Root Biomechanics Testing Challenges: Findings from Experiments on Native Australian Trees

Jiale Zhu[1*], *Abbas* El-Zein[1], *Thomas* Hubble[2] and *Guien* Miao[1,3]

[1]The University of Sydney, School of Civil Engineering, Australia

[2]The University of Sydney, School of Geosciences, Australia

[3]School of Professional Practice and Leadership, University of Technology Sydney, Sydney, Australia

Abstract. Root biomechanical properties are critical for soil reinforcement and slope stability, yet the lack of standard tensile testing procedures creates significant variability in results. This study examines three key challenges—clamping mechanisms, root irregular morphologies, and root moisture content—through experiments on four native Australian tree species. Of the three tested clamping methods, two failed: the finger-trap mechanism lacked grip on small-diameter roots, while epoxy reinforcement caused excessive moisture loss. The flat clamp with a rough surface performed best but damaged large roots under excessive force. Unexpected root irregularities, such as nodal joints and tortuous points, led to localised stress concentrations, reducing tensile strength and increasing variability. While root moisture content has been qualitatively discussed, its quantitative effects remain underexplored, with fewer than five studies addressing it. This study demonstrates that moisture content and root diameter explain up to 71% of tensile strength variability, underscoring the need for its control in testing. These findings highlight the necessity of standardised testing procedures to improve measurement reliability. While preliminary guidelines are proposed, further refinement is needed to advance predictive modelling and bioengineering applications in unsaturated soils.

1 Introduction

Root systems play a pivotal role in stabilising near-surface soils and mitigating slope erosion. Numerous experimental and field-based studies (e.g. [1–3]) have demonstrated that roots act as natural “anchors”, enhancing soil shear strength and delaying shallow slope failures. Their mechanical properties, especially their tensile strength and stiffness, are therefore of keen interest to engineers and researchers when designing nature-based solutions for slope stability. Despite this interest, standardised protocols for root tensile testing are yet to be defined. Small changes in the test setup can cause large discrepancies in measured tensile strength. This is particularly evident when clamping methods differ. Some studies have relied on glue or epoxy to hold the sample ends, while others have tested with clamps with material testing machines [4]. They were designed to minimise damage to delicate root segments. The large stiffness differences between the metal clamps and the organic root tissue often introduce stress concentrations and alter the mode of root failure from tensile fracture to alternative mechanisms.

Root moisture content (RMC) is another factor known to affect measured strengths [5,6]. In practice, the moisture level at the time of testing can vary depending on how the sample was stored or even on laboratory conditions during preparation. Since water content alters internal cell turgor and polymeric binding within the root structure, failing to standardise or at least document moisture conditions can lead to significant data scatter. Nonetheless, the extent to which RMC affect the tensile strength and RMC’s quantitative effect on tensile strength remain unclear.

This study presents three clamping mechanisms trialled on root samples of four Australian species. this paper aims to provide a more in-depth analysis of how clamping methods, irregular morphologies, and root moisture content together influence tensile strength measurements. By collecting experimental data from a range of root diameters and moisture states, our results help clarify where existing approaches fall short and how future testing can be made more consistent. Ultimately, by proposing guidelines based on existing practice for better measurement practices, we seek to enhance the reliability of root biomechanical data, which is an essential input into both slope stability modelling and eco-engineering applications.

This paper will therefore examine: (1) the performance of three distinct clamping techniques in securing small-diameter roots during tensile loading and the issues that occur when using each technique, (2) the presence of natural irregularities such as tortuous growth or nodal joints and (3) the quantitative impact of root

* Corresponding author: jiale.zhu@sydney.edu.au

moisture content. Although the discussion here focuses on four Australian native species, the findings are relevant to practitioners and researchers worldwide who face similar challenges measuring mechanical behaviour of roots

2 Methodology

2.1. Root Sampling and Preparation

In this study, *A. costata*, *B. integrifolia*, *E. reticulatus*, and *E. racemosa* were selected as target species for testing. The selection was based on established botanical guidelines for native Australian vegetation [7–9], considering ecological suitability and recommendations from practitioners. The roots were sampled from four species of trees collected from a local nursery. Each plant was approximately 24 months old, ensuring that the root systems were sufficiently developed. Individual roots were excavated together with the surrounding soil to minimise mechanical damage, then trimmed to lengths of 100–120 mm. Following Giadrossich et al. [4], each segment's length exceeded 30 times its diameter. Immediately after excavation, roots were sealed in airtight bags (with some neighbouring soil) to retain their moisture content.

Root diameters ranged from <1 mm up to ~5 mm, although the most common size classes fell between 1–4 mm. At least 30 root segments were collected for each species to capture a broad spectrum of morphological and diameter variations. If immediate testing was not possible, specimens were briefly stored (48 hours or less) in an air-conditioned room to limit biological degradation. Additionally, segments were air-dried for two days to achieve lower RMC.

2.2 Clamping Mechanisms

In this study, three methods were proposed and tested and their results were compared. The first method used a Chinese finger-trapping technique, in which the samples were inserted into double-braided dyneema rope as shown in Fig.1.1. In the second method, steel wires or cables were tied to both ends of the root sample, then encapsulated in epoxy within small plastic tube moulds, similar to previous studies [10–12], as shown in Fig.1.2. The last method used a textured clamp (shown in Fig.1.3.) with A Tinius Olsen H5KS universal testing machine (UTM), similar to De Baets et al. [13], Hales et al. [5] and Preti and Giadrossich [14]. The setup for the three methods is shown in Figure 1. The load and displacement were measured to an accuracy of 0.01 N and 0.01 mm, respectively. The samples were pulled apart at a rate of 0.5 mm/min.

The direct output of the tests comprised information on root diameter, ultimate load (breaking force), displacement, and RMC. The root diameter was measured at the fracture location immediately following the test and prior to sealing the roots for RMC testing. For roots with cross-sections that were not circular, the longest and shortest axes were measured and the cross-sectional areas were approximated as ellipses. The bark was also included in the diameter as suggested by Giadrossich et al. [4].

Roots occasionally showed natural anomalies (e.g., nodal joints, tortuous segments). Although visible mechanical defects (e.g., excavation damage) were grounds for exclusion, naturally occurring irregularities were retained to reflect actual root conditions. If partial tearing or slippage of the bark was observed, the test was repeated where additional material was available.

Questions have arisen about data validity when roots fail near the clamp rather than in mid-span [4]. Some studies [15–18] accepted only tests that fractured in the middle, whereas Hales et al. [5] found no significant difference between middle and clamp-adjacent breaks. In this study, roots that failed near the clamp were retained if no squashing or obvious clamp damage was visible, to avoid artificially inflating the tensile strength data [4].

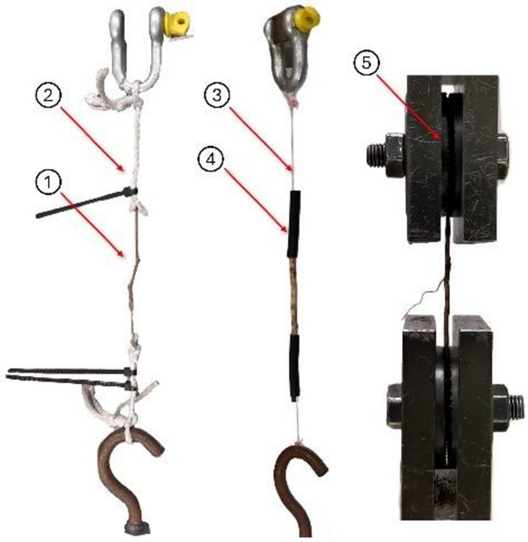

Fig. 1. Example setup of the three clamping methods tested on root samples, with ① the sample root segment, ② Dyneema rope used in the finger-trap mechanism, ③ a low-stretch cable or steer wire, ④ an epoxy connection at the root end in plastic tube sleeve, and ⑤ a textured clamp face in the universal testing machine.

2.3 Moisture Content Determination

RMC was measured immediately after each tensile test. A segment near the fracture point was sealed in a container and weighed to determine fresh mass, then oven-dried at 105°C for 24 hours to obtain dry mass., which is similar to the procedure followed AS1289.2.1.1 for soil. The RMC (%) was calculated as

$$RMC = \frac{m_{\text{fresh}} - m_{\text{dry}}}{m_{\text{dry}}} \times 100\% \quad (1)$$

where m_{fresh} and m_{dry} are the wet and oven-dry masses, respectively. A high-precision scale (Thermoline XA 82/220/X) with a 0.00001 g resolution was used to capture small mass changes, which was especially critical for fine roots. To minimise evaporation during handling, samples were stored in sealed tin containers until weighing.

2.4 Data Analysis

Force-displacement curves from each test were converted to stress–strain curves using the measured cross-sectional area at the point of rupture. Ultimate tensile stress was defined by the peak load divided by that area. The preliminary data plots informed whether the tensile strength was correlated with diameter, RMC, or potentially both. Data analysis methods included the following three steps. First, univariate power-law regression was applied to examine the individual relationships between tensile strength and both diameter and RMC. This yielded R^2 values that indicated the quality of fit for each variable separately.

Next, log–log linear checks were conducted to validate the suitability of the power-law model. Residuals were examined for normality using the Shapiro-Wilk test, ensuring that errors were randomly distributed and did not introduce systematic bias.

Finally, multicollinearity checks and multivariate regression were performed to account for the combined effects of diameter and RMC. Pearson's r and the Variance Inflation Factor (VIF) were used to confirm that the two predictor variables were sufficiently independent. The adjusted R^2 was then used to evaluate how much explanatory power improved compared to the univariate models, providing a more comprehensive understanding of the factors influencing tensile strength [19,20].

3 Results and Discussions

3.1 Performance of Clamping Methods

Clamping is one of the most challenging aspects of tensile tests on roots because of the cylindrical geometry of roots, and the large difference in hardness between root tissue and typical steel clamps [4]. This study evaluated three approaches and assessed each method's viability.

The first approach used a finger-trap mechanism. This approach was initially promising due to its success in both laboratory and in-situ pull-out tests of individual plants [21]. However, when instead used on individual roots where most of the root samples were <2 mm in diameter, the Dyneema rope did not grip the roots effectively. There was insufficient friction due to the lack of stiffness in the highly flexible fine roots and the soft, pliable rope, preventing a secure finger-trap. While the finger-trap mechanism remains theoretically viable, its effectiveness for small-diameter roots would require modifications, such as using a stiffer rope material to enhance grip stability.

The second approach reinforced both ends of a root with epoxy, similar to previous studies [10,11]. About 30 mm of each root end was wrapped with steel cable or low-stretch cable and coated with epoxy and placed in a small plastic mould. This setup is designed to distribute stress uniformly and force failures to occur near the root mid-span, so as to generate data with consistent quality. Successful tensile fracture in the middle span of the root sample was observed in over half of the trials. However, curing takes over 12 hours in a dry environment, causing root moisture levels to decrease by as much as 80%, especially in the thinner roots [6]. Fast-setting products were used to reduce curing time, but it was noted that they occasionally resulted in slippage due to a lower bonding strength. Moreover, despite the use of a low-stretch cable, there are non-negligible strains induced in the cable, which can have a significant effect on measurements used for the calculation of elastic modulus.

The third approach used a UTM with a rough clamp surface (teeth), similar to other studies [5,13,14]. This clamp reduces slippage by increasing interface roughness and contact surface normal stress. It provided 26 successful tests out of 30 in the trial experiments. Tearing of the root bark could introduce slip between the clamp and the sample, so the data were excluded when visible clamp damage occurred. It was noted that roots exceeding ~4 mm in diameter required substantial frictional force and thus higher clamping pressure and risking localised crushing (Figure 2; [4]). This meant that the method was unsuitable for larger roots.

Fig. 2. Demonstration of clamp-damaged root

In conclusion, tensile testing for fine roots (0.5–4 mm) may be better conducted using a UTM with a roughened clamp. Future research should refine these methods to improve their efficacy, prevent root damage, and accommodate a wider range of root sizes. A potential solution is the extension of clamp length (which would necessitate longer samples) to increase the total clamping force, whilst also decreasing local stresses on the roots. This may provide adequate grip while avoiding sample crushing.

3.2 Irregular root morphology

Giadrossich et al. [4] highlighted the significance of visual analysis of specimens prior to conducting tensile strength testing. For instance, Mattia et al. [22] chose only root specimens without any visible defects, whereas Ji et al. [23] specifically selected straight root segments that showed no sign of damage. However, root strength can also be influenced by irregular morphologies that occur during growth [24,25]. Such irregular morphologies may include nodal joints and tortuous segments. In this study, the root specimens were not washed with water to preserve the RMC and were thus covered with light layers of soil, which made these morphologies difficult to visually identify until after the test.

As Loades et al. [26] and Schwarz et al. [3] found, root systems have high individual strength variability due to these natural weak points and their structures. These findings on irregular morphologies have also been reported in Zhu et al. [27]. Excluding them risks systematically biasing measured tensile strength as these features are part of a root's natural development. Hence, in this study, naturally occurring irregular morphologies were retained in the regression analyses.

The first type of irregularity observed was tortuous points (Figure 3.1), namely any deviation of the root from a straight path. Such tortuosity aids anchorage and nutrient uptake but can create local stress concentrations during tensile loading. Schwarz et al. [3] highlighted the significance of these tortuous points in calculating single-root pull-out stress, as they contribute to additional anchorage. Due to bending moments imposed by axial tension, tortuous points can fracture at lower strengths than comparable straight segments; however, the few tortuous points noted in this study appeared to fail at similar strength.

Another form of irregular morphology was the ball-shaped nodal joint. These joints can arise from natural growth damage or nutrient storage in roots. These were difficult to spot initially, but were visible post-test, as one end pulled free from the nodal joint with some bark still attached. This resembles the fish-bead analogue employed by Schwarz et al. [3] to simulate branching. Figure 3.2 shows an example of such a node, where the measured diameter at the fracture point was larger than that of the neighbouring straight segments. Consequently, the calculated stress was lower due to the increased cross-sectional area at the node.

Fig. 3. Example of irregular morphologies ① tortuous point, ② nodal joint

In this study, such irregular morphologies were considered an unavoidable occurrence and included in the analysis. However, their influence on tensile strength measurements remains uncertain, and their inclusion may not always be desirable. Future studies should consider standardised pre-test inspection protocols and criteria. Non-destructive imaging techniques can be used to better characterise root morphology while preserving in-situ moisture conditions.

3.3 Root Moisture Content

Diameter has traditionally been recognised as a primary determinant of root tensile strength, generally following a negative power-law relationship [10,12,13,16,18,22,28,29] in the form of $T_r = k_{d1}\,(d_r)^{k_{d2}}$, where T_r is the tensile strength, d_r is the root diameter, k_1 and k_2 are the power-law regression parameters. Nevertheless, researchers have also highlighted the importance of RMC [28,30,31].

In this study, a univariate power-law fit between tensile strength and RMC was applied after initial inspection of the data. The expression used is $T_r = k_{RMC1}\,(RMC)^{k_{RMC2}}$, where T_r is the tensile strength, d_r is the root diameter, k_{RMC1} and k_{RMC2} are power-law regression parameters. This produced R^2 values ranging from about 0.14 to 0.59 (depending on the species), indicating a moderate association that cannot be ignored. Detailed regression information can be seen in Table 1, which presents the regression parameters for both diameter and root moisture content, along with R^2 values that indicate the strength of these relationships. This approach has also been further examined in Zhu et al. [27].

The table includes test statistics (W) and p-values from the Shapiro-Wilk test to assess whether the residuals meet the normality assumption, ensuring the validity of the regression models. The W values were all close to 1, indicating a good fit to normality. At a significance level of 0.05, all the p-values exceeded this threshold, meaning there was no significant evidence to reject the assumption of normality. These results confirm that the residuals follow a normal distribution, supporting the reliability of the regression models.

Table 1. Regression parameters and statistics test results

Species	k_{d1}	k_{d1}	R^2	W	p
A. costata	24.26	-0.83	0.44	0.99	0.77
B. integrifolia	13.26	-0.84	0.61	0.96	0.16
E. reticulatus	31.18	-0.96	0.64	0.96	0.06
E. racemosa	13.15	-0.56	0.67	0.97	0.45
Species	k_{RMC1}	k_{RMC2}	R^2	W	p
A. costata	14.42	-0.37	0.59	0.98	0.33
B. integrifolia	15.79	-0.93	0.38	0.98	0.65
E. reticulatus	35.01	-0.20	0.14	0.97	0.20
E. racemosa	14.40	-0.36	0.44	0.97	0.53

Because both diameter and moisture content each show low-moderate correlations with tensile strength, we next investigated whether combining these two variables in a single model could more accurately predict root tensile strength.

Firstly, potential multicollinearity was evaluated through r and VIF. Typically, an r over 0.8 or below -0.8 indicates multicollinearity [32] while a VIF value of 1 indicates no multicollinearity and a VIF value above 5 is considered a sign of multicollinearity [33]. The results showed that the r values vary between -0.06 to 0.6 while VIF-values vary between 1 to 1.6. These results showed no strong correlation between these two variables was present in the dataset and thus the data was suitable for a multivariate analysis. This outcome reflected the fact that each tested root was measured only once at a final moisture state; although a single root may experience a decrease in both diameter and hydration over time [28], those effects are less evident when each root is sampled just once.

Table 2. VIF test results, multivariate regression parameters and statistics test results

Species	VIF	Covariance	r
A. costata	1.2	0.31	0.42
B. integrifolia	1.6	0.17	0.60
E. reticulatus	1.0	-0.01	-0.06
E. racemosa	1.0	0.14	0.49

Species	k_0	k_1	k_2	Adj. R^2
A. costata	19.58	-0.24	-0.28	0.62
B. integrifolia	13.24	-0.38	-0.91	0.66
E. reticulatus	32.84	-0.12	-0.75	0.71
E. racemosa	13.63	-0.05	-0.53	0.66

A double power-law model of the form shown in Equation 2 was applied, where k_0, k_1 and k_2 are fitting parameters

$$T_r = k_0 \, (\mathrm{RMC})^{k_1} \, (d_r)^{k_2} \quad (2)$$

To aid interpretation, Figure 4 visualises the relationship between tensile strength, root diameter, and moisture content per Equation 2.

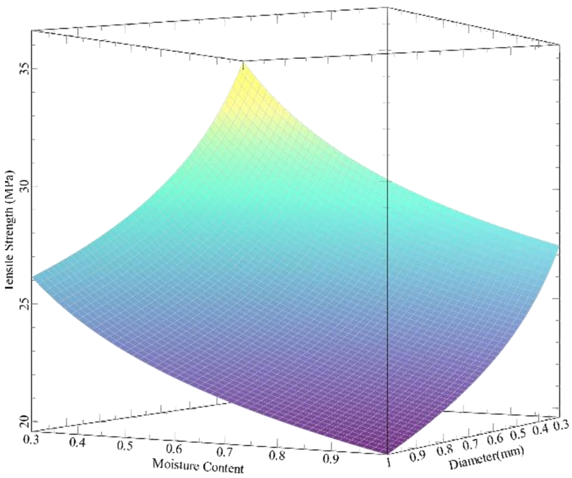

Fig. 4. Graphical representation of Equation 2 showing the effect of diameter and moisture content on tensile strength.

Comparing adjusted R^2 values to univariate fits, tensile strength was consistently predicted more accurately when diameter and RMC were both considered. As shown in Table 2, for *A. costata*, *B. integrifolia* and *E. reticulatus* , the goodness-of-fit of the Multivariate Regression Analysis (MRA) model is markedly better than its equivalent univariate regressions and, for *E. racemosa* , similar (diameter) or better (RMC).

While diameter remains a robust predictor of root strength, the non-trivial effect of RMC suggests that neglecting moisture could lead to poor estimates of root contribution in slope stability modelling. Ultimately, using a multivariate analysis clarifies how diameter and RMC together determine root mechanical behaviour and future experiments might minimise this uncertainty by conducting the tensile test at a standard RMC.

3.4 Limitations and future outlook

This study did not test roots at full saturation, as suggested by Boldrin et al. [6] and Zhang et al. [28], to avoid hysteresis effects from hydration-dehydration cycles. While RMC and diameter at failure were key predictor variables, the influence of full saturation remains unexplored and warrants further investigation.

Another major challenge encountered was selecting a suitable clamping method. While Giadrossich et al. [4] provided valuable recommendations, such as measuring root diameter with the bark intact and refining procedural considerations, significant issues persisted. Despite adjustments, achieving a secure grip without damaging the roots remained difficult, particularly for fine roots. Further refinements in clamping techniques are necessary to improve the reliability of tensile testing.

Beyond clamping, uncertainties regarding root biomechanical properties also remain. Key issues include identifying optimal storage conditions to preserve mechanical integrity and quantifying the impact of RMC on tensile strength. These factors may significantly influence experimental outcomes.

Additionally, root reinforcement models, such as the Root Bundle Model with Weibull survival function (RBMw) [34], demand more comprehensive elastic modulus data. The lack of standardised methods for measuring and incorporating these mechanical parameters into models poses a challenge for accurate predictions. Therefore, an effort to establish testing protocols would improve the reliability and comparability of the data, which would benefit future research on root biomechanics and soil reinforcement models.

4 Conclusion

This study highlighted key challenges in root tensile testing, focusing on clamping methods, irregular morphologies, and the influence of RMC. Results showed that the UTM clamp was the most effective for fine roots, but had limitations for larger specimens, while finger-trap and epoxy methods struggled with grip issues and moisture loss. Irregular root morphologies, such as nodal joints and tortuous growth, were found to reduce tensile strength due to localised stress concentrations, adding further variability to measurements. RMC also played a non-trivial role, highlighting the need for careful moisture control during testing.

Despite these insights, standardisation remains a major challenge. The lack of consistent protocols for sample preparation, storage, and moisture regulation continues to limit data comparability across studies.

Clamping techniques require further refinement to prevent stress concentrations and sample damage, especially for larger roots. Additionally, models such as RBMw still require better constraints on elastic modulus and other biomechanical parameters, which are often overlooked.

Moving forward, a coordinated effort is needed to establish clear testing standards. Researchers must work towards defining best practices for root sample handling, moisture control, and mechanical testing. Addressing these gaps will ultimately enhance the accuracy of root-soil interaction models, making nature-based solutions more effective in geotechnical applications.

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