determined for a sample of live Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) roots collected in the Oregon Coast Range. Most of the roots displayed both a "form" modulus of elasticity and a "material" modulus of elasticity. The form modulus occurred as a tortuous root straightened out, whereas the material modulus developed following this initial straightening as the wood fibers within the root directly resisted elongation. The average form and material moduli of elasticity were, respectively, 185 and 503 MPa, whereas the average tensile strength was 17 MPa.

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Le module d'élasticité et la résistance à la traction d'un échantillon vivant de racines de sapin de Douglas (*Pseudotsuga menziesii* (Mirb.) Franco) recueilli dans la chaine Côtière en Orégon ont été déterminés. La plupart des racines présentaient un module d'élasticité de «forme» et un module d'élasticité de «matériau.» Le module d'élasticité de forme était mesuré lorsqu'une racine tortueuse se redressait alors que la module d'élasticité de matériau était mesuré à la suite de ce redressement initial, lorsque les fibres du bois de la racine résistaient directement à l'allongement. Les modules de forme et de matériau s'établissaient en moyenne respectivement à 185 et à 503 MPa, alors que la résistance à la traction était de 17 MPa.

Introduction

Throughout the steep forest lands of the Pacific Northwest, landslides occur both naturally and as a result of forest management activities. Much effort has been directed at minimizing the occurrence of management-related failures. Minimizing such landslides requires an increased understanding of the stability and mechanisms of failure of steep forest land. One area of research that has received much attention is the potential reinforcement of soil by tree roots. Laboratory and *in situ* direct shear tests have demonstrated that roots can increase the shear strength of soil (Waldron 1977; O'Loughlin *et al.* 1982; Waldron and Dakessian 1982; Waldron *et al.* 1983). Unfortunately, numerous confounding factors make it difficult to determine the true magnitude of this reinforcement effect in the field. For example, shear-strength measurements are extremely sensitive to variability in rooting density and soil properties, both of which are highly variable under forested conditions (Luckman *et al.* 1981).

A number of models have been developed that attempt to describe the mechanism by which tree roots reinforce forest soil. Because few data on the material properties of roots are available from the literature, material properties are often assumed (Waldron 1977) or extrapolated from studies that are not always applicable to soil–root systems (Shewbridge and Sitar 1985). More information on the material properties of tree roots would provide better estimates for input into soil–root system models.

Typical analytical soil–root models assume flexible roots crossing a shear zone of known thickness (Waldron 1977; Wu *et al.* 1979). As a result of shear displacement on the shear zone and the mobilization of shear stresses between the root and the soil, tensile forces develop in the root. The tensile force in the segment of the root within the shear zone can be resolved into two components, a component parallel to the shear plane (T_t) and a component normal to the shear plane (T_n). A root will thus increase soil strength in two ways: T_t directly resists shear, whereas T_n increases the frictional resistance along the shear plane. This situation is usually represented mathematically by an equation of the form

$$[1] \quad \Delta S = S_t + S_n \tan \phi'$$

where

ΔS is strength increase due to root
$S_t = T_t/A$
$S_n = T_n/A$
A is area over which root acts
ϕ' is effective angle of internal friction of the soil

The tensile force components, T_t and T_n, will be a function of the shear-stress transfer between roots and soil and the modulus of elasticity of roots (E). In addition, the maximum increase in soil strength due to roots will depend on the tensile strength of roots (σ_{ult}). This paper presents the results of experimentally determined material properties (E and σ_{ult}) of Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) roots. The results of laboratory pull-out tests, carried out to determine the shear-stress transfer between roots and soil, are presented elsewhere (Commandeur 1987).

Methods

A site stocked with 20-year-old Douglas-fir was selected on Bureau of Land Management forest land near Harlan in the Oregon Coast Range. Live roots were collected (fall 1986 to spring 1987) below the humus layer up to a depth of about 30 cm. Relatively small roots ranging in size from 0.25 to 2.0 cm in diameter and

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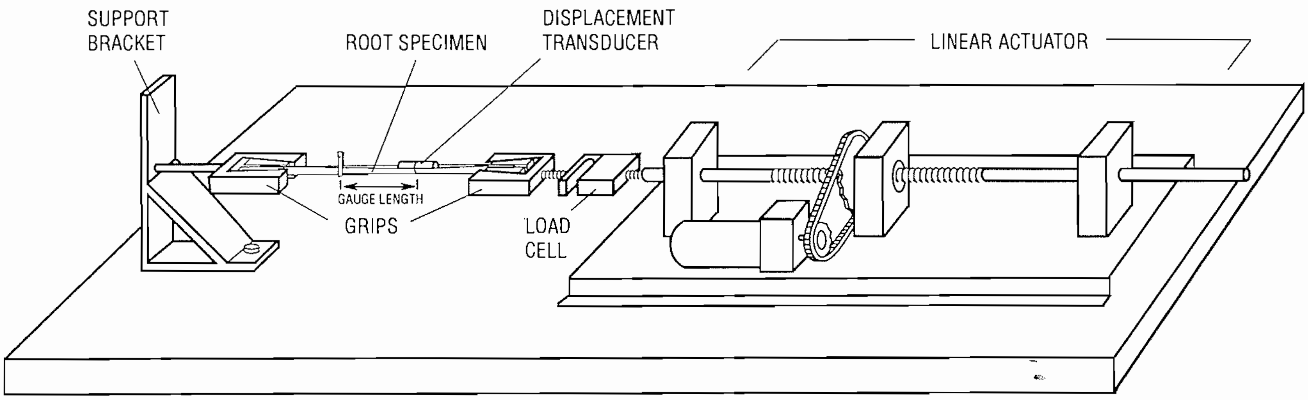

FIG. 1. Laboratory equipment used to conduct the root tensile tests.

approximately 5–10 years old were chosen within 3 m of the tree stem. The roots were generally straight and free of major imperfections. The roots were packed in a mixture of moist moss, humus, and mineral soil and sealed in plastic bags. Upon return to the laboratory, the roots were stored in a refrigerator (10°C) to prevent desiccation and maintain freshness. Tests were conducted on the roots generally within 2 weeks of being collected.

Two types of tests have been used to determine or estimate the tensile strength and (or) the modulus of elasticity of roots. A shearing apparatus has been used to obtain the shear strength, which in turn was used to predict the tensile strength (Ziemer and Swanston 1977; Ziemer 1978), or roots have been tested in tension using a loading frame and the tensile load versus deformation relationship is determined directly (O'Loughlin 1974; Burroughs and Thomas 1977; Waldron and Dakessian 1981).

The laboratory equipment used in this study was of the tensile load type (Fig. 1). The components were as follows: a linear actuator for loading the root in tension, wedge-type grips for holding the root in place, an L-shaped bracket for anchoring one end of the root, a load cell for measuring the tensile force the root was subjected to, and a linear variable differential transformer (LVDT) for measuring the elongation of the gauged section of the root. The load cell and the LVDT were connected to a Valydine strain gauge amplifier (model SG71) and a signal demodulator (model CD148), respectively, contained in a Valydine modular control unit (model MC1). The control module was linked to a Hewlett-Packard data acquisition unit (model 3421A), and a Hewlett-Packard computer (model 87) was used for program control and data storage.

Twenty-one tensile tests were conducted. For each tensile test, a root was selected and the ends of the root were debarked to prevent slippage in the grips. For 10 of the tests, the roots were completely debarked to help define the effect of bark on the tensile load versus deformation behavior. To avoid the influence of end effects on the determination of the modulus of elasticity, the gauge length was smaller than the distance between the grips. For 19 of the roots the gauge length varied in between 13.5 and 18 cm, and for the other 2 roots the length was approximately 8 cm. The average distance between the grips was 7.9 cm greater than the gauge length. During a test, tensile force and displacement measurements were taken at discrete points in time, and a graph of the tensile load versus the elongation of the root was plotted.

For each test, the crook or tortuosity (t) of the root was either measured directly or obtained from a photograph. There are a number of root parameters associated with tortuosity that could affect the behavior of a root. These include the wavelength, the cross-sectional shape, the thickness of the bark along the member, and the influence of branching. We simply define tortuosity as the largest perpendicular deviation from a straight line joining both ends of the root (Fig. 2). The additional variables associated with tortuosity were not found to be significant to this study.

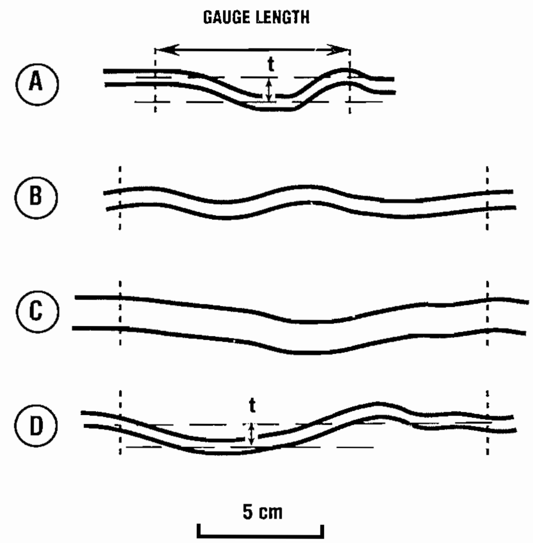

FIG. 2. Sketch of root shape for roots. (A) R15 (DIB = 0.363 cm, gauge length = 8.02 cm, tortuosity (t) = 0.89 cm). (B) R19 (DIB = 0.610 cm, gauge length = 14.68 cm, t = 0.51 cm). (C) R21 (DIB = 1.16 cm, gauge length = 15.06 cm, t = 0.76). (D) R23 (DIB = 0.480 cm, gauge length = 14.86 cm, t = 0.76 cm).

Results and discussion

For most of the tests, the relationship of tensile stress versus strain behavior was typically as illustrated in Fig. 3A: the curve proceeded along a moderate slope for an initial period and then increased and attained a steeper slope followed by a gradual flattening of the curve as the peak tensile load was asymptotically approached (sigmoid curve). For four tests the behavior approximated a hyperbolic curve (Fig. 3B). For two roots the test was terminated before tensile failure occurred. In one case the LVDT was found to be operating outside of its range, which prevented completion of the test, and in a second case the root was saved for subsequent use.

Modulus of elasticity

Modulus of elasticity is defined as the proportionality between stress and strain

$$[2] \quad E = \frac{\Delta\text{stress}}{\Delta\text{strain}}$$

For a value of E to be representative of a material, there must be some agreement on where over the range of strains on a stress–strain curve it will be determined. The standard

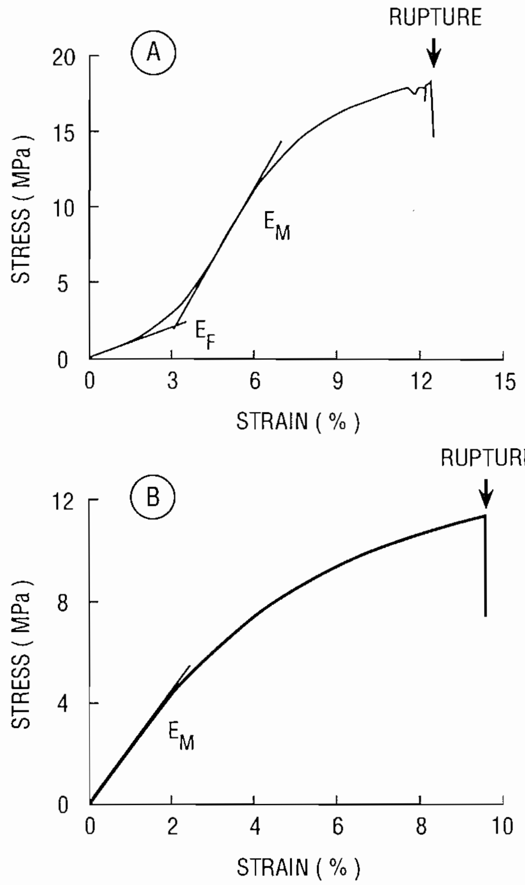

FIG. 3. Stress versus strain for (A) root displaying sigmoid behavior (R15) and (B) root displaying hyperbolic behavior (R19).

value of E determined for most materials is that which applies to the linear elastic portion of the stress–strain curve. The reason for selecting the linear elastic portion of the stress–strain curve is that most analyses of material behavior focus on this range. Root reinforcement of soil may ultimately have to consider strains beyond the elastic range, but any analysis of reinforcement should begin with the linear elastic range.

Since the tensile tests on roots did not behave in the classic stress–strain pattern, some interpretation of the results is necessary. For the hyperbolic type of behavior (Fig. 3B), E was determined for the initial straight-line portion of the curve. For the sigmoid type of behavior (Fig. 3A), two different straight-line portions can be delineated. Thus, two moduli of elasticity can be calculated for a root that behaves in this manner. During a test, the first straight-line portion occurred as a tortuous root straightened out, and after the root had straightened out to a large degree, the curve steepened to produce the second straight-line portion. From the first straight-line segment we can calculate a modulus of elasticity that can be termed form modulus (E_F), because the tortuosity or form of the root largely affects the tensile load versus elongation behavior in this case. The modulus of elasticity that corresponds to the second straight-line segment can be termed the material modulus (E_M), because the shape of the root no longer plays a significant role and the wood fibers within the root largely determine the tensile load versus elongation behavior. The tests that produced a hyperbolic tensile load versus elongation curve were classified as having only a material modulus.

TABLE 1. Modulus of elasticity results

	E_F^* (MPa)	$E_M^\dagger$ (MPa)
Roots with bark		
Mean	240	604
SE	83	191
n	9	11
Debarked roots		
Mean	123	391
SE	29	89
n	8	10
All roots combined		
Mean	185	503
SE	47	112
n	17	21

*E_F, form modulus of elasticity.
†E_M, material modulus of elasticity.

Equation 2 was used to calculate the modulus of elasticity (E) for a given straight-line portion of a tensile load versus elongation curve, where Δstress = (ΔT/area) and Δstrain = ($\Delta l/l_0$), ΔT is the change in tensile load along the straight-line portion of the curve, Δl is the corresponding elongation of the root, area is the initial cross-sectional area of the root, and l_0 is the initial gauge length of the root. Mean values of the form (E_F) and material (E_M) moduli of elasticity were calculated for roots with bark, for debarked roots, and for all roots combined, and are presented in Table 1.

A t-test was conducted to test the null hypothesis, which states that the ratio of the form modulus to the material modulus (E_F/E_M) is equal to 1, versus the alternative hypothesis, which states that the ratio is less than 1. For the three groups tested (roots with bark, debarked roots, and all roots combined), the null hypothesis was rejected (99% confidence level). This indicates that E_F/E_M is less than 1, which implies that the form modulus is smaller than the material modulus. A t-statistic was also computed to test the difference between the mean value of E_F for roots with and without bark. A similar test was conducted for E_M. The results were not significant at the 90% confidence level. In other words, for the given sample size the removal of bark could not be shown to affect the modulus of elasticity of Dogulas-fir roots. For all roots combined, the material modulus (503 MPa) is almost 3 times as large as the form modulus (185 MPa). For Douglas-fir roots collected in southwestern British Columbia, O'Loughlin (1974) obtained an average modulus of elasticity equal to 855 MPa. This is considerably higher than but of the same order of magnitude as the average material modulus obtained in this study.

For each root, a normalized tortuosity was obtained by dividing the tortuosity (t) by the diameter inside bark (DIB). This was considered appropriate since a large root with a given tortuosity will not display as much form modulus as a smaller root with the same tortuosity. A simple linear regression of E_F/E_M on t/DIB (Fig. 4) was performed and is significant at the 99.9% confidence level (r^2 = 0.44). The relationship indicates that the ratio of the form modulus to the material modulus decreases with increasing normalized tortuosity. In other words, a tortuous root will display a more distinct form modulus when compared with the material modulus than will a straight root. The four cases

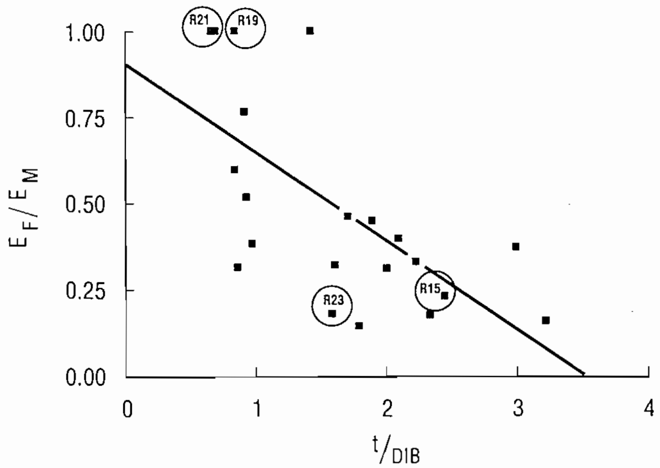

FIG. 4. Regression of the moduli ratio on normalized tortuosity with roots R15, R19, R21, and R23 delineated; $E_F/E_M = 0.902 - 0.259(t/\mathrm{DIB})$. F-ratio p-value = 0.001.

for which E_F/E_M is equal to 1 represent relatively straight roots that only displayed one modulus (hyperbolic behavior).

Waldron and Dakessian (1981) reported that the modulus of elasticity of pine (*Pinus ponderosa* Laws.) roots decreased as the diameter increased ($E = 57.7(D)^{-0.389}$, in units of MPa (converted from g/cm^2) and cm). Linear regressions of E_F and E_M on DIB indicated that no such relationship exists for the roots collected in this study (F-ratios were not significant at the 90% confidence level).

Tensile strength

The tensile strength was calculated for each root by dividing the maximum tensile load by the cross-sectional area of the root. For 11 of the 19 roots that failed in tension, the location of the failure was at or near the grips. In those cases, the tensile strength (σ_{ult}) may have been affected by the development of stress concentrations in the root sections near the grips. The roots that failed away from the grips (M-roots) have been analyzed separately from those that failed at or near the grips (G-roots). Figure 5 illustrates the regression of σ_{ult} on DIB for the two subsets of roots. The G-roots regression is not significant ($p = 0.2875$), but the M-roots regression shows a significant relationship between σ_{ult} and DIB ($\sigma_{ult} = 25.4 - 20.0(\mathrm{DIB})$; $p = 0.037$; $r^2 = 0.54$). It appears that the grips affected the tensile strength versus DIB relationship for the G-roots. However, the average σ_{ult} for the G-roots (16.42 MPa) is not significantly different from the average M-roots value (16.97 MPa). For the M-roots, the tensile strength decreases as DIB increases. This relationship is supported by Turmanina (1965) who states that small roots have greater strength than large roots because of the different composition (cellulose versus lignin) of young versus older roots.

In materials testing, the modulus of elasticity measured in tension or compression is greater than that measured in bending (Jessome 1977). This is due to shear stresses that develop under bending. In a similar way, a crooked root will develop shear stresses when pulled in tension. This will result in lower tensile stresses and a lower modulus of elasticity than for a straight root. This effect will be more pronounced for larger roots where bending moments and shear stresses are greater, which provides another explanation for the decreasing tensile strength with increasing DIB relationship observed in Fig. 5.

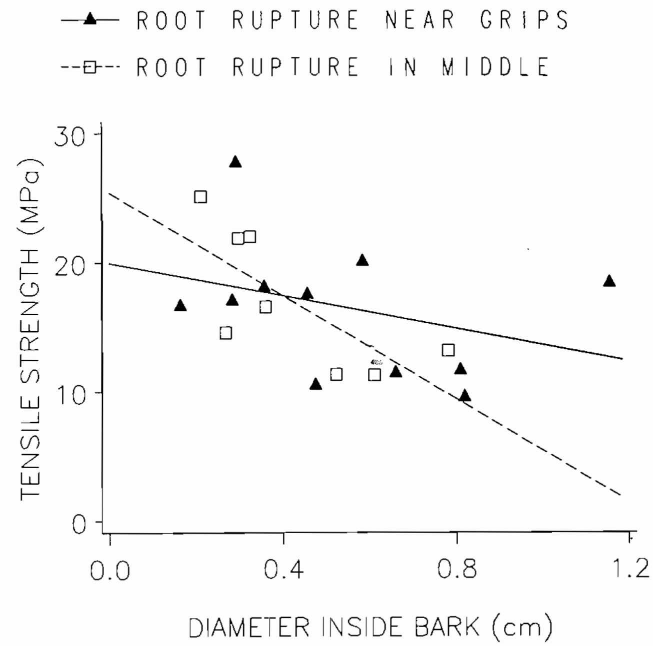

FIG. 5. Tensile strength versus diameter relationships for roots that failed at or near the grips ($n = 11$) and for roots that failed away from the grips ($n = 8$).

Conclusion

Douglas-fir roots exhibit two distinct moduli of elasticity, form and material, which is attributable to their tortuous nature. The degree to which the form modulus will develop *in situ* depends on the significance of the lateral restraint imposed on the root by the surrounding soil. According to Wu *et al.* (1988) the soil resistance for roots at shallow depth and weak soil is not sufficient to prevent roots from straightening out. On the other hand, for stronger, more cohesive soils and at greater soil depths, tortuous roots may not fully straighten out.

The material properties of roots for other tree species and in other regions will probably be determined by researchers in the future. The form modulus is therefore instructive because it indicates to researchers and modelers what to expect and how to interpret future laboratory and *in situ* tests. The form modulus represents an important parameter that should be given its proper place in a soil–root system model.

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