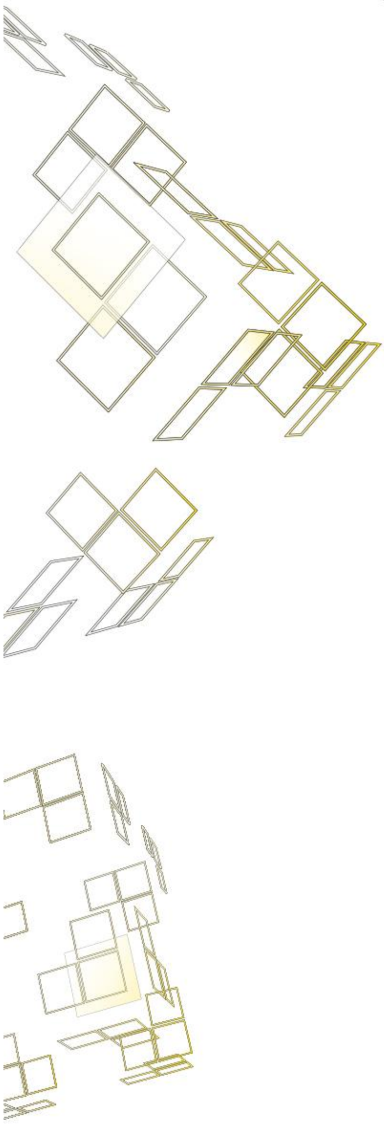

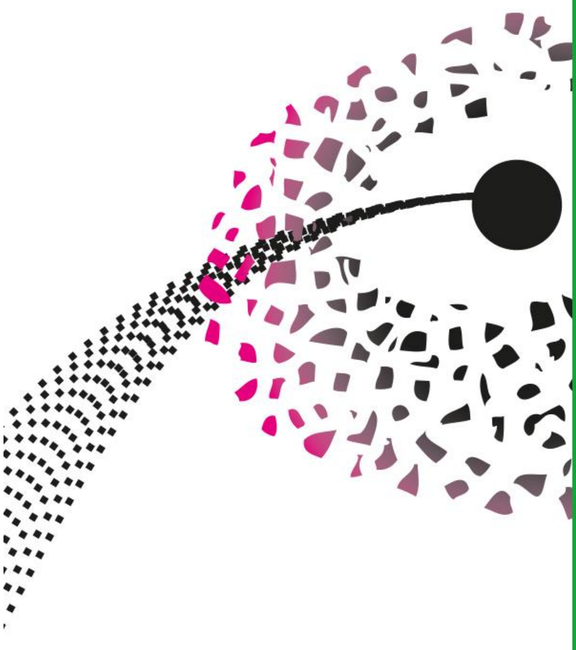

MSC THESIS

THE EFFECT OF HERBACEOUS PLANT ROOT CHARACTERISTICS ON HYDRAULIC STREAM BANK EROSION

A CASE STUDY FOR THE RIPARIAN ZONE OF THE RIVER DINKEL

AUTHOR(S)

FLORIS COUWENBERG

DATE

10-12-2023

UNIVERSITY OF TWENTE.

COLOPHON

UNIVERSITY OF TWENTE
MANAGEMENT
Department Civil Engineering and Management (CEM)
POSTAL ADDRESS
P.O. Box 217
7500 AE Enschede
WEBSITE
www.utwente.nl
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DAILY SUPERVISOR
Dr. Ir. E.M. Horstman (Erik)

HEAD OF GRADUATION COMMITTEE
Prof. Dr. K.M. Wijnberg (Kathelijne)

AUTHOR(S)
F.J.R. Couwenberg

PREFACE

This MSc thesis about the effect of herbaceous plant root characteristics on hydraulic stream bank erosion provided me the opportunity to execute field and laboratory measurements to collect my own data. This was an interesting journey, from which I learned a lot about plant roots and their role in bank stability and erosion. Moreover I discovered that a lot more about this topic can be researched. Next tot that I learned a lot about the tests and experiments performed in this research: the Shear Vane Test, Direct shear test and the flume studies at the NIOZ research institute. I experienced the sometimes practical complications and limitations of these tests and experiments. This experience and knowledge gained during this MSc thesis project are a valuable addition to the knowledge and skills obtained during my study at the university of Twente.

The research process is supervised by Erik Horstman and Kathelijne Wijnberg. I would thank you both for your guidance, feedback, and expertise which helped me considerably with my research. In addition, I appreciated your flexibility a lot during the process which helped me enormous to complete this research. I am also very grateful for the expertise and enthusiasm of Floriana Anselmucci. Floriana Anselmucci helped me a lot with the use of the direct shear test and with the interpretation of the direct shear test results. Moreover Floriana Anselmucci provided me a lot of knowledge about the effect of roots on soil properties. Lastly I want to thank Marte Stoorvogel a lot for the help with the set-up and guidance of the flume studies at the NIOZ research institute.

I hope this report is interesting to read and encourages further research in this topic.

Floris Couwenberg
Enschede, 19th of January 2024

ABSTRACT

Stream bank erosion can be can be a large environmental problem, with large ecological and societal consequences. Nowadays, many stream restoration projects use ecological engineering to cope with this problem. Herein riparian vegetation is often used to increase bank stability and reduce erosion. The resulting reduction of hydraulic erosion is mainly attributed to reduction in near-bed flow by the aboveground vegetation properties and the increased bank stability as a result of the greater strength of root permeated soils. This greater strength of root permeated soils might contribute to the hydraulic erosion reduction. However it is not fully known to what extent this increased strength contributes to the reduction of hydraulic erosion and which root permeated soil properties are important for this contribution.

In order to improve the understanding and quantification of the effects of the roots of riparian vegetation on the erosion of vegetated stream banks, this research studies the effects of several root characteristics on soil shear strength and hydraulic erosion, specifically for species in the riparian zone of the river Dinkel stream bank. The studied species in this research were the *Leersia oryzoides*, *Rumex obtusifolius* and *Digitaria sanguinalis*. The considered root characteristics are the wet weight of the root system, the dry weight of the root system, the root diameter and the number of roots. The shear strength of the (un)vegetated soil was determined by the in-situ shear vane test and the laboratory direct shear test. The erodibility of the (un)vegetated soil was then estimated with flume experiments at the NIOZ research institute. For the flume experiments and direct shear test (vegetated and unvegetated) soil samples were extracted from the riparian zone of the river Dinkel. For each of these samples the root characteristics were determined and the shear strength was measured with the shear vane test.

According the direct shear test results, no significantly larger shear strength was measured for root permeated soils of the studied species than for the bare soil samples. However the measured soil strengths varied largely along the Dinkel bank, but also the results between the shear vane test and direct shear test differed a lot. The shear vane test measured shear strengths mostly between 1 and 10 kN/m^2, with some exceptions up to 25 kN/m^2. The direct shear test measured shear strengths between 11 and 21 kN/m^2. No significant correlation was observed between the results of these tests either. In general the shear strength by shear vane test had much lower values than the shear strength by direct shear test. Next to that, the studied species showed different variation in shear strength by both tests. The difference in these results can be clarified by the measuring method and the root system architecture of the researched species. Of all root characteristics, the wet weight of the root system showed the strongest correlation with the shear strength.

The measured erosion of the samples showed large variations on small spatial scales, across and between samples, in the flume studies. The obtained erosion rates varied between 0.08 cm hr^{-1} and 0.35 cm hr^{-1}. These erosion rates showed a significant correlation with the shear strength, the relation between these properties was best described by a negative exponential relation. None of the studied root characteristics had a significant correlation with the erosion rates. However, observations during the flume experiments indicated that the organic content of the soil might have a large influence on the erodibility of the soils.

In general, the studied root characteristics showed a weak correlation with the soil strength and erosion rate. The measured root characteristics, shear strengths and erosion rates showed large differences on small (cm to m) spatial scales on the Dinkel bank. Although the different species had quite some differences in root characteristics, the shear strengths and erosion rates of their root permeated soils did not deviate considerably from each other.

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1. INTRODUCTION

This chapter introduces the stream bank erosion research topic and area in section 1.1. Furthermore, this chapter discusses the current state of the art in this research topic in section 1.2. From the current state of the art the problem description is constructed in section 1.3. The research aims and objectives are defined in section 1.4. In the next section 1.5 the research questions and their substation are described. This chapter ends with an outline of this report.

1.1 CONTEXT

In many river basins, stream bank erosion supplies over 50 percent of the catchment sediment output(Lawler et al., 1999). This erosion of stream banks can have a large negative influence on the water quality. In the longer-term, stream bank erosion and slope failure has an impact on riparian ecosystems (Figure 1), communities near the flood plain and stream related infrastructure, such as quays, bridges and dams (Wynn & Mostaghimi, 2006). Therefore, streambank erosion and slope failure can be a large environmental problem with economic and societal consequences (Gasser et al., 2020; Löbmann et al., 2020; Pollen, 2007; Wynn & Mostaghimi, 2006). Despite this evident ecological, societal and economic impact, bank erosion is often an overlooked problem, because the consequences of stream bank erosion often only become apparent in the long term (Löbmann et al., 2020).

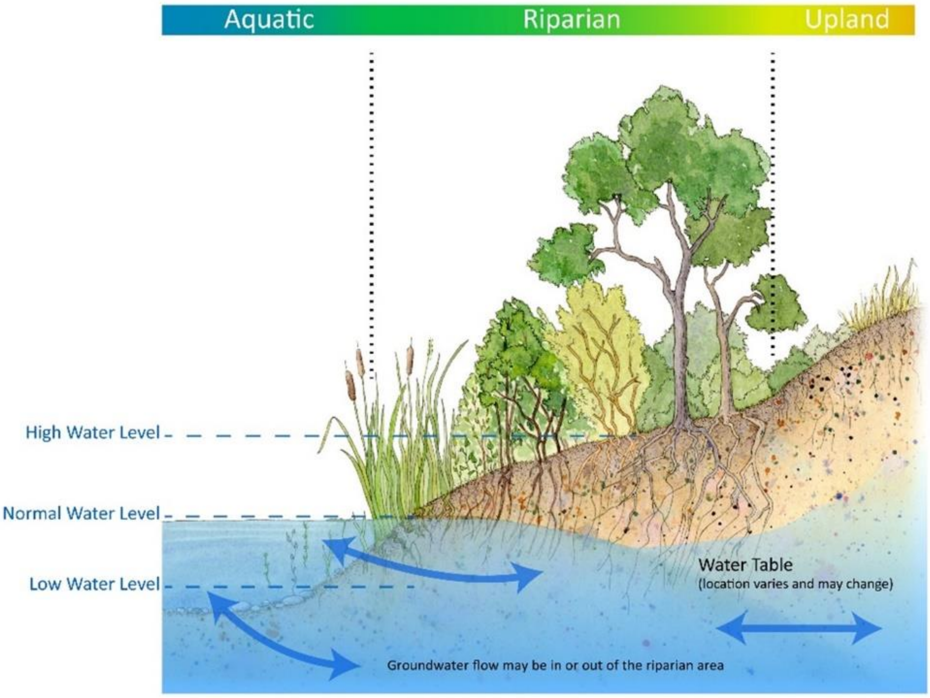

*Figure 1 Cross-section of river stream bank, which indicates the different zones of vegetation: Aquatic, Riparian and Upland retrieved from (*Riparian Areas*, n.d.)*

It is widely acknowledged that riparian vegetation (Figure 1) contributes to bank stability and reduces bank erosion(Capobianco et al., 2021; Hopkinson & Wynn, 2009; Löbmann et al., 2020; Simon & Collison, 2002). Therefore many stream restoration projects use riparian vegetation in order to prevent erosion (Löbmann et al., 2020; Simon & Collison, 2002; Wynn & Mostaghimi, 2006). On top of that, vegetation has several environmental benefits. Riparian vegetation reduces water pollution and increases biodiversity (Gasser et al., 2020). Nowadays, ecological engineering solutions for erosion prevention receive more attention and significant progress has been made in this research topic (Löbmann et al., 2020).

Despite this progress, major knowledge gaps still exist and more knowledge is required to successfully implement ecological engineering solutions to reduce bank erosion. Currently, many studies are lacking ways to quantify the reduction of erosion rates of vegetated stream banks (Pollen, 2007; Simon & Collison, 2002). As a result, there are still some large challenges and knowledge gaps in quantifying the erosion on vegetated stream banks. The quantification of the erosion rate and stability factor could be a useful tool to assess the effectiveness of vegetation in stream restoration projects. An accurate quantification method of the vegetated stream bank parameters will contribute to a better understanding of the effect of erosion reduction measures. This knowledge could help in the decision making for species or vegetation types in stream restoration.

This study will focus on the river Dinkel, an example of a stream with a riparian zone that is regularly flooded. In Figure 2 the riparian zone of the river Dinkel is depicted in low flow conditions and high flow conditions. Currently, there are a lot of stream restoration and ecological improvement projects along the river Dinkel, where this riparian vegetation plays an important role in the stream restoration objectives (*Projecten Dinkeldal*, 2023). The river Dinkel is located closely to German border in the eastern part of the Netherlands.

Figure 2 Two pictures of the river Dinkel riparian zone near Losser: (left) inundated riparian zone during high water, (right) emergent riparian vegetation during normal flow conditions

1.2 STATE OF THE ART

“Stream bank slope stability is determined by the balance of shear stress and shear strength” (Krzeminska et al., 2019, p. 87). These shear stresses and strength are dependent on many hydraulic, hydrological, and mechanical properties of the stream bank (Krzeminska et al., 2019), which are influenced by the vegetation characteristics and the soil properties. Some of these vegetation properties are either stabilizing, destabilizing or both. Therefore, the net contribution to bank erosion may be unknown or difficult to quantify (Pollen, 2007; Simon & Collison, 2002).

The mechanical stabilizing effects of vegetation are the mechanical reinforcement by the root system and the reduction of the soil moisture content. The mechanical reinforcement by the root system is caused by the tensile strength of the roots as well as the structure of the root systems. In general soil has large compressive strength, but has very low tensile strength. For fibrous roots of vegetation like trees and herbaceous species the opposite counts. Therefore, these roots combined with the soil form strong composite material (Simon & Collison, 2002; Waldron, 1977). This is the result of the intermingled structure of the vegetation roots that binds soil portions into a monolithic mass, which improves apparent cohesion that enhances the soil strength (Waldron, 1977). This increased cohesion results in larger shear strength of the soil, which contributes to bank stability (Razali et al., 2023; Simon & Collison, 2002). “The degree of reinforcement varies with the temporal and spatial characteristics of the roots (e.g., root density, distribution with depth, and diameter), root tensile strength, and soil moisture.” (Yu et al., 2020, p. 2). On the contrary the extra load on the stream bank due to the vegetation weight might have a destabilizing effect. However, according to Abernethy & Rutherfurd (2000) this so-called surcharge has minimal impact on bank instability.

Hydrological processes influence the mechanical stream bank stability by the moisture content of the soil. The lower the soil moisture content, the larger the matric suction due to the decreased pore pressure, which increases shear strength and results in more stability. Pollen & Simon (2010) showed that hydrological processes have considerable effect on the matric suction, which varies throughout the year. The reduction of the soil moisture by vegetation consists out of two hydrological processes, the interception of precipitation by the vegetation canopy and the transpiration. The first process, interception by the vegetation canopy, prevents that precipitation infiltrates into the subsurface by evaporation of the intercepted precipitation, which reduces the soil moisture content. The second process, transpiration, extracts water from the soil via the vegetation roots and subsequent transpiration via the vegetation canopy, which also reduces the soil moisture content (Fan & Su, 2008; Pollen, 2007; Simon & Collison, 2002). However, vegetation can also increase the soil moisture content, by enhanced infiltration as result of the concentrated water inflow from the leaves and as a result of the increased soil porosity by the roots. The net contribution of these hydrologic processes is still hard to quantify (Capobianco et al., 2021; Krzeminska et al., 2019; Simon &

Collison, 2002). The hydrologic effect of vegetation in models is often neglected, despite the relevance of hydrological processes for the mechanical bank properties (Capobianco et al., 2021; Gasser et al., 2020; Krzeminska et al., 2019).

Research on the effect of vegetation on hydraulic processes shows that the submerged part of vegetation reduces the flow velocity near the bed and bank, which reduces the erosion of the bank (Hopkinson & Wynn, 2009; J. Q. Yang et al., 2015). In addition, the submerged vegetation strongly affects the flow pattern, which complicates the estimation of the bed shear stress and increases the uncertainty of this parameter (Hopkinson & Wynn, 2009; J. Q. Yang et al., 2015). Critical bed shear stress is often used as a parameter to estimate the erosion of a stream bank (Gasser et al., 2020; Zi et al., 2023). However, the use of critical bed shear stress for estimating the erosion rate on stream banks is contested by several studies (Zi et al., 2023). Ma et al. (2020) and Knapen et al. (2009) argued that flow velocity is an optimal parameter to estimate this erosion rate. According to Zhu et al.(2020) stream power is a suitable predictor for bank erosion and according to Yang et al.(2018) the most appropriate parameter is the unit stream power to estimate bank erosion. Accordingly, there have been significant inconsistencies in assessments of the optimal hydraulic parameter to quantify bank erosion in recent decades (Zi et al., 2023).

Despite the large number of modelling approaches for vegetated stream bank erosion, very few modelling approaches consider the effects of vegetation roots (Gasser et al., 2020). Moreover, quantitative research about the effect of root permeated soils on the critical shear stress is rarely available (Gasser et al., 2020). Field research of Gyssels & Poesen (2003) revealed that the increase in root density resulted in an exponential decrease of flow erosion rates. The relation between the erosion reduction by root characteristics is often described in negative exponential form (Vannoppen et al., 2017):

$$SDR = e^{-b*R(L)D} \tag{1}$$

Herein SDR is the soil detachment ratio (the ratio between the absolute detachment rate of a root permeated soil and a bare soil), b a regression parameter and $R(L)D$ the RD root density or RLD the root length density. Examples of such a relation are derived by Gyssels et al. (2005), Vannoppen et al. (2017) and Zi et al. (2023). However, these relations are derived for rills and gullies on slopes (Gyssels et al., 2005; Vannoppen et al., 2017; Zi et al., 2023), and therefore their applicability for larger streams might be questionable. Next to that, several stream bank erosion models exist that consider the different effects of roots on bank stability, as indicated in Table 1.

Table 1 Overview of stream bank erosion models that consider the effect of vegetation roots based on Gasser et al (2020)

Model Name	Modelled Processes	Modelled root effect
BSTEM & RipRoot	Geotechnical bank erosion	Root reinforcement by adapting apparent cohesion based on literature values
	Hydraulic bank erosion	Adaptation of critical shear stress based on literature values
CONCEPTS & REMM	Geotechnical bank erosion	Root reinforcement by adapting apparent cohesion
	Hydraulic bank erosion	-
SWAT	Geotechnical bank erosion	Root reinforcement by adapting apparent cohesion
	Hydraulic bank erosion	Adapting critical shear stress based on an empirical effect that relies on a channel vegetation coefficient
	Bed erosion	Adapting critical shear stress based on an empirical effect that relies on a channel vegetation coefficient
SedNet	Hydraulic bank erosion	Consideration of vegetation cover by using a vegetation factor that describes the effect by the extent of vegetation cover
BankforNET	Hydraulic bank erosion	adapting the critical shear stress of the soil based on a linear relationship of root density

These models mostly emphasize the geotechnical effects of the vegetation roots. Often this geotechnical effect, an increased apparent cohesion, is used to estimate the critical shear stress to parameterize the bank erosion or a dimensionless vegetation coefficient is used to adapt the critical shear stress to estimate bank erosion (Gasser et al., 2020). These dimensionless vegetation coefficients include the effect of roots, but the effect of roots is not isolated from other parameters of vegetated stream banks. Generally these models do not link the effect of roots to the root characteristics, except BankforNET which links the critical shear stress to root density (Gasser et al., 2020). Most models link the effect of roots only to an increased critical shear strength, which is decisive for the erosion estimation by these models (Gasser et al., 2020). However as earlier mentioned by Zi et al. (2023) the use of this parameter for estimating erosion is questioned. Therefore there is limited quantitative knowledge about the effect of root(characteristics) on the hydraulic bank erosion. A clear quantitative relation of the effects of roots and their characteristics on the erosion rate is still missing. Next to that these existing models are coupled to a hydrodynamic model to estimate the hydraulic properties, which often requires a high level of parametrization (Gasser et al., 2020). This high level of parametrization is the result of several processes at different spatiotemporal scales. These factors and processes are the continuous change of the channel hydrogeomorphology pre post and during erosion events, fluctuating flow properties (e.g. velocity, duration and direction) and the spatiotemporal variability of precipitation events that influence the aforementioned processes. Moreover, there are more factors that complicate these processes and increase the parametrization of these processes, such as the heterogeneity of soil properties on the streambank and the presence of vegetation (Gasser et al., 2020).

1.3 PROBLEM DESCRIPTION

There is still limited knowledge about the erosion of vegetated stream banks and especially regarding the role of roots herein, despite their importance in all vegetated stream bank processes and the widespread occurrence of vegetated stream banks. As a result, existing erosion quantification methods have their limitations. A large limitation in these existing quantification methods is often the focus on geotechnical effects of roots, which also determines the hydraulic erodibility by an increased shear strength. Therefore, the role of roots in hydraulic scour is not fully understood and incorporated in the model (Gasser et al., 2020). Another limitation is the use of uniform factors or literature values for including the vegetation effect (Gasser et al., 2020), which might not represent the research area and its variability of vegetation characteristics. In addition, some methods are developed for rills and gullies as in Gyssels & Poesen (2003) and Zi et al. (2023) , application for larger streams might be questionable. Next to that most models do not consider the influence of hydrological processes or seasonal variability on streambank properties (Capobianco et al., 2021). Moreover, current models do not consider many root characteristics (Gasser et al., 2020; Vannoppen et al., 2017). The focus is on one parameter, which is often an increased apparent cohesion or root area ratio, which leaves other relevant characteristics out of scope. There are still some challenges to overcome these limitations and derive useful and practical relations to quantify the erosion of root permeated soils.

First, there are several processes present in vegetated stream bank erosion that interfere with each other. This complicates the quantification of the net effect of vegetation roots on the stream bank erosion. Examples of this are the stabilizing effect of vegetation roots and the destabilizing surcharge of vegetation, the increasing and decreasing infiltration by different hydrological processes as described in section xx and the complex flow patterns due the presence of submerged vegetation.

Second, there is no optimal hydraulic parameter to parameterize the hydraulic erosion of vegetated stream banks (Zi et al., 2023). In addition the relevant or decisive root characteristics for stream bank erosion have been rarely evaluated. Often a relation based on the Root Area Ratio (RAR) or increased cohesion term is used to parameterize the increased strength of root permeated stream bank (Gasser et al., 2020). These parameters are very applicable to stream bank stability, but their applicability towards hydraulic scour can be questioned. Therefore, it is not known what an optimal (set of) root parameter(s) is to predict the erosion of root permeated soils.

Third, data acquisition is often a limiting factor for the quantification of vegetation effects on stream bank stability (Wu, 2013). This especially applies to data acquisition of root characteristics. Data acquisition methods are costly, time consuming and might damage the stream bank due to the complexity of the root systems and the opaque medium in which these grow (Pollen, 2007; Wu, 2013). In vegetated bank erosion models mostly literature values from field studies and lab measurements are used for parameterization of the vegetation effects. Also, the properties of roots and/or soil are often implemented in models as spatially and temporally uniform parameters (Gasser et al., 2020). However, the vegetation and root characteristics are highly variable over time and space (Löbmann et al., 2020; Yu et al., 2020), because of variations in the specific local and seasonal growth conditions, location-specific requirements, specie compositions and plant health (Löbmann et al., 2020). Even within a study area on a very small spatial scale there is a high variation in root characteristics over space for example the root diameter and density over depth (Yu et al., 2020). This makes collecting root characteristics very data demanded due to the many spatial and temporal variations.

1.4 RESEARCH AIM AND SCOPE

This research will mainly focus the effect of vegetation roots on hydraulic stream bank erosion. As indicated in the state of the art , this is a major knowledge gap in studies on stream bank stability, which causes quite some limitations in the quantification of the erosion of vegetated stream banks as described in the problem description. Filling this knowledge gap and reducing the current limitations in stream bank erosion models are relevant for the assessment and application of vegetation in stream restoration projects. Considering these observations the following research aim is constructed:

"To improve the understanding and quantification of the effects of riparian vegetation roots on the erosion reduction of vegetated stream banks."

Within this research aim the intended final objective is to derive an empirical relation that estimates the reduction of the stream bank erosion rate based on stream bank vegetation root properties. To achieve this aim and objective several root parameters are researched. The correlation and relation of these root parameters is tested, such that their suitability for estimating erosion of root permeated soils can be evaluated.

The problem definition indicates several challenges and limitations in the current quantification methods of vegetated stream bank erosion. The main topics from the problem definition that will be dealt with within this research are: the relation between the geotechnical stability (the shear strength) of root permeated soils and their erosion rate, the variability of root permeated soils properties in the field, and evaluation of data acquisition methods that minimize the required resources (e.g. time, effort and tools). Since the focus of the research aim lies on the impact of roots on hydraulic scour, interference with other hydrological and mechanical processes is outside the scope of this research. Therefore, the effects of these processes on experimental outcomes in this study will be limited by keeping these conditions as constant as much as possible. The scope of this research is further limited to the herbaceous species present in the riparian zone of the research area at the river Dinkel bank.

1.5 RESEARCH QUESTIONS

1. **What variation in root permeated soil properties of herbaceous vegetation covers can be observed along the Dinkel stream bank?**
    1.1. Which herbaceous species are present on the Dinkel stream bank and what above ground properties do they have?
    1.2. What are the root characteristics of the herbaceous species on the river Dinkel stream bank?
    1.3. What is the soil composition of the river Dinkel stream bank?

These aforementioned questions are meant to gain insight into the variation of root permeated soil properties that can be observed in the field. The answers to these questions should provide a clear context for interpretation of further results in this research. The answer of question 1.1. provides a short description of the researched species. The results of question 1.2. indicate the bandwidth of the researched root characteristics, which will be relevant for the derivation of relations between root characteristics and erodibility.

Question 1.3. is relevant for this research, because the soil composition does affect the erodibility and stability of the stream bank. If large variations in soil compositions exist, this should be accounted for in the analysis of strength and erodibility results. The answer to question 1.3. is also important for comparison with different locations and other research.

2. **What is the shear strength of herbaceous root permeated soils with different root characteristics along the Dinkel stream bank and how is this related to the measured root characteristics?**
    2.1. What is the shear strength measured by field tests with the shear vane test?
    2.2. What is the shear strength measured by lab tests with the direct shear test?
    2.3. To what extent do the results obtained from lab and field tests agree?
    2.4. Which correlations exist between the measured root characteristics and the measured shear strengths?

The rate of hydraulic induced erosion is often parameterized in models by (critical) shear strength in models (Gasser et al., 2020). Moreover, roots can increase the bank stability (i.e. shear strength). The shear strength is an important parameter in the estimation of stream bank erosion (Capobianco et al., 2021; Collison & Anderson, 1996; Langendoen & Simon, 2008; Löbmann et al., 2020; Simon & Collison, 2002; Yu et al., 2020). Two methods for measuring the shear strength have been selected, to evaluate whether less resource demanding field test (Shear Vane Test) can measure the effect of roots on the shear strength of root permeated soils as well as more intensive lab tests such as the Direct Shear Test. The answers to question 2.1-2.3 are helpful for further research in this topic, because data acquisition is often a limitation in this field. Since in this research different root characteristics are researched than existing in literature, it is evaluated if and how these root characteristics relate to shear strength in question 2.4.

3. **Which relations exist between the measured herbaceous root permeated soil properties of the Dinkel stream bank and its erosion rate?**
    3.1. What are the erosion rates of the herbaceous root permeated soils?
    3.2. What relation exists between the shear strength and erosion rate of the herbaceous root permeated soils of the Dinkel stream bank?
    3.3. What relation exists between the root characteristics and erosion rate of the herbaceous root permeated soils of the Dinkel stream bank?

The third main research question and sub questions link the measured properties of root permeated soils (i.e. shear strength and root characteristics) to the observed erosion rates of these soils. These relations are not yet fully understood or even derived, as indicated in state of the art and problem description. The answers to these questions could provide the aimed for quantification of the effects of riparian vegetation roots on the erosion reduction of vegetated stream banks.

1.6 REPORT OUTLINE

Chapter 2 starts with describing the research area and continues with describing the used methodology in this research. Firstly the collection of the field data and soil samples for lab research is described. In this chapter also the selection process of species is described. Secondly the laboratory data collection of the shear strength by the Direct shear test, of erosion rate in the Fast Flow Flume and the methodology for measuring root characteristics and soil properties is explained.

Next Chapter 3 depicts and describes the obtained results and answers the sub questions of this research. Firstly the studied species are introduced, and the gathered field data, the measured root characteristics and grains size distributions of the soil are presented. Secondly the gathered shear strength by Shear Vane Test and Direct Shear Test results are shown and their correlation with each other is determined and statistically tested. Also the relation of the shear strength by Direct Shear Test and the measured root characteristics is determined and statistically tested. Thirdly the Flume results are presented. Hereby also the relation of erosion rate with the shear strength by Shear Vane Test and measured root characteristics is shown. The correlations between these root permeated properties and erosion rate is determined and statistically tested.

In chapter 4 the results and their limitations are discussed in the following order: first the measured root characteristics, second the measured shear strength by Shear Vane Test and Direct Shear Test and last the erodibility results. In Chapter 5 the conclusion of this research is given and the answers to the main research questions are provided. Lastly, recommendations for further research in this topic are described in Chapter 6

2. METHODOLOGY

This research is executed in the river Dinkel environment. The location of the research area is depicted in Figure 3. In appendix 7.1.4 the exact sample and measurement locations are depicted. In this research area, in situ measurements were done and samples for lab tests were collected to study the root characteristics, the shear strength and erodibility of vegetated soils on stream banks of the river Dinkel. The shear strength of samples was tested with the in situ Shear Vane Test (SVT) and the lab Direct Shear Test (DST). The erodibility or erosion rate was tested with a flume study at the NIOZ research institute.

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Figure 3 Location and aerial picture of the research area

2.1 FIELD DATA COLLECTION AND SAMPLING

This section starts with a description how the species for this research were selected. Furthermore, it is described how the field data is collected. The collected field data are the aboveground vegetation characteristics, location and shear strength by SVT. After field data collection samples were collected for the two different lab tests: the direct shear test (DST) and the soil erosion studies in the fast flow flume (FFF)of the NIOZ research institute. Therefore it is generally described how these samples were extracted from the field in this section as well. The stepwise procedures for field data collection and sampling are described in appendix section 7.1. In total 9 field visits were conducted. Of these field visits the first three were used to find suitable spot on the river bank, determine and select the species for this research and execute some initializing tests to improve the test set up and sampling method for the different tests. The last six field visits includes the data collection that is presented in this report. During field visit 4-6 the fast flow flume samples were collected and during field visit 7-9 the direct shear test samples were collected.

In this research different measurements and data is gathered of a sample. To be able to link all these measurements and data to their corresponding sample, every sample is labelled with a sample ID code. With this all different data can traced back to one specific sample. In Figure 4 an example of a sample ID code is given. Part A presents the number of the field study that indicates which field visit it is of the nine field visits. Part B presents the location number that is linked to an location at the specific field visit, so samples that have the same middle numbers from the same field study are on the same location. This does not imply that same middle numbers of a different field correspond to same location. Part C indicates which sample it is of the field study, this number is assigned on sampling order. This means that the first sample of the field visit is 01 and the fifth sample 05

$$\underbrace{1}_{A}\ \underbrace{02}_{B}\ \underbrace{03}_{C}$$

Figure 4 example of sample ID code, A) field study number B) location number C) sample number

2.1.1 Selection and determination of herbaceous species

The vegetation for this research is selected on the occurrence of the vegetation specie in the riparian zone of the researched bank by some exploratory field study in the research area. Next to that the species for this selection are based on different above ground appearance, such as length and leaf shape. The leaf shape includes also different leaf sizes. The selection based on these characteristics is meant to include different types of root systems within this research. The selection is based on a visual inspection of the research area. The limitations in testing capacity resulted in three selected species, with a different length and leaf shape. This selection is also limited to species that have sizes (width/radius) that is suitable for the equipment DST (6x6cm see Figure 6) and FFF(see Figure 8).

The specie name is determined by the iNaturalist software. This software can determine the specie name of plants, based on pictures and the corresponding location of these pictures. Therefore, of the selected species pictures were taken to determine the specie names. These pictures are taken of every plant that is sampled for DST and FFF. This means that for every specie 8 pictures are used in the software.

2.1.2 Field data acquisition

For data collection individual vegetation patches were selected based on the size for the DST and FFF, such that these will suit in the equipment well. For every sample the location is recorded by GPS, a picture is taken of the vegetation patch, the minimum and maximum vegetation height of the vegetation patch is measured with measuring rod and soil shear strength is measured by Shear Vane Test. The minimum and maximum vegetation height of each were further analysed on specie level. Hereby the minimum and maximum vegetation height is put in one database that provides the range of the vegetation height

It should be noted that the soil shear strength by SVT is not measured on the sample but around the sample, such that the sample remains undisturbed. For every sample several measurements with the SVT were executed to cover the spatial variability. For the DST only four SVT's were executed. Because the surface of this sample is very small, more measurements do not provide more representative data and the sample will be disturbed too much. The size of FFF samples are larger, in order to cover this spatial variability more measurements are taken dependent on the measured variability.

In Figure 5 the used SVT-testing device is depicted. The test proceeds as follows: the vane (Figure 5 C) is pressed perpendicular into the soil. After initializing the dial (Figure 5 A) the outer ring must be rotated until soil fails. Then the apparatus can be released from the soil and the shear strength can deduced from the shear number depicted on the inner dial(Figure 5 A). More detailed step by step procedure of the field data acquisition can be found in appendix section 7.1.1. The measured shear numbers [kg/cm^2] were converted into shear strength [kN/m^2]. Since the standard Vane was used no additional conversion was needed. The measured shear vane number/shear strengths per sample were averaged to obtain the shear strength of the sample The shear strengths by SVT were further analysed and presented on specie and sample level. However, to indicate the spread along the river Dinkel the raw measurements are depicted in a box plot. Hereby some outliers are defined to give a better understanding of the spread.

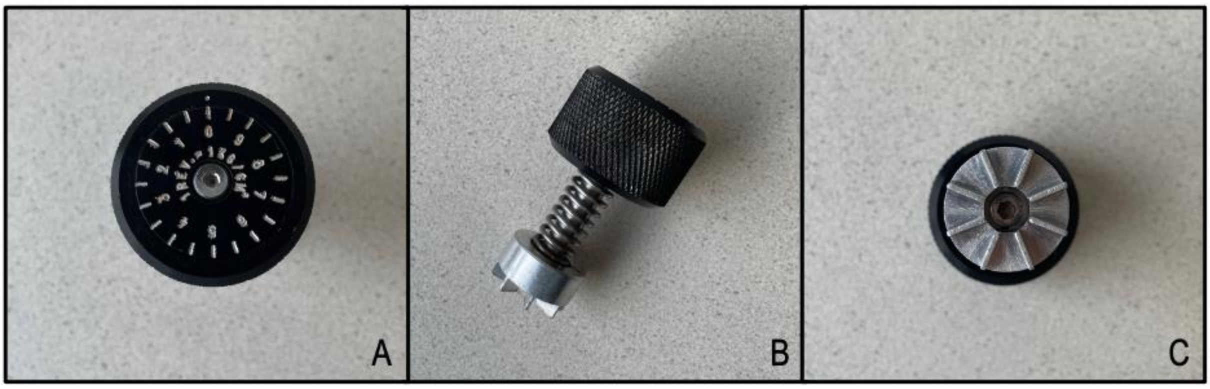

Figure 5 The Shear Vane Test apparatus A) the top view of the dial B) the side view of the apparatus C) the bottom of the vane

2.1.3 Sampling for Direct Shear Test

The samples needed for the Direct Shear Test apparatus have a size of 6.0 x 6.0 x 3.5 cm (length x width x height). Therefore, a custom made sample device is used as depicted in Figure 6. This square sampling device consists of two loose components, the box or core without a bottom where the sample is collected in and a press out plate with a stick in the box. The sampling with this device is done by pressing and drilling the device with the bottom into the soil, cutting the device loose from soil and dig it out while support the sample. More details of these procedure can be found in appendix 7.1.2.

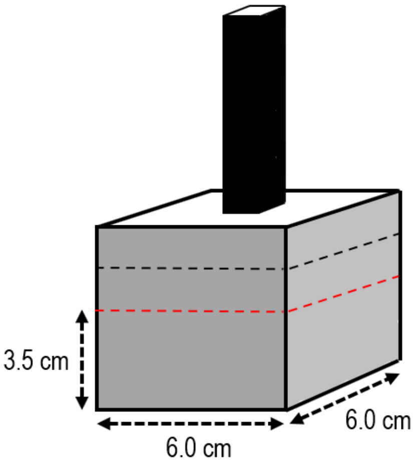

Figure 6 sampling device for Direct Shear Test, black dotted line indicates top and the red dotted the bottom of the pressing plate

2.1.4 Sampling Fast Flow Flume

The dimensions for the FFF samples are 13 x 32 x 12 cm (width x length x height). However, the collected samples are larger namely 40 cm long instead of 32 cm. However, this part of 8 cm long is removed from the sample and used for determination of the root characteristics of the FFF sample. The FFF is designed and constructed for larger and deeper silty and clayey soil samples. Therefore, the sample containers that are placed in the flume were adjusted for this research. On the left side of Figure 8 the original sample container is depicted, which is a box with a bottom plate(brown) two closed sides(white plates) and two open ones. The black cylinders are spikes to prevent that the core as a whole slips through the flume. In the middle and top right of Figure 8 the top view, side view and cross section of the adjusted sample container are depicted. This adjustment is a platform on top of the spikes with and a side wall on top of the platform. This construction provides a smaller container within a container. In Figure 7 displays a picture of the used sampling device to collect soil samples in the field and a picture of the original sample container holder.

Figure 7 Picture of sampling device (left) and original sample container (right)

The sampling for the FFF is done by drilling the sampling device into the soil and dig the sample with sample device out. Then the sampling device was placed on top of the sample container. The 8 cm part was removed from the sampling device and collected in a bag for researching of the root characteristics. The rest of the sample in de sampling device was pushed into the sampling container. A more detailed description of the FFF sampling procedure can be found in appendix 0.

The main reason of this adjustment is to reduce the depth of the sample, because the exploratory field studies revealed that most roots are in the upper layer until around 12 cm deep. Also, the soil changes abruptly around that point from more clayey sand with high organic content, to white sand with low organic content. For this research the top soil is more relevant, therefore this depth of 12 cm sampling is used. In addition, the bank is less disturbed by less deep sampling, which is better for restoration after sampling. The side wall on the adjusted platform is constructed to prevent that the sample as whole slips from the container out of the flume during the flume experiments. It also prevents damage/disturbance during transport. As can be observed in the top right of Figure 8 this wall is 3 cm lower than the sample height. This is done to allow erosion in the flume of the top layer only. The side wall also prevents micro instability, drainage and piping processes during the flume experiments, because the water can only flow over the sample due to the wall and the wall functions as a earth retaining wall, see Figure 8. This set up creates a situation where only hydraulic scour takes place, which excludes cliff erosion. This simulates the situation of a sample on the river Dinkel streambank better, where sample is part of large soil mass.

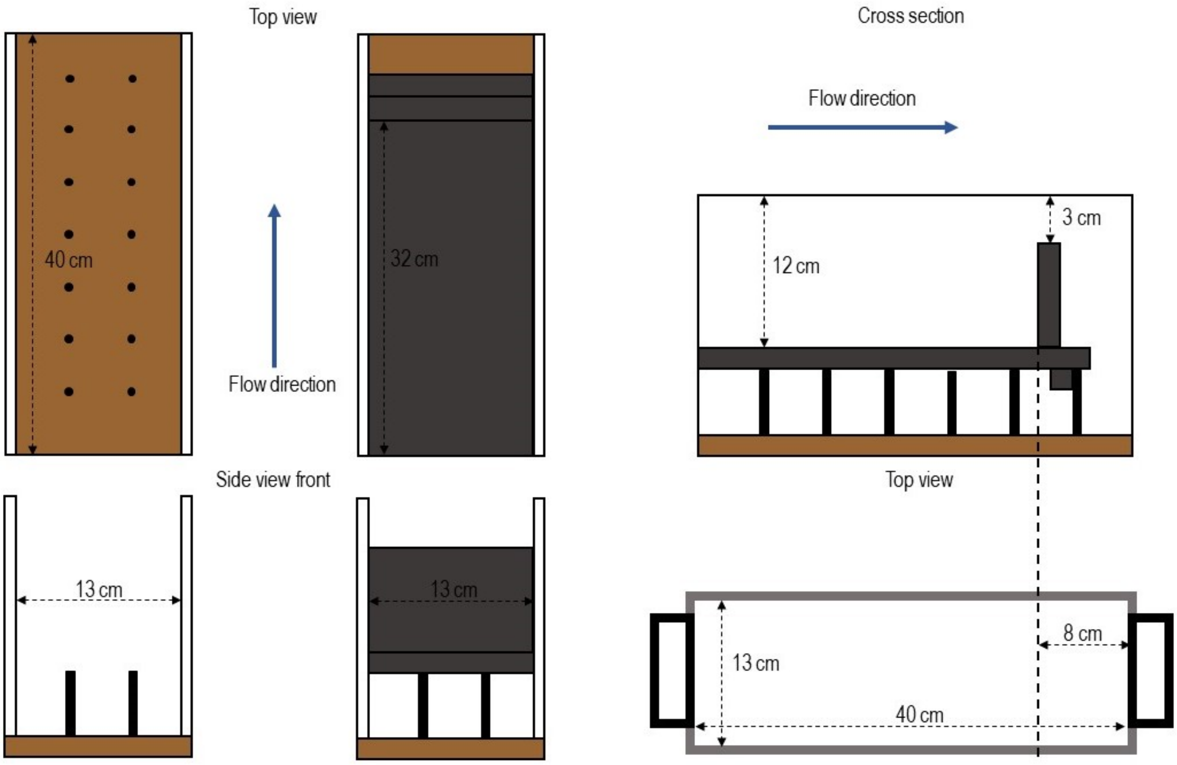

Figure 8 Dimensions and set up of the sample container (left and top right) and sampling device (bottom right) for Fast Flow Flume. Dashed line (right pictures) indicates the position of the side wall relative to dimensions of the sampling device, in order to indicate which part of the sample is transferred into the sample container for FFF studies (left of this line) and which part is used for determination of the root characteristics (right of this line)

2.2 LAB DATA COLLECTION

This chapter describes how the DST and FFF experiments were executed and how the data from these experiments is recorded. Also this chapter explains how the root characteristics of the collected samples are measured. In the end of this chapter the soil analysis of the river Dinkel stream bank are explained.

2.2.1 Direct Shear Test

In Figure 9 the set-up of the Direct Shear Test is depicted in a cross section of the apparatus. The direct shear test is a commonly used test to assess the shear strength of soils. It is also considered as one of the most simple ones. In addition, by using the Mohr-Coulomb criterium, the friction angle and the cohesion of the soil sample can be derived with this test. The test can be used for undisturbed and disturbed soil samples(Suits et al., 2008). On top of that the test can be used for vegetated or root permeated soils as well(Pallewattha et al., 2019; Wu, 2013).

The test proceeds as follows: The sample in the so called shear box is subjected to a constant vertical load on the brass retaining plate see Figure 9. On the lower half of the shear box an increasing horizontal force is applied to maintain a constant shearing rate(a constant horizontal displacement over time of the lower shear box). During the test the horizontal displacement, the vertical displacement and applied force are recorded with constant logging rate. The tests starts with zero horizontal force, which increases over time to maintain the shearing rate until the soil fails. The sample fails when the force drops to maintain the shearing rate. This stage indicates the end of the test. In Figure 10 the theoretical horizontal displacement-force curve of the direct shear test is depicted. Herein the maximum force can be easily observed and the curve clearly shows the drop in force and failure of the soil. The maximum measured force determines the shear strength of the soil. In this research this force is divided by the original cross sectional area of the shear box to obtain the shear strength. The obtained results per sample are used to find relations between the different properties of root permeated soils and the data is summarized on specie level to observe differences between these species.

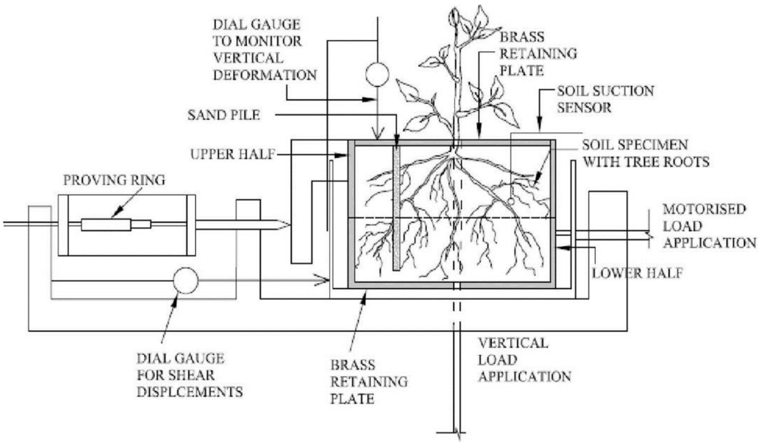

Figure 9 Schematized cross-section of Direct Shear Test apparatus with root permeated sample (Pallewattha et al., 2019)

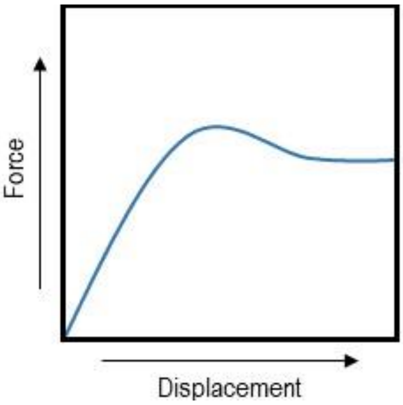

Figure 10 Conceptual figure of theoretical force displacement curve

Before the samples were placed into the apparatus, the samples were transferred from the sample device into the shear box of the apparatus. This was done by placing the sampling device in the position of Figure 6 on top of the shear box and then pushing the black stick down, such that the plate within the device pushes the sample into the shear box. When the sample was out the sample device and in the shear box, the sample was further pushed into the shear box with the lid of the shear box. After the placing the sample in the shear box, the sample in the open shear box was wetted with water until the sample was fully saturated. This is done to test the samples in the same state, which also represents field conditions during high flow. In addition, it makes comparison better, because it limits the effects of different soil moisture content. Since the samples were collected over several days the moisture content might vary a lot. The location might have also an effect on this, for example due to better drainage on top of the bank.

After placing the prepared shear box with sample in the DST apparatus and aligning the dial gauges for horizontal and vertical displacement, every sample was consolidated until the vertical displacement did not change within 10 seconds. The applied vertical load for every sample was the empty weight of the hanger, which is 5.03 kg and applies a load of 13.7 kN/m^2 on the sample. The used shearing rate for all samples was 0.5mm/minute and the logging rate for all samples was 0.01 mm.

2.2.2 Fast Flow Flume

For the flume experiments the Fast Flow Flume of the NIOZ research institute is used, depicted in Figure 11 C. In this flume the samples can be exposed to a water flow over the soil sample's surface and the alteration in sample height can be measured to determine the erosion of the sample. The flume functions as follows: water is pumped from the basin into the tank at a constant rate, from the tank the water flows tthrough a regulated opening into the flume as depicted in Figure 11 B. The size of this opening and the water level in the tank after initializing determines the flow velocity over the sample. In this research the flow velocity aimed for was1 m/s, which required an opening height of 8 cm and resulted in a tank water height of 8.5 cm.

The flume is designed to test 4 samples simultaneously. However only two samples were tested simultaneously per flume as shown in Figure 11 D, because of the limited amount of samples and for time efficiency. The time efficiency is increased by measuring less samples at once but. During measuring the flow is stopped, which delays the exposure to the flow. Therefore multiple separate operating flume devices are used with two samples in each, to minimise these flow pauses for the samples such that more samples can be tested within a day. In order to reduce the boundary effects on the sample, an extra plate is mounted on the flume to align the sample better with the flume see Figure 11 E.

The soil sample surface height is measured with the set up in Figure 11 A. The height of the sample is measured from a steady reference level and the height is always measured on the exact same location. With this set up, 10 height measurements were done on one-third of the width from both sides of the sample, so 20 measurements in total per sample for each time step. The sample height is measured before the sample was exposed to water flow and after 10, 30, 90, 150 and 210 minutes of exposure to water flow. The erosion on a timestep is calculated by subtracting the measured height at a time step with the height of the previous one. For the first time step (10 minutes) the base measurement of time 0 was used as previous time step. The erosion rate on each time step is calculated by the erosion on the time step divided by the time between the time step and the previous one. Note that these timesteps were not consistent.

Figure 11 Fast Flow Flume of the NIOZ research institute: A) the height measuring set-up B) the flow regulating plate C) the operating Flume D) two samples placed in the flume E) the boundary reducing alignment plate

2.2.3 Root characteristics

From each of the samples used in the DST and FFF the root characteristics were determined. Before the root characteristics of the samples could be determined the roots were washed out from the soil with water. The root characteristics measured in this research are: the wet weight of the root system, the dry weight of the root system, the root diameter and number of roots. The root diameter and number of roots were determined by the main roots, which were determined as the roots directly connected to the main stem(s) of the plant and larger than 0.5 mm in diameter. Using only the decisive roots instead of all roots on the sample is done to limit the work. Because, it should be noted that measuring all small fibrous roots of herbaceous species is nearly impossible to execute by hand at all. In addition, it makes sense to measure only these decisive roots, because these roots contribute the most to the strength of the soil due to their large contribution to the root area ratio (Simon & Collison, 2002) or root mass density (Zi et al., 2023) compared to very small roots. Moreover the size of these decisive roots is often a measure for the size of the root network and the amount of the small fibrous roots. However, this relation varies per species and depends on the root system architecture (Ghestem et al., 2014).

In Table 2 an overview is given of the root characteristics, their definition, their measuring method and their measuring unit for this research. For analysis, comparison and interpretation of the results the wet weight and dry weight of the root system are standardized as the weight per 5^3 cm^3 volume(g/cm^3), because of the different sizes of the DST and FFF samples. The reason for choosing a cube with dimensions of 5 cm is to display realistic values for the root density. Values expressed in g/cm^3 or g/m^3 would not represent the great spatial variability of the root density observed along the Dinkel.

Table 2 The definition, measuring method and unit of the researched root characteristics

Characteristic of the sample	**Definition**	**Measuring method**	**Unit**
Root diameter	The average root diameter of the decisive roots	Measuring the thickness of the decisive wet roots as close as possible by the main stem of the sample with a calliper	mm
# of roots	The number of measured decisive roots	Counting the number of measurements of the main root diameters per sample	-
Wet weight of the root system	Weight of the cleaned root system before drying	Weighing the cleaned root system on a scale	g
Dry weight of the root system	Weight of the root system without soil after drying	Weighing the cleaned root system on a scale after drying in the oven for 45 minutes at 60 degrees Celsius	g

2.2.4 Soil analysis

The soil composition of the river Dinkel bank is analysed to provide context for the shear strength and erodibility results. Also a large variation in soil composition along the Dinkel influences the individual results of the shear strength and erodibility strongly. Therefore, a sieve analysis is executed to determine the grain size distribution of the samples along the stream bank. With these grain size distributions the soil composition of the Dinkel bank and variation over the Dinkel bank can be observed. These results will provide context for interpretation of the shear strength and erodibility tests. Moreover the grain size distributions can be used to classify the soil, which already provides a rough indication of the shear strength and erodibility range.

The used samples for this sieve analysis are the sample parts for determination of the root characteristics for the flume samples gathered during field study 6. Therefore, the sample locations of this data correspond with the sample locations of field study 6. These samples were taken at various locations in the research area along the stream bank and across the stream bank visible in Figure 28 in the appendix 7.1.4. These samples did not contain much vegetation and are therefore suitable for this purpose. However these soil samples still contained a lot of organic matter, especially in the top layer of the samples. Therefore, the soil was roughly sieved (sieve size 6) and the large compounds of organic matter were removed. After that the soil was dried at 80 degrees Celsius for one hour. Normally 100 degrees is advised for drying a sandy soil, but due to the small clay content and presence of organic matter a lower temperature is used to prevent the baking of clay and the burning of organic matter. Since the soil grains were clustered in coarse particles, the dried soil was gently crushed into loose grains. These loosened grains were tested in the sieve apparatus with the sieve sizes mentioned in Table 3. The measurements of the soil analysis are consisted out of empty and full weight of the sieves, from which an grain size distribution is derived based on the mass.

Table 3 Sieve sizes from large to small

Nr	Sieve size [mm]
1	4
2	2
3	1,4
4	1
5	0,85
6	0,5
7	0,3
8	0,25
9	0,125
10	0,09
11	0,063
12	0

3. RESULTS

3.1 HERBACEAOUS SPECIES AND ROOT PERMEATED SOIL PROPERTIES ON THE RIVER DINKEL BANK

This section answers the first research question “What variation in the root characteristics of herbaceous vegetation covers can be observed along the Dinkel stream bank?” and corresponding sub questions. This chapter describes the three species that were included in this research, depicted in Figure 12. Furthermore, the root characteristics and aboveground characteristics of these species are discussed. Finally, the soil properties of the river Dinkel stream bank are discussed.

Figure 12 The studied plant species (A) Leersia oryzoides (B) Rumex obtusifolius (C) Digitaria sanguinalis

3.1.1 Herbaceous species on the river Dinkel stream bank

In this research three species were included, see Figure 12. These species were very common in the research area, based on the visual inspection. Next these three species differ a lot in leaf shape as well as in height. The species name and type are derived with the iNaturalist software. The three species Latin names are the *Leersia oryzoides, Rumex obtusifolius* and *Digitaria sanguinalis*.In Table 4 the corresponding Dutch & English names, family and genus are depicted. However, it should be mentioned, that these plants might be a different species than derived. Based on the collected pictures of the field studies there is high confidence that these species correspond to the derived family and genus. However, there is some uncertainty about the precise species, because there are more species that look very similar and may be present in the research area according to the software. The quality of the picture partly determines the confidence. The pictures of the field studies contain a lot of background, which makes it more difficult for the software and increases the suggestions for the plant species. Therefore, multiple pictures are used to decrease the uncertainty. For every species 8 pictures are used equal to the amount of samples taken for the species

Table 4 Latin name, English name, Dutch Name, family and genus of the researched plant species as shown in Figure 12

Species A	Species B	Species C
Leersia oryzoides	*Rumex obtusifolius*	*Digitaria sanguinalis*
Cut-grass	Broad-leaved Dock	Crab-grass / Hairy Finger-grass
Rijstgras	Ridder zuring	Harig vingergras
Poaceae	*Polygonaceae*	*Poaceae*
Leersia	*Rumex*	*Digitaria*

In this research the measured above ground characteristics are the minimum and maximum vegetation height of each sample. These measurements were done to have some insight in the size of the plants in relation to their root network.. Figure 13 shows that the *Leersia oryzoides* in general has the largest height with a median of 60 cm compared to a median of 15 cm and 21 of the *Rumex obtusifolius* and *Digitaria Sanguinalis* respectively. The *Leersia oryzoides* also shows the largest variation in height with a height range between 19 and 135cm. For the *Digitaria sanguinalis* the height and variation in height is smaller (ranging between 6 and 50 cm). The *Rumex obtusifolius* is not only the smallest species, but also has the smallest variation in height with a range between 10 and 30 cm .

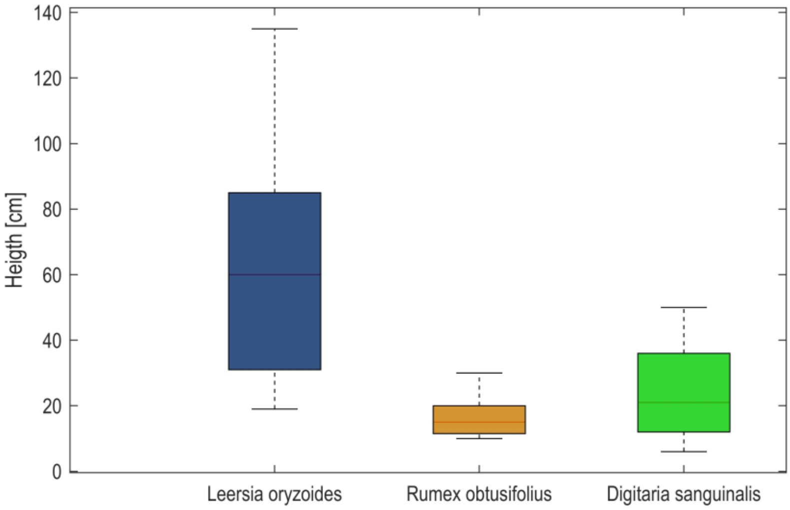

Figure 13 Boxplot of the measured the maximum and minimum vegetation height of the studied species

3.1.2 Root characteristics

The measured root characteristics are wet weight, dry weight and the root diameter, depicted in Figure 14. The data of the wet weigh an dry weight is plotted per sample type, because these data is strongly influenced by sample size of these different samples. This effect of different sample sizes is further elaborated in the discussion in section 4.1.2. The FFF weight results show lower weight results per volume than DST weight results. Taking this into account, large different trends can be still observed between the boxplots of the FFF (Figure 14 A&C) and the DST (Figure 14 B&D).

These different trends can be clarified by the fact that the position of the sampling device during sampling determines how much vegetation of the patch was subjected to the flume and how much was researched for root characteristics, especially this was a large issue for coarse or less dense vegetation patches. For the DST samples this was not a large, because these samples were much smaller and sampled around the main stem. Therefore the measurements of the DST are more consistent and better for comparison on a species level. Moreover the FFF vegetated samples contain some data gaps due to this problem, where the vegetated part was subjected to the flume and the non-vegetated part was researched for root characteristics.

Since the root diameters are only measured for the decisive roots around the main stem(s), the effect of different sample sizes for the DST and flume has very limited influence for this root characteristic. The measured root diameters of the FFF samples and DST samples were of the same order. Therefore the data of both sample types are summarized in Figure 14. Herein it can be observed that the variation in root diameter is smallest for the *Leersia oryzoides* and largest for the *Rumex obtusifolius*.

The number of roots measured per sample can be found in appendix 7.2, the amount of measured roots per sample differs between 1 and 20 roots. In general the amount of measured roots of the *Leersia oryzoides* (average of 11 roots measured per sample) is little bit more than the *Rumex obtusifolius* (average of 6 roots measured per sample) and the *Digitaria sanguinalis* (average of 5.75 roots measured per sample). However this does not imply that the *Leersia oryzoides* has more roots than the other species, because these roots are the decisive roots. From field study observations it can be said that the *Digitaria sanguinalis* samples had more roots in total than the *Leersia oryzoides* samples, but this is not quantified by this research. In general, more roots were measured for the FFF samples than for the DST samples. The average measured roots per type sample are 10 and 6 roots respectively. In these statistics the data gaps of the samples where the root characteristics could not be determined were neglected.

From field observations it can be said that the vegetation density of the *Leersia oryzoides* over space was more constant and dense than the other species. This observation can also be seen in the weight of the root system data of the DST samples, the variation of the *Leersia oryzoides* is quite small with a range of 1.1-4.5 g 5^3 cm^3 and 0.5-1.3 g 5^3 cm^3 for wet and dry weight respectively compared to measured range of dry and wet weigh of the other species. For the *Rumex obtusifolius* the measured range of the wet and dry and constant was 2.6-16 and 1.5-13 g 5^3 cm^3, and for the *Digitaria sanguinalis* these ranges are 1.6-19 and 0.4-12 g 5^3 cm^3 respectively.

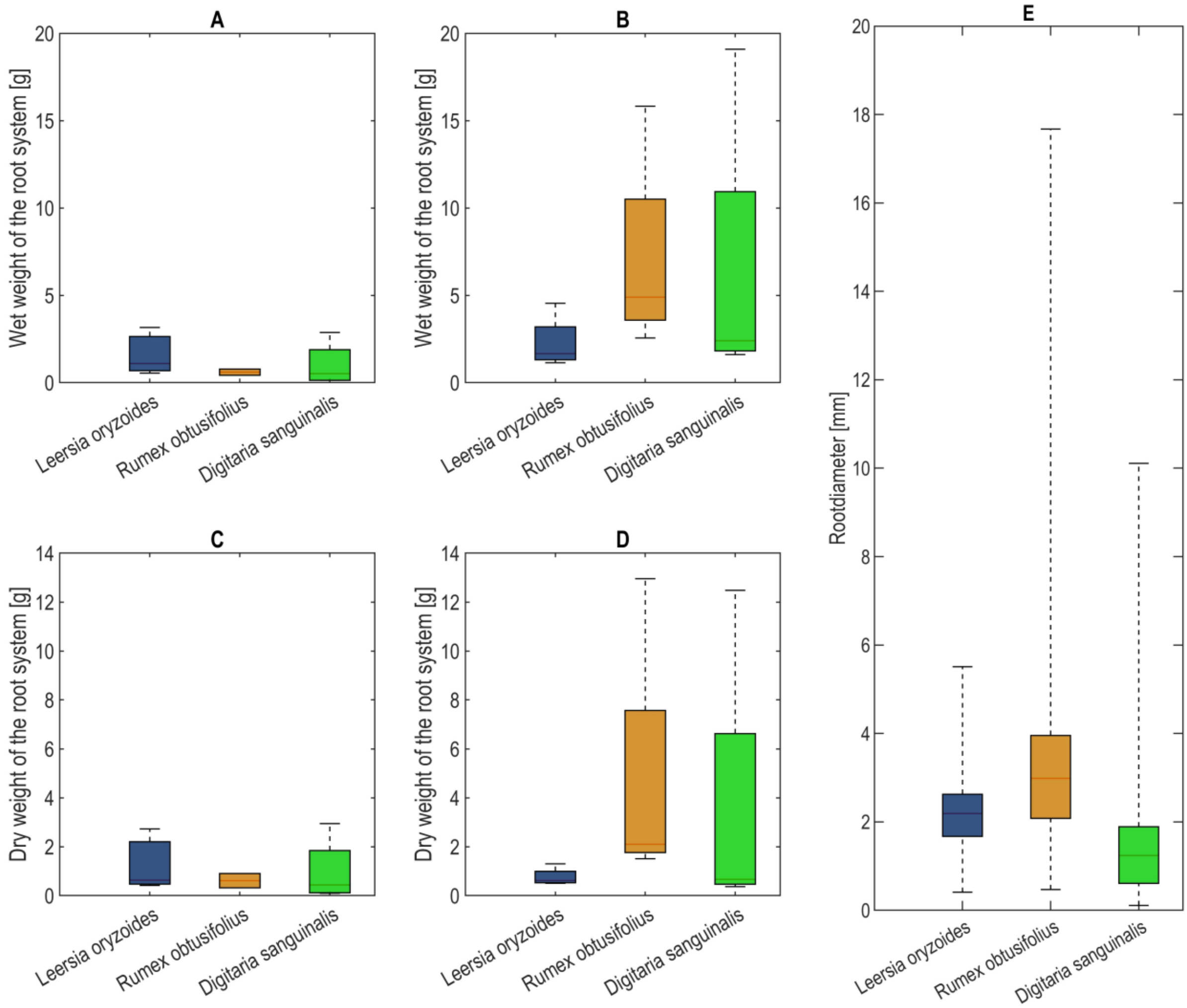

Figure 14 Variation in root characteristics per species (A) Wet weight of the root system of the Fast Flow Flume samples per 5^3 cm^3 (B) Wet weight of the root system of the Direct shear test samples per 5^3 cm^3 (C) Dry weight of the root system of the Fast Flow Flume samples per 5^3 cm^3 (D) Dry weight of the root system of the Direct shear test samples per 5^3 cm^3 (E) Root diameter of all samples

3.1.3 Soil properties

In Figure 15 the grain size distributions of the sieve analysis is depicted. From these grainsize distributions the percentage of mass passing a sieve per diameter can be observed. In general the different samples show similar grain size distributions. However the lower curves of sample 60505 and 60606 indicate that these samples had slightly larger fractions of larger sand particles. These samples were taken on the top of the bank, which indicates that on top of the bank the soil contains slightly more larger sand particles than on the lower bank.

In Table 5 the range of diameter (D) for the percentage passing(denoted in subscript) of these grainsize distributions for several percentages is depicted, derived from the grain size distributions in Figure 15. These values indicate the diameter (range) for which percentage is smaller than this value and are called the percentage values. These values were used to determine the soil classification according the USCS soil classification system, displayed in Table 11 in appendix 7.2. According the USCS soil classification in Table 11 in appendix 7.2 the soil can be classified as clean sand, which means that these samples did not have significant portion of clay and silt particles and did not contain coarse gravel particles. The sand can also be further classified as fine sand (diameter of 0.075-0.42mm) according Table 12 in appendix 7.2, because the largest portion of the soil has diameter in this range. However still a portion around 15% of the soil samples is classified as coarse sand according this table.

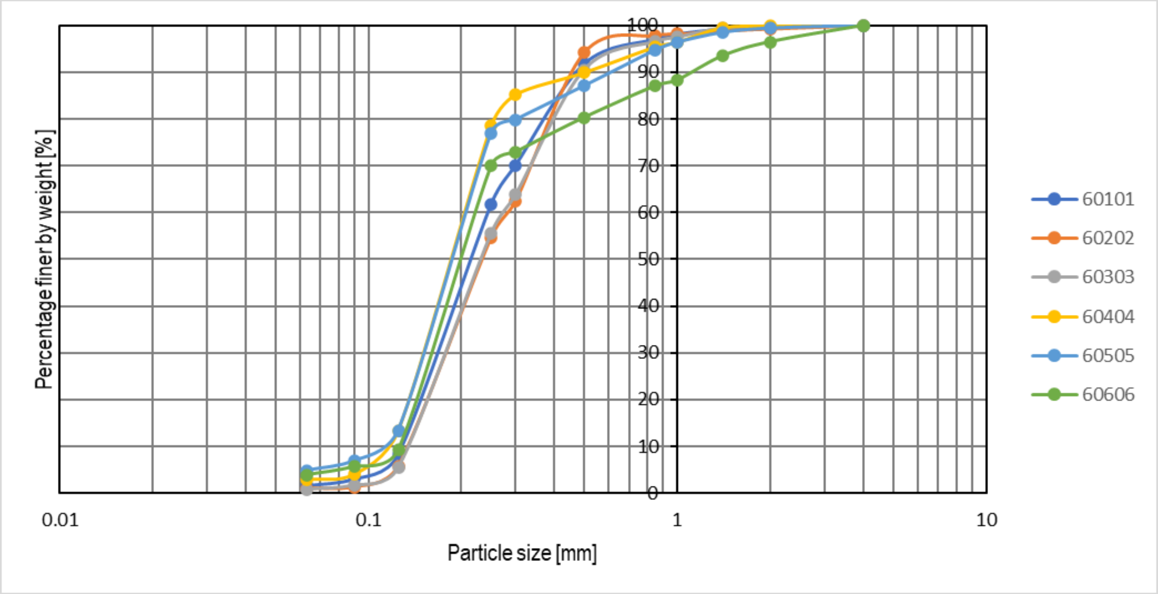

Figure 15 Grain size distributions of the Dinkel river bank (numbers correspond to sample ID)

Table 5 Percentile value range of the grain size distributions in Figure 15: Numbers in the subscript of diameter symbol (D) indicate the percentage of mass fraction

Diameter of percentage passing	Range [mm]
D_{90}	0.450-1.15
D_{50}	0.185-0.230
D_{12}	0.123-0.140

3.2 SHEAR STRENGTH OF THE ROOT PERMEATED SOILS ON THE RIVER DINKEL BANK

This section answers the following research question: What is the shear strength of herbaceous root permeated soils with different root characteristics along the Dinkel stream bank and how is this related to the measured root characteristics? The section starts with displaying the shear strength measurements by Shear Vane Test and by Direct Shear Test per species. This answers first sub questions What is the shear strength measured by field/lab tests with Shear Vane Test/Direct Shear Test? Then the correlation between these tests is determined to find an answer on the question: To what extent do the results obtained from lab and field tests agree? Moreover in this section the relations between the root characteristics and shear strength are discussed. This answers the last sub question of this research question: Which correlations exist between the measured root characteristics and the measured shear strengths?

3.2.1 Shear strength by Shear Vane Test

As can be observed in Figure 16 the median value for every species is very close to each other as well as the variation in measured shear strength by Shear Vane Test. Most values are between the 1 and 10 kN/m^2 and the median for all species is between 4 and 5 kN/m^2. This data provides a good indication of the surface shear strength of the stream bank in the research area, due to the large number of measurements and the number of different locations. Moreover Figure 15 depicts the raw measurements large values are not averaged out, which shows the true measured variation in surface shear strength on the stream bank. Although in Figure 16 some values are marked as outliers, in further data analysis these values are included in the averaged shear strength by Shear Vane Test per sample.

For the results in Table 6 the shear strength is averaged per sample. Herein the measured variation is less visible. The average shear strength of the species varied between 3.4 and 5.4 4 kN/m^2 with standard deviation ranging from 1.7 up to 2.7 kN/m^2. Moreover in Table 6 it is indicated that the average shear strength of the DST samples is smaller than the FFF samples in the measured shear strength of the FFF samples and the DST samples. This difference is the largest for the *Digitaria sanguinalis*, for which the average of the DST samples was 3.2 kN/m^2 lower than the average of FFF samples. Comparing all data for the different species it can be concluded that the shear strength by SVT does not show major differences between these species, except for the *Digitaria sanguinalis*. This is mainly due to the much lower shear strength of the DST samples, because the FFF samples show agreement with the other species with an average of 5.0 kN/m^2 and standard deviation of 0.6 kN/m^2.

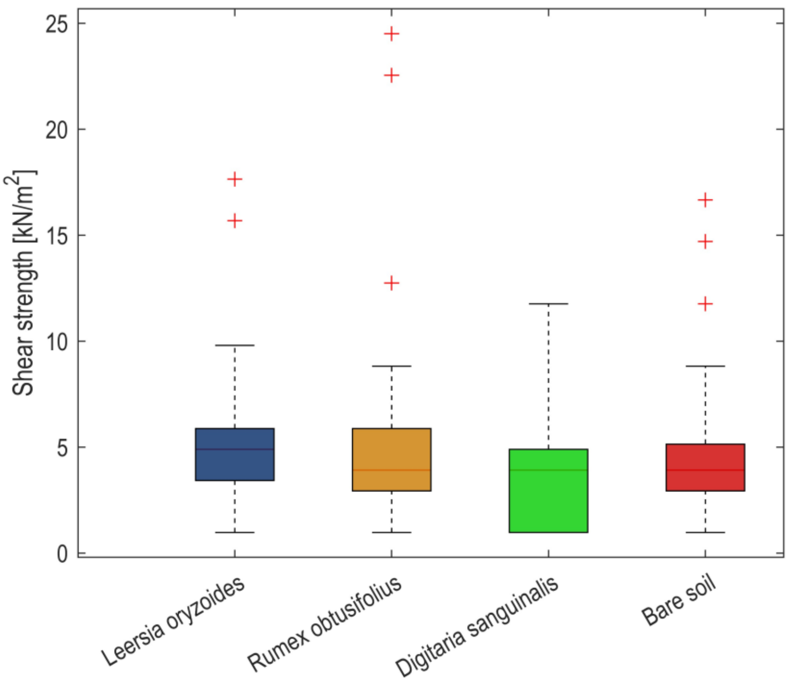

Figure 16 Box plots with Measured shear strengths by Shear Vane Test per species and indicated outliers(These values are defined as outlier when their value is two times the inter quartile range larger than the third quartile)

Table 6 Shear strength in kN/m^2 by Shear Vane Test (Mean(M) and Standard deviation (SD) per species, per sample type and for all data combined

Species:	***Leersia oryzoides***		***Rumex obtusifolius***		***Digitaria sanguinalis***		***Bare soil***	
	M	SD	M	SD	M	SD	M	SD
FFF	6.6	1.8	5.4	3.4	5.0	0.6	5.5	2.5
DST	4.2	2.0	4.5	1.8	1.8	0.6	3.7	0.9
All data	5.4	2.2	5.0	2.7	3.4	1.7	4.6	2.1

3.2.2 Shear strength by Direct Shear Test

As described in the methodology in section 2.2.1, the DST apparatus records the applied force and horizontal displacement of the sample to determine the maximum shear strength. These results are depicted in Figure 17, herein the maximum applied force on the sample is highlighted. Most maximum forces occurred at large displacements close to or at the limit of the device, which is around 5.6 mm. For the bare soil tests this occurred the least. Of the four tests this occurred one time. For the *Leersia oryzoides*, *Rumex Obtusifolius* and *Digitaria Sanguinalis* the maximum force was measured close to or at the limit: 3 out of 4, 3 out of 4 and 4 out of 4 tests respectively. This maximum applied force is used to determine the shear strength of the soil by dividing this force by the original cross-sectional area of the shear box. The maximum force and corresponding shear strength values per sample is presented in appendix 7.2.

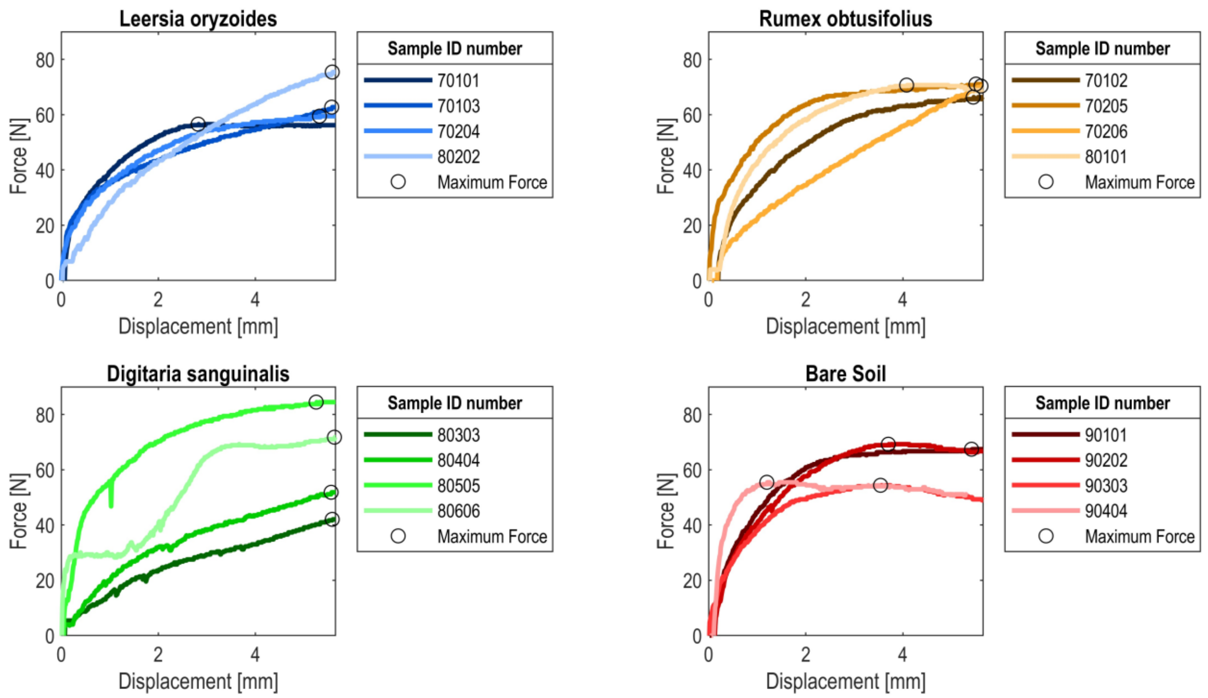

Figure 17 Force-displacement diagrams of the Direct Shear Test: each line represents an individual sample; circles indicate the maximum shear force at which the maximum displacement is observed.

The summarizing statistics of the shear strength per species are presented in Table 7. The shear strength of the different species and bare soil is quite close to each other, with average shear strength per species varying between 17.12 and 19.34 kN/m^2. The *Rumex obtusifolius* has a relatively higher average (19.34 kN/m^2) than the average of other species and bare soil (17.12-17.65 kN/m^2), but this average is not significant larger than the other species and bare soil according to a one tail two sample t-tests with 5% significance level and. Moreover the shear strength by DST of root permeated soils of the different species is not significant larger according to the one tail two sample t-tests with 5% significance level as well.

The variation in shear strength by DST is remarkably larger for the *Digitaria sanguinalis* than for the other species. This is also clearly visible in Figure 17. It can hardly be explained by the variation in root characteristics (Figure 14) or shear vane results (Figure 16), because similar large variations in these results are present by the *Rumex obtusifolius*, which shows less variation in shear strength.

Table 7 Summarizing results of the shear strength by Direct Shear Test

Species	Leersia oryzoides	Rumex obtusifolius	Digitaria sanguinalis	Bare soil
Average shear strength [kN/m^2]	17.65	19.34	17.37	17.12
standard deviation [kN/m^2]	2.00	0.53	4.61	1.87
Minimum [kN/m^2]	15.71	18.43	11.68	15.11
Maximum [kN/m^2]	20.95	19.74	23.47	19.24

3.2.3 Correlation between Shear Vane Test and Direct Shear Test

In general, the shear strength by SVT is substantially lower than the shear strength by DST. The SVT and DST test a different shear strength. SVT measures the shear strength at the surface and DST measures the shear strength at a shear plane around 1.5 cm below the surface level with an additional normal load. The shear plane in the DST plane is stronger due to the presence of more and thicker roots, but also due to the applied load which increases the shear strength according the Mohr-Coulomb criteria. Since the DST measures the shear strength in a more rooted plane than the SVT, the result of this test is probably more affected by the roots. Therefore this test is more favourable for determining the effect of roots on shear strength.

However this systematic lower shear strength by SVT might still be useful to provide a simple estimate of the shear strength of DST based on in-situ measurements with the shear vane test, when there is astrong relationship between those shear strengths. Figure 18 displays the scatterplot of results of both tests. Herein it can be observed that shear strength by SVT does not show a strong correlation with the DST. The Pearson correlation coefficient for this dataset is 0.0755. This value suggests a very small positive linear correlation between the results of both tests. However, this value is statistically not significant according a two tailed student test with significance level of 5%: t(14)=0.28. For this Pearson correlation it was tested whether the DST and SVT data is normally distributed by a One-sample Kolmogorov-Smirnov test, which is the case for both tests with a 5% significance level. The DST results are normally distributed with a mean of 17.87 and a standard deviation of 2.92. The SVT results are normally distributed with a mean of 3.6 and a standard deviation of 1.8. Based on the data in Figure 18 a linear regression model is constructed (y=17.4+0.12x), with a very low coefficient of determination (R^2) of 0.0057. This low value could be expected due to the poor correlation.

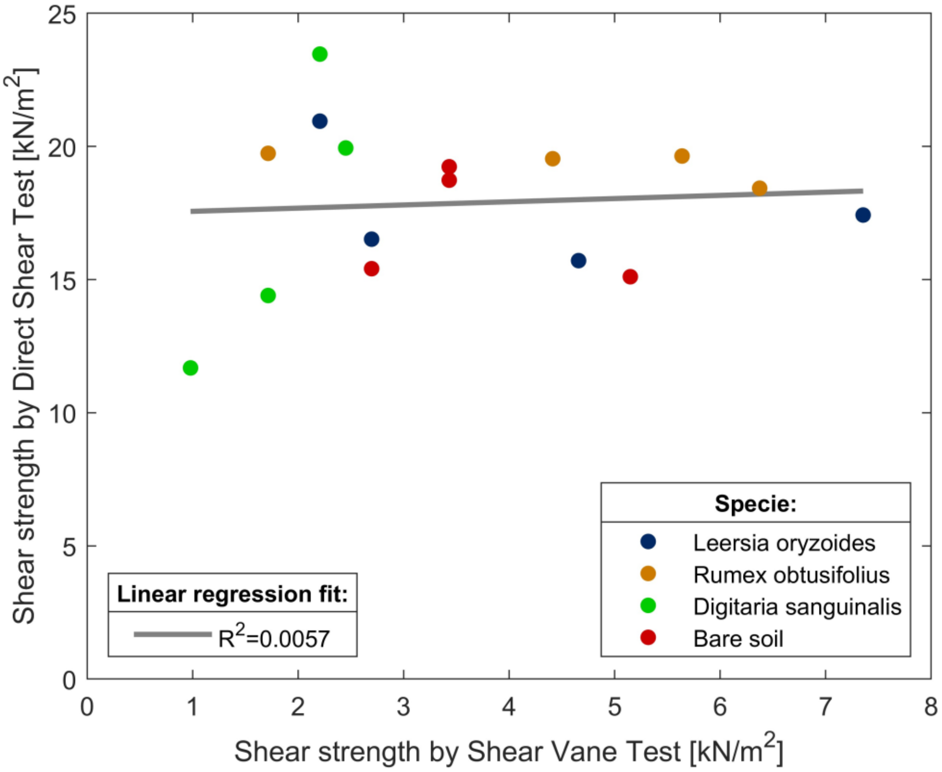

Figure 18 Scatterplot of the Shear strength by Direct shear test versus the shear strength measured by the Shear Vane Test

3.2.4 The influence of the root system mass on shear strength

In order to observe the relation between the root system weight and the shear strength the scatter plots depicted in Figure 19 were created. Herein it can be observed there are two large root system weights measured compared to the other data. To find the optimal fit for a relation between shear strength and root weight, these weights are included and excluded for testing the different models. These two large root weights do not show a larger shear strength compared to the other data points. There might be different explanations for this: these samples were disturbed a lot before the DST, these values are just outliers not representative for dense rooted samples, or there is decreasing/stabilizing trend in shear strength for more dense root permeated soils. This stabilizing/decreasing trend can be clarified by the increased porosity of highly dense rooted samples, which have larger weights. At a certain point the positive stabilizing effects of roots might be reduced or surpassed by the destabilizing effects by increased porosity (Löbmann et al., 2020).

Since a non-linear trend is expected a spearman correlation coefficient is calculated of the wet weight and dry weight data with the shear strength obtained with the DST in order to estimate the measure of correlation of these data. The wet weight data had a spearman correlation of 0.2933 and the dry weight data has a value of 0.3082 with the DST shear strength. These values suggest a weak positive correlation between the increase in root system mass and shear strength. However, both correlations are not significant to sustain this according to a two tailed t-test with %5 significance level: t(14)=1.14 & t(14)=1.21. This weak relation between shear strength and weight of the root system does not imply that weight of the root system cannot be a good predictor of the shear strength. Therefore a second order polynomial is fitted for the shear strength by the DST with both the wet weight and dry weight ($Y=-0.0726x^2+1.2138x+16.3437$ and $Y=-0.1208x^2+1.4220x+17.2386$ respectively, Figure 19). These polynomials were tested with an R^2 to estimate whether the relation predicts the data correctly. The performance of the fitted relations of the DST shear strength with the wet weight had an R^2-value of 0.4431 and the dry weight an R^2-value of 0.3082. This shows that both relations have a poor fit, but also shows that the shear strength can be better predicted with the wet weight of the root system than the dry weight of the root system.

The two isolated data points with large weight affect the shape of the polynomial considerably. For this data without the outliers (root weight < 6 g only) an increasing linear trend can be observed and a stabilizing second order trend for both the wet data and dry data. It should be noted that the shear strength data with and without outliers is normally distributed. The same applies for the wet and dry weight according to the executed One-sample Kolmogorov-Smirnov test for this data. The used data is all normally distributed and this justifies the use of a Pearson correlation coefficient. For the wet and dry weight data the Pearson correlation coefficients are 0.4932 and 0.4127 respectively.These Pearson correlation values of this data show for the wet weight as well as for the dry weight no significant correlation according to a two tailed t-test with 5% significance level: t(12)=1.96 and t(12)=1.56 respectively.

Also Spearman correlation coefficient is calculated to estimate the correlation for a non-linear correlation. The Spearman correlation coefficient for the shear strength by DST with the wet weight of the root system is 0.5623 and with the dry weight of the root system 0.5445. These values show significant a stronger positive correlation than the Pearson values, according to a two tailed t- test with 5% significance level(wet weight data: t(12)=2.17 and dry weight data t(12)=2.25). This might imply that the shear strength by DST is not linearly correlated for the wet weight as well as for the dry weight.

In order to research whether this data set with only weights less than 6 g can predict the shear strength more accurate, more relations were fitted on this smaller dataset. Firstly two linear trends were tested (Y=0.7086x+16.7889 and Y=1.4365x+17.1229 see Figure 18) for the root systems with a wet and dry weight lower than 6 g. The coefficients of determination R^2 of these relations were 0.2433 and 0.1703 for the wet weight and dry weigh data respectively. The coefficients of determination show poor prediction of the data by the linear relations. Secondly two second order polynomial were tested for the wet data and dry data without outliers, which had the form of Y=-0.1050x2+1.2168x+16.5050 and Y=-1.4255x^2+4.3455x+16.4656 respectively(Figure 18). The R^2-value of these relationships was 0.2566 and 0.2380 respectively, which is a poor performance of both polynomials to estimate the data. Furthermore all results are summarized in Table 8.

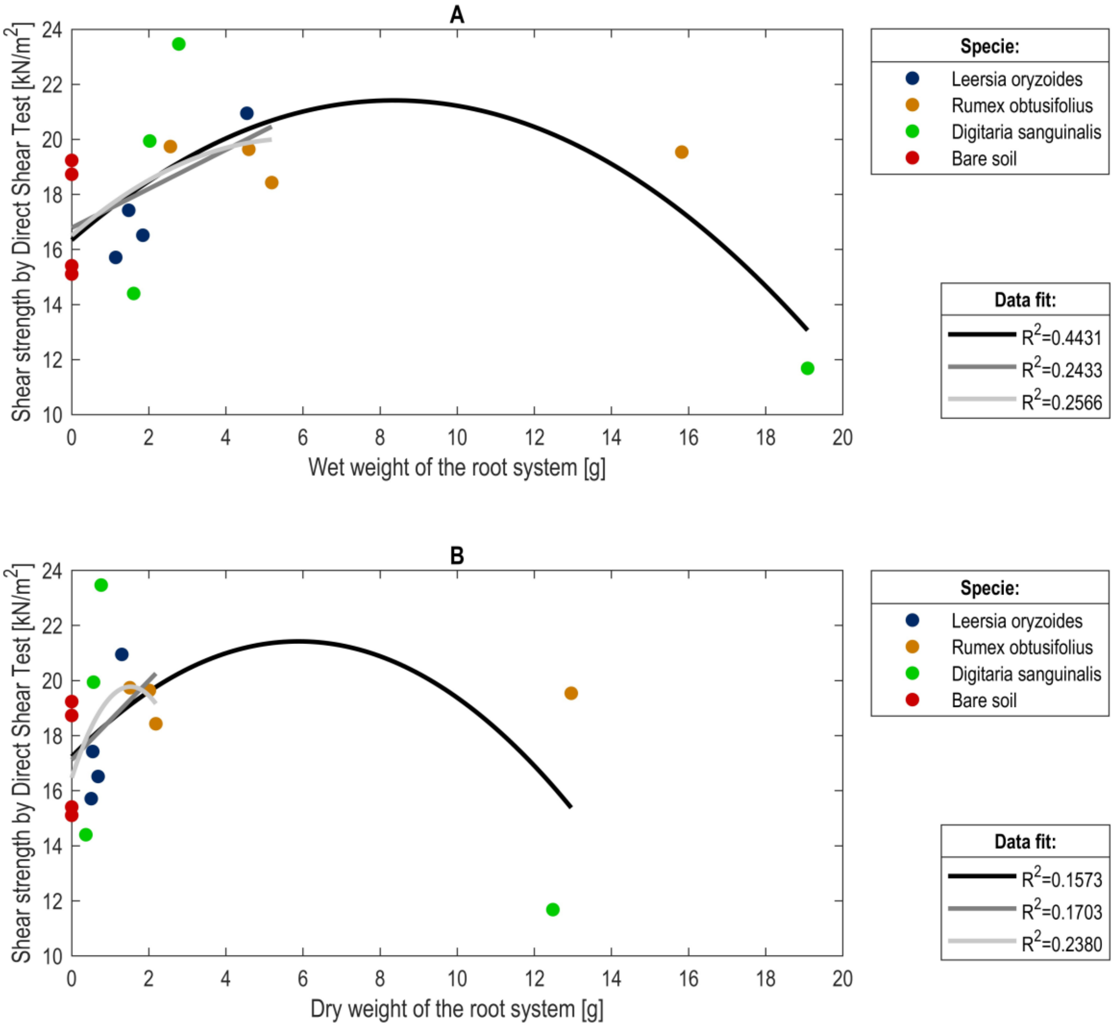

Figure 19 Scatter plot of the Shear strength by Direct Shear Test versus the wet weight of the root system (A) and the dry weight of the root system (B)

Table 8 Fitted relations for different data sets of the weight of the root system, corresponding R^2 and correlation coefficients

Fit	**Function (Y=shear strength in kN/m^2 and x= weight of root system in g)**	**R^2-value**	**Pearson correlation coefficient**	**Spearman correlation coefficient**
Wet weight of the root system				
2nd order all data	$Y=-0.0726x^2+1.2138x+16.3437$	0.4431	-	0.2933
1st order without outliers	$Y=0.7086x+16.7889$	0.2433	0.4932	0.5623
2nd order without outliers	$Y=-0.1050x^2+1.2168x+16.5050$	0.2566		
Dry weight of the root system				
2nd order all data	$Y=-0.1208x^2+1.4220x+17.2386$	0.1573	-	0.3082
1st order without outliers	$Y=1.4365x+17.1229$	0.1703	0.4127	0.5445
2nd order without outliers	$Y=-1.4255x^2+4.3455x+16.4656$	0.2380		

In Table 8 it can be observed that the relations between shear strength and wet weight of the root system generally have a higher accuracy than the relations between the shear strength and dry weight of the root system. Considering all measurements the Spearman correlations indicate almost no difference in correlation between the wet weight of the root system and the shear strength than the dry weight of the root system and shear strength. However for the data without outliers both the Pearson and the Spearman correlation coefficient show a slightly stronger correlation between the wet weight of the root system and the shear strength compared to the dry weight of the root system and shear strength.

3.2.5 Influence of root diameter and number of roots on shear strength

In Figure 20 A the scatter plot of the shear strength against the (average measured) root diameter is depicted. Figure 20 A does not show a clear relation or trend between the root diameter and the shear strength. For this data the calculated Spearman correlation of 0.2785 suggests that there is a very weak positive correlation, which is not significant according to a two tailed t-test with 5% significance level(t(14)=1.08). Most data points have an average root diameter of less than 4 mm, which creates kind of data gap for larger root diameters. Since these much larger root diameters were measured for the studied species in this research.

In Figure 20 B the scatter plot of the shear strength against the measured number of roots is depicted. From this plot hardly any trend can be, because the observed data is scattered along an horizontal line. The Spearman correlation of this data is 0.1948, which is not significant according to a two tailed t-test wit 5% significance level (t(14)=0.74). It seems that this parameter does not have any relation with the shear strength, because the number of roots data is evenly spread over the measured domain and no trend can be observed.

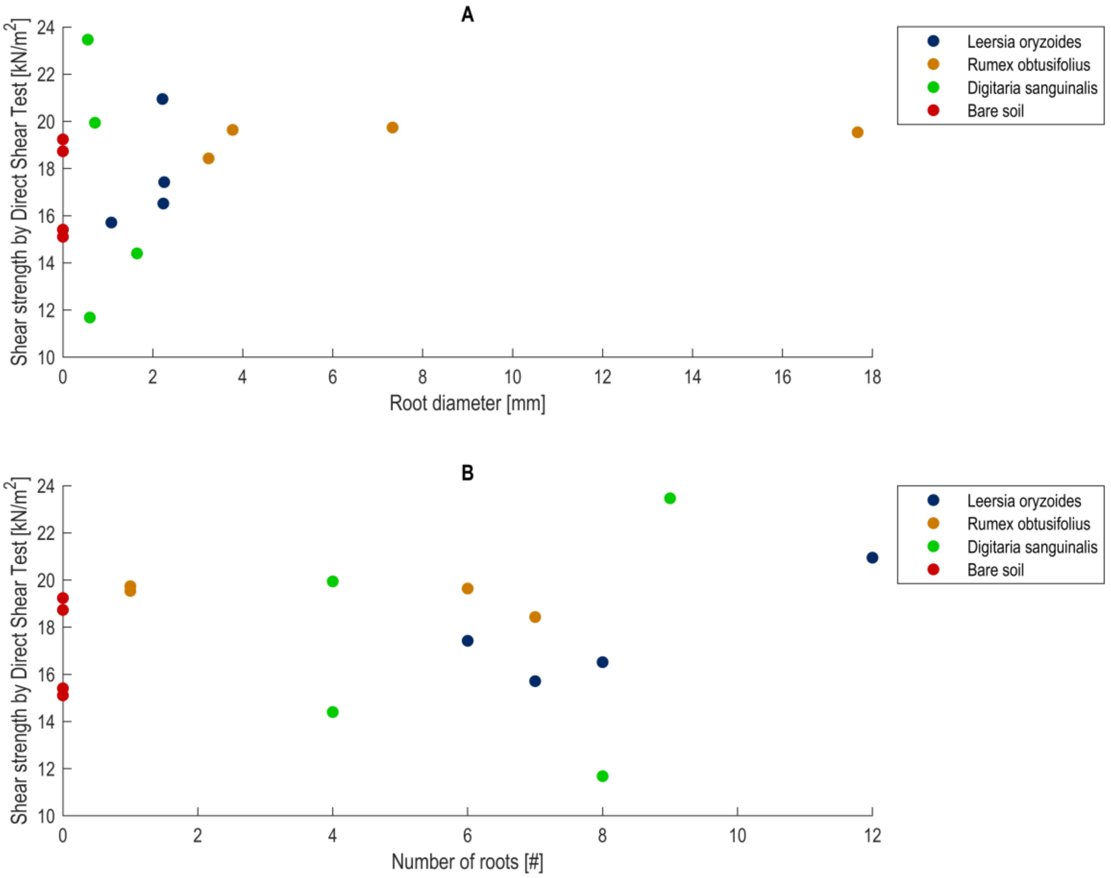

Figure 20 The scatterplot of the shear strength by Direct Shear Test versus the Root diameter (A) and number of roots (B)

3.3 EROSION RATE AND THE MEASURED HERBACEOUS ROOT PERMEATED SOIL PROPERTIES OF THE RIVER DINKEL BANK

This section describes the results of the Fast Flow Flume at NIOZ research institute and provides an answer to the research question: Which relations exist between the measured herbaceous root permeated soil properties of the Dinkel stream bank and its erosion rate? Section 3.3.1 answers the first sub question: What are the erosion rates of the herbaceous root permeated soils?. In this section the raw results and averaged results per species are depicted and discussed. The next section 3.3.2 shows the measured relation between the shear strength by SVT and the erosion rate, which answers research question: What relation exists between the shear strength and erosion rate of the herbaceous root permeated soils of the Dinkel stream bank? The final section 3.3.3 and 3.3.4 discusses the obtained relations between the erosion rate and root characteristics and provides an answer on the last subquestion: What relation exists between the root characteristics and erosion rates of the herbaceous root permeated soils of the Dinkel stream bank? In section 3.3.4 the influence of the wet weight and dry weight of the root system on the erosion rate is discussed and in section 3.3.4 the influence of the root diameter and the number of roots on the erosion rate is discussed.

3.3.1 Erosion rates on the river Dinkel bank

As mentioned in the methodology, at different time steps (0, 10, 30, 90, 150 and 210 min) the sample height with respect to reference level is measured and on each time step 20 measurements were performed on each sample. For some measurement locations on the samples on a time step the sample was eroded to the bottom of the sample container or no measurements was possible due to the presence of garbage in the sample. For these situations no height is denoted instead, these measurements were registered as not a numbers. These not a numbers are not included in further data analysis and processing. As a result further data processing is based on less than 20 measurements for time steps or samples where these situations occurred.

In Figure 21 it can be observed that the *Rumex obtusifolius* samples had the most consistent results, with sample averaged cumulative erosion ranging from 0.98 up to 1.55 cm after 210 minutes exposed to flow. This is quite a smaller range than for the *Leersia oryzoides* (0.67-4.51 cm), *Digitaria sanguinalis* (0.91-6.55 cm) and bare soil (0.77-7.19 cm). However individual measurements for a sample show larger variations as indicated by the error bars in Figure 21. As can be seen in Figure 21 not all samples have data for all timesteps, because these samples were already fully eroded on these timesteps or the erosion on the sample was already that large that further reliable results were not possible. This had to do with the set-up of the sample container discussed in section 2.1.4. When the erosion is more than 3 cm, the retaining wall of the sample container causes extra resistance against the flow which affects the results significantly. Next to that negative erosion/sedimentation can also be observed in at certain time steps, this is further discussed in section 4.3.

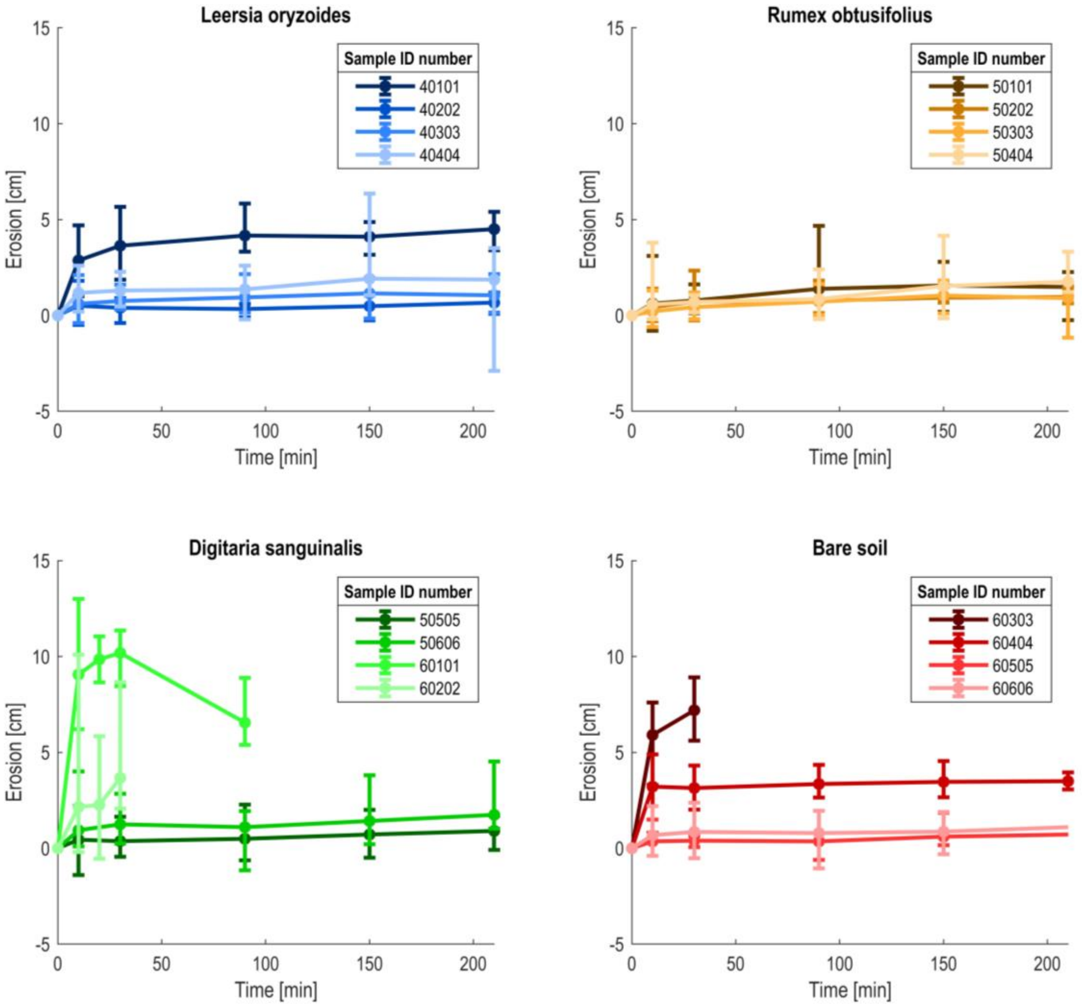

Figure 21 Cumulative erosion of the Fast Flow Flume samples, with measured error over the sample

For further comparison of the erodibility of the samples with different vegetation species over time, the average erosion rate per species for every timestep is calculated, which is shown in Figure 22 A & B. In figure A it can be observed that the erosion rate stabilizes after 90 minutes of exposure to water flow for every species. However the results do still vary a lot over time, which is more clearly visible in Figure 22 B. In Figure 22 B a data gap exists for the *Digitaria sanguinalis* since one value shows a negative erosion rate, which cannot be plotted on a logarithmic scale. In Figure 22 A & B it is visible that average erosion rate over time for the different species is within same range (several cm hr^{-1} reducing to mm hr^{-1}). This range changes over time: after 10 minutes of exposure to flow the erosion rate is ranging from 2 up to 19 cm hr^{-1}, after 30 minutes this is reduced to several cm hr^{-1} (0.6-3 cm hr^{-1}), and after 90 minutes this is further reduced to 0.04-0.33 cm hr^{-1}.

Despite the fact that it seems that the erosion rate stabilizes after 90 minutes for most species, still some fluctuations are visible over time. In order to determine the long term erosion rate over the samples the average is taken over erosion rates at time step 90, 150 and 210 minutes. For some of the samples no erosion is measured at these time steps, this data is not used for further analysis. The averaged long term erosion rates per sample are depicted in appendix 7.4 and their summarizing statistics in Table 9. Herein it is seen that the results for the different species are not very different with an average of 0.17, 0.21 and 0.17 cm hr^{-1} for the *Leersia oryzoides, Rumex obtusifolius* and *Digitaria sanguinalis* respectively. Something that is remarkable is the relative high standard deviation (0.10) of the *Rumex obtusifolius* compared to other species (0.08 and 0.01 for the *Leersia oryzoides* and *Digitaria sanguinalis* respectively), because the results in Figure 21 show quite good agreement with each other.

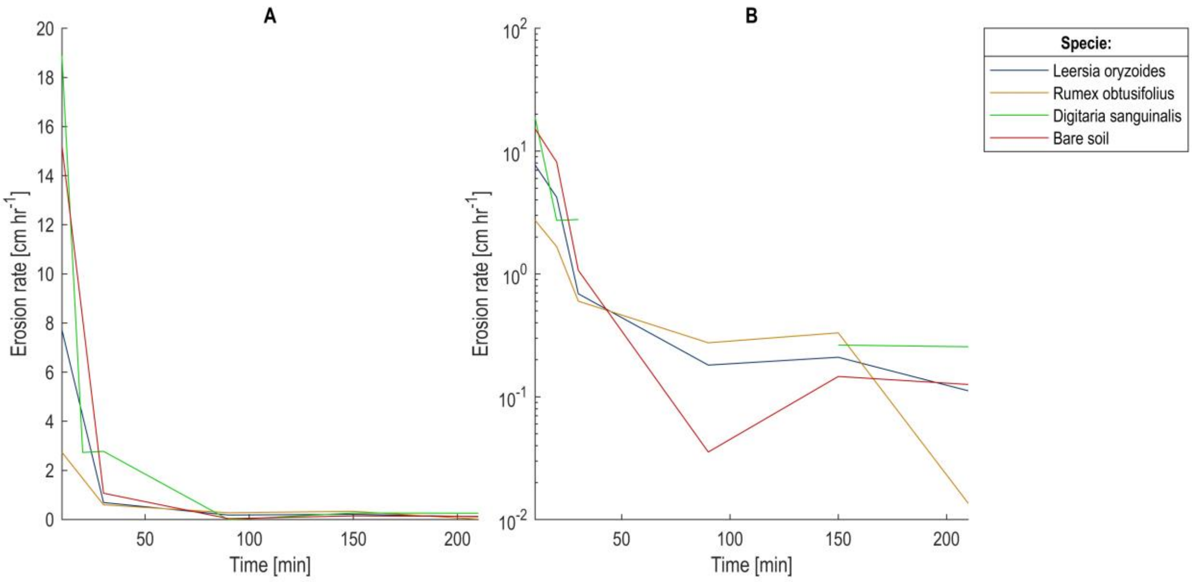

Figure 22 Averaged erosion rate per species over time against linear scale (A) and Logarithmic scale (B)

Another observation in Table 9 is the lower erodibility of the bare soil, which is 0.10 cm hr-1. This difference with all vegetated samples (mean 0.18 and standard deviation 0.08) is significant according to a one tailed t-test with 5% significance level (t(11)=2.72). The bare soil contained quite some organic content that contained some roots, which was observed during sieving of these samples and during the flume studies. The organic content and the roots in these sample are not quantified. However, this might have affected these erodibility results as further discussed in section 4.3.

Table 9 Summarizing erodibility results per species

	Leersia oryzoides	**Rumex obtusifolius**	**Digitaria sanguinalis**	**Bare soil**
Average long term erosion rate [cm hr^{-1}]	0.17	0.21	0.17	0.10
standard deviaton [cm hr-1]	0.08	0.10	0.01	0.01

3.3.2 Erosion and shear strength

In Figure 23 some remarkable values can be observed (indicated with a cross): two samples had low shear strength and low erosion rate compared to other data and one sample had showed the opposite high shear strength with high erosion rate. This is remarkable since low erosion rates are expected to have high shear strength and vice versa. These three values also largely deviate from the mean of the shear strength results of the SVT of their corresponding species. The shear strength by SVT of the *Rumex obtusifolius* had a mean of 5.0 and a standard deviation of 2.7. The *Rumex obtusifolius* values indicated with a cross in Figure 23 are 2.2 (sample id: 50202) and 11 kN/m^2 (sample id:50101). The shear strength by SVT of the bare soil had a mean of 4.6 and a standard deviation of 2.1 kN/m^2. The bare soil shear strength of the value indicated with a cross in Figure 23 is 3.3 kN/m^2 (sample id:60606). Despite these values deviated strongly from the mean, these values are not uncommon measurements in this study.

From the flume studies it was known that two of these samples (50202 & 60606) had higher sample heights than should be. Samples with larger height did not align well in the flume which results in more flow obstruction and lower velocities. The other sample (50101) had a subsurface channel or tunnel in the sample after exposure to flow. Probably large part of the flow did pas underneath the sample. In addition the results of these samples (50101, 50202 & 60606) did not correspond with the trend of the other data points. It is questionable whether the shear strength and/or the erosion rate did represent the sample properties. Therefore these values of sample 50101, 50202 and 60606 are not used in analysing the relation between erosion rate and shear strength.

For the remaining data set the Pearson correlation coefficient is -0.6264 and the Spearman correlation coefficient of -0.7090. These values show a convincing relation of decreasing erosion with increase in shear strength. This relation is significant according a two tailed t-test with 5% significance level(t(13)=2.66 for Pearson correlation and t(13)=3.33 for the Spearman correlation). For this data points two different functions were fitted a linear decreasing trend and a negative exponential (Y=0.3589-0.0297x and Y=-0.05465+0.5394 exp(-0.1426x) respectively), with a coefficient of determination of 0.3924 and

0.4009 respectively. The negative exponential fit has a slightly better fit than the linear fit. In addition the Spearman correlation is shows a stronger trend, which might suggest that this relation probably is non-linear.

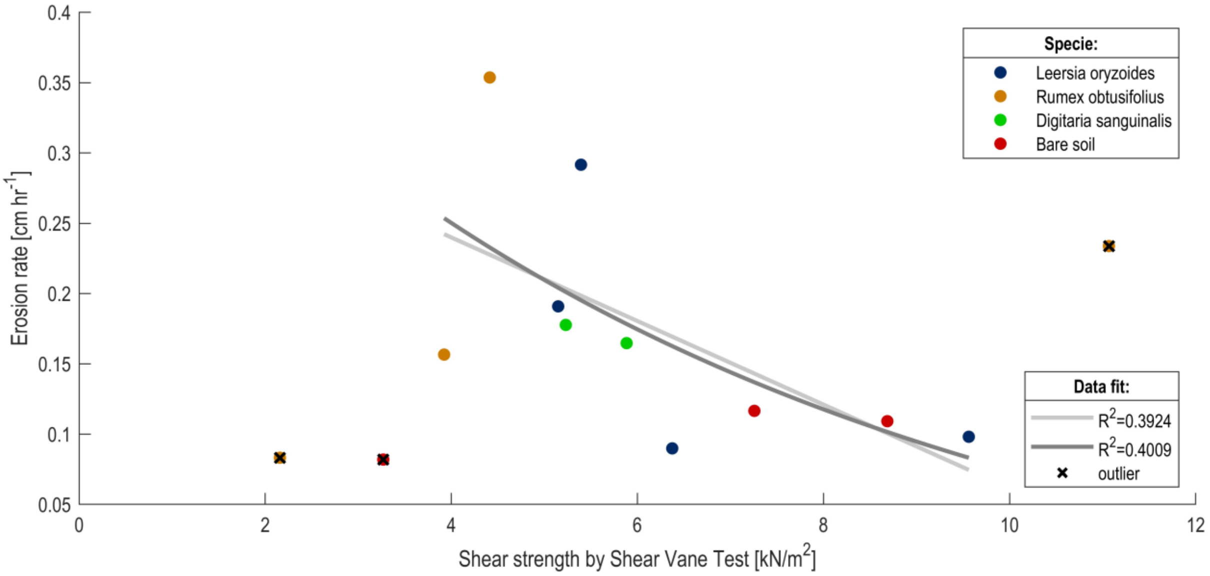

Figure 23 Scatterplot Erosion rate versus the shear strength by Shear Vane Test

3.3.3 Erosion and weight of the root system

As is discussed section 3.3.1,the bare soil had lower erosion rates than the root permeated soils. These bare soil samples were contaminated with quite some organic content and (fine) roots. The amount of and weight of these (fine) roots is not quantified. Therefore, these bare soil samples are not considered in the analysis of the weight of the root system, because the erosion rate of the bare soil samples does not represent a fully unrooted soil. Also for some vegetated samples it was not possible to measure the root characteristics of these samples as discussed in section 3.1.2.

For the remaining data Pearson correlation values of -0.3260 and -0.1607 were obtained for the wet and dry weight data respectively. The Spearman correlation values showed different correlations between the erosion and weight of the root system, namely -0.4012 and 0.0973 for the wet and dry weight data respectively. The erosion data as well as the weight data of these samples are normally distributed. None of the correlation coefficients showed a significant correlation between the weight of the root system and the erosion rate, according to a two tailed t-test with 5% significance level(t(8)=0.98, t(8)=0.46, t(8)=1.24 and t(8)=0.28 respectively). The shear strength and weight of the system was non-linearly correlated with each other for weight below 6 g (5^3 cm^3) see 3.2.2 and the relation between shear strength and erosion rate could be best estimated with a negative exponential relation. Therefore for both data sets a negative exponential of the form Y = a-b*exp(-c*x) is fitted, which had a coefficient of determination of 0.4604 and 0.2056 see Figure 24 A&B. The values of the fitting parameters are depicted in Table 10.

Table 10 Parameters of the fitted relations

Parameter	Wet weight data	Dry weight data
a	0.1615	-3.334
b	-599.8	-3.534
c	18.94	0.004221

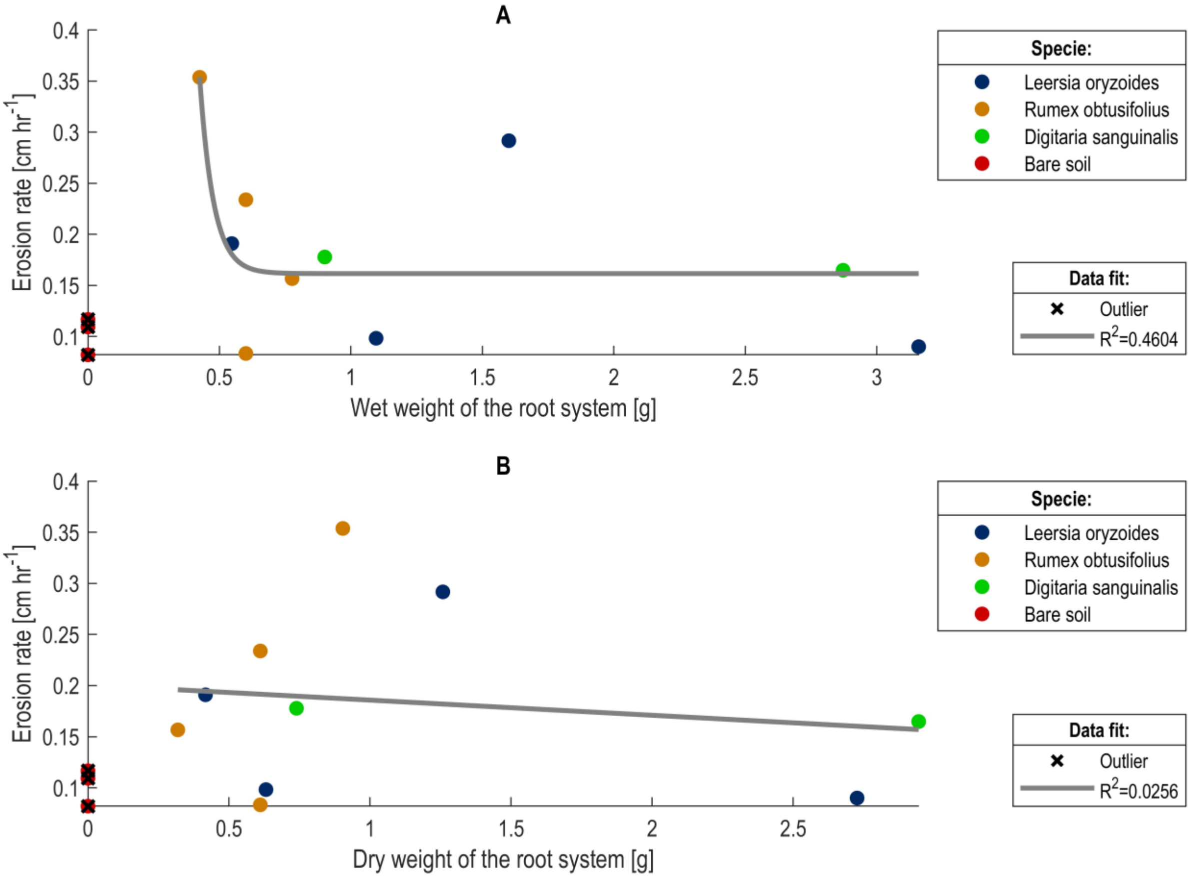

Figure 24 Scatterplot of the erosion rate versus the wet weight of the root system (A) and dry weight of the root system (B)

3.3.4 Erosion, root diameter and number of roots

As mentioned before the bare soil samples did not contain some fine roots. However from observations it could be concluded that these roots were very fine and almost not really measurable. Next to that, these fine roots did not meet the requirements or definition of the decisive roots that are considered in this study. Therefore it is not expected that these roots will affect the relation of the root diameter and number of roots with the erosion rate, because the roots observed in the bare soil samples are not included in the definition of both root characteristics.

In Figure 25 A the erosion rate is plotted against the average root diameter of the FFF samples. In this figure it can be observed that most data is scattered in one cloud, which does not show a clear relationship between the average root diameter and the erosion rate. The Pearson and Spearman correlation coefficient, 0.3939 and 0.1743 respectively, indicate no significant correlation according to a two tailed t-test with 5% significance level (t(11)=1.42 and t(11)=0.59 respectively). For the erosion rate and the number of roots an even more unclear relation can be observed in Figure 25 B, which is corroborated by an insignificant Pearson (0.2790) and Spearman (0.1939) correlation as well by a two tailed t-test with 5% significance level (t(11)=0.96 and t(11)=0.66 respectively). Since no link between erosion rate and these two root characteristics is observed or expected anymore, no relationship is fitted to this data.

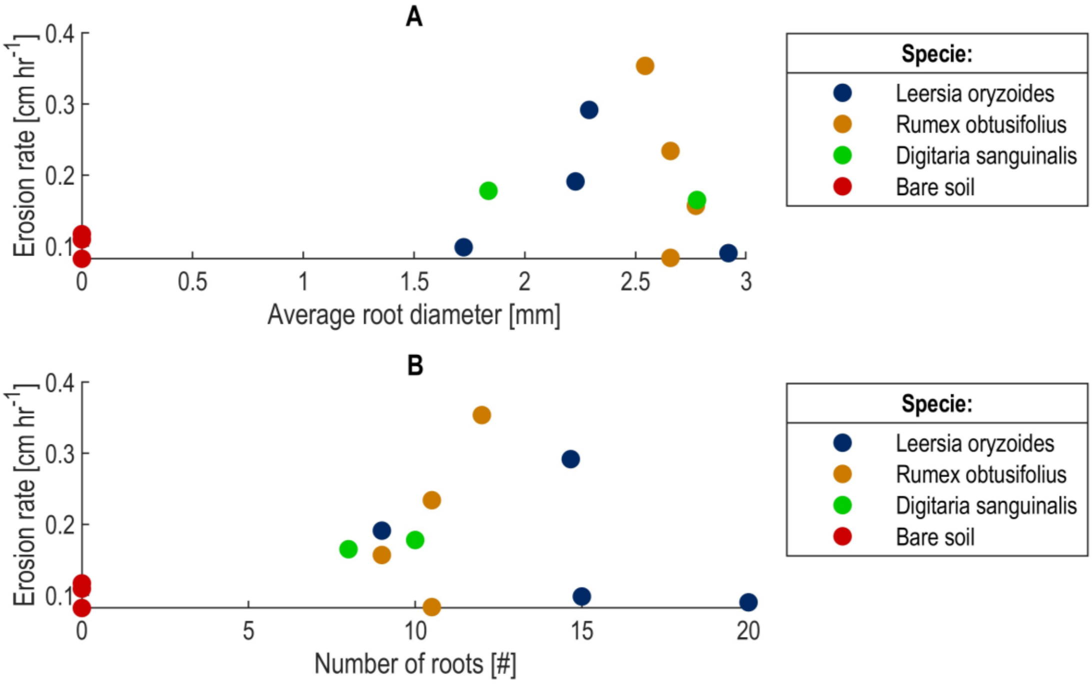

Figure 25 Scatterplot of the erosion rate versus the root diameter (A) and the number of roots (B)

4. DISCUSSION

4.1 MEASURED HERBACEAOUS SPECIES AND ROOT PERMEATED SOIL PROPERTIES

4.1.1 Aboveground properties

The measured above ground properties of vegetation were the minimum a maximum vegetation height of the species. These values give an indication of the size of the plants included in this research. However, it is not researched whether this are relevant characteristics for root properties. This could be studied with the data presented in Table 16 in appendix 7.5. Li et al. (2008) suggests the maximum vegetation height could be relevant for root properties of grasses, but there are more aboveground characteristics that might be relevant such as the leaf area index (LAI)(Liedgens & Richner, 2001) and the stem diameter (Gasser et al., 2020). The stem diameter is not really applicable for grassy species, but can be for certain herbaceous species that consist out of one or multiple rigid stems. These relations will become of more importance when clear and strong relations exist between root properties and erosion rates, because then more easily measured aboveground properties could be used for estimating erosion of root permeated soils.

As mentioned before the derived species names of the researched species have some uncertainty, the accuracy of these results is not known. However this could be improved by taking pictures without background noise. On the other hand the software used more inputs than the pictures only, the location was also an important criteria in the software. The considered earlier observations and natural presence/occurrence of these species in the neighbourhood. Moreover after the software suggested the best options, more detailed properties of the vegetation were checked. For example, the micro climatic environmental properties, the amount and type of nutrients these plants like and the degree of moisture these plants like or the closeness of

4.1.2 Root characteristics

As indicated in the results, the root weight of the root system per volume is largely influenced by the sample size, the results between the DST and FFF could be hardly compared and linked to each other. This difference can be explained by the different sample sizes, which is 6x6x3.5 cm for the DST and 12x8x13 cm for the flume. Root density is variable over space and depth (Löbmann et al., 2020; Yu et al., 2020). Mostly, root density decreases over depth and over space, the further away from the main stem the smaller the root density (Gasser et al., 2020; H. Li et al., 2017). During the sampling it was observed that, the root systems generally have a depth of 6-8 cm and the width is around same range. The highest root densities were observed within the radius 3 cm from the main stem(s). The centre of the samples of the DST was located on the main stem(s) of the vegetation where also the largest root density is present. For the flume samples the researched part for the root characteristics was less concentrated around the main stem(s), because the most densely vegetated parts of the flume samples were often placed in the flume and the less densely vegetated were used for determining the root characteristics. Also the flume samples were wider and deeper than the DST samples, which means that these samples contained more dense rooted soils. Therefore, the flume samples had lower weights of root system than the DST. This different type of sampling resulted also in some data gaps for vegetated flume samples see appendix 7.5. Therefore, it could be argued that the root characteristics of the flume samples were not very representative for the whole sample.

Next to that, the washing of the roots for measuring the root characteristics might affected the results of the weight of the root system, because during this process also a lot of the finest roots were washed away. Therefore, the measured weight probably lower than the true value of the weight, but it is expected to be a minor influence since these roots were very light and small. The root diameter and the number of roots measurements were not affected by these issues (missing small roots and sample size), since the definition and their measuring method already excludes the small roots.

The researched root characteristics did not show very strong correlations with the shear strength and erosion rates. This could be caused by several reasons as further discussed in the next sections. However, it is important to mention that in literature different root characteristics are used for researching the effect of roots on shear strength and erodibility of soils. These root characteristics are often more difficult measure and demand more resources, which is the reason these characteristics are not considered in this research. Several examples are the Root Area Ratio (RAR), Root length Density (RLD) and Root Density (RD). The RAR is the ratio between the surface occupied by roots and the surface in a cross section of a sample, the RLD is the total length of all roots within a volume of soil and the RD is the weight of root system of a volume soil (Gasser et al., 2020; Pallewattha et al., 2019; Vannoppen et al., 2017; Zi et al., 2023).

A large limitation of the results is the small range of the measured root characteristics. These small range limits the validity of the of the results and also their applicability. In this research three species were considered, but there are many more species present in the research area. Also these selected species and vegetation patches had certain dimensions suitable for the for the equipment; the DST and FFF apparatus. Therefore these results might have limited validity for the whole research area.

4.1.3 Soil properties

The grain size distributions of river Dinkel bank soil samples showed good agreement with each other. Some samples had more coarser grains, which were located more on top of the bank. However these differences might also be caused due level of crushing the clustered grains. The soils on the river Dinkel bank had a very high level of organic content. The researched soil contained blankets of layered vegetation leaves, a humus layer, which was one monolithic part with the soil. The level of organic content is not measured, despite this might have large impacts on the results. According to the study of Ekwue (1990) this influences the shear strength. This influence can be an increase or a decrease, and is dependent on the quantity of organic content (Ekwue, 1990). Zi et al. (2023) derived a strong relation between the organic content and soil detachment. This relation indicates a soil detachment reduction by increasing organic content. In this study, this relation between soil detachment and organic content can be substantiated by the observation that organic material was the harder to remove from the roots than the soil.

4.2 SHEAR STRENGHTH OF THE ROOT PERMEATED SOILS

4.2.1 Shear strength by Shear Vane Test

In general, the measured shear strength by Shear Vane Test is low er compared to most studies, because this test is more often used for cohesive soils for which it is more suitable as well(Ameratunga et al., 2016). In this study of the Dinkel bank most measurements ranged between 1 and 10 kN/m^2, with several larger values up to 25 kN/m^2. The sample averages varied between 1 and 12 kN/m^2.

Quite large standard deviations relative to the average shear strength by SVT were observed for the different species species. The average per species varied between 3.4 and 5.4 kN/m^2 with standard deviations varying between 1.7 and 2.2 kN/m^2. This did limits the observation of differences on species level. However, it still could be that the shear strength of the soil surrounded by these species does not differ at all.

These values show similar results to the shear strengths of 3.80-17.30 kN/m^2 obtained by Cabalar et al. (2020), for soils with a similar grainsize distribution as this research area (grainsizes varying between 0.3-0.6mm and D_{50} of 0.45 mm). This grainsize distribution is coarser than the grainsize in this study (D_{50} of 0.185-0.230), but in the study of Cabalar et al. (2020) the sand is mixed with clay. These measurements were also executed with a water content range of 18-24%, which is not known for this study.

The coarse organic matter was removed from the soil in the shear vane tests, but most of the tests were still executed on the humus top soil layer. This top soil layer is also not representative for slightly deeper layers with more sand particles and roots. To improve these measurements, a larger shear vane could be used for a larger shear vane the failure of the soil could be easier observed and noticed due the greater shear surface and the resulting stronger release in force. To better measure the root permeated soil strength below the surface, a deeper shear vane or drilling a small hole would be recommended. These below-surface measurements could also be more in line with the shear strengths obtained by DST as was shown by Park et al. (2016).

4.2.2 Shear strength by Direct Shear Test and effect of roots

The graphs in Figure 17 indicate more properties of the sample than the shear strength. The shape of these graphs shows some indication of the compaction of the soil. A loose soil shows a trend like Figure 26 A and a more dense compacted soil a trend like Figure 26 B. The different shape observed in Figure 17, shows that the samples had different compaction levels, which affects the Direct Shear Test results. Compacted soils have more friction and therefore higher shear strength (*Direct Shear Test*, 2023; Islam, 2017).

Next to that the shape also indicates whether the sample has fully failed or not. In Figure 26 C an example is given of a sample that is not fully failed. This can be recognized by the fact that the graph is not fully flattened and neither had a peak. The reason that not all samples were fully failed had to do with limitations of the apparatus. The apparatus stops with shearing after 5.5 mm of displacement to prevent damage to the apparatus. The graphs of sample 80303&80404 (*Digitaria sanguinalis*, Figure 17) are good examples of a sample that is probably not fully failed, this might have influenced the results considerably since the other samples failed at higher applied force. However, it still might be possible that the sample fails after very small increase in force of several N. These values still provide a good indication of the strength, because the decreasing steepness of these curves in this study showed that the sample already started failing.

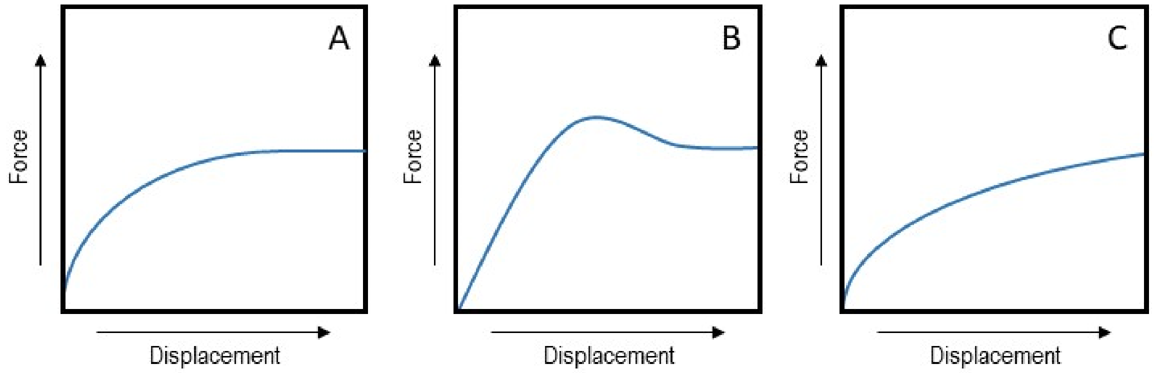

Figure 26 Different types of Direct Shear Test force-displacement diagrams (A) Loose soil (B) Compacted soil (C) Not fully failed soil sample

Moreover there are more events that can be observed in the graphs of Figure 17. The sample 80505 shows a very steep decrease and increase in force around the displacement of 1 mm. This event might be a root that breaks, which suddenly results in larger displacement with less force. After that the remaining roots and soil mass will be activated. Another remarkable event can be observed in the graph of sample 80606. Between the 0.5 and 2 mm displacement the force stabilizes quickly, but after 2 mm displacement increases significantly again. This event might be caused by the activation of (a) root(s), that was little but loose in the soil and due to the displacement became under tension.

These shear strength results by DST did not show an significant increase in shear strength for root permeated soils. A similar study by Pallewattha et al. (2019) to the effect of roots on shear strength by showed that the increase in shear strength due to roots is around 2-3 kN/m^2 for large moisture contents (0.35-0.43). This increase in shear strength is in the same order as the standard deviations (4.61-0.53 kN/m^2) observed for the results of the different species in this study. Therefore these increase in shear strength might be only observed in very accurate and controlled environments as in by Pallewattha et al. (2019), or with more measurements from field samples to cover the natural variability. The density of the root system through the shearing plane is also decisive for the obtained shear strength. When this density through the shearing plane is not considerably almost no effect could be expected. Pallewattha et al. (2019) used a different root characteristic the Root Area Ratio (RAR), which is not comparable with the measured root characteristics within this study.

The wet weight of the root system showed the best correlation with shear strength. Probably this parameters did represent the root density the best and its strength in the shear plane as well of the considered root characteristics in this study. The root diameter and number of roots is measured at the top of the sample which probably not really representative for the conditions in the shear plane. That the dry weight of the root system had a slightly poorer corelation (spearman correlation of 0.54 for the dry weight versus 0.56 for the wet weight) with the shear strength could not be really clarified in this study.

4.2.3 Differences between Shear Vane Test results and Direct Shear Test results

From section 3.2.1 and section 3.2.2 it can be observed that there are large differences between the shear strength by SVT and DST, which can be partly clarified by the different methods to measure shear strength described in section 3.2.3. Another contribution to these differences could be the different soil moisture content (Pallewattha et al., 2019). These measurements were executed on almost the same soil mass, such that soil properties of both tests were the same. However, the in-situ SVT tests were tested on the hydrological conditions present during the field studies and the DST tests were executed on controlled wetted samples. Large part of the SVT in-situ measurements were executed in quite wet conditions similar to the level of the DST samples in the laboratory. The moisture content for both tests is not measured, so the difference between moisture content cannot be quantified.

In the scatterplot of Figure 18 more trends can be observed on species level. The *Digitaria sanguinalis* has a larger variation in DST shear strength (standard deviation of 4.61 kN/m^2) than in SV shear strength (standard deviation of 0.6 kN/m^2). For the *Leersia oryzoides* and *Rumex obtusifolius* the opposite is visible with standard deviations for the DST of 2.00-0.53 and for the SVT 2.0-1.8. These observations can be clarified by the root system architecture (RSA) of the plants, because the shear strength is measured at different shear planes by the two tests.

In Figure 27 several type of root system architectures are presented, the *Leersia oryzoides* had a true adventitious type of roots, the *Rumex obtusifolius* had tap root system and the *Digitaria sanguinalis* had a fibrous root system. For *the Leersia oryzoides* and *Rumex obtusifolius* the presence of roots is higher in the top soil layer, which clarifies the higher variation in shear strength by SV than for DST due to the lower shear plane of the DST. For the *Digitaria sanguinalis* the presence of roots is higher at a lower soil layer, where the shear plane is of the DST.

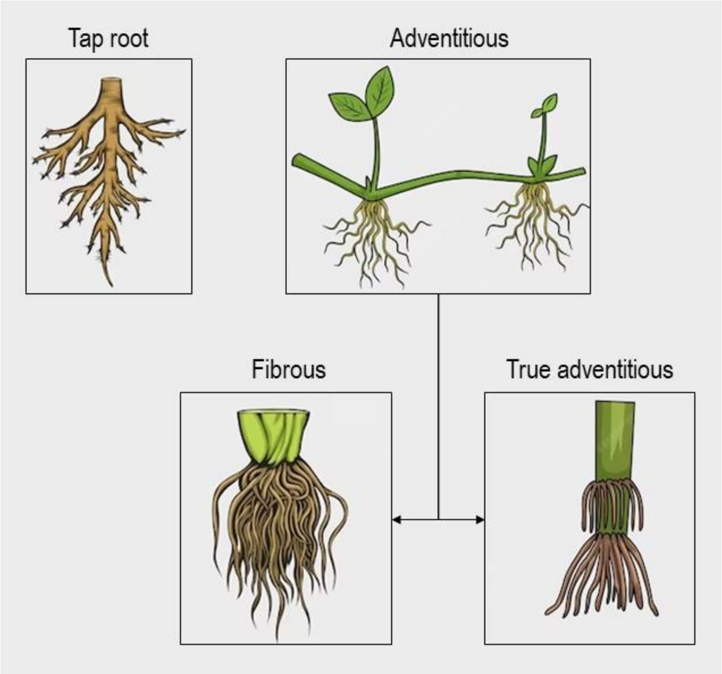

Figure 27 Root system architectures of several root types: adventitious root types is subdivided in fibrous roots and true adventitious roots

4.3 EROSION OF THE ROOT PERMEATED SOILS

The erosion results of the different species are not very different. The average erosion was 0.17, 0.21, 0.17 and 0.10 cm hr $^{-1}$ for the *Leersia oryzoides, Rumex obtusifolius, Digitaria sanguinalis* and bare soil respectively. However, it is quite remarkable that the standard deviation of the *Rumex obtusifolius* is the largest (0.10 cm hr $^{-1}$) compared to the other species (0.01-0.08 cm hr $^{-1}$) , because the results in Figure 21 show quite good agreement with each other. In Figure 21 the average erosion over time of the *Rumex obtusifolius* samples coincides the best. Despite these minimum differences of the averaged erosion in Figure 22 and Table 9, it should take in mind that the erosion varied a lot over the individual samples. This can be clearly observed in Figure 21 by the error bars, which have bandwidth of several cm. Another remarkable result is that the erosion rate of soil samples without vegetation (bare soil) were lower than for the vegetated soil samples. A few explanations could be:

- The soil samples of the river Dinkel consisted out layers with humus and leaves which formed quite strong and smooth uniform cover over the sample. It could be that these layers had better properties than for the vegetated samples, because these were not disturbed by vegetation stems. Observations during the flume study showed that when the top layer was damaged, the erosion increased significantly.
- For the flume experiments the aboveground vegetation was removed. After the first erosion the small stems of the plants and roots were exposed to the water flow. This might have changed the flow patterns over the samples and potentially enhanced the local scour at certain points, which increased the erosion rate over the sample.
- Since the root characteristics of unvegetated bare soil samples not were measured, it is not known to what extent roots were present in these samples. Before the sieving analysis quite some organic matter with some roots were removed from the leftover parts of bare soil samples that were used in the flume.
- Also the bare soil samples were the last tested samples, during the research the use of the flume is slightly improved by more careful placement of the samples. This decreases the disturbance of the samples, but also the connection to the boundaries of the flume was improved.
- As already mentioned in section 4.1.3 Zi et al. (2023) observed a strong relationship between the increase in organic content in soil and reduction of soil detachment. The organic content is not measured and it might be case that these unvegetated soils had higher organic contents than the vegetated.

Another interesting observation regarding the organic content is that the organic matter sticked very well to the roots system. This was observed during the flume studies and washing out the roots before measuring the root characteristics. This suggest that combination of organic matter and roots enhances erosion reduction. Next to these fundamental points, there are also some minor limitations and notations by the flume experiments:

- At different locations the negative erosion is measured due to uprising of the root system. The root system was sometimes eroded from one part of the sample, but deposited somewhere else on the sample because it was still partly connected to the sample. This deposition resulted in local height increases in time and clarifies the negative erosions measured.

- Despite carefully sampling, the samples had minor differences in sample height. These height differences were clearly visible after placing the samples in the flume, because a bumps and cliffs occur between the transition between flume bottom and top of the sample
- The determined flow velocity might differ significant from the applied flow velocities, because the different flumes showed different water heights. Also pitot tube measurements indicated that the velocity was different over time and between samples. These velocity differences probably are caused by the different roughness of the samples over time and between different samples.
- The retaining wall of the sample container might influenced the results significantly after 3 cm of erosion, because this wall starts then to block the flow.

That the erosion rate and (surface) shear strength by SVT had a strong significant correlation (Spearman correlation of 0.70) in this study is not surprisingly. Estimation of the erosion with the excess shear stress equation is widely used and accepted parameterization. Herein the erosion decreases with an increasing (critical surface) shear strength (Gasser et al., 2020). In this study the relation between the erosion rate and soil shear strength could be best described by a negative exponential relation with R^2. Zi et al. (2023) found an exponential relations between the erosion rate and applied shear stress by flow with R^2 ranging between 0.35 and 0.68.

None of the root characteristics had significant correlations with the erosion rate. This might be the result of the not representative root characteristic measurements for the flume samples or that the organic content interfered too much. Zi et al. (2023) and Vannoppen et al. (2017) derived relations between the soil detachment and root characteristics (RD and RLD) that poorly predicted the data gathered in these studies. However, the RD and RLD show significant negative correlations with the soil detachment (Vannoppen et al., 2017; Zi et al., 2023). Probably the erosion of root permeated soils cannot be estimated with one root characteristic, because these systems are too complicated and too diverse to be parametrized in one parameter.

5. CONCLUSION

This chapter describes the main findings of this research. First the main research questions are answered and last the most important findings of this research and recommendations for further research are summarized in the final remarks.

5.1 MAIN RESEARCH QUESTIONS

1. **What variation in the root permeated soil properties of herbaceous vegetation covers can be observed along the Dinkel stream bank?**

In this research three vegetation types were included: the *Leersia oryzoides*, the *Rumex obtusifolius* and the *Digitaria sanguinalis*. These different species have a different aboveground appearance, which all three have a different root system architecture as well. The measured vegetation and root properties diverge a lot for the different species, but also showed a large variation and spread on species level as well.

The *Leersia oryzoides* shows also the largest variation in heigh with a height range between 19 and135cm. For the *Digitaria sanguinalis* the height and variation in height is smaller (ranging between 6 and 50 cm). The *Rumex obtusifolius* is not only the smallest species, but also has the smallest variation in height with a range between 10 and 30 cm

The wet weight of the roots system varied between the 1.1 and 19 g 5^3 cm^3 and the dry weight of the root system varied between the 0.5 and 13 g 5^3 cm^3. The measured root diameters ranged between the 0.52 and 17.67 mm. The number of roots measured of the DST samples ranged from 1 up to 12 roots. For the FFF samples this number ranged from 1 up to 20 roots.

The measured soil properties of the research are were quite consistent over space with a D_{50} between 0.185-0.230, only a minor difference between lower bank and upper bank could be notified. On the top of the bank more coarser particles were measured. In general the soil can be classified as clean fine sand according the USCS soil classification system.

2. **What is the is the shear strength of herbaceous root permeated soils with different root characteristics along the Dinkel stream bank and how is this related to the measured root characteristics?**

The individual shear strength measurements by SVT varied strongly along the Dinkel bank with measurements between 1 and 25 kN/m^2. This variation was observed for all species and for the bare soil as well. However the average shear strength by SVT of sample showed more consistent results with averages between the 3.4-5.4 kN/m^2 and standard deviations between 1.7-2.7 kN/m^2 for the researched species and bare soil. There were no clear differences observed between the results of the different species and bare soil for the shear strength by SVT. The DST measured on average a larger shear strength for all species compared to the SVT results with the average of the species and bare soil ranging between 17.12-19.34. The standard deviations for this data ranged between 0.53-4.61 kN/^{2}.

The large differences between the results of the DST and SVT, can be clarified by their measuring method and the root system architecture of the researched species. The SVT and DST measure a different shear plane. The roots of the different species had different lay out and orientation, which were mostly below the shear plane of the SVT but in the shear plane of the DST. There was no correlation observed between the shear strength measured by SVT and DST. Next to that a linear fitted relation between these results could poorly predict the shear strength DST by SVT shear strength (R^2 of 0.0057).

The root characteristics had minor influence on the shear strength by DST. The wet weight of the root system had the most effect on the shear strength with and significant Spearman correlation of 0.56. The dry weight had a slightly less correlation with the shear strength(Spearman correlation of 0.54). The correlations between the number of roots and average root diameter, were not significant.

3. **Which relations exist between the measured herbaceous root permeated soil properties of the Dinkel stream bank and its erosion rate?**

The average erosion rates for the studied species in this study are: 0.17, 0.21, 0.17 and 0.10 cm hr^{-1} for *the Leersia oryzoides, Rumex obtusifolius, Digitaria sanguinalis* and bare soil respectively. The averaged erosion of samples showed quite good agreement (standard deviations for the different species ranging between 0.01 and 0.10 cm hr^{-1}). However, over the individual samples large variations of several cm in erosion existed over time as well over space. The bare soil had a significant lower erosion rate than the root permeated soils. This difference might be caused due to the organic hummus layer present on these samples, which probably had better properties than the for the vegetated samples.

The erosion rate showed a strong correlation (-0.70, $p<0.05$) with the shear strength obtained by SVT. The shear strength is also the most suitable parameter to estimate the erosion rate (R^2 of 0.40). The studied root characteristics did not show significant correlation or clear relation with the erosion rate. This does not align with the studies of Zi et al. (2023) and Vannoppen et al. (2017), where soil detachment had significant strong correlations with other root characteristics. However, the erosion rate could be poorly estimated by one characteristic in the studies of Zi et al. (2023) and Vannoppen et al. (2017).

Therefore, it might be that the erosion reduction of root permeated soils cannot be assigned to one root characteristic, because these systems are too complicated and too diverse to summarize in one parameter.

5.2 FINAL REMARKS

- Despite this study lacks strong evidence that roots increase shear strength, numerous studies have shown that roots do increase the shear strength(Capobianco et al., 2021; Collison & Anderson, 1996; Fan & Su, 2008; Ghestem et al., 2014; Greenway, 1987; Löbmann et al., 2020; Pallewattha et al., 2019; Simon & Collison, 2002; Yu et al., 2020).
- In this study wet weight of the root system was the most promising parameter to estimate the shear strength of root permeated soils.
- Organic content influences the shear strength and erodibility of soils (Ekwue, 1990; Zi et al., 2023). This is substantiated by the observations in this research. Therefore, further research in this topic should consider this soil property.
- The high spatial variability of this research indicates that sufficient and representative measurements are crucial for further research and implementation of uniform vegetation root parameters in shear strength and erosion models
- The shear strength of root permeated soils seemed the most promising parameter to estimate the erosion of root permeated soils in this research. It seemed that individual root characteristics are not suitable for estimating the erosion of root permeated soils. There might be more potential for combinations of several root characteristics.

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7. APPENDICES

7.1 FIELD WORK AND SAMPLING PROCEDURES

This section describes how the field data and samples step by step were collected

7.1.1 Field data collection

1) The first step in the field procedure was to find suitable a vegetation patch or unvegetated part on the river bank for the DST or the FFF. These spots and sample locations are depicted in Figure 28 and in 7.1.4. On the spot of the measurement location the GPS device was turned on to initialize the device in order to determine the exact location.
2) Of these vegetation patches pictures were taken to identify the species
3) After that the vegetation height is measured of the vegetation patch. Hereby the highest part and the lowest part of the vegetation patch is measured to have some insight in the variation over the patch. This measuring was executed with a measuring rod from the soil surface to the top of the vegetation.
4) When the above ground characteristics were recorded, the aboveground vegetation was removed by cutting this vegetation of at the soil surface. Also, the loose vegetation parts and organic matter on the surface were removed, to prepare the surface for the SVT
5) On the empty root permeated or bare soil the Shear Vane Test is executed on the soil around the spots were the samples will be taken. For DST samples this test was only executed 4 times, because this sample is quite small and taking more measurements does not contribute to more reliable results. For the samples of FFF more measurements were taken, because of the larger samples and corresponding variability. Depending on the variation 4 up to 10 measurements were taken. The used vane for this research is the standard vane of the Humboldt H-4212MH Pocket Shear Vane Tester. The Shear Vane Test is executed as follows:

   > First the apparatus is aligned to the default modus, which was done by rotating the inner anti clockwise. until the marker on the outering is aligned with the zero on the inner ring. Then the vane of the apparatus is pressed perpendicular into the topsoil until the blades of the vane are covered by the soil. The test started with rotating the outer ring with constant speed under constant pressure. The test ended when the soil failed, which occurs when the vane is rotating as well. After that the outer ring was slowly released, in this way the marker stays in place. Then the apparatus released from the soil and the shear number on the device is record. After a test the vanes were cleaned before the next test was executed.

6) After these measurements of vegetation patch, the location was recorded with GPS device. This device was turned on earlier to obtain a more accurate location. GPS location determination becomes more accurate over time. Trial and error from pre data gathering field studies showed that time required to obtain an accurate location took as long as step 1 until 5, which is around 5-10 minutes. Longer initialisation time did not make the measurement more accurate.
7) The last step in the field study was to collect the sample for the FFF and DST. For the FFF the sample collection is described in 7.1.3 and for the DST in 7.1.2.

7.1.2 Sampling DST

The procedure for sampling with this device is as follows:

1) The press out plate is placed in the box with the stick pointing out through the hole on the top as shown in Figure 6 sampling device for Direct Shear Test, black dotted line indicates top and the red dotted the bottom of the pressing plate. This set up is placed on soil on the “cleaned” soil (without aboveground vegetation and organic material on the surface) on the main stem in the middle of the vegetation patch.
2) After placing the device in the right position, the device is pressed into the ground by pushing on the top of the box (not on the stick of the press out plate!) until the device is in the soil to the red dotted line level. When there is quite some resistance a hammer is used to drill the box to the red dotted level, by hammering on the top of the box(not on the stick of the press out plate!)
3) Now the sample is in the box. In order to remove it from the river bank, there is cut along the four sides of the box to disconnect the sample of the soil and the larger root system.
4) The sample in the device is removed from the soil with help of the knife such that the sample remains intact in the box.
5) Lastly the soil and roots that stick out of the bottom of the box are removed by a cut along the bottom plane of the box.

7.1.3 Sampling FFF

The sampling procedure for the FFF is as follows:

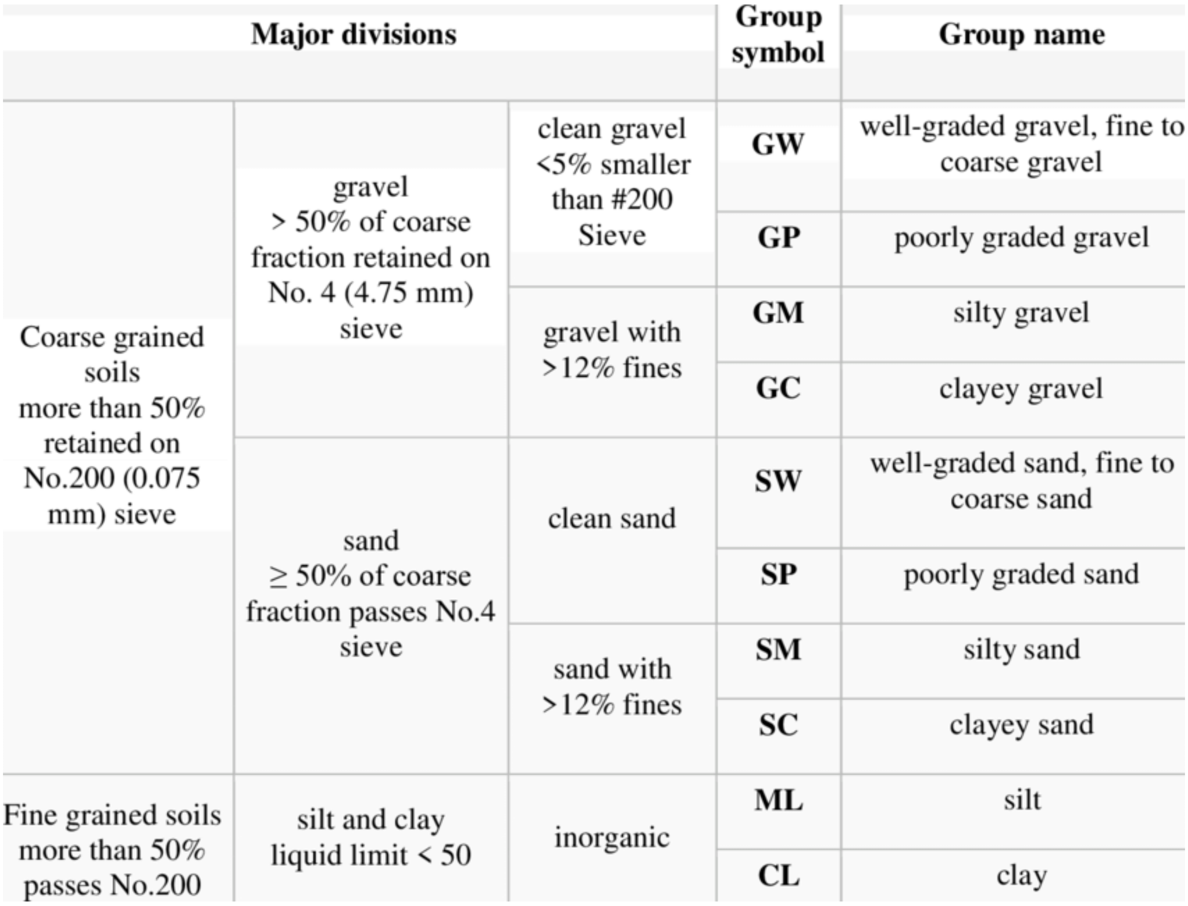
1) The metal sampling container (depicted in Figure 7 & Figure 8) is placed on the surface, where the sample will be collected.
2) Then the sampling container is pressed into the surface.
3) When the resistance becomes too much, the sampling container was drilled further into the soil with a hammer. Hereby a plate is mounted on top of the sampling container so that the force is equally spread over the edges of the sample. The drilling continued by the until the container was 12 cm deep.
4) After this the container is dug out of the surrounding soil and carefully lifted out of the soil with some support on the bottom of the sample. The sampling container with sample was placed on top of the sample container.
5) From this position the sample was placed from the sampling container into the sample container for the flume. Before this the 8 cm from the back of was cut of the rest of sample in the sampling container. Then the sample for the flume was carefully pushed into the sample container.
6) The remaining 8 cm part in the sampling container was collected in a bag for the lab research of the root characteristics.

7.1.4 Sample locations

Figure 28 locations of the samples in the research area: indicated with pointer and sample number

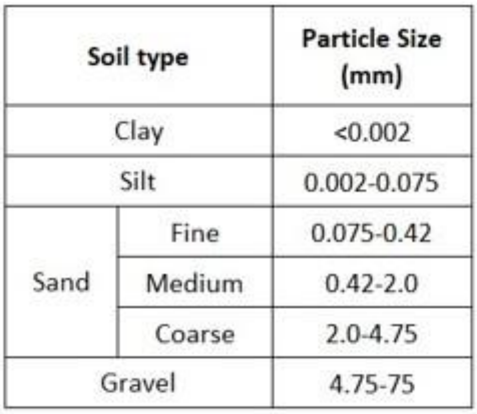
7.2 USCS SOIL CLASSIFICATION SYSTEM

Table 11 USCS soil classification system(Shahab Jan & Farooq, 2020)



Major divisions			Group symbol	Group name
Coarse grained soils more than 50% retained on No.200 (0.075 mm) sieve	gravel > 50% of coarse fraction retained on No. 4 (4.75 mm) sieve	clean gravel <5% smaller than #200 Sieve	**GW**	well-graded gravel, fine to coarse gravel
			GP	poorly graded gravel
		gravel with >12% fines	**GM**	silty gravel
			GC	clayey gravel
	sand ≥ 50% of coarse fraction passes No.4 sieve	clean sand	**SW**	well-graded sand, fine to coarse sand
			SP	poorly graded sand
		sand with >12% fines	**SM**	silty sand
			SC	clayey sand
Fine grained soils more than 50% passes No.200	silt and clay liquid limit < 50	inorganic	**ML**	silt
			CL	clay

*Table 12 Particle size classification according USCS soil classification system (*Step-by-Step Guide for Grain Size Analysis*, n.d.)*



Soil type		Particle Size (mm)
Clay		<0.002
Silt		0.002-0.075
Sand	Fine	0.075-0.42
	Medium	0.42-2.0
	Coarse	2.0-4.75
Gravel		4.75-75

7.3 DIRECT SHEAR TEST RESULTS

Table 13 Direct shear test results per sample: maximum force exerted on the sample and corresponding shear strength

Leersia oryzoides	force [N]	Shear strength [KN/m^2]
70101	56.56273	15.71186944
70103	62.726617	17.42406028
70204	59.463382	16.51760611
80202	75.416973	20.94915917
Rumex obtusifolius	force [N]	Shear strength [KN/m^2]
70102	66.352433	18.43123139
70205	71.065994	19.74055389
70206	70.34083	19.53911944
80101	70.703412	19.63983667
Digitaria sanguinalis	force [N]	Shear strength [KN/m^2]
80303	42.059466	11.683185
80404	51.849169	14.40254694
80505	84.481513	23.46708694
80606	71.791157	19.94198806
Bare soil	force [N]	Shear strength [KN/m^2]
90101	67.440178	18.73338278
90202	69.253086	19.23696833
90303	54.38724	15.10756667
90404	55.474985	15.40971806

7.4 FAST FLOW FLUME RESULTS

Table 14 Averaged erosion rate of the samples: average is based on erosion measured after 90, 150 and 210 minutes of exposure to flow compared to the previous erosion measured time step.

Leersia oryzoides		**Rumex obtusifolius**		**Digitaria sanguinalis**		**Bare soil**	
Sample ID	Erosion rate [cm hr^{-1}]	Sample ID	Erosion rate [cm hr^{-1}]	Sample ID	Erosion rate [cm hr^{-1}]	Sample ID	Erosion rate [cm hr^{-1}]
70101	0.291667	70102	0.23386	80303	0.177778	90101	NaN
70103	0.09	70205	0.083333	80404	0.164815	90202	0.116667
70204	0.098246	70206	0.156667	80505	NaN	90303	0.109314
80202	0.190965	80101	0.353704	80606	NaN	90404	0.082043

7.5 RAW DATA ROOT CHARACTERISTICS

Table 15 Data of the root characteristics depicted per sample ID: sample ID starting with 4 up to 6 were samples used in the flume (upper half of the table) and sample ID starting with numbers starting with 7 up to 9 were samples used in the direct shear test apparatus (lower half of the table)

Sample ID	40101	40202	40303	40404	50101	50202	50303	50404	50505	50606	60101	60202	60303	60404	60505	60606
Vegetation height lower bound [cm]	90	75	60	80	10	10	15	15	40	20	6	17	x	x	x	x
Vegetation height upper bound [cm]	110	135	70	90	20	15	30	30	50	30	12	22	x	x	x	x
Average root thickness [mm]	0.00	2.92	1.72	2.23	x	x	2.77	2.54	1.84	2.78	1.42	1.99	x	x	x	x
Minium measured root thickness [mm]	x	1.68	1.17	1.56	x	x	1.48	0.47	1.28	1.2	0.55	1.99	x	x	x	x
Maximum measured root thickness [mm]	x	5.51	2.55	2.68	x	x	5.45	5.19	2.18	10.11	2.29	1.99	x	x	x	x
# of measured roots [-]	x	20	15	9	x	x	9	12	10	8	2	1	x	x	x	x
Wet weigth of the roots [g]	0	31.54	10.94	5.46	x	x	7.75	4.24	8.99	28.67	1.35	1.31	x	x	x	x
Dry weighth of the roots [g]	0	13.61	3.15	2.08	x	x	1.59	4.51	3.69	14.7	0.66	0.49	x	x	x	x
Sample ID	**70101**	**70103**	**70204**	**80202**	**70102**	**70205**	**70206**	**80101**	**80303**	**80404**	**80505**	**80606**	**90101**	**90202**	**90303**	**90404**
Vegetation height lower bound [cm]	50	28	30	19	10	15	20	10	32	30	12	7	x	x	x	x
Vegetation height upper bound [cm]	60	32	35	24	13	18	25	13	42	40	14	9	x	x	x	x
Average root thickness [mm]	1.08	2.25	2.23	2.21	3.24	7.33	17.67	3.78	0.60	1.65	0.55	0.71	x	x	x	x
Minium measured root thickness [mm]	0.41	1.65	1.45	1.22	2.04	7.33	17.67	2.67	0.36	1.34	0.11	0.52	x	x	x	x
Maximum measured root thickness [mm]	4.09	2.98	2.76	2.99	3.97	7.33	17.67	5.18	0.78	2.44	0.96	0.99	x	x	x	x
# of measured roots [-]	7	6	8	12	7	1	1	6	8	4	9	4	x	x	x	x
Wet weigth of the roots [g]	1.15	1.49	1.86	4.58	5.23	2.58	15.95	4.63	19.24	1.62	2.8	2.04	x	x	x	x
Dry weighth of the roots [g]	0.51	0.55	0.69	1.31	2.2	1.52	13.06	2.03	12.58	0.37	0.77	0.57	x	x	x	x

Table 16 Raw data measured root diameters displayed per sample

Sample ID	**Root diameter [mm]**																			
40101	x																			
40202	2.28	2.69	2.64	5.51	3.59	2.80	3.21	2.26	3.93	2.81	2.57	2.21	4.25	2.61	2.50	1.68	2.00	3.89	3.11	1.85
40303	1.41	1.30	1.68	1.42	1.49	1.52	1.93	1.17	1.26	2.55	2.07	2.18	1.99	2.28	1.61					
40404	2.02	2.33	2.68	2.62	1.56	2.48	2.40	1.83	2.14											
50101	x																			
50202	x																			
50303	2.05	2.35	2.49	3.90	1.48	2.85	5.45	2.20	2.18											
50404	5.19	2.97	4.00	5.11	1.86	1.48	0.47	1.16	1.43	1.69	3.00	2.16								
50505	1.89	2.00	2.18	1.97	1.28	1.76	1.68	2.18	1.64	1.78										
50606	1.39	1.20	1.37	2.04	2.02	1.85	2.24	10.11												
60101	2.29	0.55																		
60202	1.99																			
60303	x																			
60404	x																			
60505	x																			
60606	x																			
70101	4.09	0.52	0.59	0.55	0.72	0.66	0.41													
70102	3.49	3.94	3.24	2.11	3.89	3.97	2.04													
70103	2.12	2.13	2.98	1.69	2.94	1.65														
70204	1.76	2.12	2.66	1.45	2.42	2.76	2.14	2.55												
70205	7.33																			
70206	17.67																			
80101	4.09	3.42	2.67	5.18	3.89	3.40														
80202	1.88	2.19	2.26	2.39	2.45	2.99	1.58	2.58	2.75	1.22	2.38	1.90								
80303	0.68	0.60	0.36	0.56	0.78	0.49	0.61	0.71												
80404	1.34	1.44	2.44	1.37																
80505	0.26	0.21	0.11	0.65	0.85	0.63	0.52	0.96	0.79											
80606	0.57	0.99	0.52	0.77																
90101	x																			
90202	x																			
90303	x																			
90404	x																			

Table 17 Measured shear vane numbers of each sample: shear strength in kN/m² can be obtained by multiplying with 9.81

Sample ID	Shear vane number									
40101	0.5	0.6	0.6	0.5						
40202	0.7	0.5	0.7	0.7						
40303	0.5	0.6	1.0	1.8						
40404	0.7	0.5	0.4	0.5						
50101	0.5	0.5	0.9	2.3	0.5	2.5	0.7			
50202	0.2	0.3	0.1	0.2	0.3					
50303	0.4	0.4	0.4	0.4	0.4					
50404	0.3	0.6	0.5	0.4						
50505	1.2	0.4	0.7	0.1	0.4	0.4				
50606	0.4	0.4	0.5	1.0	0.7					
60101	0.5	0.4	0.6	0.4	0.5	0.5				
60202	0.4	0.5	0.6	0.7	0.3	0.1	0.1	0.5	0.4	0.6
60303	0.1	0.2	0.5	0.3	0.3	0.3	0.2	0.4	0.2	0.5
60404	0.4	0.4	1.5	0.7	1.7	0.3	0.4	0.3	0.5	1.2
60505	0.5	0.9	1.5	1.2	0.1	0.5	1.5			
60606	0.5	0.6	0.3	0.1	0.2	0.3				
70101	0.5	0.6	0.3	0.5						
70102	0.4	0.5	0.4	1.3						
70103	1.6	0.6	0.3	0.5						
70204	0.2	0.3	0.1	0.5						
70205	0.3	0.1	0.1	0.2						
70206	0.6	0.6	0.4	0.2						
80101	0.4	0.5	0.6	0.8						
80202	0.4	0.3	0.1	0.1						
80303	0.1	0.1	0.1	0.1						
80404	0.1	0.2	0.1	0.3						
80505	0.2	0.3	0.3	0.1						
80606	0.4	0.1	0.1	0.4						
90101	0.2	0.4	0.6	0.2						
90202	0.3	0.3	0.3	0.5						
90303	0.6	0.5	0.4	0.6						
90404	0.1	0.4	0.3	0.3