ROOTING FOR BIOBASED RETAINING STRUCTURES

A study on riparian vegetated soils

Master Thesis

K.P.M. van Bergen

Delft University of Technology

TU Delft

ROOTING FOR BIOBASED RETAINING STRUCTURES

A study on riparian vegetated soils

by

K.P.M. van Bergen

Student Name	Student Number
Karine van Bergen	4476646

Thesis Committee:	Prof.dr.ir. J.W.G. van de Kuilen	Biobased Structures and Materials
	Dr.ir. G.J.P. Ravenhorst	Biobased Structures and Materials
	Dr. M.A. Cabrera	Geo-Engineering
	Dr.ir. A.C. Kamath	Biobased Structures and Materials
Project Duration:	July, 2022 - July, 2023	
Faculty:	Faculty of Civil Engineering, Delft	

Cover: https://ampagronomy.com/wp-content/uploads/2019/05/Root-Development-4.jpg

TU Delft

Preface

It is with great pleasure that I present this master thesis, a culmination of months of dedicated study, research, and experiments with my corkscrew set-up. None of this would have been possible without the guidance and support of everyone around me who have supported me through this process.

First of all, I would like to thank my supervisors meneer van de Kuilen, meneer Ravenhorst, meneer Cabrera and Abhijith, whose expertise, encouragement, and valuable feedback have been indispensable in shaping this research. Their knowledge have been a constant source of inspiration. Abhijith, I really appreciate your mentoring, your reassurance and your guiding when I was lost. I'm also very glad that I made you discover dropjes and dropfruit, they are the best.

I am also grateful to the macrolab and staff who created in the lab a friendly and fun environment when I was counting, analysing and measuring my multiple roots. Shout out to John, who made an amazing corkscrew set-up for my research.

I also spend a lot of time in the Botanical garden of the TU Delft, I would like to thank Ernst and Dan and all the staff for their kindness. They helped me whenever they could and gave me useful advice.

Additionally, I am thankful for my family and friends for bearing with me during these past months. I would like to thank my parents, for making a wonderful study-space in their home and my brothers for supporting me and encouraging me. I would also like to thank my friends for coming to the rescue and listening to me whenever I needed it. I would also like to thank my roommates from the "Church" for the "gezelligheid", for their encouragement and for always cooking for me :). And a final thank you to TB, thank you for your patience and supporting me.

I embark on the next chapter of my journey with a sense of accomplishment, armed with new knowledge, skills, and a commitment to making a positive impact in my chosen field. As I conclude this preface, I am filled with gratitude and a deep appreciation for the opportunities and experiences that have shaped my academic growth.

K.P.M. van Bergen
Delft, July 2023

Summary

Riparian ecosystems are crucial for maintaining ecological balance in riverine landscapes, offering diverse habitats, regulating water quality, and preventing soil erosion. However, these ecosystems are vulnerable to slope instability, leading to detrimental effects such as land loss, habitat destruction, and increased sedimentation in water bodies. In the Netherlands, the banks of waterways are typically protected using various materials, some of which emit significant carbon during production. To meet environmental goals such as the Paris Agreement (2022) [64], there is a need for alternative bank protection structures that utilise natural materials.

Root reinforcement, which refers to the ability of plant roots to enhance soil strength and stability, plays a crucial role in assessing slope stability. The presence of roots influences soil strength through hydrological and mechanical effects. Existing methods for quantifying root reinforcement involve mechanical models or time-consuming in-situ measurements using large equipment. Therefore, the corkscrew extraction method has been developed as a quicker, lighter, and simpler approach to measure shear strength in root-reinforced soil. Previous studies have demonstrated the potential of this method for quantifying root reinforcement in field conditions, providing rapid data collection on shear strength at different depths and steep slopes. Throughout the thesis, a corkscrew set-up, inspired from [36], was used to assess root reinforcement in riparian environments. Also, it was determined whether this technique is applicable in riparian conditions.

The corkscrew device consists of a garden corkscrew weeder, a tripod with a ratchet winch, a steel cable, a load cell, and a draw wire sensor. The corkscrew is maunally rotated into the soil, and the load and displacement are measured during extraction. The force-displacement curves are analysed to determine rooted soil parameters.

The measurements were conducted at two locations in the Netherlands: the Botanical Garden of the TU Delft in Delft and a testing site in Middenmeer. The Delft location had fields with reed plants (*Phragmites australis*) and willow trees (*Salix fragilis* and *Salix purpurea*), while the Middenmeer site was planted with hawthorn (*Crataegus laevigata*). Corkscrew extractions produce force-displacement curves, which exhibit different patterns depending on the root content (root area ratio).

The study finds that the corkscrew method is a promising technique for measuring root reinforcement in challenging terrains like riparian areas. It offers advantages in terms of time efficiency, field applicability, and non-destructiveness compared to complex and destructive methods. However, challenges related to root recovery and the limited testing depth need to be addressed through further research.

The thesis also examined root and strength parameters related to root reinforcement. While root biomass provides information about the quantity of roots, it may not accurately quantify root reinforcement. The root area ratio was found to affect soil behaviour and showed correlations with strength parameters for certain selected species. However, other factors such as moisture content, the soil conditions and root diameter could also influence the relationship between root area ratio and shear strength. The force-displacement graphs obtained from corkscrew measurements highlight the significant influence of roots crossing the shear surface on soil behaviour by comparing the pattern of the curves. Also, root breakages are identified as sudden drops in force displacement graphs.

The presence of roots mobilising at higher displacements than the peak strength of bare soil is crucial for slope stability. The combination of species might provide the best reinforcement effect for stability owing to difference in root paterns spatially and with depth.

Contents

1 INTRODUCTION

1.1. Background

Canals, rivers and streams are numerously present in the Netherlands. Riparian ecosystems play a critical role in maintaining the ecological balance of riverine landscapes by providing diverse habitats, regulating water quality, and preventing soil erosion. However, these delicate ecosystems are often subjected to slope instability, which can result in devastating consequences, including land loss, habitat destruction, and increased sedimentation in water bodies. Addressing slope stability in riparian areas is of utmost importance to ensure the preservation and sustainable management of these valuable ecosystems. In the Netherlands, the banks of waterways are either unprotected or protected by various bank protection materials such as rocks, concrete, steel, asphalt, and timber. Among these materials, the first four are known to emit a significant amount of carbon during their production process, whereas FSC timber is considered an environmentally friendly material in terms of carbon emissions [17][53]. To meet the Paris agreement, alternatives for traditional bank protection structures are needed using natural materials.

A previous research [25], has shown the possibility of a combination of local timber sheet pile and vegetation for stream bank protection structure as an alternative for conventional structures using timber available in the Netherlands, see Figure 1.1. In the study, the root-soil composite and the timber sheet pile-vegetation system of the bio engineered earth retaining system (BEERS) were investigated. When used in stream bank protections, local timber is prone to decay after a certain time. Two approaches to include the effect of vegetation in timber sheet pile-vegetation system were discussed. The first one consists of the reduction of horizontal pressure, bending moments and shear stresses against the sheet pile due to the root-reinforcement. The second one consisting of the full support of the top parts of the bank due to vegetation after the timber has decayed. In order to determine whether it is possible to combine rooted vegetation with wooden sheet piles to form a BEERS to protect Dutch canals and banks, the influence of the roots of vegetation on the stability of the slope needs to be determined.

Root reinforcement, the ability of plant roots to enhance soil strength and stability, is a significant factor in assessing slope stability. The presence of roots affects the strength of the rooted soil through both hydrological (enhancing suctions, rainfall interception) and mechanical (fibre reinforcement, soil nailing) effects. It has been recognised that vegetation can protect the soil, for example reed along riverbanks or mangrove trees along coasts and deltas reduce current velocities and waves and keep the sediment in place. Understanding and quantifying root reinforcement mechanisms provide valuable insights for designing effective measures to mitigate slope failures in riparian conditions.

Despite the widespread recognition of the importance of root reinforcement in soil, majority of the studies focus on evaluating the increase in stability of slopes against landslides. Few research studies the contribution of riparian vegetation to stream bank stability. For quantifying root-reinforcement, two approaches are commonly used. The first one consists of mechanical models where an additional soil cohesion term is used. However, models often contain many assumptions and do not accurately estimate the increase of apparent cohesion due to presence of roots in the soil. The second approach consists of directly making in-situ measurements of root-reinforced soil, most commonly using a large

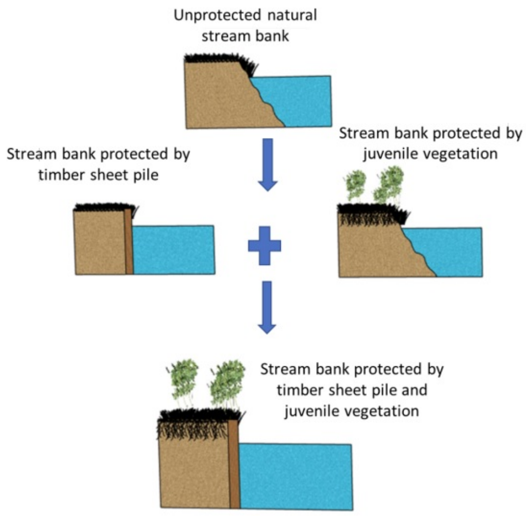


Figure 1.1: The timber sheet pile-vegetation composite stream bank protection structure from the study [25].

direct shear apparatus (DSA) in the field. However, this is a time-consuming method and it requires heavy equipment as well as being not practical in difficult terrain.

Therefore, new methods have been developed which are quicker, lighter and simpler to measure the shear strength of root-reinforced soil [35]. One of these is the corkscrew extraction method. According to studies [35][36], this method is a useful tool for quantifying root-reinforcement of soil in field conditions. Bringing a relatively rapid way of obtaining shear strength data of root-reinforced soil at varying depths as well as on a steep slope [37]. Despite the high potential of the corkscrew method, the method is still experimental and future research should be done to extend the database of field data. Also, the precision of quantifying root-reinforcement through the combination of root counts and interpretative models is greatly influenced by the dependability of the chosen model and the accuracy of sampling.

This research aims to use a corkscrew-like tool, inspired from previous studies on the corkscrew method [35][36][37], to assessing root reinforcement in riparian environments. It is an useful, light and fast testing tool. Specifically, this study focuses on soil planted with reed plants (*Phragmites australis*) and different willow trees (*Salix Fragilis* and *Salix purpurea*), three commonly found vegetation types in riparian ecosystems known for their root system characteristics and soil stabilisation potential.

1.2. Research objectives and questions

To achieve the goals mentioned above, the following sub-objectives are defined:

- Use or adapt the corkscrew apparatus from [36] for field testing of vegetated stream banks and determine the benefits and limitations of using the corkscrew method in riparian conditions.
- Identify and correlate vegetation root parameters with strength parameters.
- Can the outcomes of the corkscrew extraction method reveal the presence and occurrence of root breakages, and how does the force-displacement curves of vegetated soil differ from fallow soil?
- What are relevant root parameters to assess the most suitable vegetation to protect stream banks and do the selected species have the potential to be used as vegetation to protect stream banks?
- How does the root reinforcement obtained from the corkscrew extraction technique vary among the different species investigated in the study?

1.3. Thesis organisation

This thesis is organised into seven chapters designed to provide a clear and comprehensive presentation of the current study.

The current chapter, **Chapter 1 - Introduction** provides an overview of the research questions, the significance of the study and the scope of the investigation. It introduces the research problem, states the research objectives, and describes the research methodology used to address the research questions.

Chapter 2 - Literature study provides an in-depth analysis of the existing research in the field, highlighting the gaps that the current study aims to fill. It reviews relevant literature and theoretical frameworks to provide a conceptual background for the study.

Chapter 3 - Methods and materials details the research design, data collection, and analysis methods used to answer the research questions. It describes the data collection process, research sample, and data analysis techniques to enable other researchers to replicate the study. This chapter is divided into two parts: the experimental part consisting of the corkscrew extraction method and the modelling part.

Chapter 4 - Results presents the findings of the study, including tables and graphs. It reports the empirical results of the study and provides an objective presentation of the data collected and analysed during the research process.

Chapter 5 - Discussion interprets the results in light of the research questions and the existing literature. It discusses the implications of the study's findings, identifies patterns and themes emerging from the data, and compares the results with the literature.

Chapter 6 - Conclusions summarises the key findings and their implications for the field. It offers a concise summary of the research project's main findings, answers the research questions, and outlines the limitations of the study.

Chapter 7 - Recommendations suggests directions for future research and practical applications. It provides recommendations based on the research findings, and the gaps identified in the literature study to guide future research in the field.

2

LITERATURE STUDY

2.1. Corkscrew method

The mechanical stability of soils can be significantly improved by the presence of roots which penetrate unstable soil zones and reinforce soil. Vegetation affects both mechanical and hydrological mechanisms [20]. Therefore, vegetation reinforcement is a crucial factor in protecting stream banks and slopes from soil shear failure [7][22][23][69]. Compared to conventional civil engineering approaches, vegetation represents a cost-effective and eco-friendly alternative [58]. However, quantifying the reinforcing effect of vegetation is challenging.

Laboratory experiments have been conducted to obtain quantitative information on root reinforcement of soil [19][39][46], with some researchers controlling the location and quantity of roots to minimise soil physical heterogeneity [2]. Other studies have examined reinforcement by fibres [21][69], allowing for greater control over sample properties. Nonetheless, such laboratory tests may not fully represent field conditions because of the size of the sample or due to various factors which could not be considered and reproduced, such as natural processes and natural growth patterns [51]. Therefore, caution must be taken when extrapolating laboratory results to field conditions [19]. For example, laboratory tests of [19] have indicated that *R. communis* and species with a similar type of root system are efficient at stabilising steep slopes, but the root system of *R. communis* is not wide-spreading, see Figure 2.1, and in the field, it would not occupy as much underground space as other root systems, which may lead to soil failure.

Several in-situ studies have evaluated the reinforcing effect of roots of various tree and grass species through direct shear tests, offering valuable insights into mechanical stabilisation [5][6][10][15][16][24][41][45][71][73], an example is shown in Figure 2.2. Also, recent research has emphasised the hydrologic effects on soil mechanical properties, as local hydrological conditions around individuals in field conditions can vary [19] and, the impact of soil moisture conditions on the root failure mode affects the magnitude of the root reinforcement [51][57]. Therefore, testing and gathering data on root-reinforced sloped stream banks is crucial.

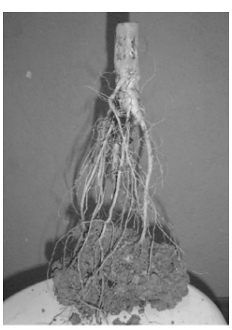


Figure 2.1: Root system of *R. communis*, it has a large stem-root base which tapered rapidly and from which several highly branched long sinkers emerged [19].

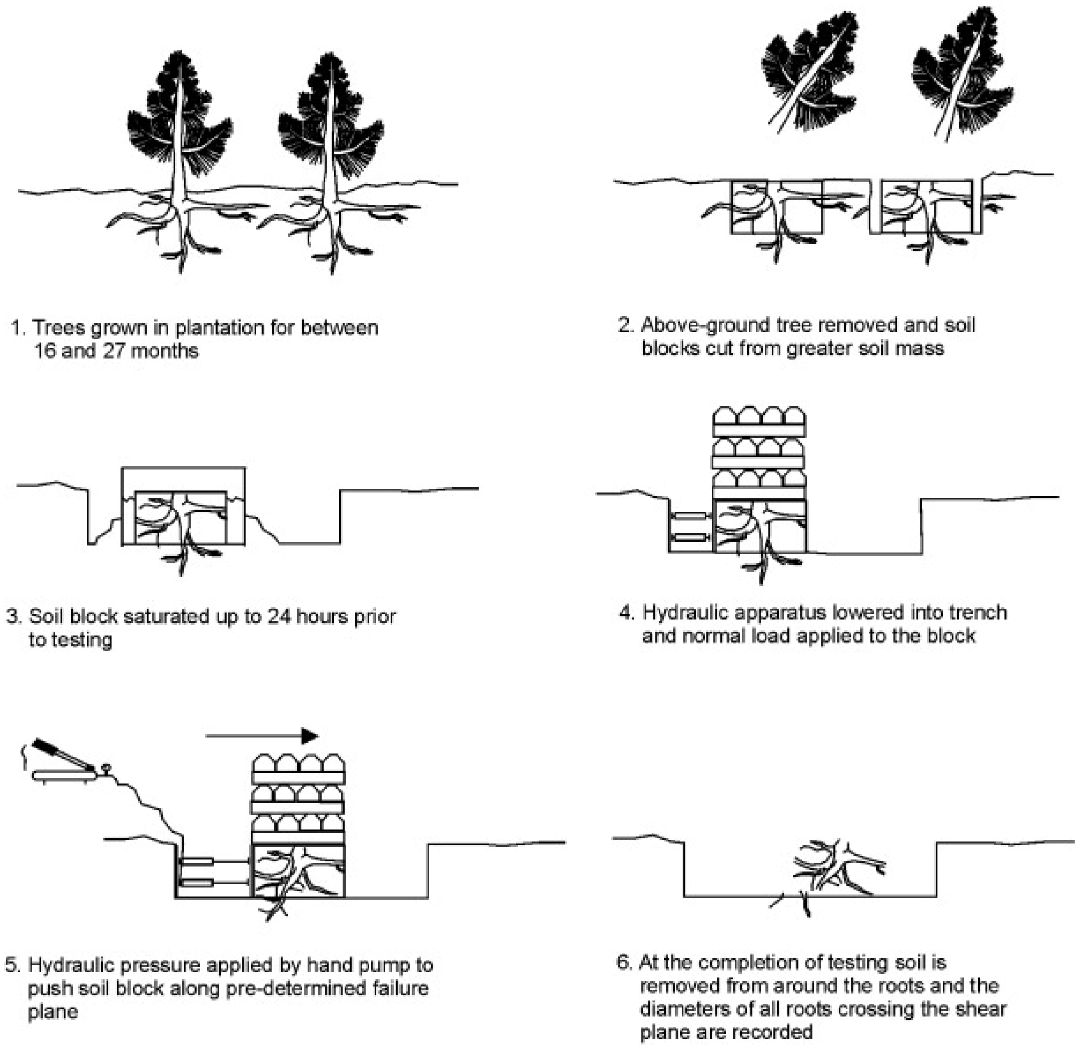


Figure 2.2: In-situ shear test methodology [10].

(a) (b) (c)

Figure 2.3: (a) Technical drawing of the corkscrew from [35]. All dimensions are in mm, (b) typical extracted rooted soil in corkscrew tests from [35] and (c) picture of the corkscrew set-up from [36].

However, conventional shear testing methods are destructive, time-consuming and require heavy equipment (Figure 2.2), making them less suitable to characterise large sloped areas and to assess variability of rooted soil shear characteristics.

Therefore, new techniques have been developed, namely the corkscrew method. This technique is capable of accurately assess root reinforcement and involves using a hollow corkscrew-shaped device to extract a soil block containing roots, see Figure 2.3, while simultaneously measuring the required pull out force and the displacement. By rotating the corkscrew into the soil, the method minimises soil and root disturbance, in contrast to direct in-situ shear testing (Figure 2.2). Studies show that the corkscrew method is rapid, easy to use and provides reliable and accurate measurements of root reinforcement. It has been proven to be applicable on different soil types and root systems in both laboratory experiments [35] and field testing [36][37], including difficult-to-access areas such as steep natural slopes and forested regions. However, it has not yet been evaluated on stream banks, where the soil properties are significantly different.

2.2. Vegetation

2.2.1. Phragmites australis

Phragmites australis, commonly known as common reed, is a widespread wetland plant that can form dense stands in a variety of aquatic and wetland habitats. A drawing of the typical morphology of common reed is displayed in Figure 2.4. The root system of common reed is extensive and can have a significant impact on wetland soil stability. The roots are generally shallow, with a majority of the roots found in the top 20 centimeters of the soil [8]. However, studies [30][40][47][59] have also found that common reed roots forms a dense network of roots and rhizomes that can grow for several meters deep to reach deep ground water, see Figure 2.5. Studies have shown that the mechanical properties of common reed roots can vary depending on environmental conditions and other factors [28]. Also, the roots of *P. australis* spread horizontally which have been shown to play a crucial role in stabilising wetland soils, preventing erosion, and providing habitat for aquatic organisms. In addition to their role in stabilising wetland soils, *P. australis* roots can also have a significant impact on nutrient cycling and carbon sequestration. *P. australis* roots can store significant amounts of carbon in wetland soils, which can help mitigate the effects of climate change. Additionally, the extensive root system of common reed can help remove excess nutrients from wetland soils, improving water quality.

2.2.2. Salix fragilis and Salix purpurea

Salix fragilis and *Salix purpurea* (Figure 2.6), also known as crack willow and purple willow respectively, are shrubs belonging to the Salicaceae family, and are widely distributed throughout the Northern Hemisphere. Both *Salix fragilis* and *Salix purpurea* possess a highly branching and extensive root system which is characterised by numerous fine roots that extensively branch out from the main root structure and proliferate in all directions to absorb water and nutrients. The lateral roots can spread up to several meters away from the main trunk. Overall, root number of willow decreases with the depth and the root density is generally higher near the soil surface [24][39][71]. Few examples of the rooting system of different willows are shown in Figure 2.7. Furthermore, studies [43] have shown that the roots of *Salix purpurea* can extend up to 3 meters deep in well-drained soils, while in soils with higher water tables, they tend to stay shallower, typically between 1-2 meters deep. The rooting depth of Salix fragilis and *Salix purpurea* can vary depending on environmental conditions and other factors, such as soil type, distance from the water source, and the age and size of the tree. Willows adjacent to a water stream, given the riparian ecosystem, are expected that their roots will also be situated near the water table [48][50][63].

Their root systems play a vital role in slope stability, soil erosion control, and water quality improvement [7] and is well adapted to riparian environments, including riverbanks. Studies have shown that the roots of *Salix* are characterised by a high tensile strength, which can be attributed to their fibrous structure and high lignin content [39].

Figure 2.4: Typical morphology of *Phragmites australis* showing (a) panicle, (b) leaf sheath, (c) leaf blade, (d) spikelet, (e) stoma and (f) horizontal and vertical rhizomes with roots [47].

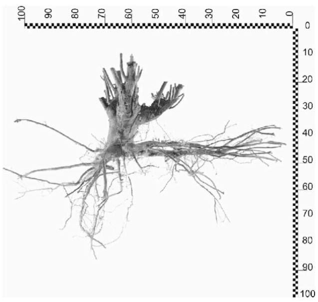
(a) **(b)**

Figure 2.5: Rhizomes of *Phragmites australis*: (a) rhizomes exposed by wave action and (b) close-up view of rhizomes [59]

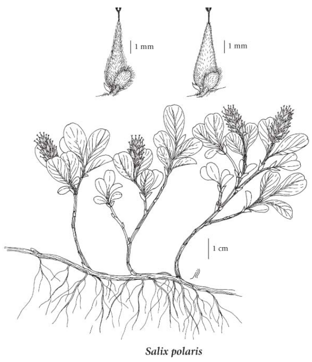
(a)

(b)

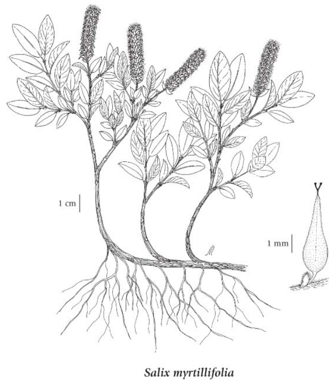
Figure 2.6: Typical morphology of (a) *Salix fragilis* and (b) *Salix purpurea* [32].



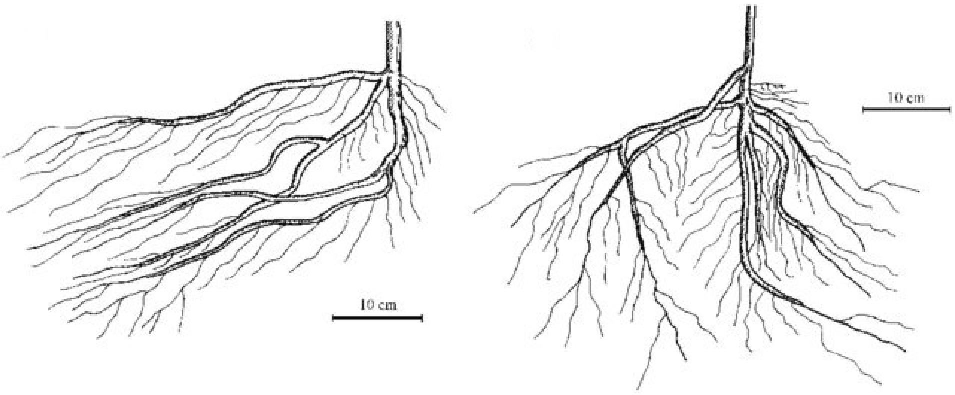
(a)



(b)

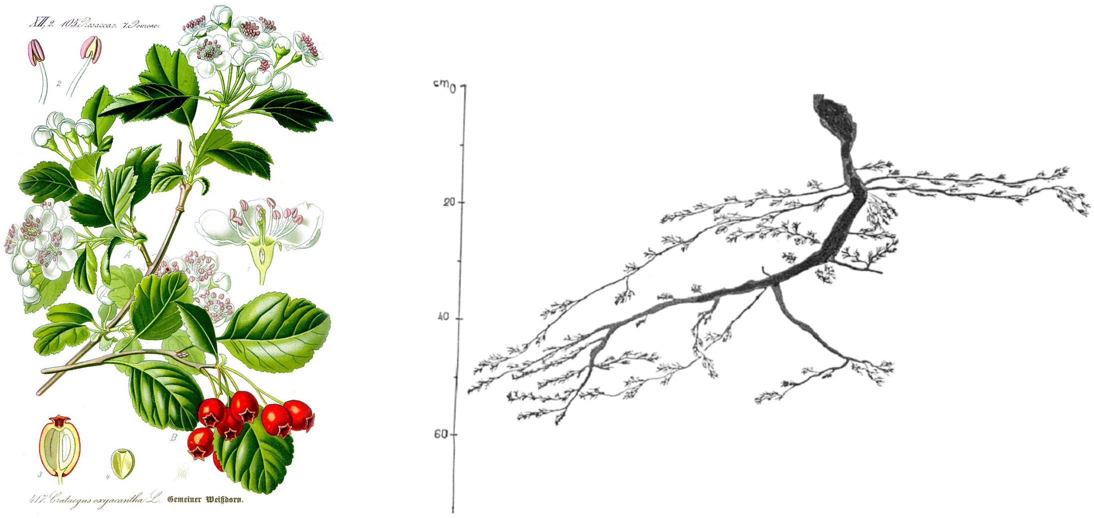


(c)



(d)

Figure 2.7: Examples of the root system of different willow trees: (a) *Salix spp* [49], (b) *Salix polaris* [11], (c) *Salix myrtillifolia* [11] and (d) *Salix caprea* [12].



(a) (b)

Figure 2.8: (a) Typical morphology of *Crataegus laevigata* [62] and (b) picture of the root system of *Crataegus laevigata* [9].

2.2.3. Crataegus laevigata

Crataegus laevigata, commonly referred to as the Midland hawthorn, is a shrub or small tree belonging to the Rosaceae family, see Figure 2.8. The plant has garnered considerable attention in scientific research owing to its noteworthy medicinal properties and ecological significance. While research on various parts of *C. laevigata*, such as its leaves, flowers, and fruits, is relatively abundant, information specifically dedicated to its roots is limited.

The roots of Crataegus laevigata exhibit variability in terms of size, shape, and branching patterns, influenced by environmental conditions. Additionally, the roots can extend to different depths in the soil, allowing for efficient water uptake and stability in various soil conditions [61]. Studies [9][42] characterised the root system of *C. laevigata* as shallow and plate-like, see Figure 2.8b. The research findings revealed rooting depths of up to 0.5 meters below ground level. Furthermore, the base of the trunk exhibited a significant presence of lateral roots that radiated in diverse directions. Based on these observations,[42] suggested a potential suitability of *C. laevigata*, along with other plant species, as a viable bioengineering approach for the stabilisation of slopes.

2.3. Force-displacement graphs

The corkscrew extraction method yields a force-displacement graph which can provide valuable information, particularly from the shape of the curve. Several studies [10][19][39] have observed distinct types of graphs and significant differences in shear behaviour between planted and non-planted samples, as well as differences between species. The force-displacement curve shape is characterised by a rapid increase in shear resistance at the beginning of the test until failure of the soil-root matrix, followed by a gradual increase in resistance for the reinforced soil, while the non-reinforced soil graph shows a decrease in resistance at larger displacements [10][19][39]. Some examples of force-displacement graphs are displayed in Figure 2.9. Previous studies have also reported these findings [1][14][44][66][70], where sharp and well-defined peaks occurred in force-displacement graphs of non-planted soils, while broader and flatter peaks occurred in experiments on planted soils. Curves with no peak, which continued to increase in shear resistance during the test were also observed [10][19][39]. However, the shear tests of these studies were unable to produce sufficient shear displacements in order to let all roots fail in tension and to mobilise their full tensile strength. The increase in shear stress after the failure of the soil-root matrix can be attributed to the action of roots, which continue to confer resistance to shear, either because they are not all broken or because they still provide friction even if they are broken [10]. Some authors have concluded that soil with roots is mobilised at a larger shear displacement than fallow soil but the position of the peak on non-peaked curves is not always clearly explained [1][10][14][33][44][46][66][70].

2.4. Root failure

The failure mode of roots is influenced by their depth in the soil, with deeper roots slipping out of the soil while surface roots are more prone to breaking under tension [39]. Roots that experience tension are more likely to break instead of slip, resisting failure until they reached their ultimate tensile strength. In contrast, roots experiencing bending tend to slip rather than break, resulting in a high residual stress and their ultimate strength not being fully mobilised [19]. In addition, the force-displacement graphs obtained from the corkscrew extraction method show sudden drops in shear stress at various displacements after reaching the peak resistance [10][36][39]. These drops were often accompanied by audible root breakage and were therefore associated with root tension failure [10]. After such drops, a more gradual reduction in shear stress was observed as the root pulled free from the soil [10]. Examples of force-displacement graphs experiencing sudden drops are shown in Figure 2.10. [10] showed that species with high branching roots exhibited force-displacement graphs with multiple peaks as different branches failed at different displacements, whereas species with low branching roots exhibited plots with fewer peaks, see Figure 2.10b. Similar observations have been reported in previous studies on *Acer saccharum* (Sugar Maple) and *Fraxinus americana* (White ash) roots by [54], and on *Eucalyptus camaldulensis* (River Red Gum) and *Melaleuca ericifolia* (Swamp Paperbark) roots by [3].

[36] suggested that information on the diameter of the roots crossing the shear plane could be extracted from the magnitude of the sudden drops in the force-displacement graphs of the corkscrew extractions. However, the results obtained by the interpretative models were inconclusive since the natural variation of the root material behaviour and root cross-section were not considered.

2.5. Root parameters

In regards to slope stability, the various below-ground characteristics of plants are the most significant traits. Multiple studies have shown that the presence of roots, whether in the number of roots (root biomass) [1][19][26][27][33][72][73] or in the cross-sectional area of roots (root area ratio) [10][16][39][67][69][71][73] crossing the shear plane, significantly increases the shear resistance of the soil. The cross-sectional area of roots crossing the shear plane is also called the root area ratio (RAR) and is expressed as:

$$RAR = \frac{\Sigma_i n_i A_{r,i}}{A} \tag{2.1}$$

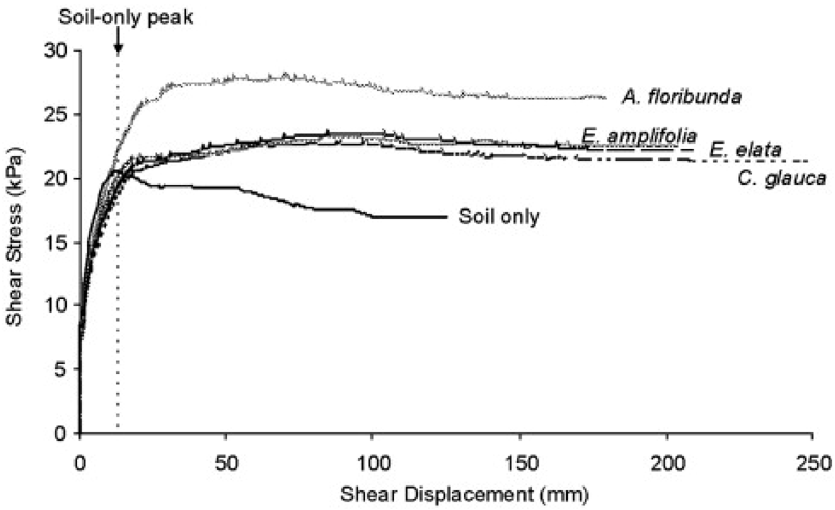
where A is the shear area, n_i the number of roots with diameter i crossing this plane and $A_{r,i}$ the cross sectional area of a single root.

Several factors play a significant role in the determination of the soil shear strength: the root tensile strength and the modulus of elasticity, which describes the root's ability to resist deformation under an applied load. Also, the energy absorbed by the soil permeated by roots and the strain corresponding to the peak shear stress play an important role in the assessment of the soil shear strength [14][18][19][38][39].

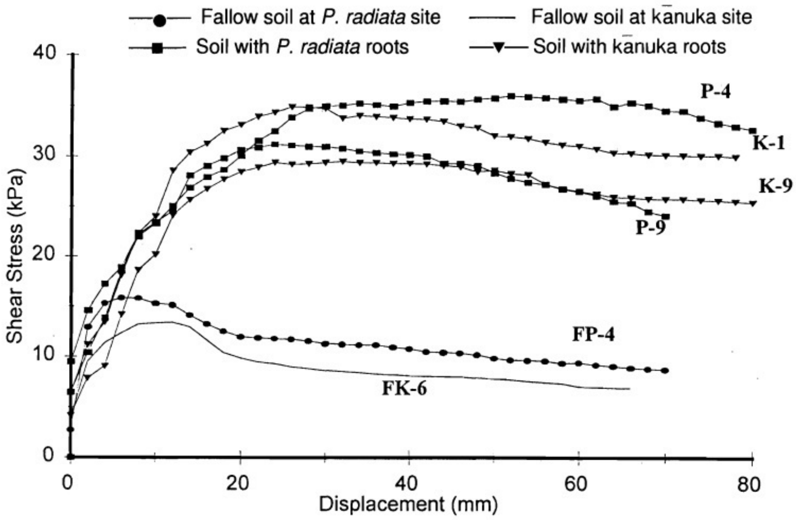
Furthermore, it was shown that the magnitude of increase in shear strength is species-dependent since the species tested in [10] provided greater increase in shear strength at comparative RAR values than the species tested in previous direct in-situ shear tests [16][69][71][73], see Figure 2.11. The difference is attributed to inter-species differences in root strength and morphology, as well as site conditions. The species of plants and the moisture content both have a significant impact on mechanical properties, with species having a more significant influence [19].

Samples with a greater root area ratio may result in a wider shear zone [56], allowing for greater root deformation before their full tensile strength is mobilised. Moreover, the presence of roots influences the displacement at which peak shear resistance is reached. Planted samples failed at much higher displacements than bare soil samples with a smaller number of roots crossing the shear plane [10][14][39], see Table 2.1. Additionally, it was reported that the peak shear stress for planted samples was higher than the shear stress of bare soil samples at the corresponding displacement [39].

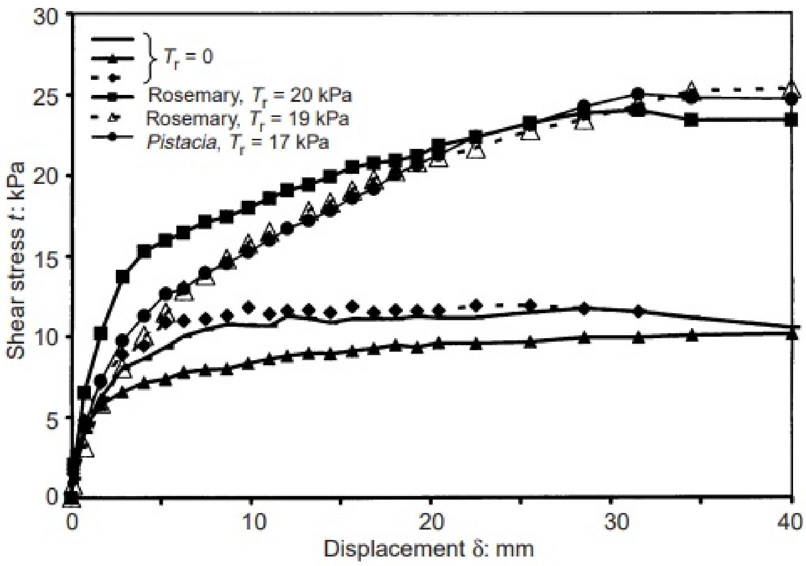
[19] reported that root number is a more effective indicator for soil resistance than root cross-sectional area at the shear plane [19]. However, determining the root area ratio at the shear surface provides a useful method of estimating the increased soil shear strength [39].



(a)

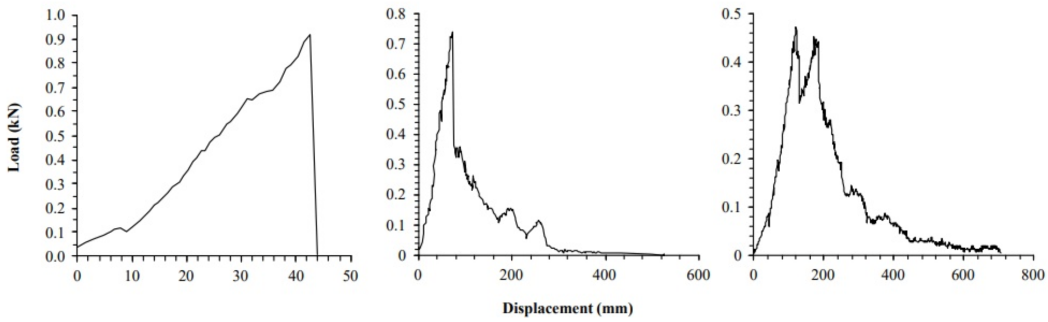


(b)

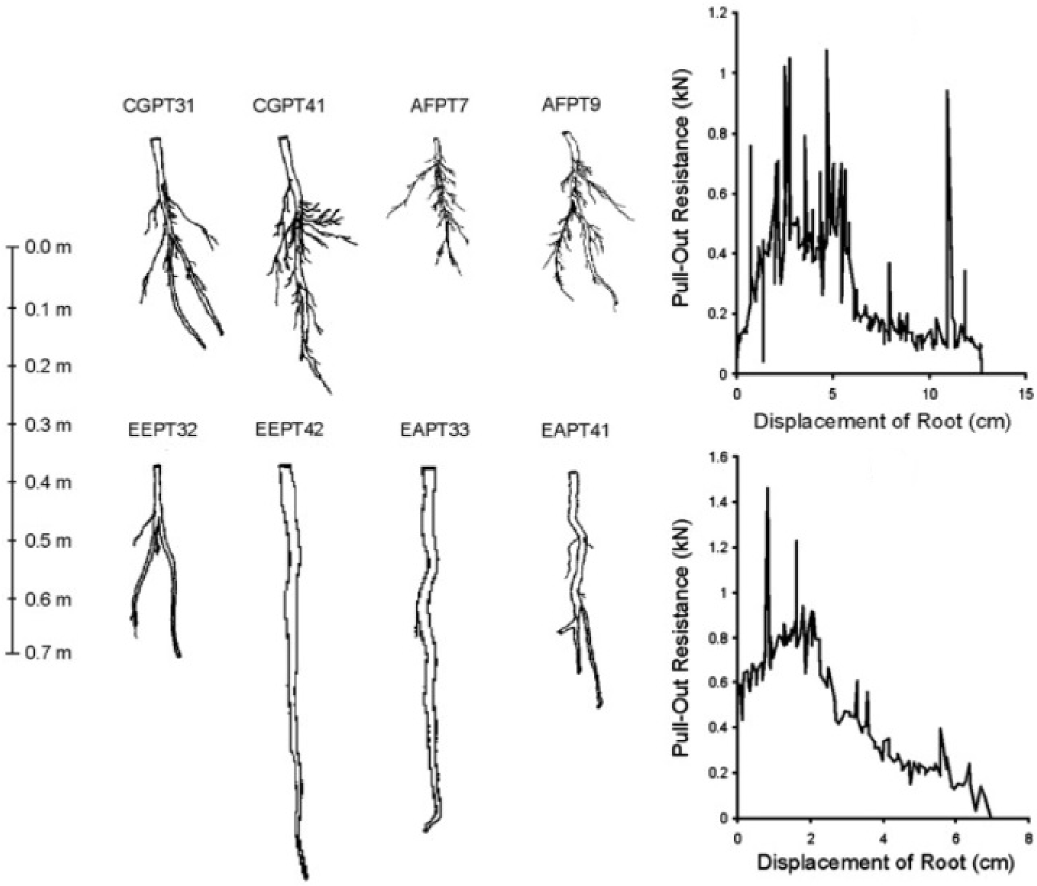


(c)

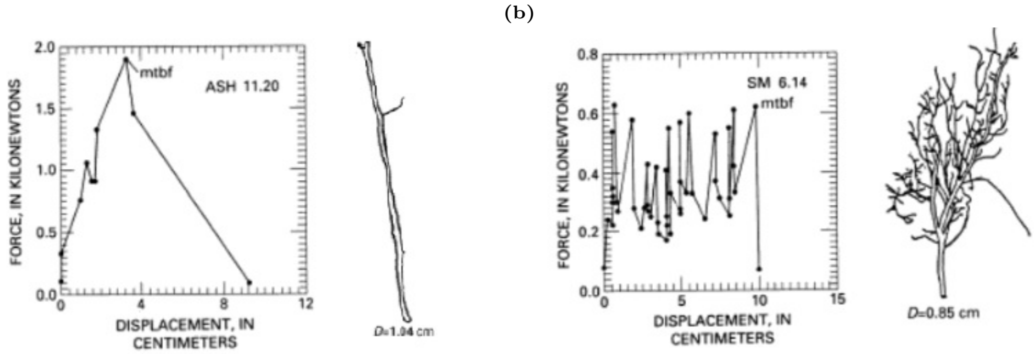
Figure 2.9: Examples of shear stress versus displacement plots for fallow soil and different species: (a) *Acacia floribunda, Eucalyptus amplifolia, Eucalyptus elata* and *Casuarina glauca* [10], (b) *Kunzea ericoides* and *Pinus radiata* [13] and (c) *Pistacia* and rosemary [46].



(a)



(b)



(c)

Figure 2.10: Examples of typical load-displacement plots of root tensile strength tests of different species under field conditions: (a) river red gum [3], (b) *Acacia Floribunda, Eucalyptus Amplifolia, Casuarina Glauca, Eucalytpus Elata* [10] and (c) sugar maple and white ash [54]. The multiple sudden drops shown in the load-displacement plot correspond to the multiple root failures required to pull out the different roots from the soil.

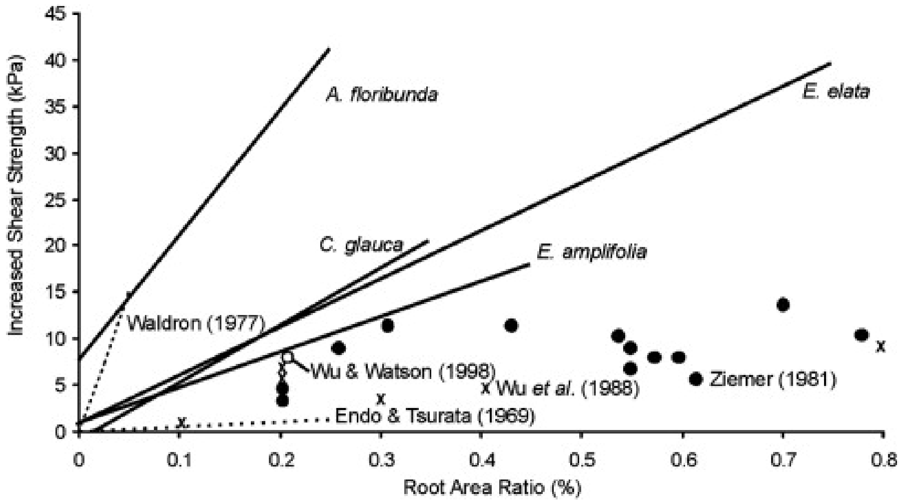


Figure 2.11: Increased shear strengths for direct shear tests conducted on soil containing roots. Direct in-situ tests were conducted by all researchers except for [66] who conducted laboratory shear tests on barley roots. [71] examined *Pinus radiata*, [16] *Betula japonica* and *Alnus japonica*, [72] *Pinus contorta*, [69] Western hemlock and [10] *Acacia floribunda, Eucalyptus elata, Casuarina glauca* and *Eucalyptus amplifolia* [10]
.

2.6. Root reinforcement model

In riverbank stability modeling where the effects of vegetation are considered, accurate estimation of the root reinforcement effect is crucial. For slopes without vegetation, the shear strength of fallow soil is typically estimated using the linear Mohr-Coulomb failure criterion. However, applying this criterion to vegetated slopes has found to be challenging in stability analysis [1][45][60][70]. Consequently, the strength of soil with roots is often estimated by adding the contribution of the roots to the strength of bare soil. This can be achieved by either measuring the strength increase from roots using in-situ shear tests or by predicting the shear strength contribution of individual roots through theoretical root-soil interaction models.

The Wu/Waldron model (WWM), independently developed by [66][68][70], is a widely recognised approach for quantifying the effect of plant roots on slope stability through root reinforcement. The model simulates the idealised situation of a tree's vertical roots extending across a potential sliding surface in a slope. It consists of a flexible, elastic root that extends vertically across a horizontal shear zone. As the soil is sheared, a tensile force T_r develops in the roots. To develop the model, field surveys were conducted in various natural and engineered slopes with different vegetation types to observe and measure root system characteristics, such as root density, root diameter, root area ratio and root mechanical properties. Laboratory experiments were performed to determine the mechanical properties of roots, including root tensile strength and modulus of elasticity. Root samples from different plant species were subjected to pull-out tests and tensile tests to measure the strength and properties of the roots. Based on the collected field and laboratory data, Wu and Waldron developed a theoretical model that related root properties to the soil reinforcement effect. The WWM is easy to use, requires simple input parameters and expresses the increase in soil shear strength due to plant roots as an additional soil cohesion term c_r:

$$c_r = k'\sigma_t RAR \tag{2.2}$$

where k' is a root orientation factor, (often assumed as $k' = 1.2$ [70]), σ_t is the tensile strength of the root and RAR denotes the root area ratio.

The Wu/Waldron model has been applied in numerous studies to evaluate the root reinforcement effect in various slope stability scenarios, yielding results that correspond to field observations [7][23]. These applications encompass a wide range of vegetation types, slope angles, soil conditions, and climatic zones. The model offers several advantages, including its ability to estimate root reinforcement and its simplicity.

However, the WWM has been shown to significantly overestimate root reinforcement due to the assumption that all roots fail simultaneously [10][23][39][52][71]. In reality, root pull-out resistance is

Authors (Year)	Vegetation	Root area ratio [%]	Peak displacement [mm]	Peak shear stress [kPa]
Docker and Hubble (2008)	Fallow soil	-	16	21.01
	Casuarina Glauca	0.143	70	25.20
	Eucalyptus Amplifolia	0.211	73	25.85
	Eucalyptus Elata	0.221	63	26.04
	Acacia Floribunda	0.082	57	31.97
Ekanayake et al. (1997)	Fallow soil	-	13	15.43
	Pinus radiata	0.220	30	31.22
	Kunzea ericoides	0.211	27	30.12
Mickovski et al. (2009)	Fallow soil	-	35	4.22
	Salix viminalis	0.247	78	34.57

Table 2.1: Mean experimental results for direct shear tests conducted on fallow soil and on soil containing roots. Direct in-situ tests were conducted by Docker and Hubble (2008) [10] on *Casuarina Glauca, Eucalyptus Amplifolia, Eucalyptus Elata* and *Acacia Floribunda*, and Ekanayake et al. (1997) [13] on *Pinus radiata* and *Kunzea ericoides.* Mickovski et al. (2009) [39] conducted controlled laboratory direct shear tests on *Salix viminalis.*

mobilised gradually and roots fail gradually in tension at different displacements, depending on their individual morphology [10][52]. Therefore, adding the contribution of the roots to the soil strength using the WWM may not accurately reflect the actual strength of the soil-root system at failure, see Figure 2.12.

Additionally, the variability in root tensile strength can impact the accuracy of the Wu/Waldron model. Tensile strength tests on individual roots have shown that tensile strength often depends on root diameter and follows power laws. Using fitted root tensile strength relations instead of individual root properties has been found to result in significant overestimation of root reinforcement [10][39][46].

As an alternative, [52] employed the Fibre Bundle Model (FBM), which assumes that the maximum load sustained by a collection of fibres is less than the sum of their individual strengths. This is because, as load is applied, the fibres will progressively break, redistributing the load among the remaining intact fibres, enabling the assumption of progressive failure of roots. Previous investigations have reported evidence of progressive failure [23][54][71]. [54] concluded that root pull-out resistance is mobilised gradually, with roots failing at different displacements based on their individual morphology.

Although the Wu/Waldron model is simple and requires few input parameters, it is not suitable to estimate the total reinforcement provided by roots by summing the reinforcement calculated for each individual root during this current study. This is because different roots contribute to reinforcement at different displacements across the shear plane, based on factors such as their location, size and orientation relative to the shear plane. A more suitable alternative, might be the Fibre Bundle Model. However, the input parameters are complex and beyond the scope of this research.

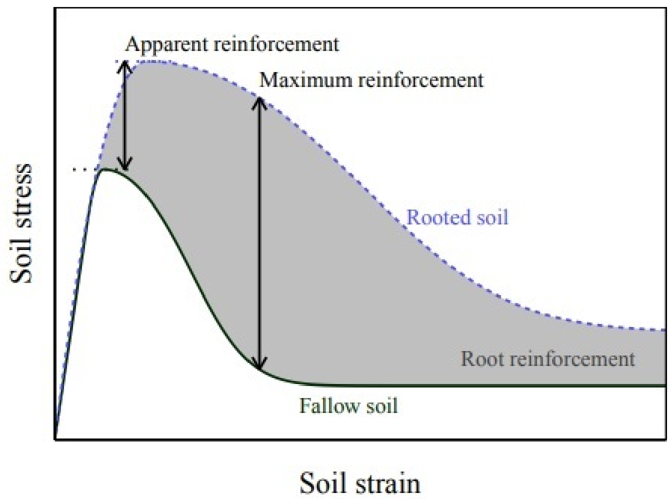


Figure 2.12: Schematic rooted and non-rooted soil stress-strain curves [36].

3

METHODS AND MATERIALS

3.1. Field sites

Measurements were conducted at two locations in the Netherlands, namely the Botanical Garden of the TU Delft in Delft and a testing site in Middenmeer, as depicted in Figure 3.1. The Delft location had three fields situated next to a small stream, out of which the first field was planted with reed plants (*Phragmites australis*) without any other vegetation nearby, as shown in Figure 3.2a. Testing was conducted over two days in September 2022. Prior to the first testing day, the plants were cut without removing the roots to facilitate the corkscrew extractions. The other two fields each had a different type of willow tree (*Salix fragilis* and *Salix purpurea*) and grass was present nearby, as illustrated in Figure 3.2b and 3.2c. The testing field with the *S. fragilis* was evaluated over two days in October 2022, while the testing field with the *S. purpurea* was assessed over three days in March 2023. Prior to the testing in October 2022, the branches of the trees were cut to facilitate the corkscrew experiments. The site in Middenmeer was planted with hawthorns (*Crataegus laevigata*) and no other vegetation nearby was found, as depicted in Figure 3.2d. Testing was carried out on two hawthorns on a single day in March 2023. In addition, on each sites, the soil dry bulk density and water content were measured adjacent to the testing areas. The rainfall and temperature were reported during each day of testing, as shown in Figure 3.3.

3.2. Corkscrew device and setup

The corkscrew method has been previously experimented in the laboratory as well as in the field [35][36]. In field conditions, the corkscrew demonstrated to be a useful tool for measuring root-reinforcement. Its self-drilling helical structure facilitates simple installation in rooted soils without causing significant disturbance, and the test itself is rapid and requires lightweight equipment. Additionally, the outcomes are easily interpretable. In order to conduct corkscrew experiments across the different sites, a tool similar to the one employed in prior research was reproduced [35][36]. It consists of a garden corkscrew weeder (De Wit, Kornhorn, The Netherlands), whose dimensions are presented in Figure 3.4. Since the corkscrew is not rigid, the compressive axial stiffness of the corkscrew helix (k_{cs}) needs to be evaluated. A previous study [36] reported that $k_{cs} = 54.3$ Nmm^{-1}, by using a universal testing machine within a force range of 0-600 N. Also, the tensile stiffness was reported to be equivalent to the compression stiffness. Since a similar corkscrew is used during this study, $k_{cs} = 54.3$ Nmm^{-1} is assumed.

During field testing, the corkscrew is manually rotated into the soil, followed by the placement of a tripod with a ratchet winch and a steel cable which is aligned vertically to the corkscrew. The cable and corkscrew are then attached. The load in the cable is determined by a 5 kN load cell (model KM1503 Force sensor serie, Megatron) and the displacement of the corkscrew is measured by a draw wire sensor (model WPS-250-MK30-P10, Micro-Epislon). A measurement and control unit records the load and the displacement at a frequency of 2 Hz and is mounted between the winch and the tripod. The draw wire sensor is subsequently attached to the load cell, ensuring that both draw and steel wires are parallel in order to avoid any angle-related corrections. Finally, to extract the corkscrew from the soil, the winch is manually rotated at an extraction rate of 2 mm/sec which corresponds to the displacement rate of slow landslides [36]. The measurement and control unit also reports the rate of the displacement, which

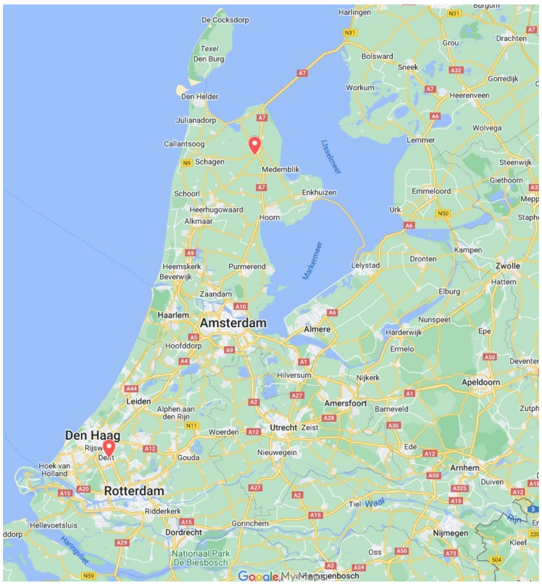


Figure 3.1: Location of the study areas in Middenmeer and in the Botanical garden in Delft where experimental work was undertaken.

enabled us to keep a constant extraction rate during testing. A schematic view of the corkscrew set up is illustrated in Figure 3.5.

3.3. Corkscrew data interpretation - root-reinforcement

Corkscrew extractions result in force-displacement curves, similar to those reported in previous studies [35][36], and exhibiting similarities to the outcomes of direct shear tests. During testing, after having manually rotated the corkscrew into the rooted soil, the force is set to zero, see Figure 3.6 and 3.7a. Afterwards, the corkscrew extraction begins. At first over a short displacement, only the soil is mobilised until its maximum resistance is reached, as indicated by point b in Figure 3.6 and 3.7b. After this point, whenever no roots are present in the soil, the soil has failed and the force decreases. However, if roots are present, they are activated and resist the pull out force, see Figure 3.7c. When the root resistance is reached, the roots fail, which is denoted by d in Figure 3.6 and 3.7d. These two distinct patterns of force-displacement curves of fallow and rooted soil are shown in Figure 3.6 and 3.8, respectively.

Additionally, the force-displacement curves are analysed to determine multiple parameters, including the peak force, the peak displacement, the total deformation energy and two moduli denoted as the S-Modulus and R-Modulus. The peak displacement corresponds to the displacement at peak force. The S-Modulus represents the elasticity of the soil when only the soil is activated. The R-Modulus corresponds to the elasticity of the roots when the roots are activated and the soil has failed. The corkscrew is slightly flexible, causing the measured draw wire displacements to exceed actual vertical soil displacement. To account for this, an estimation by [36] of the 'average' soil displacement is defined as:

$$u = u^* - \frac{1}{2}\frac{F(u^*)}{k_{cs}} \tag{3.1}$$

with u^* the measured displacement, $F(u^*)$ the measured extraction force at displacement u^* and k_{cs} the screw axial stiffness.

In order to account for the additional force provided by the roots only, the peak force of rooted-soil tests is normalised over the peak force of fallow soil tests:

$$F_n = \frac{F_{r,peak}}{F_{0,peak}} \tag{3.2}$$

where $F_{r,peak}$ corresponds to the peak force of samples considered as rooted and $F_{0,peak}$ is the peak force of the samples considered as non-rooted. The non-rooted samples, also designated as soil-only samples, are the samples with the least and relatively low root presence.

(a) (b) (c) (d)

Figure 3.2: Pictures of the location sites planted with (a) *P. australis* at the Botanical garden in Delft, (b) *S. fragilis* at the Botanical garden in Delft, (c) *S. purpurea* at the Botanical garden in Delft and (d) *C. laevigata* in Middenmeer.

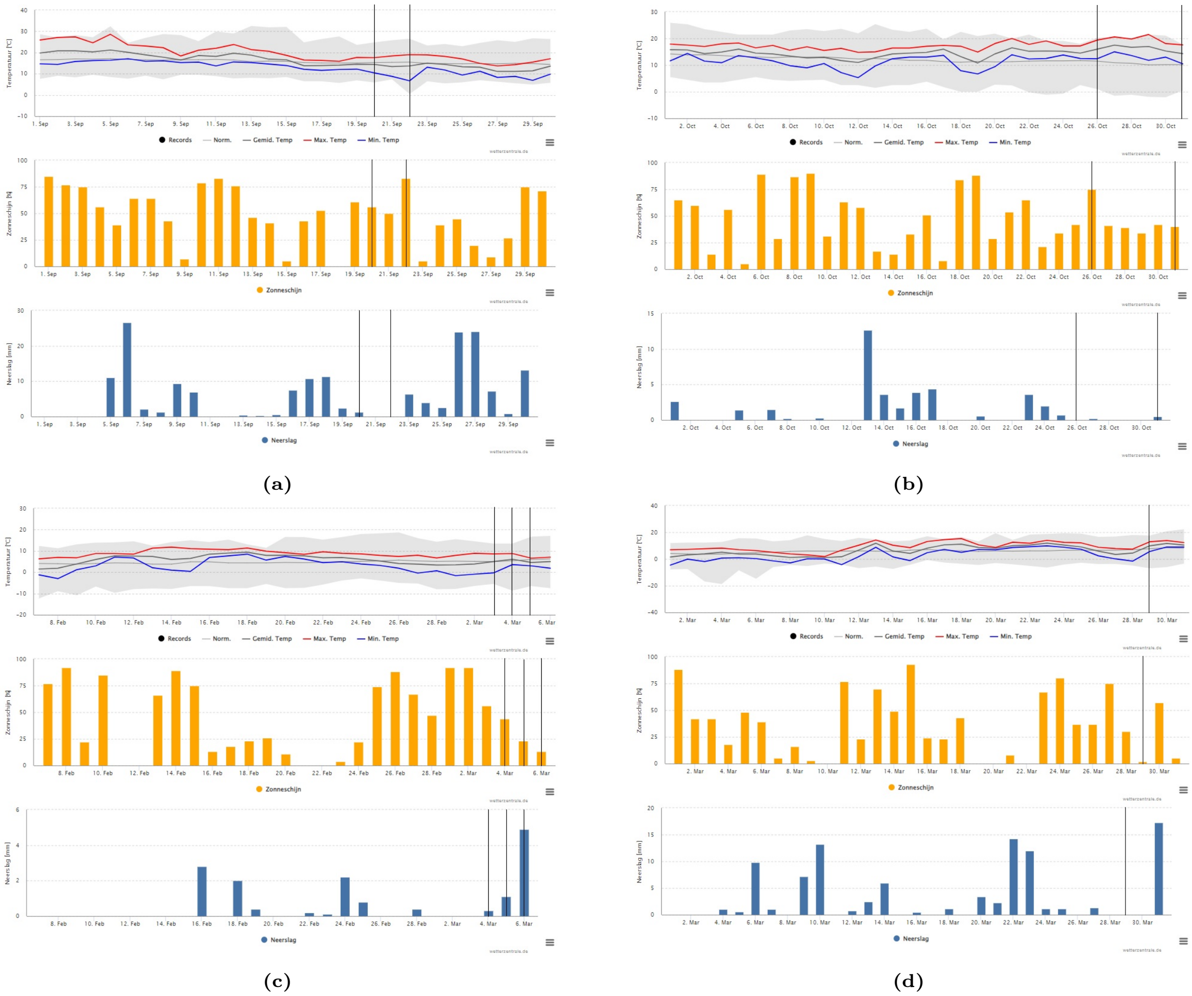


Figure 3.3: Temperature and rainfall during testing in (a) September 2022 in Delft, (b) October 2022 in Delft, (c) in March 2023 in Delft and (d) in March 2023 in Middenmeer.

The amount of energy required to extract a volume of rooted soil from the ground, denoted as J, has to be considered in the investigation of the contribution of root-reinforcement to soil shear resistance [19][36]. This parameter is quantified by calculating the total area beneath the force-displacement curve, accounting for root breakages that may occur after the peak force has occurred or after the testing depth has been reached.

$$J = \int_{u}^{u_0} F(u)du \tag{3.3}$$

with u_0=0mm and u denotes the displacement at the end of the test.

The elasticity of the soil denoted as the S-Modulus, is determined by the slope between points a and b of the force-displacement graphs in Figure 3.6 and 3.8 [19]. Notably, force-displacement graphs of rooted soil exhibit a different slope after the soil has failed and when the roots are activated. To explore the elasticity of the roots a new parameter is introduced, the R-Modulus, determined by the slope between points b and c in Figure 3.8.

3.4. Corkscrew data collection

The tests on soil rooted with *P. australis* were conducted on two distinct days at different depths: 0-125 mm, 125-250 mm and 250-375 mm. The tests were performed sequentially, with each subsequent test at a greater depth within the same hole left open by the previous test at shallower depth. A total of 27 measurements were taken from depths within the range of 0-375 mm. In Figure 3.9a, the locations of the corkscrew tests and reed plants are given. The tests on *S. fragilis* were carried out on two separate days, and at varying depths of 0-125 mm, 125-250 mm and 250-375 mm.

Figure 3.4: Picture of the corkscrew weeder (De Wit, Kornhorn, The Netherlands); height h_{cs} = 125 mm, diameter d_{cs} = 40 mm

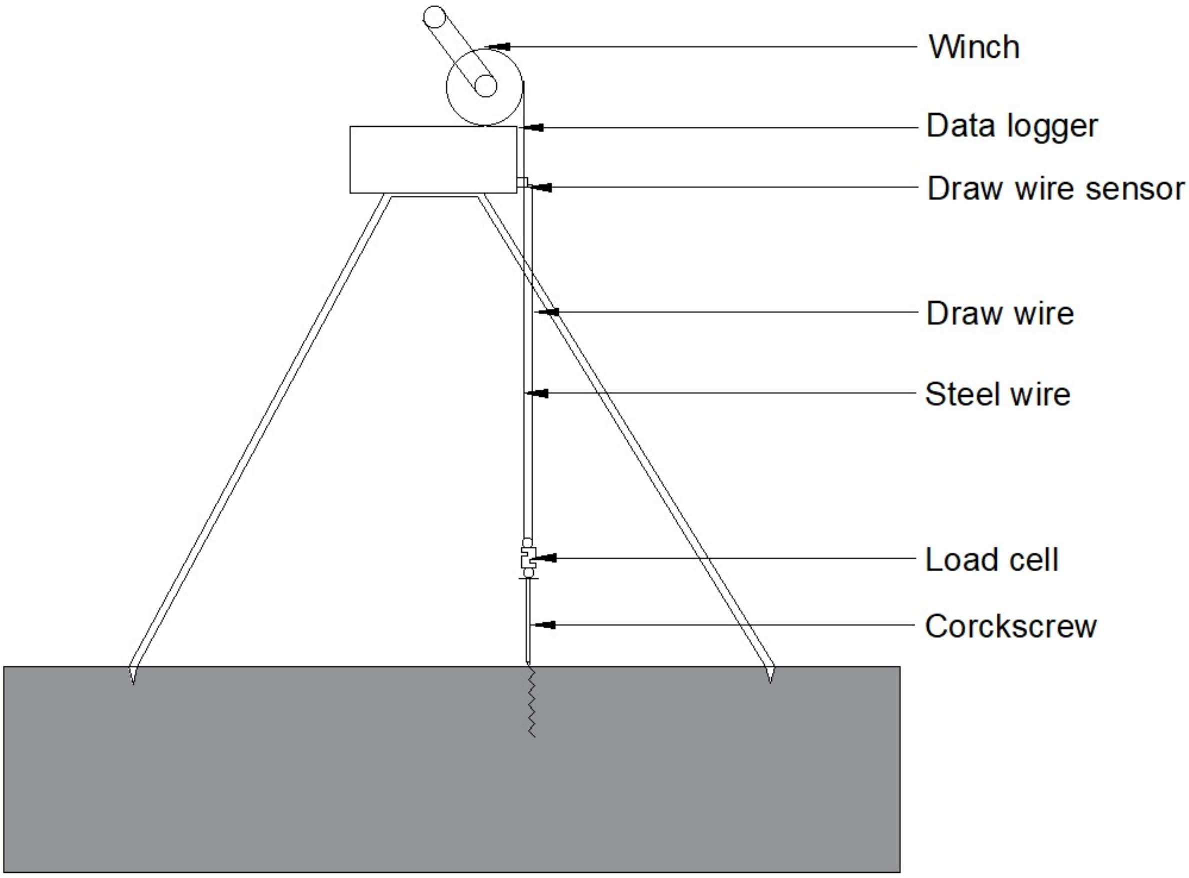


Figure 3.5: Schematic view of the corkscrew setup.

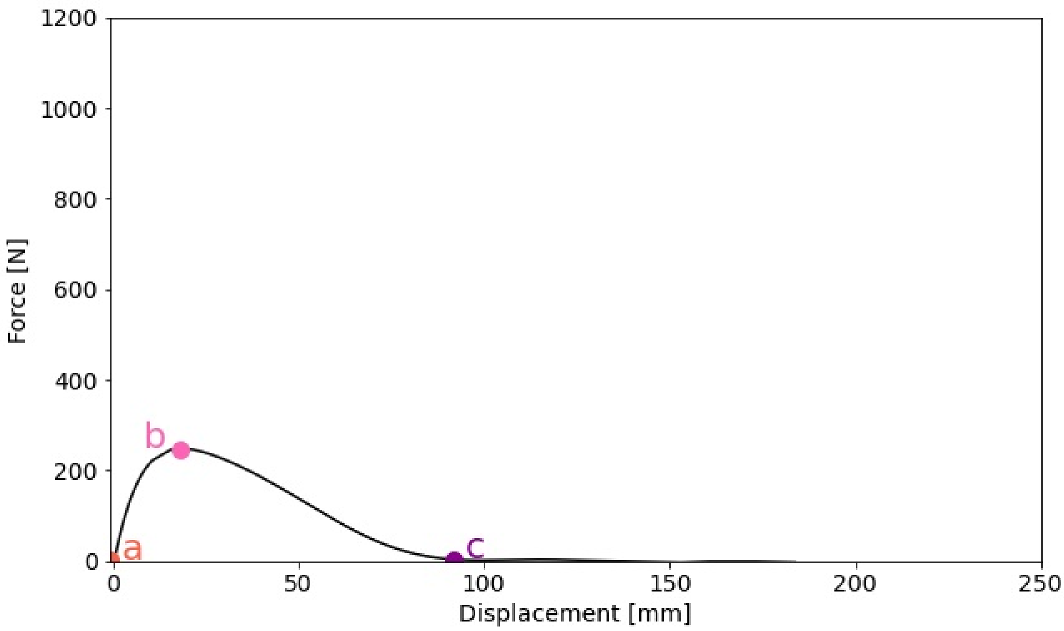
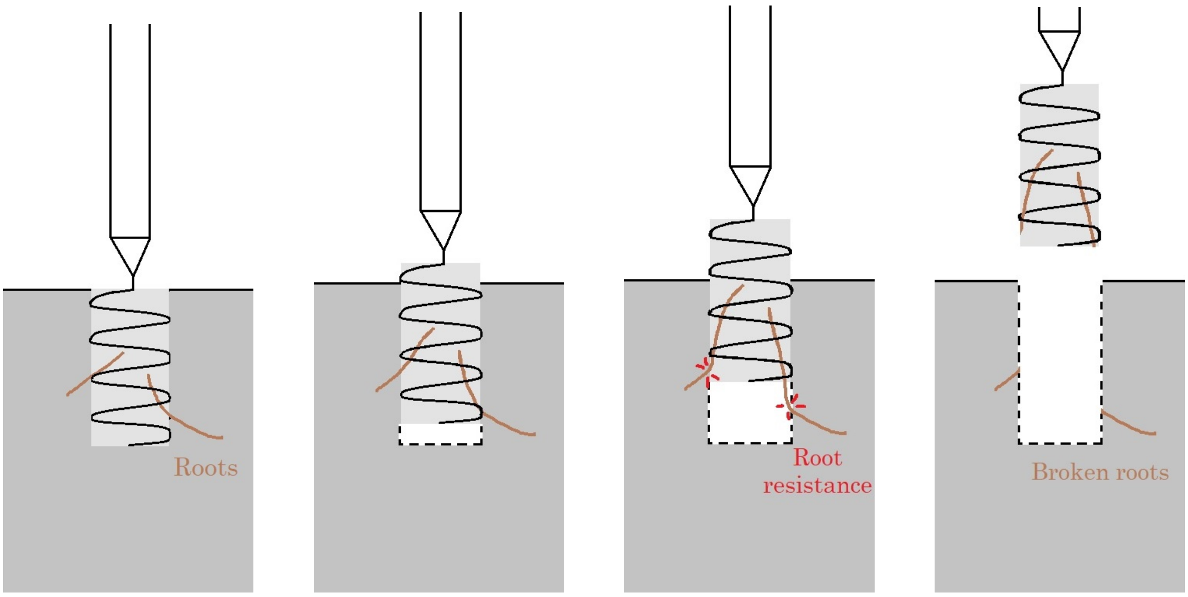


Figure 3.6: Schematic representation of a typical force–displacement behaviour of a fallow soil. The letters correspond to (a) after the corkscrew has been manually rotated into the fallow soil, (b) the peak force is reached and the soil has failed, and (c) is after extraction.



(a) **(b)** **(c)** **(d)**

Figure 3.7: (a) the corkscrew is manually rotated into a rooted soil, (b) beginning of pull-out the extraction and the soil has already failed and the roots start to mobilise, (c) before failure of the roots and (d) after extraction.

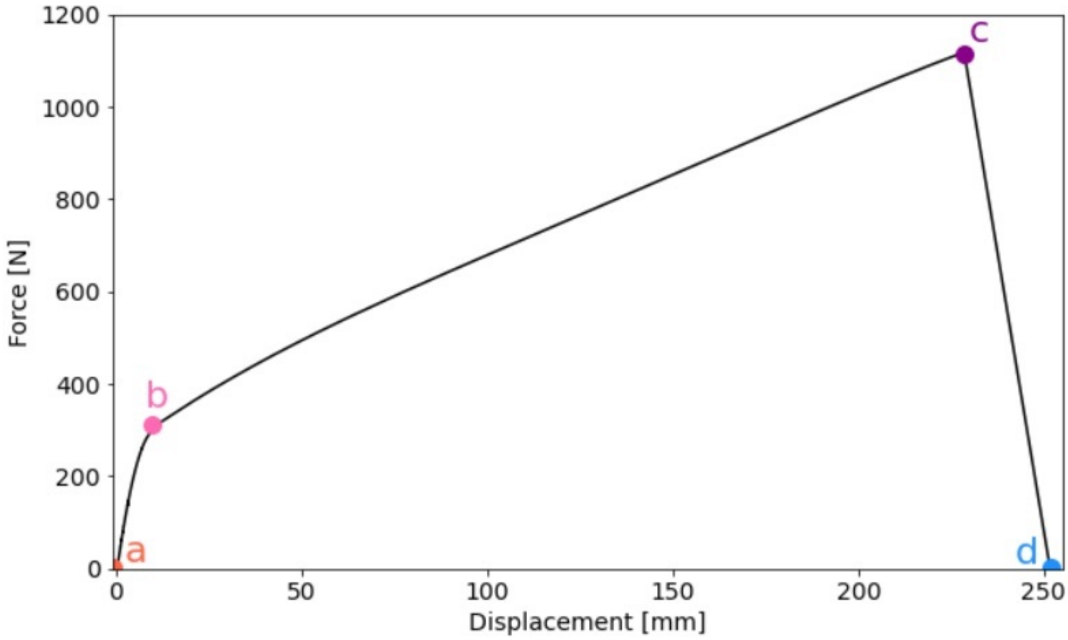


Figure 3.8: Schematic representation of a typical force–displacement behaviour of a rooted soil. The letters correspond to the state of Figure 3.7.

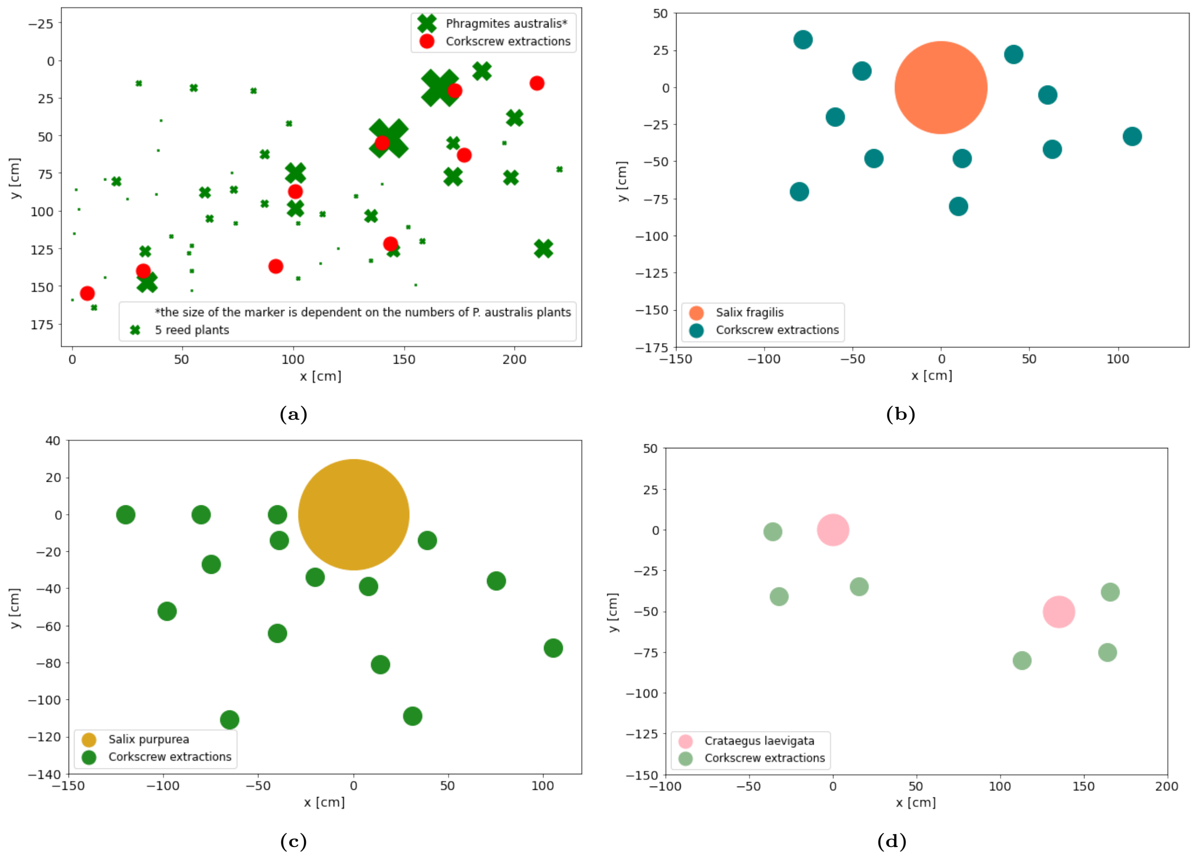


Figure 3.9: Locations of the corkscrew tests and vegetation. (a) At the *P. australis* site, the green stars correspond to the locations of the reed plants, with the size of the stars varying with the number of reed plants. (b)At the *S. fragilis* site, (c) at the *S. purpurea* site and (d) at the *C. laevigata* site.

Tested vegetation	Number of tests	Range of depth [mm]	Number of plants	Distances from the plants [mm]	Period of testing
P. australis	27	0 - 375	238	Randomly scattered	September
S. fragilis	31	0 - 375	1	200 - 600	October
S. purpurea	68	0 - 500	1	200 - 1000	March
C. laevigata	13	0 - 500	2	200	March

Table 3.1: Overview of the testing.

In total, 31 measurements were obtained from the depth range of 0-375 mm. However, some samples were not taken into account since worms were found in the samples and contributed to the peak force. The tests on *S. purpurea* were executed on three consecutive days. The distance between test points and the willow trees varied between 0.2 and 1.0 m to account for spatial variability. Tests were performed at depth levels ranging from 0-125, 125-250, 250-375 and 375-500 mm. The schematic testing plot of *S. purpurea* and the corkscrew tests is displayed in Figure 3.9c. A total of 68 measurements were taken from a depth range of 0-500 mm. In Middenmeer, the tests on *C. laevigata* were performed on one day. The distance between the test points and the trees was 0.2 m and ranged from 0 to 500 mm deep. A total of 13 measurements were obtained. An overview of the testing conditions is given in Table 3.1.

3.5. Sampling and processing of extracted corkscrew samples

After each extracted corkscrew test, broken roots which stuck out of the samples were observed and their diameters were measured using a Vernier caliper, as shown in Figure 3.10. Examples of extracted samples with different types of roots are displayed in Figure 3.11. Then, the extracted soil cores were carefully wrapped in cling film and placed in sealed bags before being stored in a box, as shown in Figure 3.12a. The cores were then weighed using a balance with a precision 0.01 g.

Afterwards, the extracted soil cores were washed over a 2 mm sieve to collect all root material, as illustrated in Figure 3.12c. The roots were then weighed and their diameters measured using a 3D scanner, as shown in Figure 3.12d. Next, the roots were oven-dried at 40 degrees Celsius for 24 hours to determine their dry biomass.

Any holes observed in the soil after corkscrew testing were examined for roots, which were then cut, measured and included with the corresponding sample core. The root area ratios were calculated based on the measured diameters.

In order to determine the moisture content of each sample, a small soil sample was taken from each extracted soil core and weighed, directly after corkscrew extraction. These samples were subsequently oven-dried at 105 degrees Celsius for 24 hours and weighed again, as illustrated in Figure 3.12b.

Figure 3.10: Determination of the diameter of the broken roots with a Vernier caliper.

(a) (b) (c) (d)

Figure 3.11: Example of the different types of samples (a) with no roots, (b) with thin roots, (c) with a thick root and (d) with a slipped root.

(a) (b)

(c) (d)

Figure 3.12: Sampling process (a) samples wrapped in clinged film and in sealed bags, (b) determination of the moisture content, (c) sieving on a 2 mm sieve and (d) example scanned roots.

4 RESULTS

4.1. Phragmites australis site

During testing on *P. australis*, a marked decline in root biomass was observed as depth increased, with 48% of the total root biomass concentrated at the shallowest depth (0-125 mm), as shown in Figure 4.1. The distribution of thin and thick roots varied among the samples, and roots grew vertically within the soil samples, leading to fewer intersections with the vertical shear plane. Anomalies in three tests were noticed in the force-displacement graph and these anomalies were attributed to inadvertently movements of the set-up. This situation was corrected during the rest of these tests and then they were deemed successful.

An overview of the soil tests with *P. australis* is presented in Table 4.1, while the force-displacement graphs of the corkscrew extraction with the highest and lowest biomass at each depth are displayed in Figure 4.2. Sudden drops, denoted as arrows, were observed in the graphs concomitant with sound consistent with soil cracking, potentially indicating the occurrence of individual root breakages.

Distinct behaviour patterns in the force-displacement response were observed across the three levels of soil depths (Figure 4.2): the force-displacement curve of the samples with the lowest biomass show expected behaviour of a non-rooted soil, meaning the force increases rapidly over a short displacement (u = 0 mm to u ≈15 mm) until the bare soil fails and gradually decreases over a longer displacement as no roots are present. As for the force of the samples with the highest biomass, it also shows a rapid increase over a short displacement until the soil fails and the roots start to mobilise. After this point, the force gradually increases as the roots provide resistance until their maximum tensile strength is reached and fail. Possibly indicated as sudden drops. However, it is notable that in Figure 4.2c, the difference in biomass of the samples is significantly smaller than the difference in biomass of the samples of Figure 4.2a and 4.2b.

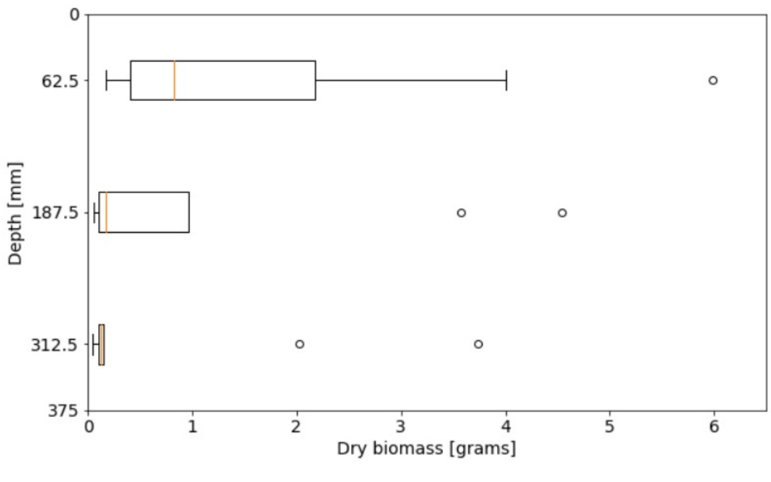
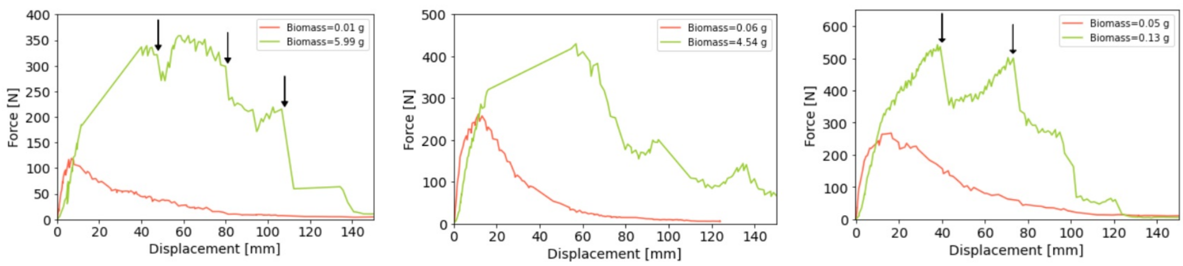


Figure 4.1: Average root biomass over the depth for *P. australis*.

Test number	Typical soil behaviour	Root breakages	Moisture content [%]	Root biomass [g]	Peak force [N]	Peak displacement [mm]	Displacement at root breakage [mm]
Test depth: 0 - 125 mm							
1	Non-rooted	0	45	0.01	119	7	-
2	Non-rooted	0	-	2.18	203	21	-
3	Non-rooted	0	26	0.41	246	14	-
4	Non-rooted	0	47	0.51	280	39	-
5	Rooted	1	36	0.28	212	47	52
6	Non-rooted	0	53	4.00	286	41	-
7	Rooted	3	127	5.99	359	62	42 and 80 and 107
8	Rooted	0	55	0.87	306	41	-
9	Non-rooted	0	40	0.82	250	21	-
Test depth: 125 - 250 mm							
1	Non-rooted	0	29	0.06	262	11	-
2	Rooted	1	25	0.07	232	8	37
3	Rooted	1	27	0.32	382	36	74
4	Rooted	0	53	0.14	354	25	-
5	Rooted	1	38	0.10	325	45	47
6	Rooted	0	55	3.57	337	29	-
7	Rooted	0	62	4.54	430	57	-
8	Rooted	0	50	0.96	469	44	-
9	Non-rooted	0	35	0.17	274	22	-
Test depth: 250 - 375 mm							
1	Non-rooted	0	19	0.12	384	22	-
2	Rooted	1	25	0.10	374	33	52
3	Non-rooted	0	36	0.09	344	32	-
4	Rooted	0	40	0.10	389	19	-
5	Rooted	2	38	0.13	542	38	38 and 73
6	Rooted	1	89	2.02	233	13	46
7	Rooted	1	46	3.74	548	57	57
8	Rooted	1	73	0.15	317	44	44
9	Non-rooted	0	39	0.05	267	16	-

Table 4.1: Summary of experimental results for corkscrew extraction tests on soil samples containing roots of *P. australis*.

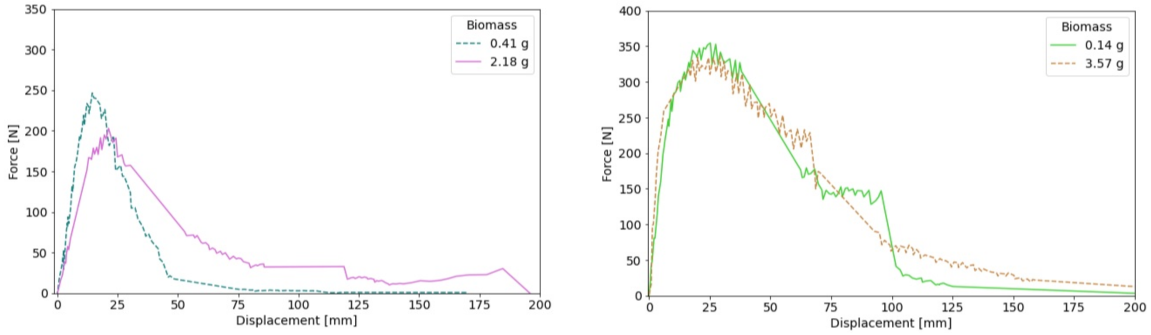


(a) (b) (c)

Figure 4.2: Example corkscrew extraction force-displacement graphs of soil samples containing roots of *P. australis* at depth (a) 0-125 mm, (b) 125-250 mm and (c) 250-375 mm. For each depth, the corkscrew test with the highest root biomass (green line) and the lowest root biomass (red line) is plotted. Arrows indicate sudden drops in resistance associated with potential root breakages.

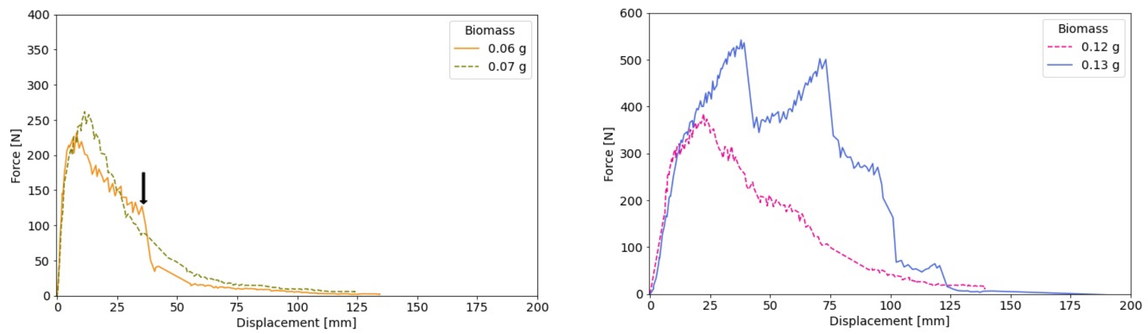
Three types of anomalies in the force-displacement graphs were observed over the three levels of soil depths: (1) tests showing similar typical soil behaviour but significantly different root biomass, for example tests 2 and 3 at depth level 0-125 mm or tests 4 and 6 at depth level 125-250 mm displayed in Figure 4.3, (2) tests demonstrating different typical soil behaviour but similar root biomass such as tests 1 and 2 at depth level 0-125 mm and tests 1 and 5 at depth level 250-375, shown in Figure 4.4, and (3) inconsistencies where tests with a certain root biomass does not have the expected corresponding typical soil behaviour for instance tests 3 and 5 at depth level 0-125 mm and tests 5 and 9 at depth level 125-250 mm. In those tests, the tests showing typical rooted behaviour have a lower biomass than the tests demonstrating typical non-rooted behaviour, see Figure 4.5. (These inconsistencies could be due to the presence of roots inside the sample without intersecting the shear area or because the root biomass is not an accurate indicator for root reinforcement of the soil.)

Additionally, it was observed in Figure 4.6 that the peak force of the rooted soil tests was higher than the peak force of the bare soil tests (considered as root biomass ≤ 0.09 g). Similarly, the displacement where these peak forces occurred, are higher for the rooted soil than for the bare soil, as shown in Figure 4.7. Moreover, potential root breakages were found at $u \gtrapprox 35$ mm, see Figure 4.8. However, no correlation was found between the normalised corkscrew peak force and root biomass (Figure 4.9a), as well as between the root biomass and the displacement where these peaks occurred (Figure 4.10). Similarly, no correlation was found between the root biomass and the normalised energy needed to pull out the sample, as shown in Figure 4.9b. Furthermore, no correlation was observed with the root biomass and both moduli at all depths (Figure 4.11a and 4.11b).



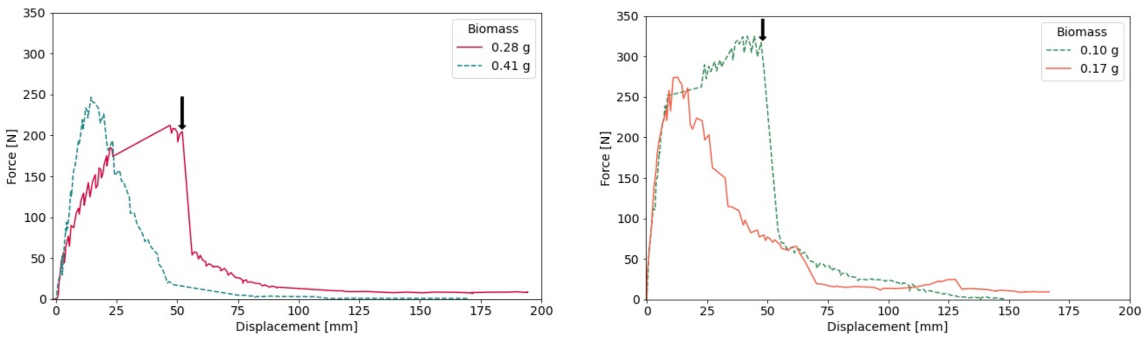
(a) **(b)**

Figure 4.3: Force-displacement graphs of soil samples containing roots of *P. australis* which have similar typical soil behaviour but significantly different root biomass.



(a) **(b)**

Figure 4.4: Force-displacement graphs of soil samples containing roots of *P. australis* which have similar root biomass but different typical soil behaviour.



(a) **(b)**

Figure 4.5: Force-displacement graphs of soil samples containing roots of *P. australis* which have different typical soil behaviour but not the expected corresponding root biomass.

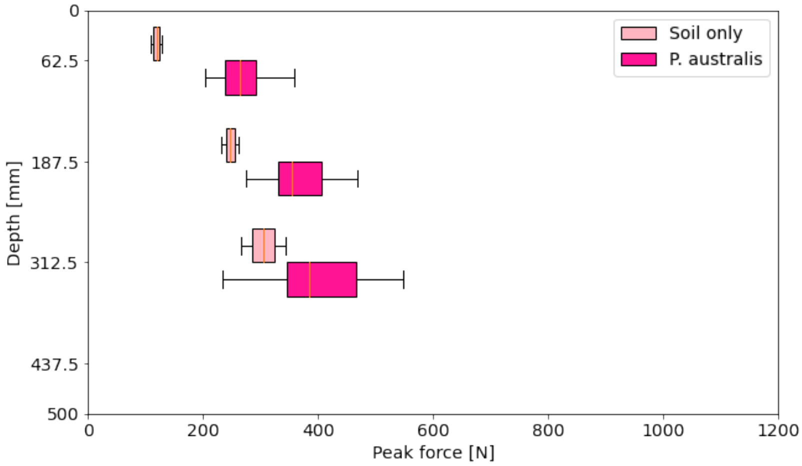


Figure 4.6: Comparison of the peak force of the soil-only samples and the soil samples containing roots of *P. australis*. In this case, soil-only samples are the samples with the lowest root biomass.

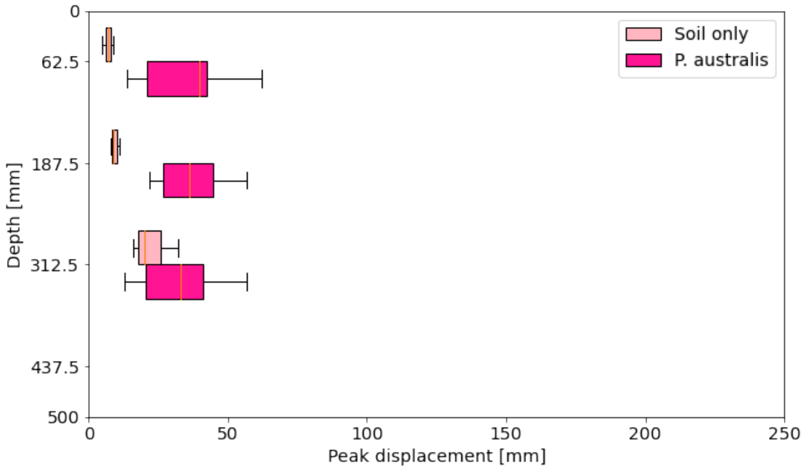


Figure 4.7: Comparison of the peak force of the soil-only samples and the soil samples containing roots of *P. australis*. In this case, soil-only samples are the samples with the lowest root biomass.

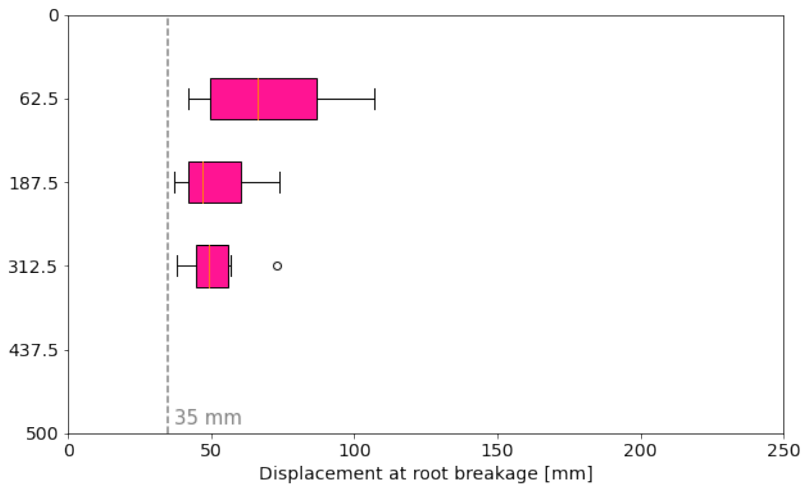


Figure 4.8: Displacement at root breakage for *P. australis*. All roots break at displacements higher than 35 mm.

(a) **(b)**

Figure 4.9: Corkscrew extraction test results at each depth levels for individual soil samples containing roots of *P. australis*. (a) The corkscrew normalised peak force versus the root biomass and (b) the peak displacement versus the root biomass.

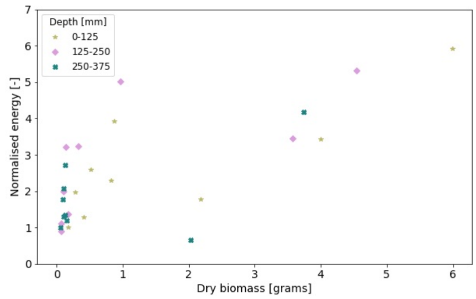
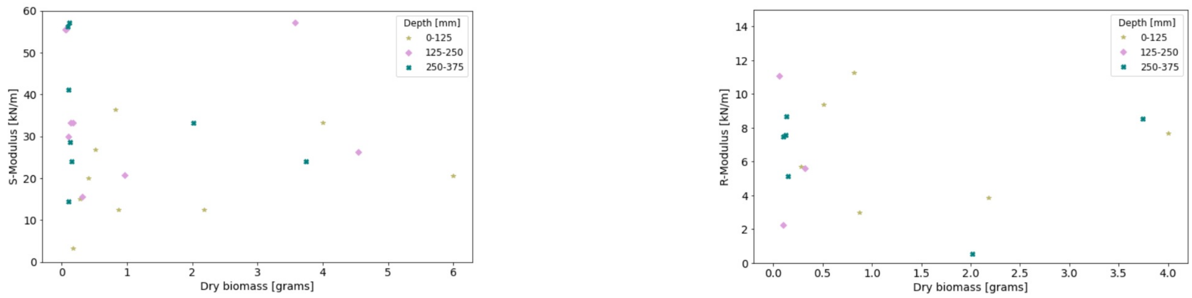


Figure 4.10: Corkscrew extraction test results at each depth levels for individual soil samples containing roots of *P. australis*. The corkscrew normalised energy versus the root biomass.



(a) **(b)**

Figure 4.11: Corkscrew extraction test results at each depth levels for individual soil samples containing roots of *P. australis*. (a) The S-Modulus and (b) R-Modulus versus the root biomass.

4.2. Salix fragilis site

Root quantities decreased rapidly with depth, with 62% of the root biomass and 65% of the RAR concentrated in the shallowest depth (0-125 mm), see Figure 4.12 and 4.13. Table 4.2 gives an overview of characteristics of the tests on *S. fragilis*. In Figure 4.14, examples of corkscrew extraction force-displacement graphs for each depth are shown. Root breakages, defined as sudden drops and denoted as arrows, were observed in the force-displacement graphs. Additionally, in plots Figure 4.14d and 4.14e, after one significant root breakage occurring at $u > 125$ mm, no force is measured anymore. This suggests that after the soil fails, roots start to mobilise and take over the load.

Marked differences in the force-displacement graphs of the samples were observed. In plots Figure 4.14d, 4.14e and 4.14b, the tests with lowest biomass or RAR show typical non-rooted soil behaviour, and the tests with the highest biomass or RAR show typical rooted soil behaviour with potential root failures. However, during analysis of the force-displacement graphs on *S. fragilis* rooted soil, similar anomalies as the ones found in the graphs of *P. australis* rooted soil were observed over the three depth levels: (1) tests 5 and 7 at depth level 0-125 mm show similar typical soil behaviour but they have significantly different root biomass (Figure 4.15), (2) tests 8 and 9 at depth level 125-250 mm have similar root biomass but different soil behaviour (Figure 4.16), and (3) tests 1 and 11 at depth level 0-125 mm where test 1 has a typical non-rooted soil behaviour and test 11 has a rooted soil behaviour but the root biomass of tests 1 is higher than the root biomass of test 11 (Figure 4.17). Now considering the root area ratio instead of the root biomass, no such anomalies are observed. Even more, tests 5 and 7 at depth level 0-125 mm show similar typical soil behaviour and have similar root area ratios, tests 8 and 9 at depth level 125-250 have different soil behaviour and their root area ratios are significantly different, and test 1 at depth level 0-125 mm, has a root area ratio which is approximately ten times lower than test 11 at the same depth level, which is in line with their soil behaviour. These inconsistencies in the comparison of the soil behaviour and the root biomass suggest that the root biomass is not an accurate indicator for root-reinforcement. Even more, the root area ratio shows to be a more accurate indicator.

Moreover, it was observed that the peak force of the soil rooted with *S. fragilis* was higher than the peak force of the bare soil at all depth levels, as shown in Figure 4.18. Similarly, the displacement where these peak forces occurred, was higher for the rooted soil than for the bare soil at depth levels 0-125 mm and 125-250 mm. However, at depth level 250-375 mm the peak displacement is similar, as displayed in Figure 4.19. Furthermore, the potential root breakages all occurred at $u \gtrapprox 30$ mm, see Figure 4.20. No correlations were found between the dry biomass and the root parameters, confirming that root biomass is not a good indicator for root-reinforcement. As illustrated in Figure 4.21b and 4.22b, positive correlations between the RAR and the normalised peak force, as well as the normalised energy, are observed. Implying that the increase in ductility of the soil increases the peak force of the soil. Moreover, no correlations were found between the RAR and both moduli, as displayed in Figure 4.23b and 4.24b.

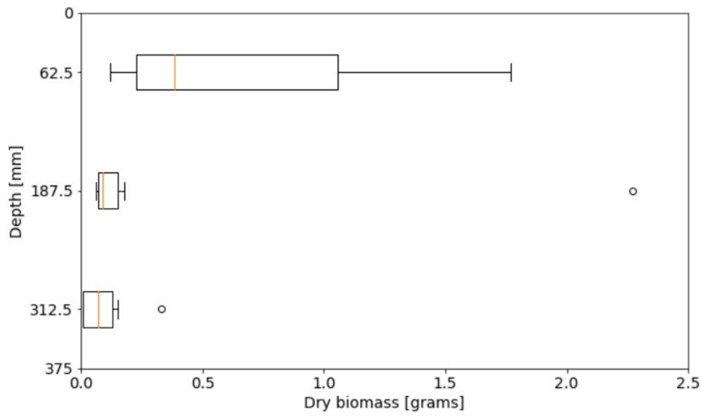


Figure 4.12: Average root biomass over the depth for *S. fragilis*.

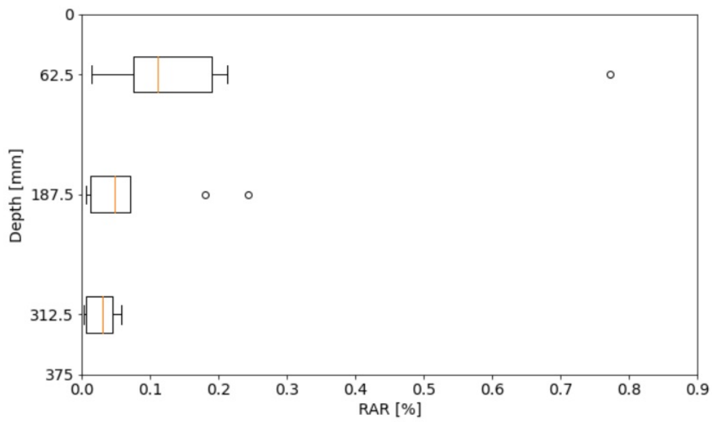


Figure 4.13: Average root area ratio over the depth for *S. fragilis*.

Test number	Typical soil behaviour	Total number of roots	Root breakages	Root biomass [g]	RAR [%]	Peak force [N]	Peak displacement [mm]	Displacement at root breakage [mm]
Test depth: 0 - 125 mm Moisture content = 37 %								
1	Non-rooted	4	0	0.20	0.014	262	24	-
2	Rooted	13	1	0.21	0.109	379	94	107
3	Rooted	6	1	1.29	0.772	588	146	146
5	Rooted	3	1	1.77	0.199	712	61	61
6	Rooted	4	2	0.71	0.074	310	74	84 and 100
7	Rooted	5	2	0.41	0.213	758	75	90 and 119
8	Rooted	3	1	1.17	0.082	301	75	140
9	Rooted	1	1	0.28	0.033	313	76	76
10	Rooted	2	2	0.36	0.162	388	38	38 and 70
11	Rooted	4	1	0.12	0.113	432	106	106
Test depth: 125 - 250 mm Moisture content = 37 %								
2	Rooted	3	0	0.18	0.048	303	13	-
4	Rooted	4	1	0.09	0.013	433	75	75
5	Rooted	1	1	0.06	0.054	722	73	73
6	Non-rooted	1	0	0.07	0.006	337	12	-
7	Rooted	3	2	2.27	0.181	900	78	78 and 120
8	Rooted	2	1	0.14	0.244	1129	228	228
9	Non-rooted	2	0	0.15	0.032	379	18	-
10	Non-rooted	2	0	0.06	0.009	447	23	-
11	Rooted	2	2	0.09	0.070	515	116	32 and 116
Test depth: 250 - 375 mm Moisture content = 34 %								
1	Rooted	3	1	0.06	0.030	273	13	134
2	Rooted	3	1	0.07	0.053	219	25	47
4	Rooted	6	0	0.09	0.045	332	10	-
5	Rooted	4	0	0.15	0.057	454	16	-
6	Rooted	5	1	0.13	0.022	487	15	68
8	Non-rooted	1	0	0.01	0.003	190	15	-
9	Rooted	0	0	0.01	0.006	328	28	-
10	Rooted	2	0	0.01	0.005	314	19	-
11	Rooted	3	1	0.33	0.040	327	18	51

Table 4.2: Summary of experimental results for corkscrew extraction tests on soil samples containing roots of *S. fragilis*.

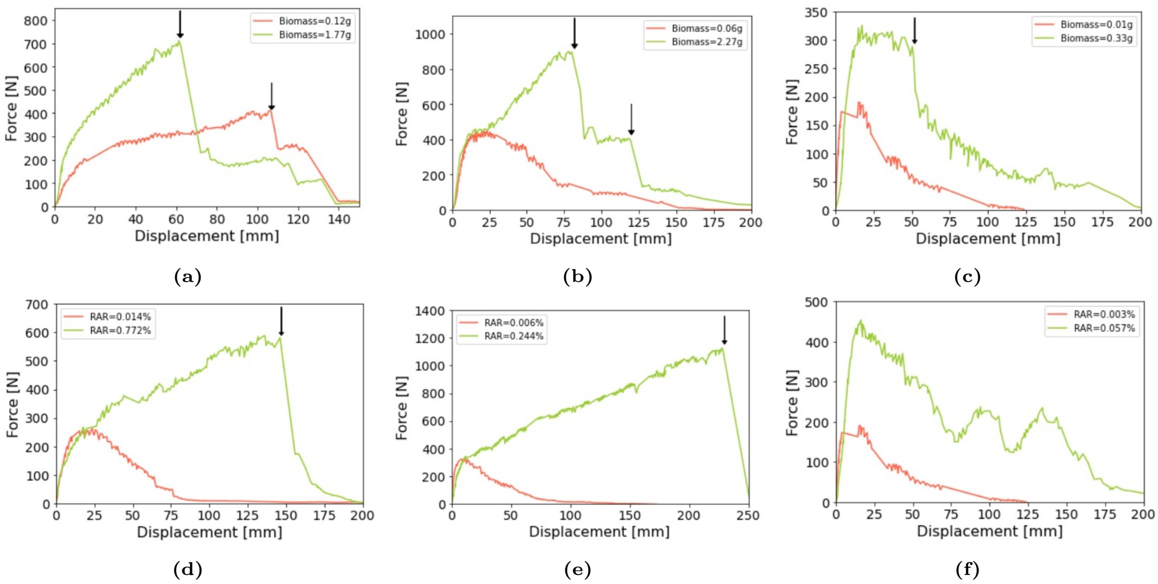


Figure 4.14: Example corkscrew extraction force-displacement graphs of soil samples containing roots of *S. fragilis* at depth (a-d) 0-125 mm, (b-e) 125-250 mm and (c-f) 250-375 mm. For each depth, the corkscrew test with the highest (green line) and lowest (red line) (a,c,e) root biomass and (b,d,f) root area ratio is plotted. Arrows indicate sudden drops in resistance associated with potential root breakages.

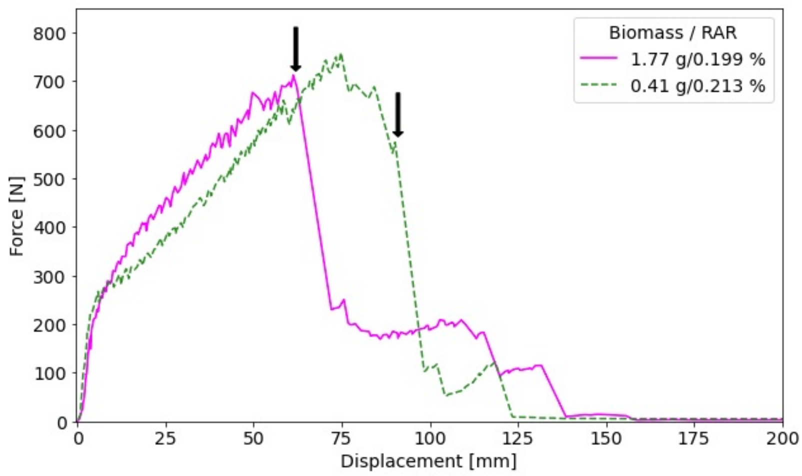


Figure 4.15: Force-displacement graphs of soil samples containing roots of *S. fragilis* which have similar typical soil behaviour but significantly different root biomass.

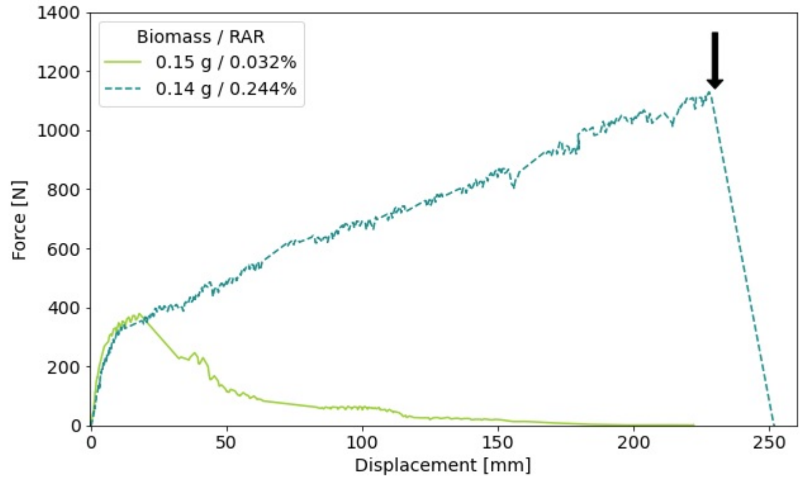


Figure 4.16: Force-displacement graphs of soil samples containing roots of *S. fragilis* which have similar root biomass but different typical soil behaviour.

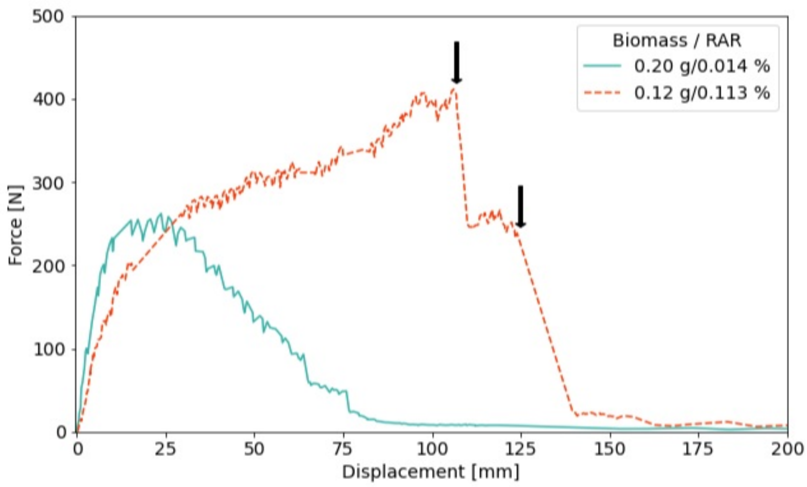


Figure 4.17: Force-displacement graphs of soil samples containing roots of *S. fragilis* which have different typical soil behaviour but not the expected corresponding root biomass.

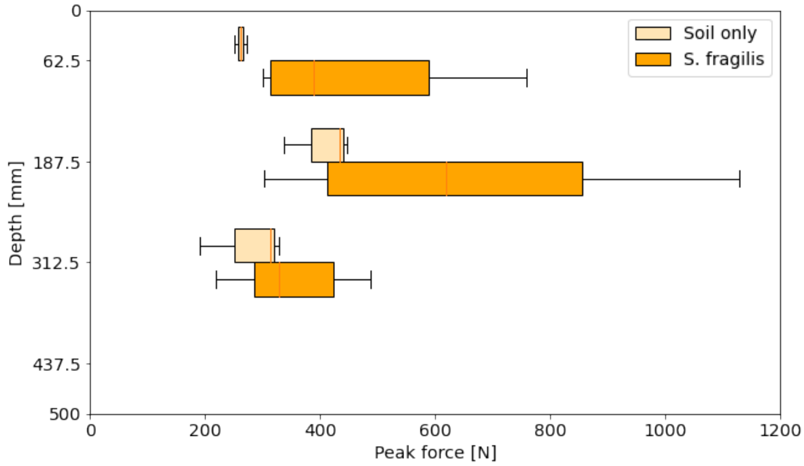


Figure 4.18: Comparison of the peak force of the soil-only samples and the soil samples containing roots of *S. fragilis*. Soil-only samples are the samples with the least and relatively low root area ratio.

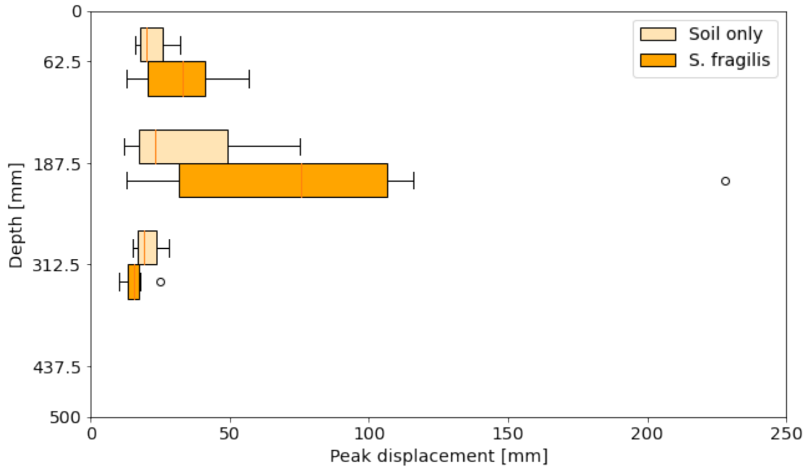


Figure 4.19: Comparison of the peak displacement of the soil-only samples and the soil samples containing roots of *S. fragilis*. Soil-only samples are the samples with the least and relatively low root area ratio.

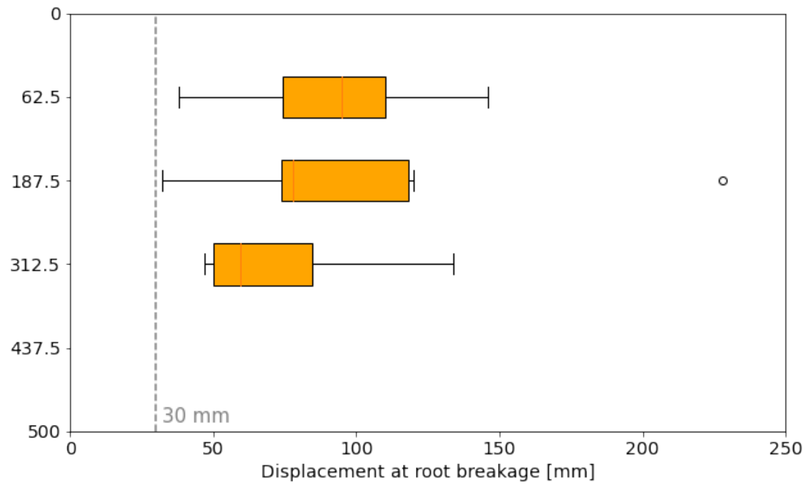


Figure 4.20: Displacement at root breakage for *S. fragilis*. All roots break at displacements higher than 30 mm.

(a) **(b)**

Figure 4.21: Corkscrew extraction test results at each depth levels for individual soil samples containing roots of *S. fragilis*. The corkscrew normalised peak force versus (a) the root biomass and (b) the root area ratio, a fitted line was drawn for all depth levels combined.

(a) **(b)**

Figure 4.22: Corkscrew extraction test results at each depth levels for individual soil samples containing roots of *S. fragilis*. The corkscrew normalised peak energy versus (a) the root biomass and (b) the root area ratio, a fitted line was drawn for all depth levels combined.

(a) **(b)**

Figure 4.23: Corkscrew extraction test results at each depth levels for individual soil samples containing roots of *S. fragilis*. The S-modulus versus (a) the root biomass and (b) the root area ratio.

(a) **(b)**

Figure 4.24: Corkscrew extraction test results at each depth levels for individual soil samples containing roots of *S. fragilis*. The R-modulus versus (a) the root biomass and (b) the root area ratio.

(a) (b)

Figure 4.25: Corkscrew extraction test results at each depth levels for individual soil samples containing roots of *S. fragilis*. The peak displacement versus (a) the root biomass and (b) the root area ratio.

4.3. Salix purpurea site

The root distribution of *S. purpurea* does not significantly vary over the depth as shown in Figure 4.26. 28 measurements were rejected due to experimental errors, namely unwanted collapse of soil into the hole formed by the corkscrew. Table 4.3 gives an overview of characteristics of each tests during testing on *S. purpurea*.

In Figure 4.27, examples of corkscrew extraction force-displacement graphs for each depth are displayed. Sudden drops, denoted as arrows and corresponding to root breakages, were observed at all depth levels except at level 375-500 mm. In plots Figure 4.27a, 4.27b and 4.27c, after one root breakage, no force is measured, indicating after the soil fails, roots are activated and take over the load. Significant difference in patterns in the force-displacement graphs were observed. Tests with the highest root area ratio showed typical rooted soil behaviour and tests with the lowest root area ratio showed typical non-rooted soil behaviour. In the force-displacement graphs of the tests on *S. purpurea* rooted soil, no anomalies were found.

Additionally, the peak force of the rooted soil is higher than the peak force of the bare soil at all depth levels, as shown in Figure 4.28 . However, the difference is significantly higher at the deeper depth levels (125-250 mm) than the shallowest depth level (0-125 mm). Moreover, the displacement where those peak forces occurred, is higher for the rooted soil than the fallow soil and especially at depth level 0-125 mm, as displayed in Figure 4.29. Also, the potential root breakages all occurred at $u \gtrsim 40$ mm, see Figure 4.30 . In Figure 4.32b, a strong positive correlation is found between the peak displacement and the root area ratio of *S. purpurea*. However, no correlation was found between the normalised peak force and the RAR, see Figure 4.31a. Similarly, no correlation was found between the normalised energy needed to pull out the sample out of the soil and the root area ratio as well as the S-modulus and the root area ratio, as shown in Figure 4.31b and 4.32a respectively.

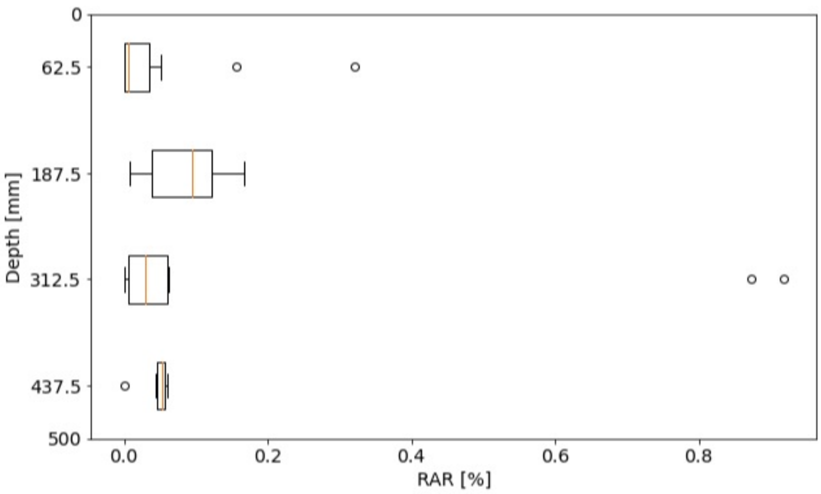


Figure 4.26: Average root area ratio over the depth for *S. purpurea*.

Test number	Typical soil behaviour	Root breakages breakages	RAR [%]	Distance from willow [mm]	Peak force [N]	Peak displacement [mm]	Displacement at root breakage [mm]
			Test depth: 0 - 125 mm Moisture content = 42%				
1	Non-rooted	0	0.001	1000	125	6	-
2	Non-rooted	0	0.032	600	246	13	-
3	Rooted	1	0.157	200	464	70	70
4	Rooted	1	0.051	1000	218	95	95
6	Non-rooted	0	0.036	200	284	8	-
7	Rooted	1	0.322	1000	284	135	135
8	Non-rooted	0	0.009	600	236	13	-
9	Non-rooted	0	0.003	200	214	12	-
10	Non-rooted	0	0.001	1000	238	13	-
11	Non-rooted	0	0.001	600	220	10	-
12	Non-rooted	0	0.001	200	220	13	-
13	Non-rooted	0	0.015	200	239	13	-
14	Rooted	1	0.003	200	258	21	69
15	Non-rooted	0	0.001	200	233	13	-
			Test depth: 125 - 250 mm Moisture content = 38%				
10	Rooted	1	0.169	200	419	41	86
11	Non-rooted	0	0.008	200	259	17	-
12	Rooted	1	0.048	200	319	26	57
13	Rooted	2	0.127	200	583	43	43 and 78
14	Rooted	2	0.108	200	693	62	70 and 103
15	Rooted	1	0.079	200	460	32	91
			Test depth: 250 - 375 mm Moisture content = 39%				
10	Rooted	1	0.918	200	1049	178	205
11	Non-rooted	0	0.004	200	177	7	-
12	Rooted	2	0.873	200	996	54	54 and 137
13	Rooted	2	0.012	200	715	39	52 and 129
14	Rooted	1	0.056	200	379	14	178
15	Rooted	0	0.062	200	541	25	-
			Test depth: 375 - 500 mm Moisture content = 43%				
10	Non-rooted	0	0.001	200	167	12	-
11	Non-rooted	0	0.051	200	366	14	-
12	Rooted	0	0.055	200	311	7	-
13	Rooted	0	0.058	200	590	23	-
14	Rooted	0	0.045	200	540	21	-
15	Rooted	0	0.061	200	650	19	-

Table 4.3: Summary of experimental results for corkscrew extraction tests on soil samples containing roots of *S. purpurea*.

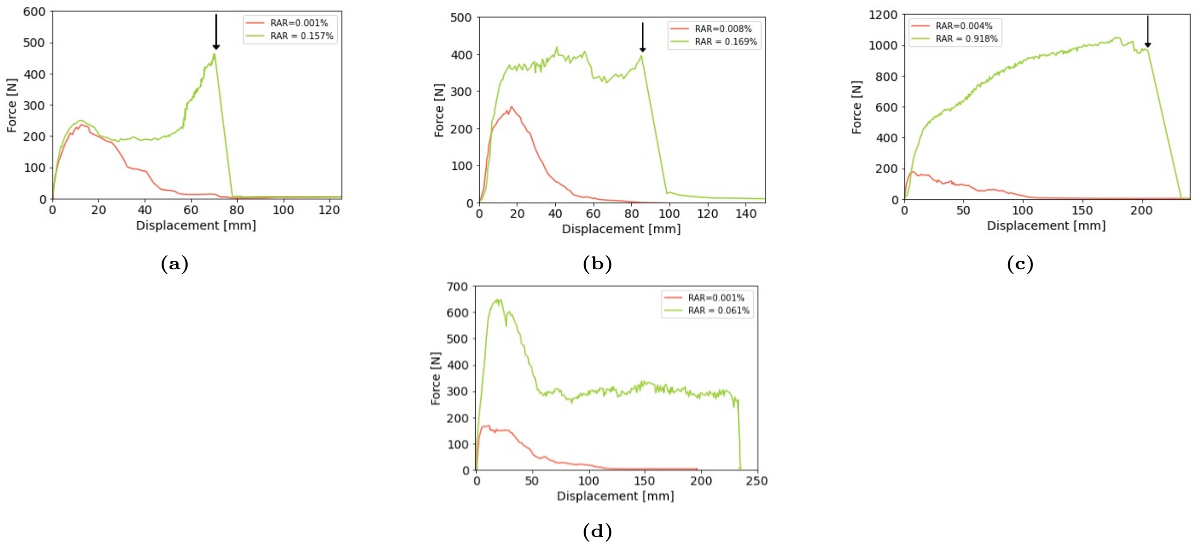


Figure 4.27: Example corkscrew extraction force-displacement graphs of soil samples containing roots of *S. purpurea* at depth (a) 0-125 mm, (b) 125-250 mm, (c) 250-375 mm and (d) 375-500 mm. For each depth, the corkscrew test with the highest root area ratio (green line) and the lowest root area ratio (red line) is plotted. Arrows indicate sudden drops in resistance associated with potential root breakages.

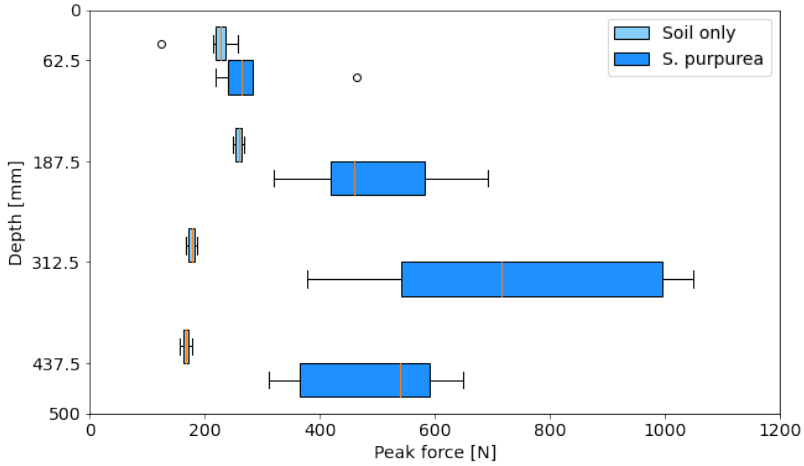


Figure 4.28: Comparison of the peak force of the soil-only samples and the soil samples containing roots of *S. purpurea*. Soil-only samples are the samples with the least and relatively low root area ratio.

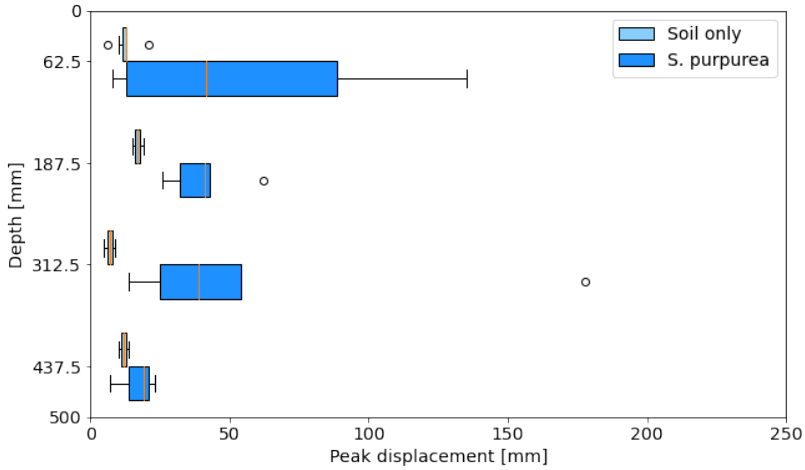


Figure 4.29: Comparison of the peak displacement of the soil-only samples and the soil samples containing roots of *S. purpurea*. Soil-only samples are the samples with the least and relatively low root area ratio.

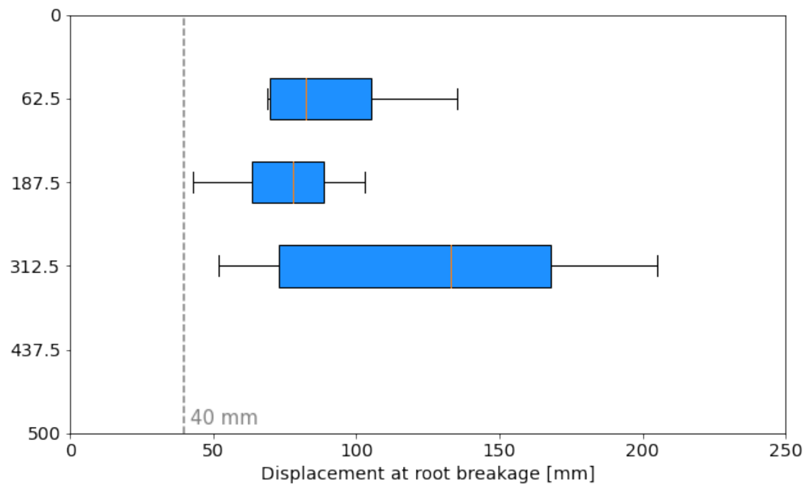


Figure 4.30: Displacement at root breakage for *S. purpurea*. All roots break at displacements higher than 40 mm.

(a) (b)

Figure 4.31: Corkscrew extraction test results at each depth levels for individual soil samples containing roots of *S. purpurea*. (a) The normalised peak force versus the root area ratio and (b) the normalised energy versus the root area ratio.

(a) (b)

Figure 4.32: Corkscrew extraction test results at each depth levels for individual soil samples containing roots of *S. purpurea*. (a) The S-modulus versus the root area ratio and (b) the peak displacement versus the root area ratio, a fitted line was drawn for all depth levels combined.

4.4. Crataegus laevigata site

A marked decline in root area ratio of the *C. laevigata* was observed as depth increased, with 53% of the total RAR concentrated at the shallowest depth (0-125 mm), see Figure 4.33.

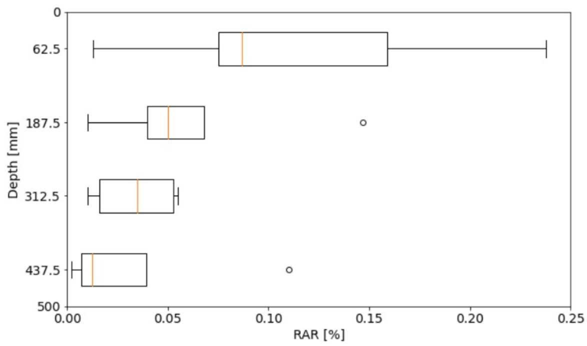
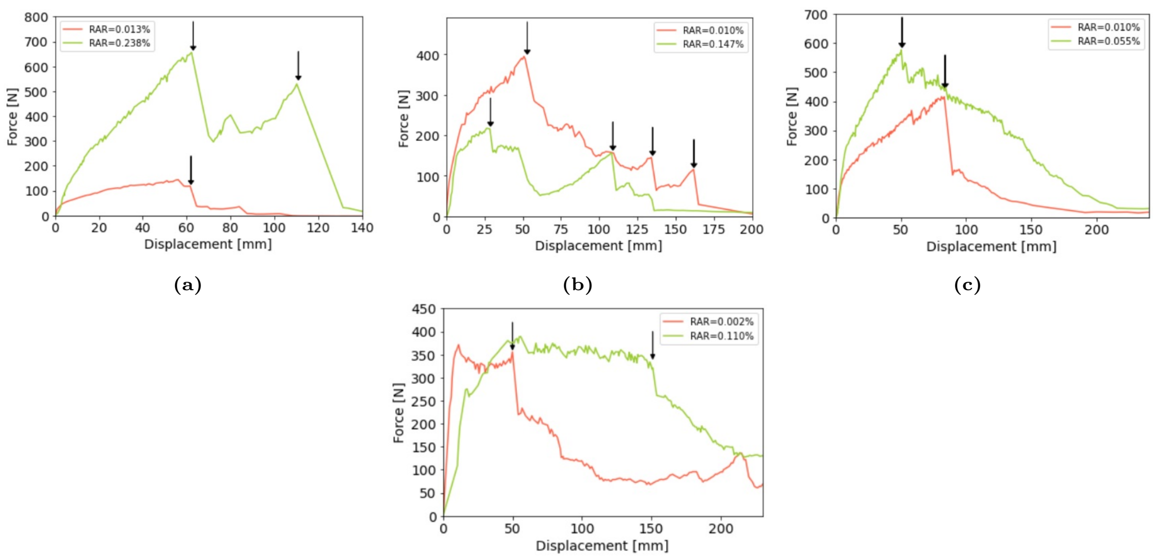


Figure 4.33: Average root area ratio over the depth for *C. laevigata*.

In Figure 4.34, examples of corkscrew extraction force-displacement graphs for each depth are shown. Sudden drops, which correspond to potential root breakages, were observed at all depth levels. It was observed that all plots show typical rooted soil behaviour, even the test with the lowest RAR, namely test 1 at level 375-500 mm with a root area ratio of 0.002%. Furthermore, in Figure 4.34b, the graph with lowest RAR (test 6) has a higher peak force than the plot with highest RAR (test 1). This might be due to the fact that a thick root slipped during test 1, whereas the roots in test 6 broke. Additionally, in Figure 4.34d, the peak forces of the two graphs do not significantly differ from each other. Again, it was observed one root slipped in test 4, whereas all roots in test 1 broke. This suggests that samples with roots which fail in tension reach higher peak forces than samples with roots that slip.

Test number	Total number of roots	Root breakages	RAR [%]	Peak force [N]	Peak displacement [mm]	Displacement at root breakage [mm]
			Test depth: 0 - 125 mm Moisture content = 46%			
1	8	1	0.013	144	56	62
2	5	1	0.087	212	111	130
3	5	2	0.182	312	125	125 and 179
4	4	3	0.159	759	70	70 and 90 and 98
5	7	2	0.075	298	40	75 and 114
6	3	2	0.238	656	62	62 and 110
			Test depth: 125 - 250 mm Moisture content = 45%			
1	7	2	0.147	217	26	29 and 109
2	2	0	0.068	180	30	-
4	8	1	0.040	350	21	53
5	6	2	0.050	401	39	39 and 46
6	6	3	0.010	395	51	51 and 134 and 159
			Test depth: 250 - 375 mm Moisture content = 42%			
1	8	2	0.018	454	114	154 and 184
2	3	1	0.010	416	81	81
4	4	1	0.052	625	52	61
5	3	1	0.055	577	50	50
			Test depth: 375 - 500 mm Moisture content = 43%			
1	2	1	0.002	371	11	50
2	3	0	0.009	296	35	-
4	6	1	0.110	389	56	151
5	3	0	0.016	350	30	-

Table 4.4: Summary of experimental results for corkscrew extraction tests on soil samples containing roots of *C. laevigata*.



(a) (b) (c) (d)

Figure 4.34: Example corkscrew extraction force-displacement graphs of soil samples containing roots of *C. laevigata* at depth (a) 0-125 mm, (b) 125-250 mm, (c) 250-375 mm and (d) 375-500 mm. For each depth, the corkscrew test with the highest root area ratio (green line) and the lowest root area ratio (red line) is plotted. Arrows indicate sudden drops in resistance associated with potential root breakages.

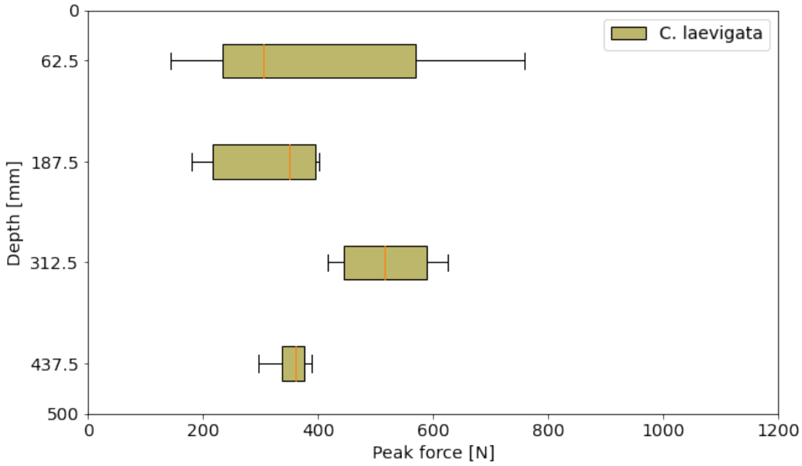


Figure 4.35: Comparison of the peak force of the soil-only samples and the soil samples containing roots of *C. laevigata*. Soil-only samples are the samples with the least and relatively low root area ratio.

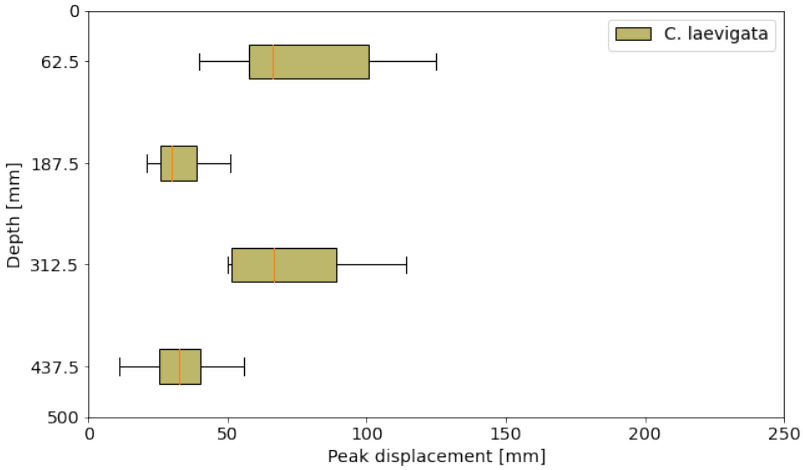


Figure 4.36: Comparison of the peak displacement of the soil-only samples and the soil samples containing roots of *C. laevigata*. Soil-only samples are the samples with the least and relatively low root area ratio.

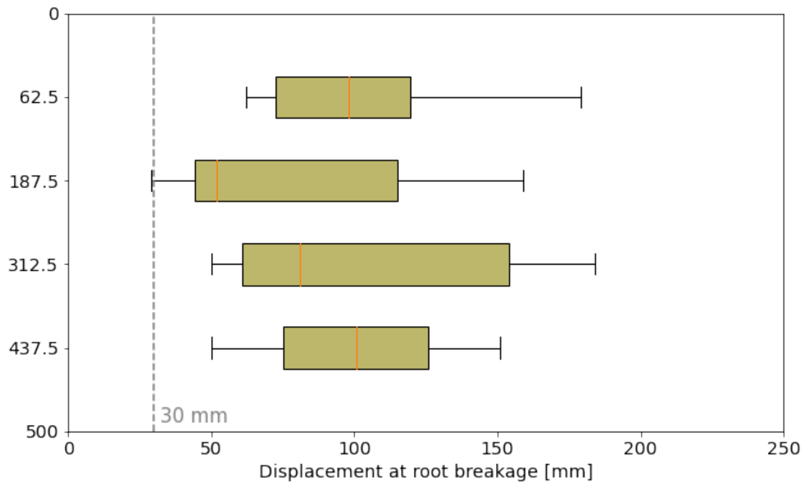
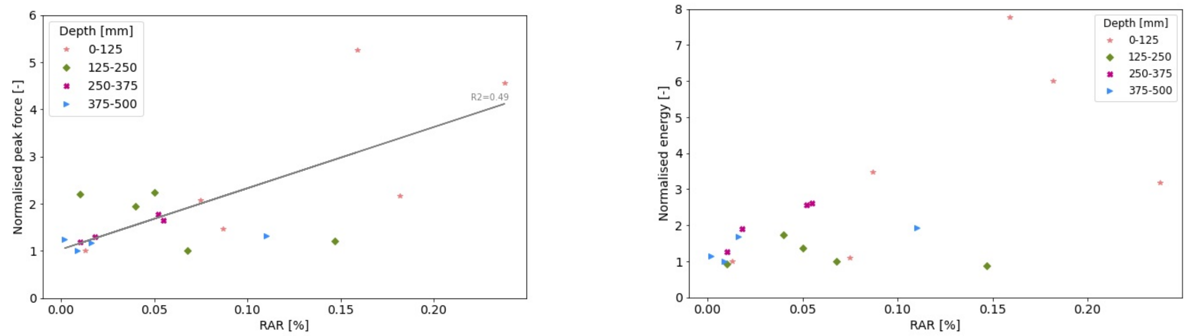


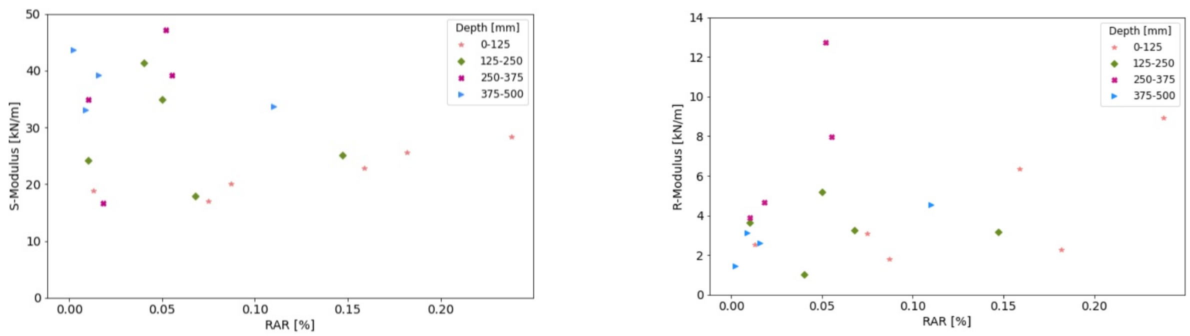
Figure 4.37: Displacement at root breakage for *C. laevigata* All roots break at displacements higher than 30 mm.

Additionally, the peak force of the rooted soil is higher than the peak force of the fallow soil at all depth levels, except at depth level 125-250 mm, see Figure 4.35. Similarly, the displacement where these peak forces occurred are higher for rooted soil than fallow soil at depth levels 0-125 mm and 375-500 mm but not for depth levels 125-250 mm and 250-375 mm, as shown in Figure 4.36. Also, the root breakages all occurred at displacements $u \gtrsim 30$ mm, as displayed in Figure 4.37. However, no correlation was found between the root area ratio and the peak displacement, see Figure 4.40. Furthermore, a positive correlation between the root area ratio and the normalised peak force was found, see Figure 4.38a, whereas no correlation was observed between the root area ratio and the normalised energy, see Figure 4.38b. It was observed that the RAR was not correlated to both moduli, as illustrated in Figure 4.39.



(a) (b)

Figure 4.38: Corkscrew extraction test results at each depth levels for individual soil samples containing roots of *C. laevigata*. (a) The normalised peak force versus the root area ratio and (b) the normalised energy versus the root area ratio. A fitted line on the normalised peak force versus the root area ratio was drawn for all depth levels combined.



(a) (b)

Figure 4.39: Corkscrew extraction test results at each depth levels for individual soil samples containing roots of *C. laevigata*. (a) The S-modulus versus the root area ratio and (b) the R-modulus versus the root area ratio.

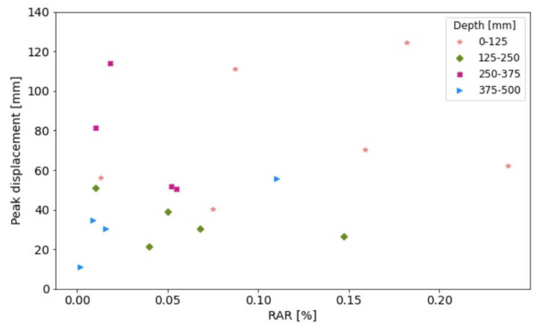


Figure 4.40: Corkscrew extraction test results at each depth levels for individual soil samples containing roots of *C. laevigata*. The peak displacement versus the root area ratio.

5
DISCUSSION

5.1. Corkscrew set-up

This study tested an corkscrew experimental set-up in riparian conditions using the set-up developed by [36] as a reference. The corkscrew method is a technique used to evaluate the reinforcement of soil provided by vegetation roots. This study shows the main benefits of this method associated with field measurement of root-reinforcement in riparian conditions: the relatively short amount of time needed to conduct a single test, leading to the possibility of conducting in-situ large-scale testing of soil. This is particularly valuable in riparian areas as they are characterised by a large spatial variation in vegetation. Furthermore, the set-up is easy to use, light and easy to install which enables field-based studies in difficult terrain such as on steep canal banks. Moreover, the technique is non-destructive which also enables monitoring for stream bank stability.

However, challenges were encountered during this study. The impact of ground disturbance during corkscrew testing on the accuracy of root reinforcement measurements is an important consideration when using the corkscrew method. In our study we observed fall back of surrounding soil into the testing hole, resulting in the incomplete testing of the soil and up to inconsistent depths beyond the corkscrew's reach. It also extracts soil fallen back into the hole, leading to inaccurate measurements. This has significant implications for the interpretation of results and the reliability of the root-reinforcement measurements. Therefore, it is important to restrict the maximum depth of each corkscrew measurement to 125 mm, leading to a total maximum extraction depth of 500 mm since the corkscrew itself measures approximately 550 mm, to ensure consistent and accurate results.

Another main challenge was the recovery of roots after corkscrew testing. In our study, it has been observed that not all roots can be recovered after corkscrew extraction (Figure 5.1), which could lead to an underestimation of the RAR. [36] suggested the use of extending foam as a possible solution to overcome this issue, but due to the high moisture of the soil during our tests, this method was not feasible. Also, the use of extending foam negates the intended purpose of corkscrew equipment as a quick and convenient way to conduct field testing.

Also, we observed that the same root could be passing through multiple cores extracted by the corkscrew, leading the testing of an already broken root. This could lead to inaccurate peak force and root reinforcement measurements. Even tough such situations rarely occur and will not significantly influence the results when conducting a large amount of tests, care was taken to examine the cores after each test to identify and avoid as much as possible such situations.

5.2. Minimum sample size corkscrew method

This study highlights the challenges encountered when conducting field measurements of root reinforcement in riparian environments. The significant variability in site characteristics makes it difficult to accurately capture the influence of individual soil and root parameters. Therefore, it is essential to conduct a substantial number of tests to adequately account for the variation in measured strengths in slope stability analyses.

To estimate the required number of corkscrew tests, the experimentally measured data was utilised, shown in Table 5.1. For each species and depth level, the peak forces were fitted with a normal

Figure 5.1: Example of an unextracted root by the corkscrew.

distribution, which was subsequently employed to estimate the sample size needed to have an 80% confidence level that the mean force of a new set of experiments would fall within 10%, 20%, or 30% of the true mean. The results indicate that more measurements are required in the surface layer (0-125 mm) for all vegetation types, with a particular emphasis on *C. laevigata*, followed by *S. fragilis*, *S. purpurea*, and *P. australis*. In the case of *C. laevigata*, fewer measurements are needed as the depth increases, while this trend does not hold true for the other sites. Based on this analysis, if we aim to determine the mean force of the slope within 20% of the true mean force with 80% certainty across all sites, a sample size of 20 should be adopted.

Monitoring slopes is essential for slope stability. Traditional methods can be expensive and time-consuming. Also, in many studies, the assessment of the root system and its contrition to slope stability involved destructive measurements. Hence, monitoring over time can only be carried out by repeated measurements of root systems at the same location [29]. Therefore, the corkscrew method may provide a non-destructive and rapid alternative for monitoring the evolution of root reinforcement over time for slope stability by conducting a large amount of tests.

5.3. Vegetation

5.3.1. Phragmites Australis

Reed plants (*Phragmites Australis*) were situated in close proximity to a canal with a high water table. *Phragmites Australis* is a grass species, often found along the streams and canal banks of the Netherlands. *Phragmites Australis* is known for its shallow roots system which generally grow horizontally and produce new rhizomes and plants.

The current study found that the roots were concentrated within the top 0.12 m of soil. Previous research by [8] on *Phragmites autralis* in constructed wetlands in Lankheet, the Netherlands, reported that belowground root biomass significantly decreased at depths exceeding 0.20 m. However, other studies [30][40][47][59] have reported that reed roots can grow horizontally to depths of several meters. Since the rooting depth of *Phragmites Australis* is subject to variability influenced by factors such as soil type, nutrient availability, water availability, and environmental conditions, direct comparisons of rooting depth between studies are impractical due to the differing conditions under which each study was conducted.

5.3.2. Salix fragilis and Salix purpurea

The willow trees (*Salix fragilis* and *Salix purpurea*) were both located near a canal with a high water table. Willows are shrub species, which are recognised for their rapid growth and easy vegetative propagation. Roots were found at distance up to 1 meter lateral from the willow tree.

Vegetation	Depth [mm]	Experiments			Additional sample size estimation N_n		
		μ [N]	σ [N]	N [-]	$x = 10\%$ [-]	$x = 20\%$ [-]	$x = 30\%$ [-]
P. australis	0-125	251	65	9	11	3	2
	125-250	341	74	9	8	2	1
	250-375	378	102	9	12	3	2
S. fragilis	0-125	444	170	10	25	7	3
	125-250	574	267	9	36	9	4
	250-375	325	91	9	13	4	2
S. purpurea	0-125	249	70	14	13	4	2
	125-250	456	148	6	18	5	2
	250-375	643	314	6	40	10	5
	375-500	437	170	6	25	7	3
C. laevigata	0-125	397	229	6	55	14	7
	125-250	309	92	5	15	4	2
	250-375	518	86	4	5	2	1
	375-500	352	35	4	2	1	1

Table 5.1: Estimation of additional corkscrew sample size. μ, σ and N correspond to the mean, standard deviation and sample size in the field measurements, respectively. N_n is the additional samples needed in order that the mean of a new set of experiments is within x% of μ with 80% confidence.

The rooting depth of willows adjacent to a water stream is subject to variation depending on several factors such as soil type, distance from the water source, water table level, nutrient availability, the age and the size of the tree. In the current study, a concentration of 74% of the root biomass of the *S. fragilis* and 41% of the RAR was observed within the uppermost 0.12 m of soil. Similarly, [31] indicated that the root dry biomass decreased significantly with an increase in soil depth, with 60% concentrated in the top soil (0-150 mm). In contrast, [24] observed a rooting depth of *Salix purpurea* extending up to 1.2 m. Findings from studies conducted by [43] reported greater rooting depths of *Salix purpurea*, reaching up to 3 meters in well-drained soils and up to 1-2 meters in soils with higher water tables. Consequently, it is expected that the roots of *Salix purpurea* roots will be situated near the water table, aligning with research conducted by [48][50][63]. This is consistent with the findings of our study, where the water table was observed at an approximate depth of 0.12 m.

5.3.3. Crataegus laevigata

Many studies were found concerning *Crataegus laevigata* as herbal medicine, but few research were found concerning their root system and distribution. During our testing on *C. laevigata*, we found that *Crataegus laevigata* has a shallow root system, with the majority of roots (53%) concentrated in the top 0.12 m of the soil. Similarly, [9][42] indicated that the rooting depth of *Crataegus laevigata* can reach 0.5 meters below ground level.

5.4. Root and strength parameters

Root reinforcement can play an important role in slope stabilisation. Accurately measuring root reinforcement is challenging and in the current study, the root biomass and the RAR were used. While root biomass provides useful information about the quantity of roots present in the soil, it has limitations and may not accurately quantify root reinforcement of the soil. In our study, during comparison of the force-displacement graphs of soil rooted with *Phragmites australis* and *Salix fragilis*, many anomalies were found between the typical soil behaviour and the corresponding root biomass. Furthermore, a comparison of the correlations between the root parameters and the strength parameters indicates that the root biomass was not correlated to the strength parameters for all species, see Table 5.2. Similar findings were observed by [58]. This could be explained by the presence of vertically growing and embedded roots within soil samples which are measured within the root biomass. However, these roots do not intersect the shear surface and therefore do not contribute to the shear strength. Another suggestion is that root biomass is not a good indicator for root-reinforcement.

The root area ratio is widely used as an indicator for quantifying root reinforcement. In the current study during testing on soil rooted with *Salix fragilis*, *Salix purpurea* and *Crataegus laevigata*, it was observed that the RAR affects the typical soil behaviour. Also, tests on *Salix fragilis*, *Salix purpurea* and *Crataegus laevigata* showed that the root area ratio is positively correlated to the normalised peak force, normalised energy and the peak displacement depending on the species. Similar findings were found by [10][16][69][71][73], who tested different species with direct in-situ shear tests and reported that the amount of increase in shear strength of soil might be dependent on the root area ratio. However, other factors that can influence the relationship between root area ratio and shear strength, as stated by [34][65].

Two moduli were examined, the soil elasticity and the root elasticity. However, the soil elasticity was defined as the initial slope of the force-displacement graph where only the soil is mobilised. Therefore, there will be no logical correlation between the elasticity of the soil and the amount of roots, which was confirmed during this study. Also, no correlations were found between the R-modulus and the root area ratio.

Vegetation	RAR/Biomass	Typical soil behaviour	Normalised peak force	Normalised energy	S-Modulus	R-Modulus	Peak displacement
P. australis	Biomass	No	No	No	No	No	No
S. fragilis	Biomass	No	No	No	No	No	No
	RAR	Yes	Positively correlated R2 = 0.65	Positively correlated R2 = 0.62	No	No	No
S. purpurea	RAR	Yes	No	No	No	-	Positively correlated R2 = 0.66
C. laevigata	RAR	Yes	Positively correlated R2 = 0.40	No	No	No	No

Table 5.2: Overview of the correlations between strength and root parameters at the four test sites.

5.5. Force-displacement graphs

Significant patterns were observed in the force-displacement graphs. In all samples there was an immediate and rapid increase in the shear force with minimal displacement upon commencement of the test, also observed by [10][19][39]. Failure of the soil-root matrix was indicated by a clear point after which, tests progressed in two different ways: typical non-rooted soil behaviour having reached their maximum shear strength and exhibited a decrease in strength as displacement increased and typical rooted soil behaviour where the shear force gradually increases until a maximum shear force was reached and sudden drops occurred. [10] also observed two types of test behaviour and suggested that these were affected by the amount of broken roots.

During testing on *Salix fragilis*, *Salix purpurea* and *Crataegus laevigata*, we observed that tests with the lowest RAR demonstrated typical non-rooted soil behaviour and tests with the highest RAR showed typical rooted soil behaviour. Similar findings were observed by [14] during in situ direct shear testing on kanuka trees and radiata pines. Also, [1][44][66][70] reported that sharp and well-defined peaks occurred in the stress-strain curves in fallow soils, and broader and flatter peaked curves occurred in tests on rooted soils.

Differences in typical soil behaviour during testing *Salix fragilis*, *Salix purpurea* and *Crataegus laevigata* were influenced by the presence of roots crossing the shear surface, whereas in the literature [10][19][39], differences in force-displacement graphs were observed to be also species-dependent. In those studies, insufficient shear strain displacement was produced in order to let all roots fail, whereas in our study extraction of the corkscrew went on until all roots have failed.

Sudden drops in force-displacement graphs were noticed during corkscrew extraction tests, especially in tests with higher root area ratio. This sudden decrease in force are attributed to root breakage. In the current study, such sudden drops were observed during testing of *Phragmites australis, Salix fragilis, Salix purpurea* and *Crataegus laevigata*. For instance, during test 8 at depth 125-250 mm at the *Salix purpurea*, a drop of 1129 Newtons accompanied by a audible root breakage was observed and the post-analysis revealed one broken root. These findings are consistent with [36], who observed sudden drops

Vegetation	Moisture content [%]	Root presence [%]				Diameter range [mm]		
		0-125 mm	125-250 mm	250-375 mm	375-500 mm	Max	Min	Mean
P. australis	45	48	32	20	-	-	-	-
S. fragilis	36	65	25	10	-	11.58	0.2	1.28
S. purpurea	41	19	16	57	8	15.68	0.15	2.29
C. laevigata	44	49	27	12	12	13.2	0.15	0.95

Table 5.3: Overview of characteristics of the four test sites such as root presence, in root biomass or root area ratio, and the diameter range of all roots collected during this study.

in strength on their study on Blackcurrant (*Ribes nigrum*) shrubs and Sitka spruce (*Picea sitchensis*) as well as [10] on their experiments on four common Australian riparian trees. Such sudden drops were also reported by [3][55].

Sudden drops in force-displacement graphs potentially corresponding to root breakages occurred at higher displacements than the displacements where fallow soil reaches its peak strength. In the current study, after the fallow soil has failed the force keeps increasing, implying that roots are activated at higher displacements than the displacement of the peak strength of soil. Similar observations were made by [3][10].

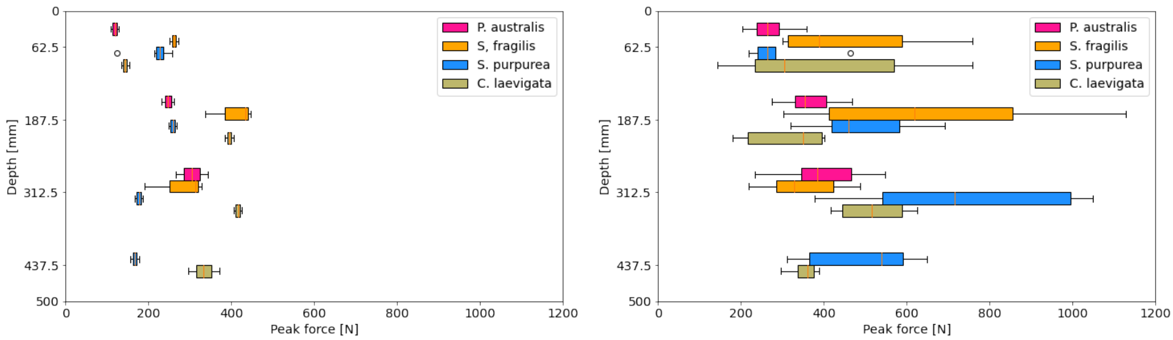
During testing at all sites, it was observed that roots continued to provide resistance at very high displacements where bare soil has already failed. In these cases, failure only occurred when the roots broke at the end of the testing displacement. Previous studies [14] reported during direct shear tests both in situ and in the laboratory, that soil with roots has the ability to withstand larger shear displacements than fallow soil. [10] reported that the tree roots provided their greatest contribution to soil strength at a displacement when the soil on its own would only provide residual strength.

Two distinct modes of root failure were observed, namely slipping and breaking of the root [7]. Studies [19][55] suggested that roots that break rather than slip have a higher resistance since their tensile strength is fully mobilised. However, the influence of these different processes strongly depends on both soil and root properties [4]. In the current study, the failure mode of the majority of the tests was root breaking, however, during the extractions of test 1 at depth 125-250 mm and test 4 at depth 375-500 mm both at the *C. laevigata* site, slipping roots were observed. In these tests, the root area ratio was significantly higher than the other tests, whereas the peak force was not. This is consistent with studies [19][55], which suggested that roots that break rather than slip have a higher resistance since their tensile strength is fully mobilised. However, the influence of these different processes strongly depends on both soil and root properties [4].

5.6. Comparison of the four sites

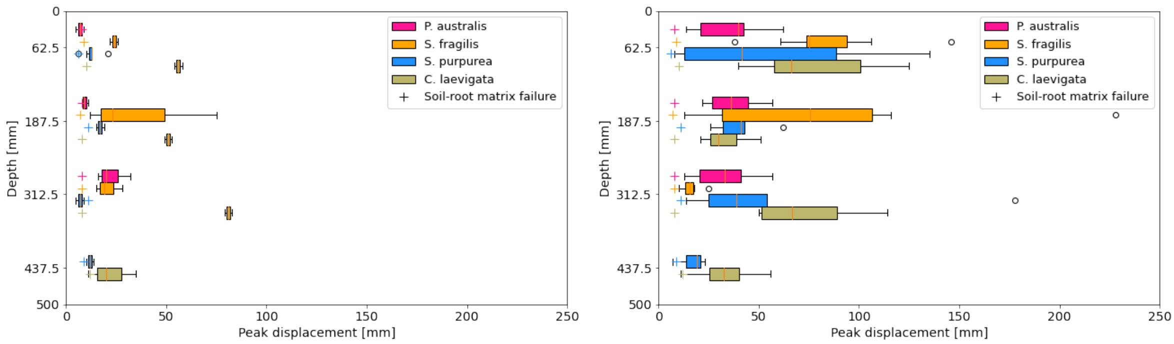
The most root quantities were found in the shallowest depth level (0-125 mm), for *P. australis, S. fragilis* and *C. laevigata*. The roots of *S. purpurea* were concentrated at depth level 250-375 mm (Table 5.3). Similarly, in literature, it was observed that the rooting depths and root distribution patterns differ between the tested vegetation. For example, willow roots have been observed to penetrate to depths up to 2.50 meters, while reed roots are primarily shallow and horizontal [30][43]. For all species, the diameter of the roots varied highly, with *S. purpurea* having the thickest roots, followed by *S. fragilis* and *C. laevigata*. The distribution of below ground biomass can be an important factor in root reinforcement and slope stability.

A comparison of the corkscrew extractions between species indicates that *S. fragilis* and *S. purpurea* require the greatest force to induce failure at depth levels 0-250 mm and 250-500 mm, respectively. For all species and depth levels, a higher peak force is reached during rooted soil testing than during bare soil testing, as shown in Figure 5.2. For the samples with *P. australis* roots, the peak force increases as the depth increases, whereas the corresponding mean biomass decreases as the depth increases, see Table 5.4. The peak force of the samples with *S. fragilis* roots increases from depth level 0-125 mm to depth level 125-250 mm and then decreases again at depth level 250-375 mm (Table 5.5). Similarly, the peak force of S. purpurea increases until depth level 250-375 mm and then decreases at deeper levels, similar trend is observed for the corresponding root area ratio. Finally, the maximum peak force of the samples with *C. laevigata* roots, was observed at depth level 250-375 mm.



(a) **(b)**

Figure 5.2: Comparison of the peak force over the depth for the four types of vegetation for (a) soil-only samples and (b) samples containing roots. The 'o' symbol indicates outliers.



(a) **(b)**

Figure 5.3: Comparison of the displacement where the peak force occurred over the depth for the four types of vegetation for (a) soil-only samples and (b) samples containing roots. The 'o' symbol indicates outliers and the '+' symbol indicates the displacement where the soil fails and the roots start to mobilise.

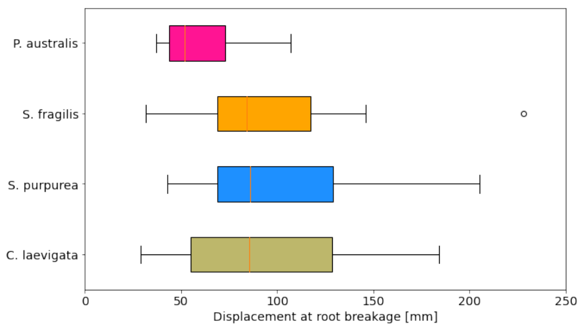


Figure 5.4: Displacement at root breakages for all four sites.

Vegetation	Depth [mm]	Peak force [N]			Corresponding biomass [g]		
		Max	Min	Mean	Max	Min	Mean
P. australis	0-125	359	119	251	5.99	0.01	1.67
	125-250	469	232	341	0.96	0.07	1.10
	250-375	548	233	378	3.74	2.02	0.72

Table 5.4: Overview of the peak force and the corresponding biomass of the samples at the testing sites of *P. australis*.

Vegetation	Depth [mm]	Peak force [N]			Corresponding RAR [%]		
		Max	Min	Mean	Max	Min	Mean
S. fragilis	0-125	758	262	444	0.213	0.014	0.178
	125-250	1129	303	574	0.244	0.048	0.073
	250-375	487	190	325	0.022	0.003	0.029
S. purpurea	0-125	464	125	249	0.157	0.001	0.045
	125-250	693	259	456	0.108	0.008	0.090
	250-375	1049	177	643	0.918	0.004	0.321
	375-500	650	167	437	0.061	0.001	0.045
C. laevigata	0-125	759	144	397	0.159	0.013	0.126
	125-250	401	180	309	0.050	0.068	0.063
	250-375	625	416	518	0.052	0.010	0.034
	375-500	389	296	352	0.110	0.009	0.034

Table 5.5: Comparison of the peak force and the corresponding RAR of the samples at the testing sites of *S. fragilis*, *S. purpurea* and *C. laevigata*.

Furthermore, the peak displacements were greater for samples containing roots than samples with no roots. The highest peak displacements were found in samples with *S. fragilis* roots at depth level 0-250 mm, followed by *C. laevigata*, *S. purpurea* and *P. australis* (Figure 5.3). On average the peak force was reached at a displacement of 35 mm for *P. australis* at all depth levels, at a displacement of 85 mm and 16 mm for *S. fragilis* at depth level 0-250 mm and 250-375 mm, respectively. When a rooted soil reaches its peak peak, root breakages occur as roots fail in tension when their ultimate tensile strength is reached. Roots are activated at high displacements after the bare soil has failed, meaning they reach their maximal resistance at high displacements as well. This means that in our current study, the roots of *Salix fragilis* reach their maximal resistance at the highest displacements at depth level 0-250 mm. As for the deeper level (250-500 mm), the roots of *Crataegus laevigata* are the ones which reach their maximum resistance at the highest displacements. Moreover, the roots of the vegetation that reaches the fastest its peak force is the roots of *P. australis.* For *S. purpurea*, the average peak force at depth levels 0-375 mm and 375-500 mm occurred at displacements 53 mm and 17 mm, respectively. The peak displacement varied over the depth for *C. laevigata*, with the largest displacements at depth levels 0-125 mm and 250-375 mm. This compared with an average of 18 mm to develop the peak force during soil-only tests. Soils containing roots of these different types of vegetation have a greater peak displacement to reach their maximum resistance than bare soils where the peak force was reached at much smaller displacements. Similar findings were observed in [10][66][67]. Figure 5.4 show that similar displacements at root breakage were provided by *S. fragilis, S. purpurea* and *C. laevigata*, followed by *P. australis.*

6
CONCLUSIONS

6.1. Corkscrew set-up

The corkscrew method shows to be a promising technique for measuring root reinforcement in difficult terrains such as riparian areas. It presents notable benefits such as time efficiency, field applicability and non-destructiveness, compared to more complex, time-consuming and destructive methods. Also, the corkscrew method disturbs minimally the soil, which enables the monitoring of slopes for slope stability. Corkscrew measurements can be conducted repeatedly on the same field and monitor the evolution of root reinforcement over time for slope stability. Nonetheless, challenges associated with root recovery and the restricted testing depth must be addressed and further research is needed to fully comprehend the applicability of the corkscrew method for assessing root reinforcement in riparian conditions.

6.2. Root and strength parameters

Root biomass shows not to be a good indicator for root-reinforcement as all roots embedded in the samples are taken into consideration, even the roots which are not crossing the shear surface and therefore not contributing to the shear strength. On the contrary, the root area ratio seems to be a better indicator for peak force and the energy needed to extract a rooted soil sample with a corkscrew.

6.3. Force-displacement graphs

The presence of roots crossing the shear surface has a significant impact on the force-displacement behaviour of the soil measured through the corkscrew measurements. During testing on *Salix fragilis*, *Salix purpurea* and *Crataegus laevigata*, the samples with the lowest root area ratio showed typical non-rooted behaviour and samples with the highest root area ratio showed typical rooted behaviour. However, during testing on soils rooted with *Phragmites ausralis*, this was not the case as root biomass was considered, taken into account roots embedded in the sample which were not crossing the shear surface.

Furthermore, roots continue to provide resistance at very high displacements where bare soil has already failed. Also, presence of roots increases the peak force and the energy needed to pull out the sample out of the ground depending on the type of vegetation. Finally, root breakages were identified in the force displacement graphs as sudden drops.

The thesis concludes that the corkscrew method shows promise as a technique for measuring root reinforcement in challenging terrains like riparian areas. Compared to complex and destructive methods, the corkscrew method offers advantages in terms of time efficiency, field applicability, and non-destructiveness. It allows for repeated measurements over time to monitor the evolution of root reinforcement and slope stability. However, the study identifies challenges related to root recovery and the limited testing depth, indicating the need for further research to fully understand the applicability of the corkscrew method in riparian conditions.

Regarding root and strength parameters, the thesis finds that root biomass alone is not a reliable indicator of root reinforcement, as it includes all roots in the sample, including those not contributing to shear strength. On the other hand, the root area ratio demonstrates potential as a better indicator for peak force and the energy required to extract a rooted soil sample using a corkscrew.

The force-displacement graphs obtained from corkscrew measurements reveal that the presence of roots crossing the shear surface significantly affects the soil's force-displacement behavior. Samples with higher root area ratios exhibit typical rooted behavior, while those with lower ratios show non-rooted behavior. However, when testing soil rooted with *Phragmites australis*, the consideration of root biomass led to the inclusion of roots that were not crossing the shear surface, impacting the results. The graphs also identify root breakages as sudden drops in force displacement.

7 RECOMMENDATIONS

- Further research should focus on exploring alternative approaches for root recovery and the limited testing depth while maintaining the practicality of the testing procedure. Future research could investigate the use of alternative materials or techniques that are effective for recovering roots in moist soil conditions, or explore other means of quantifying root reinforcement that do not rely on root recovery. Other suggestions include extending the database of field data in order to understand the usability of the corkscrew method in riparian conditions.
- Future research on the relationship between root and strength parameters should be conducted in order to determine the ideal assessment for quantifying root reinforcement.
- Future studies should consider ways to account for the effects of vertically growing roots on corkscrew test results. Additionally, further investigation is needed to determine the extent to which vertically growing roots are present in natural soil environments and how they contribute to overall soil stability.
- Further studies should focus on appropriate models which can assess root reinforcement in riparian conditions.
- Further studies should focus on the influence of the shear strain on the stability of stream banks. Other suggestions include the research on a combination of different vegetation for sheet pile-vegetation system, by determining which roots provide most resistance, mobilise at most rapidly and are active over significantly long displacement range in order to determine which combination is the most ideal one for stabilising stream banks.
- Future studies should focus on the combination of a numerical model with measured shear strength using the corkscrew method in order to investigate the effects of vegetation on slope stability determine the required root reinforcement in the soil in order to most effectively stabilise stream banks.

Bibliography

[1] Abe, K., and Iwamoto, M. Preliminary experiment on shear in soil layers with a large direct-shear apparatus. *Journal of the Japanese Forestry Society 68* (1986), 61–65.

[2] Abe, K., and Ziemer, R. R. Effect of tree roots on a shear zone: modeling reinforced shear stress. *Canadian Journal of Forest Research 21*, 7 (1991), 1012–1019.

[3] Abernethy, B., and Rutherfurd, I. D. The distribution and strength of riparian tree roots in relation to riverbank reinforcement. *Hydrological processes 15*, 1 (2001), 63–79.

[4] Bourrier, F., Kneib, F., Chareyre, B., and Fourcaud, T. Discrete modeling of granular soils reinforcement by plant roots. *Ecological Engineering 61* (2013), 646–657.

[5] Cammeraat, E., van Beek, R., and Kooijman, A. Vegetation succession and its consequences for slope stability in se spain. *Plant and soil 278* (2005), 135–147.

[6] Cazzuffi, D., and Crippa, E. Contribution of vegetation to slope stability: an overview of experimental studies carried out on different types of plants. *Erosion of Soils and Scour of Foundations* (2005), 1–12.

[7] Coppin, N. J., and Richards, I. G. *Use of vegetation in civil engineering.* Ciria Butterworths, 1990.

[8] de Klein, J. J., and van der Werf, A. K. Balancing carbon sequestration and ghg emissions in a constructed wetland. *Ecological Engineering 66* (2014), 36–42.

[9] Dobos, A. Éghajlatváltozások bizonyítékai a bükkalján geológiai feltárások alapján. *Az Eszterházy Károly Főiskola tudományos közleményei (Új sorozat 30. köt.). Tanulmányok a környezettudomány területéről= Acta Academiae Paedagogicae Agriensis. Sectio Pericemonologica* (2006), 47–70.

[10] Docker, B., and Hubble, T. Quantifying root-reinforcement of river bank soils by four australian tree species. *Geomorphology 100*, 3-4 (2008), 401–418.

[11] Douglas, G., Straley, G., Meidinger, D., and Pojar, J. Illustrated flora of british columbia, volumes 1–8. *BC Ministry of Environment, Lands and Parks* (1998).

[12] Dušek, J., and Květ, J. Seasonal dynamics of dry weight, growth rate and root/shoot ratio in different aged seedlings of salix caprea. *Biologia 61* (2006), 441–447.

[13] Ekanayake, J. C., Marden, M., Watson, A. J., and Rowan, D. Tree roots and slope stability: a comparison between pinus radiata and kanuka. *New Zealand Journal of Forestry Science 27*, 2 (1997), 216–233.

[14] Ekanayake, J. C., and Phillips, C. J. A method for stability analysis of vegetated hillslopes: an energy approach. *Canadian Geotechnical Journal 36*, 6 (1999), 1172–1184.

[15] Endo, T. Effect of tree roots upon the shear strength of soil. *JARQ (Japan Agricultural Research Quarterly) 14*, 2 (1980), 112–115.

[16] Endo, T., and Tsurata, T. Effect of tree's roots upon the shearing strength of soils. *Annual Report the Hokkaido Branch Government Forest Experiment Station*, 18 (1969), 167–182.

[17] Falk, B. Wood as a sustainable building material.

[18] Genet, M., Stokes, A., Salin, F., Mickovski, S. B., Fourcaud, T., Dumail, J.-F., and Van Beek, R. The influence of cellulose content on tensile strength in tree roots. *Plant and soil 278* (2005), 1–9.

[19] Ghestem, M., Veylon, G., Bernard, A., Vanel, Q., and Stokes, A. Influence of plant root system morphology and architectural traits on soil shear resistance. *Plant and soil 377* (2014), 43–61.

[20] Gray, D. H., and Leiser, A. T. *Biotechnical slope protection and erosion control.* Van Nostrand Reinhold Company Inc., 1982.

[21] Gray, D. H., and Ohashi, H. Mechanics of fiber reinforcement in sand. *Journal of geotechnical engineering 109*, 3 (1983), 335–353.

[22] Gray, D. H., and Sotir, R. B. *Biotechnical and soil bioengineering slope stabilization: a practical guide for erosion control.* John Wiley & Sons Inc., New York, 1996.

[23] Greenway, D. Vegetation and slope stability. *Slope stability: geotechnical engineering and geomorphology/edited by MG Anderson and KS Richards* (1987).

[24] Greenwood, J. R., Norris, J., and Wint, J. Assessing the contribution of vegetation to slope stability. *Proceedings of the Institution of Civil Engineers-Geotechnical Engineering 157*, 4 (2004), 199–207.

[25] Kamath, A. *Bio-Engineered Earth Retaining Structure (BEERS): A timber sheet pile-vegetation system for stream bank protection.* PhD thesis, Delft University of Technology, Delft, The Netherlands, 2022.

[26] Kassif G, L. A. *Strength properties of soil root systems.* 1968.

[27] Kaul, R. *The influence of roots on certain mechanical properties of an uncompacted soil.* PhD thesis, Department of Agricultural Engineering, North Carolina State University, Raleigh NC, 1965.

[28] Koerselman, W., and Meuleman, A. F. The vegetation n:p ratio: a new tool to detect the nature of nutrient limitation. *Journal of Applied Ecology 33*, 6 (1996), 1441–1450.

[29] Kumar, P., Debele, S. E., Sahani, J., Rawat, N., Marti-Cardona, B., Alfieri, S. M., Basu, B., Basu, A. S., Bowyer, P., Charizopoulos, N., et al. An overview of monitoring methods for assessing the performance of nature-based solutions against natural hazards. *Earth-Science Reviews 217* (2021), 103603.

[30] Lei, C., Yuckin, S. J., and Rooney, R. C. Rooting depth and below ground biomass in a freshwater coastal marsh invaded by european reed (phragmites australis) compared with remnant uninvaded sites at long point, ontario. *The Canadian Field-Naturalist 133*, 4 (2019), 364–371.

[31] Liang, T., Bengough, A., Knappett, J., MuirWood, D., Loades, K. W., Hallett, P. D., Boldrin, D., Leung, A. K., and Meijer, G. Scaling of the reinforcement of soil slopes by living plants in a geotechnical centrifuge. *Ecological Engineering 109* (2017), 207–227.

[32] Linnaeus, C. *Species plantarum*, vol. 3. Impensis GC Nauk, 1799.

[33] Manbeian, T. *The Influence of Soil Moisture Section, Cyclic Wetting and Drying, and Plant Roots on the Shear Strength of a Cohesive Soil and Stability of Slopes.* University of California, Berkeley, 1973.

[34] Mao, Z., Saint-Andre, L., Genet, M., Mine, F.-X., Jourdan, C., Rey, H., Courbaud, B., and Stokes, A. Engineering ecological protection against landslides in diverse mountain forests: choosing cohesion models. *Ecological Engineering 45* (2012), 55–69.

[35] Meijer, G., Bengough, A., Knappett, J., Loades, K., and Nicoll, B. New in situ techniques for measuring the properties of root-reinforced soil–laboratory evaluation. *Géotechnique 66*, 1 (2016), 27–40.

[36] Meijer, G., Bengough, A., Knappett, J., Loades, K., and Nicoll, B. C. In situ measurement of root reinforcement using corkscrew extraction method. *Canadian Geotechnical Journal 55*, 10 (2018), 1372–1390.

[37] Meijer, G., Bengough, G., Knappett, J., Loades, K., and Nicoll, B. Measuring the strength of root-reinforced soil on steep natural slopes using the corkscrew extraction method. *Forests 10*, 12 (2019), 1135.

[38] Mickovski, S., Bengough, A., Bransby, M., Davies, M., Hallett, P., and Sonnenberg, R. Material stiffness, branching pattern and soil matric potential affect the pullout resistance of model root systems. *European Journal of soil science 58*, 6 (2007), 1471–1481.

[39] Mickovski, S. B., Hallett, P. D., Bransby, M. F., Davies, M. C., Sonnenberg, R., and Bengough, A. G. Mechanical reinforcement of soil by willow roots: impacts of root properties and root failure mechanism. *Soil Science Society of America Journal 73*, 4 (2009), 1276–1285.

[40] Moore, G. E., Burdick, D. M., Peter, C. R., and Keirstead, D. R. Belowground biomass of phragmites australis in coastal marshes. *Northeastern Naturalist 19*, 4 (2012), 611–626.

[41] Nilaweera, N. Effects of tree roots on slope stability-the case of khao lunag mountain area, southern thiland. *Doctor thesis No. GT-93-2 452* (1994).

[42] Norris, J. E. Root reinforcement by hawthorn and oak roots on a highway cut-slope in southern england. *Plant and Soil 278* (2005), 43–53.

[43] Norris, J. E., Stokes, A., Mickovski, S. B., Cammeraat, E., Van Beek, R., Nicoll, B. C., and Achim, A. *Slope stability and erosion control: ecotechnological solutions*. Springer Science & Business Media, 2008.

[44] O'Loughlin, C., et al. Effectiveness of introduced forest vegetation for protection against landslides and erosion in new zealand's steeplands. In *Symposium on effects of forest land use on erosion and slope stability* (1984), University of Hawaii, pp. 275–280.

[45] O'Loughlin, C., and Ziemer, R. The importance of tree root strength and deterioration rates upon edaphic stability in steepland forest. *I.U.F.R.O. Workshop P.1.07-00 Ecology of Subalpine Ecosystems as a Key to Management* (1982), 70–78.

[46] Operstein, V., and Frydman, S. The influence of vegetation on soil strength. *Proceedings of the Institution of Civil Engineers-Ground Improvement 4*, 2 (2000), 81–89.

[47] Packer, J. G., Meyerson, L. A., Skálová, H., Pyšek, P., and Kueffer, C. Biological flora of the british isles: Phragmites australis. *Journal of Ecology 105*, 4 (2017), 1123–1162.

[48] Phillips, C. J., Marden, M., and Suzanne, L. M. Observations of root growth of young poplar and willow planting types. *New Zealand Journal of Forestry Science 44* (2014), 1–12.

[49] Pietrzykowski, M., Woś, B., Tylek, P., Kwaśniewski, D., Juliszewski, T., Walczyk, J., Likus-Cieślik, J., Ochał, W., and Tabor, S. Carbon sink potential and allocation in above-and below-ground biomass in willow coppice. *Journal of Forestry Research 32* (2021), 349–354.

[50] Plante, P.-M., Rivest, D., Vézina, A., and Vanasse, A. Root distribution of different mature tree species growing on contrasting textured soils in temperate windbreaks. *Plant and soil 380* (2014), 429–439.

[51] Pollen, N. Temporal and spatial variability in root reinforcement of streambanks: accounting for soil shear strength and moisture. *Catena 69*, 3 (2007), 197–205.

[52] Pollen, N., and Simon, A. Estimating the mechanical effects of riparian vegetation on stream bank stability using a fiber bundle model. *Water Resources Research 41*, 7 (2005).

[53] Reid, H., Huq, S., Inkinen, A., MacGregor, J., Macqueen, D., Mayers, J., Murray, L., and Tipper, R. Using wood products to mitigate climate change. *International Institute for Environment and Development, London* (2004).

[54] Riestenberg, M. M. *Anchoring of thin colluvium by roots of sugar maple and white ash on hillslopes in Cincinnati*, vol. 2059. US Government Printing Office, 1994.

[55] Schwarz, M., Cohen, D., and Or, D. Root-soil mechanical interactions during pullout and failure of root bundles. *Journal of Geophysical Research: Earth Surface 115*, F4 (2010).

[56] Shewbridge, S. E., and Sitar, N. Deformation characteristics of reinforced sand in direct shear. *Journal of geotechnical engineering 115*, 8 (1989), 1134–1147.

[57] Simon, A., and Collison, A. J. Quantifying the mechanical and hydrologic effects of riparian vegetation on streambank stability. *Earth surface processes and landforms 27*, 5 (2002), 527–546.

[58] Stokes, A., Atger, C., Bengough, A. G., Fourcaud, T., and Sidle, R. C. Desirable plant root traits for protecting natural and engineered slopes against landslides. *Plant and soil 324* (2009), 1–30.

[59] Swearingen, J., and Saltonstall, K. Phragmites field guide: distinguishing native and exotic forms of common reed (phragmites australis) in the united states. plant conservation alliance, weeds gone wild. *Weeds Gone Wild* (2010).

[60] Terwilliger, V. J., and Waldron, L. J. Assessing the contribution of roots to the strength of undisturbed, slip prone soils. *Catena 17*, 2 (1990), 151–162.

[61] Thomas, P. A., Leski, T., La Porta, N., Dering, M., and Iszkuło, G. Biological flora of the british isles: Crataegus laevigata. *Journal of Ecology 109*, 1 (2021), 572–596.

[62] Thomé, O. W. Flora von deutschland, österreich und der schweiz 1885. *Gera, Germany.*

[63] Tron, S., Perona, P., Gorla, L., Schwarz, M., Laio, F., and Ridolfi, L. The signature of randomness in riparian plant root distributions. *Geophysical Research Letters 42*, 17 (2015), 7098–7106.

[64] United Nations Environment Programme and Global Alliance for Buildings and Construction. 2021 global status report for buildings and construction: Towards a zero-emission, efficient and resilient buildings and construction sector.

[65] Vergani, C., Schwarz, M., Cohen, D., Thormann, J.-J., and Bischetti, G. Effects of root tensile force and diameter distribution variability on root reinforcement in the swiss and italian alps. *Canadian Journal of Forest Research 44*, 11 (2014), 1426–1440.

[66] Waldron, L. The shear resistance of root-permeated homogeneous and stratified soil. *Soil Science Society of America Journal 41*, 5 (1977), 843–849.

[67] Waldron, L., and Dakessian, S. Effect of grass, legume, and tree roots on soil shearing resistance. *Soil Science Society of America Journal 46*, 5 (1982), 894–899.

[68] Wu, T. H. *Investigation of landslides on prince of Wales Island, Alaska.* Ohio State University, 1976.

[69] Wu, T. H., Beal, P. E., and Lan, C. In-situ shear test of soil-root systems. *Journal of Geotechnical Engineering 114*, 12 (1988), 1376–1394.

[70] Wu, T. H., McKinnell III, W. P., and Swanston, D. N. Strength of tree roots and landslides on prince of wales island, alaska. *Canadian Geotechnical Journal 16*, 1 (1979), 19–33.

[71] Wu, T. H., and Watson, A. In situ shear tests of soil blocks with roots. *Canadian Geotechnical Journal 35*, 4 (1998), 579–590.

[72] Ziemer, R. R. The role of vegetation in the stability of forested slopes. In *Proceedings of the International Union of Forestry Research Organizations, XVII World Congress* (1981), vol. 1, IUFRO Kyoto, Japan, pp. 297–308.

[73] Ziemer, R. R. Roots and the stability of forested slopes. *Timothy R, Davies H, Andrew JP (Eds) International Association of Hydrological Sciences Publication, International Symposium on Erosion and Sediment Transport in Pacific Rim Steeplands* (1981), 343–361.

A

LITERATURE REVIEW

Authors	Title	Year	Number of citations	Information
Abe, K. and Iwamoto, M.	Preliminary experiment on shear in soil layers with a large direct-shear apparatus	1986	51	The existence of tree roots in the soil seems to increase the shearing strength compared with that of a soil block without roots. The displacement of soil-blocks of the planted plot tended to be greater than those of the bare plot.
Abe, K. and Ziemer, R. R.	Effect of tree roots on a shear zone: modeling reinforced shearstress	1991	222	Controlled laboratory experiments which showed that the presence of roots causes a widening of the shear zone. Model simulation corresponded quite well with the shear tests.
Abernethy, B. and Rutherfurd, I.D.	The distribution and strength of riparian tree roots in relation to riverbank reinforcement	2001	513	Roots of riparian-tree species growing on riverbanks occur in the upper soil profile. Force-displacement graphs with root breakages were observed.
Bourrier, F., Kneib, F., Chareyre, B., and Fourcaud, T.	Discrete modeling of granular soils reinforcement by plant roots	2013	161	Roots provide reinforcement for strains larger than the strain corresponding to the maximum soil shear resistance.
Cammeraat, E., van Beek, R., and Kooijman, A.	Vegetation succession and its consequences for slope stability in SE spain	2005	196	In situ experiments indicated that roots contributes to soil strength, but only in the upper 0.4 m of the soil.
Cazzuffi, D., and Crippa, E.	Contribution of vegetation to slope stability: an overview of experimental studies carried out on different types of plants	2005	33	Geotechnical tests were conducted to have an insight on the effect of plant roots on soil shear strength.
Coppin, N. J., and Richards, I. G.	Use of vegetation in civil engineering	1990	815	Willow for slope stability. Distinct types of root failure.
de Klein, J. J., and van der Werf, A. K.	Balancing carbon sequestration and ghg emissions in a constructed wetland	2014	109	Very low belowground biomass of *Phragmites australis* was observed at depths below 20 cm.
Docker, B., and Hubble, T.	Quantifying root-reinforcement of river bank soils by four australian tree species	2008	262	The increased shear resistance of soil due to roots calculated by the Root Area Ratio was determined in situ with a field shear-box. Two distinct types of test behaviours were observed.
Ekanayake, J. C., and Phillips, C. J.	A method for stability analysis of vegetated hillslopes: an energy approach	1999	91	Experiments show that soil with roots produces a shear stress-displacement curve with higher peak shear stress at larger shear displacements than fallow soil.
Endo, T.	Effect of tree roots upon the shear strength of soil	1980	38	
Endo, T., and Tsurata, T.	Effect of tree's roots upon the shearing strength of soils	1969	214	Shear strength of soil was studied in situ in unplanted plots and plots planted.
Falk, B.	Wood as a sustainable building material	2009	140	FSC timber is considered an environmentally friendly material in terms of carbon emissions.

Authors	Title	Year	Number of citations	Information
Genet, M., Stokes, A., Salin, F., Mickovski, S. B., Fourcaud, T., Dumail, J.-F., and Van Beek, R.	The influence of cellulose content on tensile strength in tree roots	2005	526	Tensile strength has been found to increase with decreasing root diameter.
Ghestem, M., Veylon, G., Bernard, A., Vanel, Q., and Stokes, A.	Influence of plant root system morphology and architectural traits on soil shear resistance	2014	177	Roots increased shear yield stress and deformation energy, but no significant effects on soil elasticity was observed. Roots confer resistance to shear when they are present at the shear plane.
Gray, D. H., and Leiser, A. T.	Biotechnical slope protection and erosion control	1982	872	Vegetation reinforcement is a crucial factor in protecting stream banks and slopes from soil failure, as both mechanical and hydrological mechanisms are affected by vegetation.
Gray, D. H., and Ohashi, H.	Mechanics of fiber reinforcement in sand	1983	1261	Direct shear tests were conducted on a sand reinforced wirh different types of fibers.
Gray, D. H., and Sotir, R. B.	Biotechnical and soil bioengineering slope stabilization: a practical guide for erosion control	1996	1265	Vegetation reinforcement is a crucial factor in protecting stream banks and slopes from soil failure.
Greenway, D.	Vegetation and slope stability	1987	815	Vegetation reinforcement is a crucial factor in protecting stream banks and slopes from soil failure. Vertical roots extending across a potential sliding shear surface in a slope will not fail simultaneously in tension.
Greenwood, J. R., Norris, J., and Wint, J.	Assessing the contribution of vegetation to slope stability	2004	229	A rooting depth of *Salix purpurea* extending up to 1.2 m was observed.
Kassif G.	Strength properties of soil root systems	1968	20	The number of roots crossing the shear plane significantly increases the soil resistance to shearing.
Kaul, R.	The influence of roots on certain mechanical properties of an uncompacted soil	1965	6	The number of roots crossing the shear plane significantly increases the soil resistance to shearing.
Koerselman, W., and Meuleman, A. F.	The vegetation n:p ratio: a new tool to detect the nature of nutrient limitation	1996	2611	*P. australis* roots were found to have a higher modulus of elasticity than other wetland plants.
Kumar, P., Debele, S. E., Sahani, J., Rawat, N., Marti-Cardona, B., Alfieri, S. M., Basu, B., Basu, A. S., Bowyer, P., and Charizopoulos, N.	An overview of monitoring methods for assessing the performance of nature-based solutions against natural hazards	2021	53	Monitoring over time can only be carried out by repeated measurements of root systems at the same location.
Lei, C., Yuckin, S. J., and Rooney, R. C.	Rooting depth and below ground biomass in a freshwater coastal marsh invaded by european reed (phragmites australis) compared with remnant uninvaded sites at long point, ontario	2019	5	Rooting depth of approximately 80 cm for *phragmites australis.*

Authors	Title	Year	Number of citations	Information
Liang, T., Bengough, A., Knappett, J., MuirWood, D., Loades, K. W., Hallett, P. D., Boldrin, D., Leung, A. K., and Meijer, G.	Scaling of the reinforcement of soil slopes by living plants in a geotechnical centrifuge	2017	79	The root dry biomass decreased significantly with an increase in soil depth, with 60% concentrated in the top soil (0-150 mm).
Manbeian, T.	The Influence of Soil Moisture Section, Cyclic Wetting and Drying, and Plant Roots on the Shear Strength of a Cohesive Soil and Stability of Slopes	1973	24	The number of roots crossing the shear plane significantly increases the soil resistance to shearing. Soil with roots is mobilised at a larger shear displacement than fallow soil but the position of the peak on non-peaked curves is not always clearly explained.
Mao, Z., Saint-Andre, L., Genet, M., Mine, F.-X., Jourdan, C., Rey, H., Courbaud, B., and Stokes, A.	Engineering ecological protection against landslides in diverse mountain forests: choosing cohesion models	2012	163	Factors that can influence the relationship between root area ratio and shear strength were identified.
Meijer, G., Bengough, A., Knappett, J., Loades, K., and Nicoll, B.	New in situ techniques for measuring the properties of root-reinforced soil–laboratory evaluation	2016	30	Corkscrew method.
Meuleman, A. F., Beekman, J., and Verhoeven, J. T.	Nutrient retention and nutrient-use efficiency in phragmites australis stands after wasterwater application	2002	103	More than 75% of the below-ground biomass of *Phragmites australis* was found just below soil surface (0–20 cm).
Mickovski, S., Bengough, A., Bransby, M., Davies, M., Hallett, P., and Sonnenberg, R.	Material stiffness, branching pattern and soil matric potential affect the pullout resistance of model root systems	2007	134	Root tensile strength and modulus of elasticity play a significant role in determining soil shear strength.
Mickovski, S. B., Hallett, P. D., Bransby, M. F., Davies, M. C., Sonnenberg, R., and Bengough, A. G.	Mechanical reinforcement of soil by willow roots: impacts of root properties and root failure mechanism	2009	170	Rooted soil showed significant increase in shear strength over fallow soil. Shear strength was linearly correlated with the root area ratio.
Moore, G. E., Burdick, D. M., Peter, C. R., and Keirstead, D. R.	Belowground biomass of phragmites australis in coastal marshes	2012	64	Common reed roots can grow horizontally for several meters, creating a dense network of roots that can help stabilize wetland soils.
Norris, J. E., Stokes, A., Mickovski, S. B., Cammeraat, E., Van Beek, R., Nicoll, B. C., and Achim, A.	Slope stability and erosion control: ecotechnological solutions	2008	291	The roots of *Salix purpurea* can extend up to 3 meters deep in well-drained soils, while in soils with higher water tables, they tend to stay shallower, typically between 1-2 meters deep.
O'Loughlin, C.	Effectiveness of introduced forest vegetation for protection against landslides and erosion in new zealand's steeplands	1984	69	Soil with roots is mobilised at a larger shear displacement than fallow soil but the position of the peak on non-peaked curves is not always clearly explained. Sharp and well-defined peaks occurred in the stress-strain curves in fallow soils, and broader and flatter peaked curves occurred in tests on rooted soils.

Authors	Title	Year	Number of citations	Information
Operstein, V., and Frydman, S.	The influence of vegetation on soil strength	2000	370	The increase in the shear strength of the reinforced soil is a function mainly of the tensile resistance contributed by the roots, and, to a smaller degree, of the cross-sectional area occupied by the roots in the soil.
Packer, J. G., Meyerson, L. A., Skalova, H., Pysek, P., and Kueffer, C.	Biological flora of the british isles: Phragmites australis	2017	115	Common reed roots can grow horizontally for several meters, creating a dense network of roots that can help stabilize wetland soils.
Phillips, C. J., Marden, M., and Suzanne, L. M.	Observations of root growth of young poplar and willow planting types	2014	61	It is expected that willow tree roots will be situated near the water table.
Plante, P.-M., Rivest, D., Vezina, A., and Vanasse, A.	Root distribution of different mature tree species growing on contrasting textured soils in temperate windbreaks	2014	32	It is expected that willow tree roots will be situated near the water table.
Pollen, N., and Simon, A.	Estimating the mechanical effects of riparian vegetation on stream bank stability using a fiber bundle model	2005	713	Vertical roots extending across a potential sliding shear surface in a slope will not fail simultaneously in tension.
Reid, H., Huq, S., Inkinen, A., MacGregor, J., Macqueen, D., Mayers, J., Murray, L., and Tipper, R.	Using wood products to mitigate climate change	2004	37	FSC timber is considered an environmentally friendly material in terms of carbon emissions.
Riestenberg, M. M.	Anchoring of thin colluvium by roots of sugar maple and white ash on hillslopes in Cincinnati	1994	72	Tree species with high branching roots exhibited force-displacement graphs with multiple peaks as different branches failed at different displacements, whereas species with low branching roots exhibited plots with fewer peaks.
Schwarz, M., Cohen, D., and Or, D.	Root-soil mechanical interactions during pullout and failure of root bundles	2010	180	Roots that break rather than slip have a higher resistance since their tensile strength is fully mobilised.
Simon, A., and Collison, A. J.	Quantifying the mechanical and hydrologic effects of riparian vegetation on streambank stability	2002	981	The hydrologic effects are as important as the mechanical effects, and can be either beneficial or detrimental, depending on antecedent rainfall.
Stokes, A., Atger, C., Bengough, A. G., Fourcaud, T., and Sidle, R. C.	Desirable plant root traits for protecting natural and engineered slopes against landslides	2009	635	No correlations were found between the root biomass and the analysed soil characteristics.
Swearingen, J., and Saltonstall, K.	Phragmites field guide: distinguishing native and exotic forms of common reed (phragmites australis) in the united states. plant conservation alliance, weeds gone wild	2010	33	Reed roots can grow horizontally to depths of several meters.

Authors	Title	Year	Number of citations	Information
Tron, S., Perona, P., Gorla, L., Schwarz, M., Laio, F., and Ridolfi, L.	The signature of randomness in riparian plant root distributions	2015	47	The rooting depth of the purple willow can vary widely depending on environmental conditions and other factors.
Waldron, L.	The shear resistance of root-permeated homogeneous and stratified soil	1977	966	Soil with roots is mobilised at a larger shear displacement than fallow soil but the position of the peak on non-peaked curves is not always clearly explained. Wu/Waldron model.
Waldron, L., and Dakessian, S.	Effect of grass, legume, and tree roots on soil shearing resistance	1982	143	Multiple studies have shown that the cross-sectional area of roots crossing the shear plane significantly increases the soil resistance to shearing.
Wu, T. H., McKinnell III, W. P., and Swanston, D. N.	Strength of tree roots and landslides on Prince of Wales Island, Alaska	1979	1073	A model of the soil-root system was developed to evaluate the contribution of tree roots to shear strength.
Ziemer, R.	Roots and the stability of forested slopes	1981	373	Vegetation helps stabilise steep forested slopes by reinforcing the soil through tree roots.