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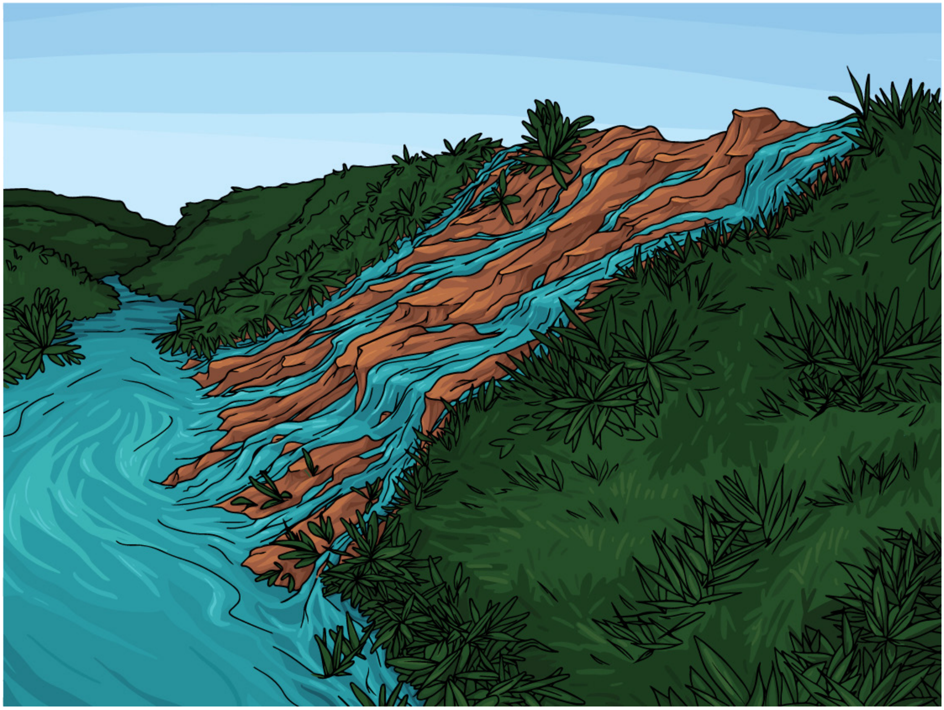
Soil Erosion and Mass Movement in Agricultural Drainage Ditches

Daniel Bernardo Aviles Ribera



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Abstract

Agricultural drainage ditches degrade over time. This degradation is often due to soil erosion, which can cause mass movement (bank failure) when the toe of the bank is eroded or the slope of the bank is too steep. Soil eroded or displaced by mass movement is either transported by the flowing water or deposited in the drainage ditch. This reduces the hydraulic capacity of the ditch creating, the need for maintenance. The efficiency of remediation measures to reduce soil erosion in agricultural drainage ditches is limited by inadequate methods to identify soils susceptible to erosion by water-induced forces and mass movement.

This thesis evaluated procedures for assessing soil susceptibility to erosion and/or mass movement. A cohesive strength meter (CSM) was used to derive an index that provides an indication of how strong a soil is to detachment compared with other soils. In addition, an approach to relate the pressures involved in a CSM test to the pressures applied on the soil surface was developed. This information could be useful for relating soil resistance to possible hydraulic pressures in the ditch. Unsaturated direct shear tests were used to determine the shear strength of soils under conditions resembling those in the field. This information is useful for characterising the stability of ditch banks to mass movement.

The results showed that the CSM is suitable for distinguishing soils that are prone to detach easily from those that exhibit more resistance to detachment. The pressures involved in the CSM tests were found to be lower (by up to 78%) than values reported in other studies. The shear strength of the soil, measured by unsaturated direct shear test, and the resistance to detachment, measured with the CSM, were both increased by the presence of vegetation roots. This positive stabilising effect of plant roots indicates that vegetation on agricultural ditch banks should be maintained or promoted, rather than remove it as is frequently done during maintenance work.

Keywords: erodibility, cohesive strength meter, roots reinforcement, bank erosion, soil shear strength, slope stability.

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Vattenerosion och släntras i diken i jordbrukslandskapet

Abstrakt

Jordbruksdiken utformning förändras över tiden. Förändringar i ett dikes dimensioner beror ofta på jorderosion, som i sin tur kan ge upphov till underskurna slänter och kollaps av dikesbankar. Kollaps av dikesbankar kan också ske om släntlutningen är för hög. Jorden som har eroderats från dikesslänten eller som har förflyttats ned i diket genom släntras kan antingen transporteras av det strömmande vattnet eller deponeras i diket. Detta minskar dikets hydrauliska kapacitet och skapar i slutändan ett behov av underhåll. Arbetet med att förhindra uppkomsten av jorderosion och släntras i diken försvåras av bristen på kunskap om hur man på ett enkelt sätt kan identifiera jordar som är känsliga för erosion och jordarnas benägenhet för släntras.

I denna avhandling utvärderades metoder för bedömning av jordars känslighet för erosion och/eller släntras. En kohesivestyrkemätare (CSM) användes för att härleda ett index som visar hur känslig en jord är för att frigöras. Detta index kan användas för att jämföra jordar inom ett område och för att identifiera dikesegment som är mer benägna för erosion och därmed kräver mer underhållsarbete. Därutöver har ett tillvägagångssätt utvecklats för att relatera vattentrycket i ett CSM-test till det vattentryck som uppkommer i kontaktytan mellan dikesväggen och rinnande vatten i ett dike. Detta test kan användas för att relatera en jords hållfasthet till möjliga hydrauliska tryck som kan uppstå i ett dike. Vidare har direkta skjuvtester använts på omättade jordprover för att bestämma jordarnas skjuvhållfasthet under förhållanden som liknar förhållanden i fält. Denna metod kan användas för att karaktärisera risken för släntras.

Resultaten visade att CSM-tester är lämpliga för att skilja jordar som är benägna att lätt eroderas från jordar som är mer resistenta mot erosion. Det hydrauliska trycket i ett CSM-test var lägre (med upp till 78 %) än vad som har rapporterats i tidigare studier. Resultaten visade också att både skjuvhållfastheten i en jord och motståndskraften mot erosion, uppmätt med ett omättad direktskjuvningstest respektive uppmätt med CSM-test, ökar vid närvaron av växtrötter. Denna positiva stabiliserande effekt av växtrötter tyder på att vegetationen på dikesslänter bör bibehållas eller främjas, snarare än att tas bort vilket ofta görs under underhållsarbetet.

Sökord: Erosionsbenägenhet, kohesivestyrkemätare, CSM, rotförstärkning, slänterosion, jordens skjuvhållfasthet, släntstabilitet

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Preface

Doing a PhD is a transformative life experience. For me, it had the effect of increasing my awareness of the limitations of my own perceptual experience of the real. It is my belief that this enhanced awareness had provided me with tools to assess the ways in which I do not know things. The path I followed while doing this investigation thought me not only things related to the subject matter of this work but also how to feel comfortable with not knowing. I no longer view "not knowing" as a fault. Rather, I see it more as an active recognition of my need for new learning.

The awareness I developed also led me to a kind of meditation, which consist simply of a sense of humility, the capacity to let myself be surprised by the phenomena I find in life, and from that experience grab some snapshots. Sheer amounts of such snapshots, glimpses of experience, can be the building blocks of ideas. The experience of constantly observing soil being detached by the action of water thus gave rise to the ideas on which this work is based. Such ideas are not entirely mine (they are, of course, shared with others working in the field) or extraordinarily new or creative. Instead, I think of them as honest attempts to reduce an incredible complex phenomenon to a measureable set of numbers in the hope of serving a purpose. That purpose is to reduce the problem of defining where erosion is more likely to happen to a, perhaps oversimplified, measurement issue. It is my belief that such measurements will eventually lead to identification of a soil property (if indeed such a property exist) that explains why certain soils are more resistant to erosion than others. This property may lie concealed within the indicator I present here as a relative measure of the susceptibility of soil to detachment. I hope that this indicator and the tool I present to measure it can help people (and benefit farmers in this case) to take decisions about where work should be made in order to preserve the land or, rather, slow down soil erosion as much as possible. This could enhance the ability to secure food production for future generations on the brink of unprecedented changes in global climate and disruption of ecosystems all over the world.

Thanks for your time and your company while I present these ideas to you in the following chapters. I hope you find the reading worthy of your time.

Daniel Bernardo Aviles Ribera
Uppsala, January 2020

Dedication

A papá
y a la memoria constante de mama.
A la lluvia, en verano
y al aroma a tierra húmeda en el camino al lago.
A la persistencia de la esperanza, a pesar de los hechos.
Al tiempo y sus regalos: Memorias
evidencias de vida.
A la resistencia que pusieron los sentimientos a ser reducidos
a objetos de la razón.
Al espejo, ahora, abierto de par en par
que me muestra los trazos de lo que se está convirtiendo
… en un ser humano.

"This unstable world of the mind (…) is a world of evanescent impressions, a world without matter or spirit, neither objective nor subjective, a world without the ideal architecture of space; a world made of time, of the absolute uniform time of [Newton's] *Principia*; a tireless labyrinth, a chaos, a dream".

A new refutation of time
Jorge Luis Borges, 1946

Contents

List of publications

This thesis is based on the work contained in the following papers, referred to by Roman numerals in the text:

I Avilés, D., Wesström, I.*, Joel, A. (2018). Status Assessment of Agricultural Drainage Ditches. *Transactions of the ASABE*, 61 (1), pp. 263-271.

II Avilés, D.*, Berglund, K., Wesström, I., Joel, A. (2019). Effect of liming products on soil detachment resistance, measured with a cohesive strength meter. *Acta Agriculturae Scandinavica Section B – Soil & Plant Science*, 70 (1), pp. 1-8

III Avilés, D.*, Villazón, M., Wesström, I., Joel, A. (2020). Measured surface pressures in the cohesive strength meter test and implications for assessment of soil erodibility. (Submitted to *Geoderma*).

IV Avilés, D.*, Wesström, I., Joel, A. (2020). Vegetation roots and its effect on soil erosion and slope stability in agricultural drainage ditches. (Manuscript)

* Corresponding author.

The contribution of Daniel Bernardo Aviles Ribera to the papers included in this thesis was as follows:

I Planned the inclusion of cohesive strength meter (CSM) tests and unsaturated direct shear tests (UDS) in the MADRAS evaluation method with the co-authors. Performed the laboratory tests. Performed analysis of the data. The writing was done with the assistance of the co-authors.

II Planned the experiment with the CSM with the co-authors. Performed the laboratory tests. Performed the analysis of the data. Writing was done with the assistance of the co-authors.

III Planned the experiment with the CSM and the pressure sensor plate with the co-authors. Performed the laboratory tests. Performed the analysis of the data. The writing was done with the assistance of the co-authors.

IV Planned the experiment with the CSM and UDS tests with the co-authors. Performed the laboratory tests. Performed the analysis of the data. The writing was done with the assistance of the co-authors.

1 Introduction

Agriculture has the fundamental task of providing food for an increasing world population. The pressure on natural resources to meet the demand for food has turned agriculture into a very intense activity that is involved in soil and water pollution, soil losses by erosion and biodiversity loss (Dollinger *et al.*, 2015). Land drainage, or the combination of irrigation and land drainage, is one of the most important input factors to maintain or to improve yields per unit of farmed land (Bos and Boers, 2006). The drainage structures constructed to achieve proper drainage of agricultural land include open ditches that are responsible for collecting surface and subsurface water and thus acting as erosion and flood control (Dollinger *et al.*, 2015). Ditches are therefore vital for proper functioning of agricultural land.

Ditches degrade over time by the action of multiple factors. Bank erosion, for example, modifies the cross-section of ditches changing their hydraulic capacity. Deposition of soil transported from surrounding land by surface and subsurface flow also changes the hydraulic capacity of ditches by modifying channel geometry. Soil piping, which involves the development of preferential water flow pathways in the soil, further promotes erosional processes such as bank erosion. In addition, overland lateral flow entering the ditch can cause surface erosion in the bank slopes of ditches. The water flowing in a ditch, under worst-case circumstances, can cause erosion in the main channel and in the channel banks.

Because of their important role for agricultural land ditches are routinely maintained in order to keep them functioning properly. However, with increasing ditch maintenance costs, there is a growing need to identify the reasons behind ditch failure and the best locations to introduce countermeasures. This need has prompted the development of methods to assess the status of agricultural ditches (i. e. Avilés *et al.*, 2018; Wesström *et al.*, 2016; Joel *et al.*, 2015; Magner *et al.*, 2010). These methods consider different parameters related to erosion processes. The most important bank erosion processes that occur within a particular channel have been identified as weathering/preparation processes, fluvial erosion and mass failure (Lawler, 1995). However, the parameters that characterise these processes, the methods used to measure them in the field and in the laboratory and the relationships that exist between them are still not completely understood.

There is thus a need for a better understanding of how to assess the status of agricultural ditches. In particular, methods for characterizing soil susceptibility to erosion (detachment and transport of soil) and mass movement (movement of blocks of soil) in agricultural ditches need to be further developed. These methods could help in prioritising ditch segments that need maintenance work. The information provided could also be used to develop better practices for maintenance work such as ditch cross-section modification or promotion of ditch bank vegetation, with the aim of creating more stable ditches, decreasing the amount of soil eroded and reducing the need for maintenance.

2 Objectives

The overall aim of this thesis was to improve understanding of how the status of agricultural ditches can be assessed in the field and in the laboratory. Particular attention was devoted to the two main processes that are responsible for the degradation of ditches, namely soil erosion and mass movement. Specific objectives were:

1. To identify ditch properties that can be evaluated visually on-site and the soil erosion processes they represent, and to define parameters that need more intensive study and suggest methods for their estimation.
2. To assess the cohesive strength meter (CSM) test capability to distinguish soils with different resistance to detachment.
3. To stablish the relationship between the pressures of CSM jets and the pressures applied to the soil surface, based on measurements made with a pressure sensor plate.
4. To assess soil resistance to detachment, using CSM tests, and soil susceptibility to mass movement, using measurements of shear strength, with and without the presence of roots and under two soil moisture conditions.

3 Background

Erosion has been a challenge for humanity through history (Dotterweich, 2013). For example, erosion has been reported as the main process in soil degradation globally and is consequently a threat to the sustainability of food production. On a global basis, the area of land estimated to be affected by water erosion is around 1094 million ha, of which 751 million ha are severely affected (Lal, 2003). Bank erosion has become an important issue since it has been shown that the contribution of bank-derived sediment to catchment sediment budgets may be higher than previously believed (Bull, 1997). Bank erosion in agricultural ditches also causes loss of fertile soil, which has prompted a search for methods to assess agricultural ditch status for maintenance work (i. e. Wesström *et al.*, 2016; Joel *et al.*, 2015; Magner *et al.*, 2010). The erosional processes in agricultural ditches are also affected by changes in the flow regime of the ditch brought about by the land use changes. For example, erosional processes may be accelerated in areas with an increasing proportion of impervious surfaces, which are known to increase surface water runoff.

The main processes leading to bank erosion have been identified as weathering/preparation processes (*i.e.* air temperature, freeze-thaw cycles and wetting-drying cycles), fluid forces and mass failure processes and how they affect each other (Lawler, 1995). However, there is an acknowledged need to relate soil physical properties to soil resistance to erosion (Knapen *et al.*, 2007). Soil resistance to erosion has been shown to be related to the physical properties of bank material (Constantine *et al.*, 2009). This opens the possibility to develop procedures that use soil physical characteristics to assess soil susceptibility to bank erosion.

Bank erosion occurs by the action of water flow, surface runoff and preferential flow. Water runoff usually modifies the geometry of the ditch and can promote mass movement (Parker *et al.*, 2008). Procedures to characterise the susceptibility of soils to erosion by flowing water are various (*i.e.* flume erosion tests, jet tests, cohesive strength meter tests etc.) and they usually report different results (Widdows *et al.*, 2007; Schaaff *et al.*, 2006; Tolhurst *et al.*, 2000). Further development of methods to assess soil erosion susceptibility through indicators such as soil erodibility, soil shear strength and/or soil critical shear stress for erosion remains necessary. In the following some processes involved in the development of bank erosion in agricultural ditches are discussed.

3.1 Mass movement in agricultural ditches

Mass movement or bank failure is the sudden movement of a mass of soil in a ditch bank. Bank failure occurs when the weight of the bank is greater than the shear strength of the soil (Wynn, 2006). Other external stresses, such as those caused by snow during winter, infrastructure (culverts, bridges etc.) or the movement of vehicles (*e. g.* the heavy machinery frequently used in agriculture) can also increase the likelihood of mass movement in the ditch banks (Merat *et al.*, 2019). A ditch bank that might seem stable may become unstable under the action of such external forces.

Mass movement is also affected by the hydraulic behaviour of the agricultural ditch. The water flow in the ditch promotes fluvial erosion. The soil particles detached and transported by fluvial erosion are often located at the toe of the ditch bank. The associated loss of support in the toe of the ditch bank promotes the occurrence of mass movement (*Figure 1*). Since mass movement occurs when the destabilising forces exceed the shear strength of the soil mass, the shear strength characteristic of the soil is important and needs to be determined.

The shear strength of a soil is affected by the degree of compaction, particle size distribution, amount of water present in the soil voids, presence of roots, soil mineralogy, soil aggregate sizes and soil structure among other factors (Das & Sivakugan, 2016; Amezketa, 1999). This makes determination of shear strength a challenging task, especially if the objective is to capture the conditions of the soil in the agricultural ditch as closely as possible.

Mass movements can often be observed in agricultural ditches, but the underlying causes remain elusive. In the geographical region examined in this thesis, where soils tend to have a high clay content (above 30 % in all cases studied here), the ditch banks remain relatively stable under conditions of high flow. During winter, when the soil is frozen and snow adds to the overall weight of the soil mass, the ditch banks still remain relatively stable. When the snow and ice start to melt in spring, the soil water content is gradually increased and the shear strength of the soil is reduced as more water fills the voids in the soil. However, mass movement only begins to occur some time after the snow and ice have started to melt, since residual frozen water inside the soil can keep the soil together, maintaining stability despite deformations caused by ice/snow melt. After all snow and ice have melted, the groundwater level may be raised to the point where an important proportion of the soil in the slope of the ditch bank is saturated, which in turn further reduces its shear strength.

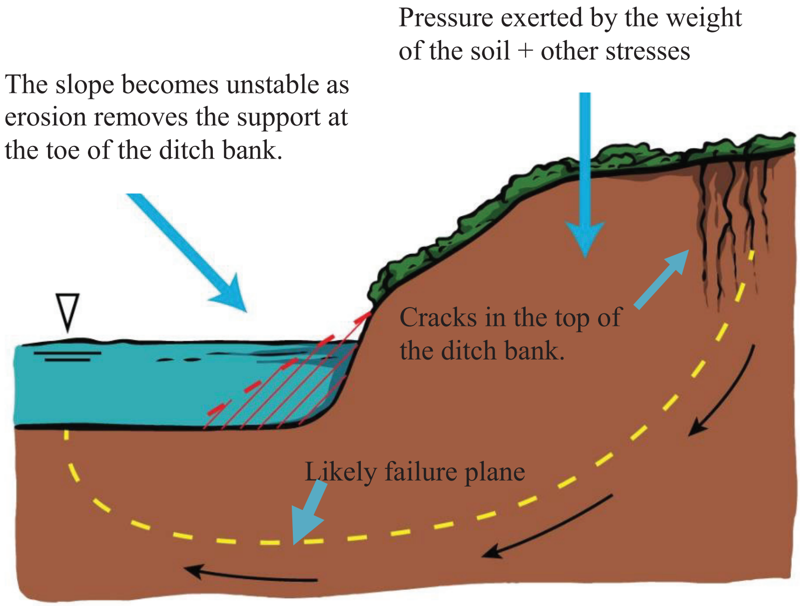

Figure 1. Mass movement of material from the banks of an agricultural ditch. The red dashed line indicates the original ditch bank geometry. (Image source: Adapted from Joel and Wesström (2013))

During the post-melt period, some cracks start to appear at the top of the ditch bank, which becomes very likely to collapse (*Figure 1*). These cracks are probably tension cracks formed as the tensile strength of the soil is exceeded by the pull of the soil mass that has started to move (Baker, 1981). These cracks facilitate mass movement since they become paths for water infiltration (Darby & Thorne, 1994).

During the post-melt period, vegetation starts to develop over the ditch bank face in certain areas, affecting the shear strength of the soil. It is commonly acknowledged that the presence of vegetation increases bank resistance to erosion. For example, Simon and Collison (2002) found that vegetation increases soil shear strength. Vegetation-associated changes in soil strength are also a function of root size, distribution and tensile strength (Wynn, 2006). Thus the shear strength of soil usually increases as more roots develop in the soil.

In general it is not under saturated conditions that the soil in ditch banks is more likely to experience mass movement events. Rather, such events are more likely under a combination of unsaturated conditions, presence/absence of vegetation, flow patterns in the ditch that might cause erosion at the toe of the ditch bank and presence/absence of cracks.

In order to gain knowledge about the actual drivers of mass movement, it is of interest to measure the shear strength of the soil when it is not fully saturated, but in an unsaturated state. Under unsaturated conditions, soil suction affects the shear strength of the soil (Fredlund *et al.*, 2012; Fredlund *et al.*, 1996; Vanapalli *et al.*, 1996). Soil suction is related to the degree of saturation of the soil. Unsaturated direct shear tests allows soil samples to be tested while controlling the degree of saturation of the soil by means of soil suction.

3.2 Fluvial erosion

Fluvial erosion refers to detachment and transport of soil particles by the action of water moving in the ditch. The rate at which the soil is detached and transported can be calculated using an excess shear equation of the form (Papanicolaou *et al.*, 2006):

$$E = k_d(\tau - \tau_c)^a \tag{1}$$

where E [m s^{-1}] is the fluvial erosion rate, k_d [m^2 s kg^{-1}] is an erodibility coefficient, τ [Pa] is the shear stress applied, τ_c [Pa] is the critical shear stress for erosion and a [dimensionless] is an empirically derived exponent. It is important to note that, with the exception of τ, all of these variables can be considered measures of soil erodibility (Grabowski *et al.*, 2011). The fluvial erosion rate is therefore characterised by the amount of shear stress that the soil particles at the interface between soil and water can withstand before experiencing detachment and transport. Fluvial erosion occurs once this critical value of shear stress is exceeded by the moving water (Tolhurst *et al.*, 1999).

Determination of the critical shear stress for erosion has been the subject of many studies. These studies have focused mainly on finding appropriate methods to measure this critical value directly in the field (Al-Madhhachi *et al.*, 2014; Al-Madhhachi *et al.*, 2013; Al-Madhhachi *et al.*, 2011; Grabowski *et al.*, 2010; Hanson & Cook, 2004; Tolhurst *et al.*, 1999; Thorne, 1981). Other studies have considered the uncertainties associated with determination of the critical shear stress for erosion by different approaches (Simon, 2010; Samadi *et al.*, 2009; Tolhurst *et al.*, 2000). One of the issues with existing methods for measuring the critical shear stress for erosion is that the way in which water-induced forces (jets) used to induce soil erosion are applied to the soil during testing may not accurately resemble the forces in the field. Determining the critical shear stress for erosion is therefore still a challenge, especially for clay soils, where other factors such as electrochemical binding forces between particles and clay mineralogy are also involved (Grabowski, 2014).

Measurements of the critical shear stress for erosion of a particular soil can be performed in the laboratory or in the field. There are many devices to measure it *in situ*, in the laboratory or both including *e. g.* the jet test and the CSM test. However, the water forces that these devices apply to the soil to induce erosion are perpendicular to the soil surface, which does not represent the actual horizontal shearing stresses caused by the flowing water in a ditch. This raises questions about the validity of the measurements obtained (Simon, 2010; Samadi *et al.*, 2009). To overcome this limitation, relationships have been developed and proposed to relate the water forces used by each particular device to the actual shear stresses caused by the water. In the case of the CSM, these relationships rely mostly on the possibility of comparison between measurements made with the equipment and measurements obtained using hydraulic flumes. Using these relationships it is possible to obtain estimates of the shear stresses involved in the erosion process. The recorded CSM values can be used to obtain the critical shear stress (τ_c) indirectly (Grabowski *et al.*, 2010). The CSM approach has been used in agricultural watersheds (Singh & Thompson, 2016) and is reported to be useful for indirect measurement of soil critical shear stress.

One drawback is that the CSM device uses only a small area for testing, which results in high variability in the results obtained if the spot in the soil space where the equipment is placed during in-situ testing is not representative of the soil as a whole (which is of course the case for most measurements performed in the field regardless of the device). Another issue is that the CSM water jets do not act directly on the soil surface. The water jet pressure is applied vertically through a layer of water inside the test chamber (so the jet is a submerged water jet) and the relationship between the pressure of the jet (at the nozzle) recorded by the device and the pressure applied to the soil surface is not clear.

Moisture content in the soil varies in the field. Rain, changes in groundwater and irrigation induce changes in the moisture content, and these changes may affect the resistance to detachment of the soil. There is evidence from other erosion test methods (hole erosion test, rotating cylinder test, slaking test) suggesting that drier soils are likely to detach more easily than saturated soils (Fell *et al.*, 2013; San Lim, 2006; Thorne, 1981). How moisture content in the soil affects CSM results have not been explored.

Plant roots keep soil particles together. A dense network of roots might thus have different effects on soil detachment resistance than a sparse network. Agricultural ditches commonly have a particular characteristic in Sweden and many other places, which is that their surfaces are covered by vegetation. Vegetation is considered to have an overall positive impact in reducing soil erosion (Zaimes *et al.*, 2019; Arnold & Toran, 2018; Liu *et al.*, 2016; Wang *et al.*, 2015; An *et al.*, 2013; Dhital *et al.*, 2013; Ruiz-Colmenero *et al.*, 2013; Vanacker *et al.*, 2013; Xu *et al.*, 2013; Li *et al.*, 2012; Fattet *et al.*, 2011; Zuazo *et al.*, 2011; Kothyari *et al.*, 2010; Hopkinson & Wynn, 2009; Nunes *et al.*, 2008; Zhou *et al.*, 2008; Simon & Collison, 2002) However, during ditch maintenance work, the vegetation cover is removed in order to increase the flow capacity of the ditch, and this could have a negative impact on the stability of the ditch banks if the roots are also removed in the process. How plant roots affect CSM results have not been determined.

4 Materials and Methods

4.1 Study sites

This thesis is based on measurements of erodibility in agricultural plots and ditches, along with measurements of soil shear strength of the banks of agricultural ditches. For this purpose, soil samples were collected at two locations in Sweden: One of these sites was Ultuna, 5 km. south of Uppsala city centre, where a ditch channel near an area called Bäcklösa (*Figure 2*), and two agricultural plots, named Ultuna 3 and Ultuna 9 (*Figure 3*), were surveyed. For a detailed description of the Bäcklösa ditch, see Paper I; for a detailed description of the agricultural plots, see Paper II. The soil in the Bäcklösa ditch consisted of 4–5.5% fine clay, 29.5–32.5% coarse clay, 51.5–56.6% silt and 11.0–19.0% sand content. The soil in the agricultural plots consisted of 5.7–6.6% fine clay, 28.4–35.2% coarse clay, 46.6–49.3% silt and 9.4–19.0% sand.

The other study site was Jönåker (*Figure 4*), 20 km. west of Nyköping city centre, where an agricultural ditch was surveyed. For a detailed description of the ditch, see paper IV. The soil consisted of 4.1–6.4% fine clay, 21.2–25.2% coarse clay, 53.3–64.2% silt and 8.4–15.1% sand. Both sites were chosen because they lie in agricultural areas where farmers are required, by regulation, to keep drainage ditches in suitable working conditions.

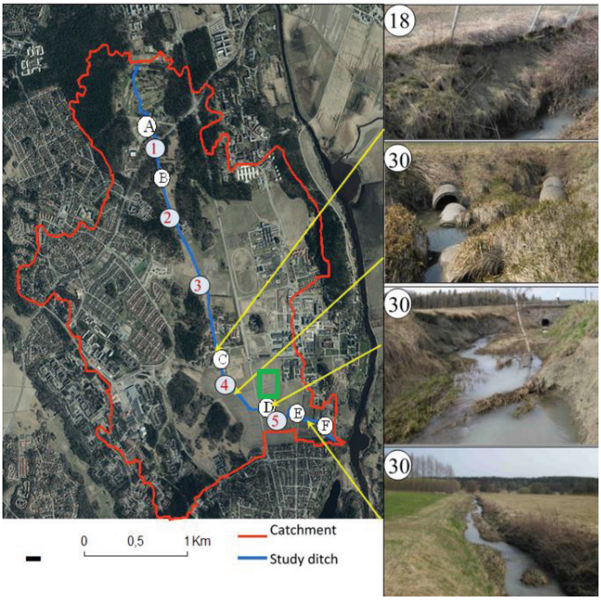

Figure 2. (Left) Bäcklösa ditch at the Ultuna study site, near Uppsala, where letters A to F indicate ditch segments and numbers 1 to 5 indicate flow accumulation points used for hydraulic computations. (Right) Close-ups of ditch segments where the numbers indicate the MADRAS final score. The rectangle in green gives the location of the agricultural plots (detailed view in *Figure 3*) (Image source: modified from Figure 1 in Paper I)

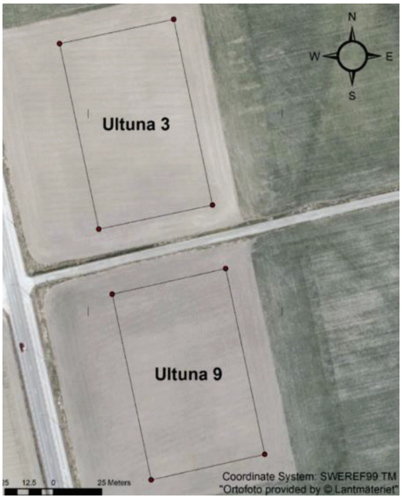

Figure 3. Agricultural plots in Ultuna, Uppsala where "Ultuna 3" and "Ultuna 9" refer to the two different plots surveyed. (Background image source: Orthophoto provided by Lantmäteriet, Image modified from Figure 1 in Paper II)

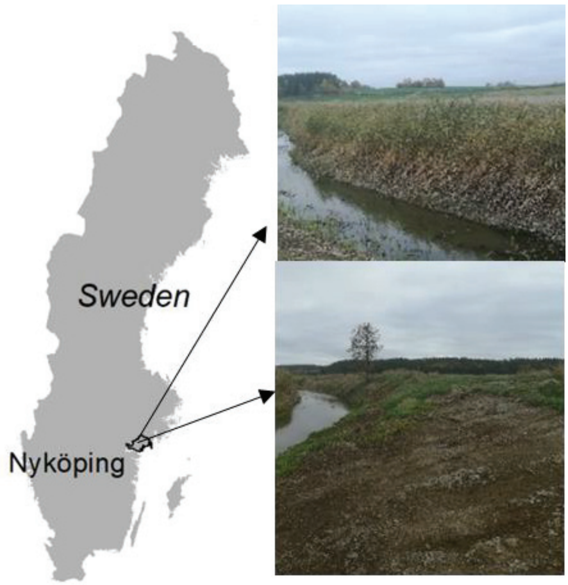

Figure 4. The Jönåker study site near Nyköping. The pictures are examples of a vegetated segment (top) and segment with the vegetation removed (bottom) along the surveyed agricultural ditch. (image source: Figure 1 in Paper IV).

4.1.1 Minnesota Agricultural Ditch Research Assessment (MADRAS)

The status of the Bäcklösa ditch segments was classified using Minnesota Agricultural Ditch Research Assessment (MADRAS), a visual evaluation technique (*e. g*. Wesström *et al.*, 2016; Joel *et al.*, 2015; Magner *et al.*, 2010). The processes included in the assessment were: (i) bank stability (erosion from surface runoff, mass failure and seepage), (ii) over widening or undercutting and (iii) deposition.

Bank instability was rated on a scale from 0 to 10 based on the occurrence of the following indicators: (i) bank erosion from surface runoff, (ii) mass failure, and (iii) groundwater intrusion. If no indicator was observed, the ditch segment was assessed as being in optimal condition and was awarded a score of 0. If three indicators were observed, or if 10% of the ditch segment was affected at any point, the ditch segment was rated as being in very poor condition and given a score of 10.

Over-widening or undercutting of banks was assessed based on the following indicators: (i) bank evenly shaped across the ditch segment, with no undercutting visible; (ii) one of the following indicators visible: irregular ditch shape, irregular channel width, vertical bank; and (iii) two of the following indicators visible: irregular ditch shape, irregular channel width, vertical bank. If no indicator was observed, the ditch segment was given a score of 0. If three indicators were present or 20% of the bank was undercut and had fallen into the channel, the segment was given a score of 10.

Deposition was assessed based on the following indicators: (i) no significant deposition; (ii) sediment depth exceeding on average 7.5 cm; (iii) sediment deposits in the channel; and (iv) banks in the water channel. The first indicator was given a score of 0, the second a score of 3, the third a score of 5, and the fourth a score of 10.

The scores from all three parameters were added together, to give a total MADRAS score ranging from 0 to 30 (see *Figure 2*). A ditch segment was considered to be in good condition if it had an overall score between 0 and 8, while marginally affected ditch segments had scores within the range 9 to 15. Affected ditch segments had scores of between 16 and 20, while a ditch segment with a score of 21 or more was considered to be in poor condition.

4.1.2 Stable/unstable ditch bank identification

The ditches at the Bäcklösa and Jönåker sites were assessed visually and classified as 'stable' and 'unstable'. In order for a ditch bank to be classified as 'unstable', signs of erosion and/or mass movement had to be clearly visible. Ditch banks were thus identified as being 'unstable' if there was visual evidence of soil deposited at the toe of the bank and a lack of vegetation that could not be attributed to recent maintenance work. Ditch banks were assessed as being 'stable' based on lack of visual evidence of soil being deposited at the toe of the bank, combined with presence of established vegetation. The visual assessment for the Bäcklösa ditch was done considering previously published work for the same area based on MADRAS (Joel *et al.*, 2015). An important aid to the identification of unstable banks in the ditch at Jönåker was information provided by neighbouring farmers who indicated locations where recent erosion and/or mass movement had been observed. 'Stable' banks were usually in the same segment, in front or adjacent to the banks identified as 'unstable'.

4.1.3 Soil sampling

For the Bäcklösa and Jönåker ditches, all measurements were performed on undisturbed soil samples taken from the first 10–15 cm of topsoil at the ditch bank. The samples from the ditches were taken from the slope face, 0.8–1 m. from the top of the ditch. Samples were taken from ditch banks that were visually identified as 'stable' or 'unstable'. Triplicate samples were analysed by two main measurement approaches in the laboratory, one to characterise soil erodibility and the other to measure soil shear strength. The samples used for the erodibility measurements consisted in soil cores of 7.2 cm diameter and 5 cm height. The soil cores used for shear strength measurements were 7.5 cm diameter and 2 cm height. Separate soil samples were taken for complementary measurements of particle size distribution. For the agricultural plots in Ultuna, only measurements of particle size distribution and soil erodibility were performed on samples taken from the first 5–10 cm of topsoil where the first 1–3 cm of topsoil was removed before sampling.

4.2 Laboratory studies

4.2.1 Soil shear strength and slope stability (Paper I and IV)

Soil shear strength was measured using unsaturated direct shear tests, details of the test can be found on Paper I and IV. It is important to emphasise that the tests were done under conditions close to saturated, rather than at full saturation. This was done because it was considered that the conditions on the field were not fully saturated. A 5 kPa suction drainage pressure was assumed to be an appropriate representation of commonly occurring field condition, and thus the suction level in all unsaturated direct shear tests was set to 5 kPa. This brought the limitation that the measured soil shear strength was slightly higher than prevailing under saturated conditions. In addition to testing the soil under a controlled suction level, the soil samples were tested with the presence of roots of varying densities. This was particularly relevant because the ditch banks identified as 'unstable' had very sparse vegetation compared with ditch banks identified as 'stable', where vegetation was well established.

4.2.2 Soil shear strength and erodibility (Paper I–IV)

Soil erodibility was assessed with a CSM device developed by Partrac©. The CSM has a testing chamber (*Figure 5*) from where water jets are directed onto the soil surface. The CSM records: (i) the pressure of the water exerted by the water jets and (ii) the turbidity of the resulting suspended sediment. A rapid decay in light transmittance is interpreted as erosion.

The CSM approach involves a choice from different "routines" (see *Table 1*) which define (i) the duration of the water jets, (ii) the intervals and total duration of the measurement of detachment and (iii) the pressure increment steps for the water jets.

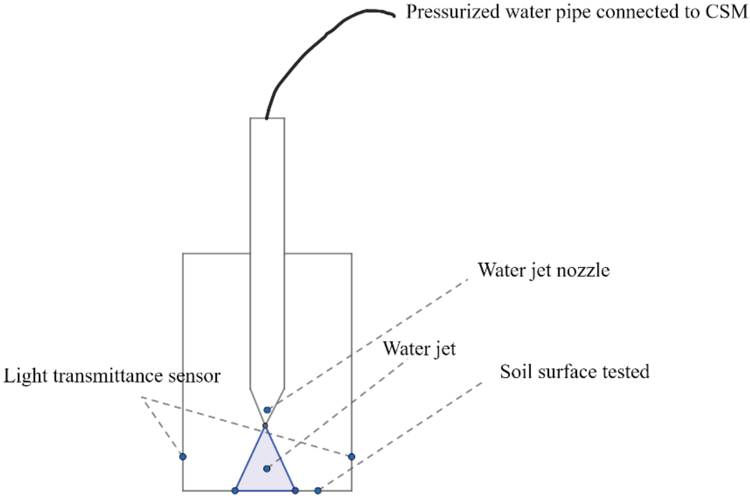

Figure 5. Cohesive strength meter test chamber.

The CSM output data can be processed to obtain estimates of the soil erodibility in terms of the critical shear stress for erosion, τ_c in Eq. (1), in the following way: From a graph light transmittance versus CSM jet pressure, a particular CSM jet pressure (P_{jet}) is identified as the one at the onset of detachment (P_{jet_c}). This is taken as the pressure by which light transmittance falls below 90 % (Tolhurst *et al.*, 1999). It is, then, possible to use P_{jet_c} in the relationship proposed by Tolhurst *et al.* (1999) to obtain τ_c:

$$\tau_c = 66.6734 \cdot \left(1 - e^{\frac{-P_{jet\_c}}{310.09433}}\right) - 195.27552 \cdot \left(1 - e^{\frac{-P_{jet\_c}}{1622.56738}}\right) \quad (2)$$

where τ_c [Pa] is the critical shear stress for erosion. However Vardy *et al.* (2007) found that it was difficult to compare values of P_{jet_c} from different CSM devices and suggested that better estimates could be obtained using an equivalent P_{jet_c} at the soil surface ($P_{surface\_c}$). In order to convert P_{jet_c} to $P_{surface\_c}$, Vardy *et al.* (2007) proposed a method in which the water discharges of each individual CSM jet (Q) can be used to have an estimate of the equivalent pressure at the surface ($P_{surface}$) by using the following equation:

$$P_{surface} = \frac{98\rho_w Q^2}{d^2(z - z_o)\pi} \quad (3)$$

where ρ_w is the density of water, Q [m^3 s^{-1}] is the water discharge per jet, d [m] is the diameter, z [m] is the vertical distance from the source and z_o [m] is the virtual origin of the jet. For a fully turbulent jet, the effect of z_o can be expected to be negligible and therefore z_o [m] can be assumed to be zero (Vardy *et al.*, 2007). Once $P_{surface\_c}$ is obtained, it can be replaced in the relationship proposed by Grabowski et al. (2010) to obtain τ_c:

$$\tau_c = 0.0013 P_{surface\_c} + 0.047 \quad (4)$$

which is valid for 40 Pa < $P_{surface\_c}$ < 90 Pa. In this thesis, several aspects of the process to obtain τ_c are explored.

Table 1. *Cohesive strength meter (CSM) routines used in this thesis (source: CSM default test routines MKIV (Partrac, 2011)*

	Routine name			
	Sand 1	Sand 9	Mud 9	Fine 1
Jet duration [s]	0.3	1.0	1.0	1.0
Data logged for [s]	3.0	3.0	30.0	3.0
Data logged every [s]	0.1	0.1	1.0	0.1
Starting pressure [kPa]	2.1	3.4	3.4	0.7
Pressure increment [kPa]	2.1	3.4	3.4	0.7
Up to [kPa]	82.7	34.4	34.4	16.5
Then from [kPa]		41.4	41.4	18.6
Increasing by [kPa]		6.9	6.9	2.1
Up to [kPa]		413.7	413.7	41.4
Then from [kPa]				55.1
Increasing by [kPa]				13.7
Up to [kPa]				413.7

4.2.3 Evaluation of the suitability of the CSM to assess the erodibility of soils from agricultural ditches (Paper I)

Since the CSM had not been used previously for assessing the erodibility of agricultural ditch banks, the first task was to assess the response of soil in agricultural ditch banks to the action of the CSM jets in different routines. The results were used to help decide whether the CSM was an appropriate tool for assessing the erodibility of soil in agricultural ditches.

For this purpose, soil from banks along the Bäcklösa ditch were tested with different CSM routines (described in *Table 1*). The ditch bank samples subjected to CSM testing were taken from segments previously assessed with the MADRAS tool and also assessed visually on-site to select ditch banks identified as ‘unstable’ and ‘stable’ with respect to bank erosion following the criteria described in section 4.1.2. This sampling site selection process allowed possible differences in the CSM results for soils from ‘stable’ and ‘unstable’ banks to be assessed.

4.2.4 Evaluation of the capacity of the CSM to distinguish soils with different erodibility characteristics achieved by the use of liming treatments (Paper II)

The capacity of the CSM to distinguish soils with different erodibility was also explored. To achieve that, natural soils and soils of known increased resistance to detachment were used. The increased resistance was imparted to the soil by means of different liming treatments, as lime is known to enhance soil aggregate stability (*Table 2*). These liming treatments were applied to soil in the two plots at Ultuna (see *Figure 3*). The enhanced aggregate stability was assumed to enhance soil resistance to detachment which would be captured by the CSM results. The expectation was that soil samples from the liming treatments would show increased resistance to detachment compared with corresponding soil samples without any treatment. This was determined by simple inspection of the CSM curves, where soils more resistant to detachment would detach less under a given CSM jet pressure.

Table 2. *Lime treatments used to induce enhanced resistance to erosion in soil from the plots at Ultuna.*

Lime treatment	Description of composition
Mixed lime	A mixture of approximately 15% slaked lime [$Ca(OH)_2$] and 85% calcium carbonate [$CaCO_3$]
Slaked lime	Slaked lime [$Ca(OH)_2$]
Tunnel kiln slag	A mixture of approximately 20% calcium oxide [CaO], charcoal and silica oxides [SiO_2]

4.2.5 Measurement of the pressures applied to the soil during a CSM test (Paper III).

Since the actual pressures that the CSM jets impose on the soil surface are important, a relationship between P_{jet} and $P_{surface}$ was also developed. To achieve this, the value of $P_{surface}$ for every P_{jet} was measured with the aid of a pressure sensor plate. The pressure sensor plate is a flat square plate with evenly spaced pressure sensing areas. The pressure plate used in the tests was waterproof, so it was possible to apply the CSM water jets directly onto it to measure the pressures exerted upon it.

When measuring the values of $P_{surface}$, the CSM testing chamber was placed on the sensor plate and CSM tests were carried out using the routines Sand 9 and Fine 1 (see *Table 1*). When values of $P_{surface}$ had been obtained for every P_{jet}, a regression line was obtained.

For comparison with previously published work, the relationship between P_{jet} and $P_{surface}$ was also determined using the method proposed by Vardy *et al.* (2007). To this end, measurements of water discharge (Q) were made for every CSM jet. For this, pre-weighed test tubes were used to collect the water released by every CSM jet and then the test tubes were weighed again to obtain the amount of water. From these measurements, volumes of water for every CSM jet were derived. The values of Q were simply taken as these volumes divided by the time for which each CSM jet acted (see *Table 1*). The Q values were then entered into Eq. (3) to calculate the values of $P_{surface}$. Using the values of $P_{surface}$ for every P_{jet}, a regression line was created.

4.2.6 Assessment of soil resistance to detachment with the CSM for different root densities and different moisture conditions (Paper IV).

The effect of moisture conditions in the soil on its resistance to detachment was assessed here with the CSM. The experiment consisted of running CSM tests on samples from the same soil with two different initial moisture conditions, one where the soil was saturated and the other where the soil was drained previously under a suction of 5 kPa. The CSM results from the two conditions were compared by inspecting the CSM curves.

The effect of soil roots on soil résistance to detachment was assessed with the CSM. CSM tests were performed on soils with varying root densities taken from the ditch banks at Jönåker. Root density was determined on the soil samples after CSM testing by gently washing the soil away from the roots, after which the roots were dried and then weighed. The weight of the roots was divided by the approximate volume of the soil sample to obtain an approximation of the root density in the soil. CSM curves from soils with varying root densities were compared to determine the effect of root density on soil resistance to detachment.

4.3 CSM parametrisation

In this thesis, an alternative way of analysing CSM output data was developed. The procedure was motivated by a note on data analysis that accompanied the CSM device (Black, 2015). It suggest a procedure to derive the critical shear stress that involves conversion of percentage transmittance to soil concentration (g L^{-1}) and conversion of CSM jet pressures (kN m^{-1}) to equivalent shear stresses (N m^{-1}). From the graph of test duration (min) versus soil concentration (g L^{-1}), two slopes are constructed and, from the intersection of the two slopes, the critical shear stress is estimated. However, definition of the required two lines is not a straightforward task, since the decision on which points to include in the linear regression needed to derive both lines is partly arbitrary. Using the procedure developed in this thesis, if estimation of the critical shear stress is not of the utmost importance, a relative measure of detachment resistance suitable for comparisons of soils can be obtained from the CSM output data.

The procedure then becomes simple and involves regression analysis. The output data from a typical CSM test comprise values of percentage light transmittance per unit time and per applied CSM water jet pressure. A criterion can be chosen to summarise the recorded values of transmittance over time for each CSM water jet pressure. One alternative could be the minimum value so that, for each applied CSM water jet pressure, the minimum recorded transmittance value is considered. Choosing other criteria, for instance the average or maximum, might change the shape of the curve. In this thesis the average over time of light transmittance values is used as an example. A table of average light transmittance values, for each applied CSM water jet pressure, is then obtained. From this table, a regression line between average light transmittance values for each water jet pressure can be derived.

Suitable models for the regression line can differ depending on the shape of the curve of average light transmittance values versus applied CSM water jet pressure for a particular site and for a particular routine used. In this thesis, an exponential model was found to be suitable based on the CSM test results from Figure 5 in Paper I, Figure 3 in Paper II and Figure 3 in Paper IV. The model proposed is then:

$$T = a \cdot \mathrm{e}^{b \cdot P_{jet}} \tag{5}$$

where T [%] is light transmittance, P_{jet} [kPa] is the CSM jet pressures and a and b are the estimated parameters. It is considered that a gives an indication of how sensitive the soil is to the initial test set-up, when the soil is subject to a water column during filling of the CSM test chamber. The parameter b gives an indication of how easily the detachment process evolves at increasing pressure for a given CSM test result. Since a represents how much soil is put into suspension during test set-up, it is considered that b can be used to assess which soils are easier to detach than others.

4.4 Modelling soil slope stability (Paper IV)

The measurements of shear strength for soils with varying root densities were used to analyse the stability of the banks in the Bäcklösa and Jönåker ditches (*Figure 2* and *Figure 4*). With the adoption of the Mohr-Coulomb criteria for the shear stresses, the measurements provided estimates of the cohesion and angle of friction for the different soil samples. The additional shear strength provided by the roots were assigned to the total cohesion of the soil as 'extra root cohesion' in the equation for calculating the the shear strength (Chok *et al.*, 2015):

$$c_T = c' + c_r \tag{6}$$

where c_T is total cohesion (used in slope stability analysis), c' is effective cohesion and c_r is root cohesion.

Slope stability analysis provided estimates of the factor of safety (FoS), where a values above 1 indicate stable conditions and values below 1 indicate unstable conditions with respect to mass movement. The slope stability analysis was performed using a freely available finite element code named Slope64 (Griffiths & Lane, 1999)

Since the geometry of the Bäcklösa and Jönåker ditches varies greatly, an idealised trapezoidal section was used for the slope stability analysis (*Figure 6*). Three scenarios were considered: (i) the entire cross-section with soil with low root density (not shown in *Figure 6*), (ii) the head of the slope with a soil layer of higher root density (green areas, bottom in *Figure 6*) and (iii) the head and the bank slope with a soil layer of higher root density (green areas, top in *Figure 6*). In addition, two depths of the layer with roots were considered, 10 cm and 60 cm ('h' in *Figure 6*) and three slopes, 1:0.25 , 1:0.5 and 1:1, were considered ('s' in *Figure 6*). It is important to note that, in the field, root depths can go deeper. The modelling approach thus assessed the root reinforcement effect by considering a bank slope with and without a layer of soil with a high density of roots. The rest of the slope was considered to be soil with low root density.

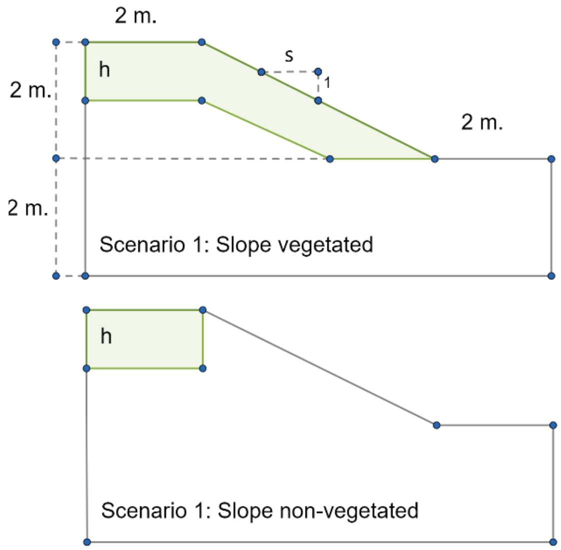

Figure 6. Idealised trapezoidal cross-section used in the slope stability analysis. The green area of depth '*h*' represents soil with vegetation established (high root density). 's' is the horizontal length of the slope. The values on both axes are ditch dimensions in meters. (Modified from Figure 2 in Paper IV)

5 Results and discussion

5.1 MADRAS (Paper I)

The scores obtained from MADRAS for the Bäcklösa ditch are shown in *Table 3* (see also *Figure 2*). Based on the results, segments in poor condition were identified (segments C to F). These segments were selected for further assessment of susceptibility to erosion and mass movement.

Table 3. *Results from MADRAS on segments A-F of the Bäcklösa ditch (Source: Data from Table 2 in Paper I)*

	Ditch segment (see *Figure 2*)					
	A	B	C	D	E	F[1]
Bank stability	0	5	5	10	10	-
Over-widening or undercutting	3	3	10	10	10	-
Sediment deposition	0	0	3	10	10	-
Total score	3	8	18	30	30	-

[1] Segment F was extremely degraded, so it was not possible to assign scores.

5.2 Characterisation of soil susceptibility to detachment with the CSM (Papers I–IV).

Tests on soils from different segments of the Bäcklösa ditch showed the effect of choosing different routines for testing with the CSM (Paper I). From *Figure 7* (produced from Figure 5 in paper I, but without the error bars for clarity), it can be seen that the different routines produced different shapes for the curve of average percentage light transmittance versus CSM water jet pressure. However, by considering the whole curve it can be seen that a soil identified as 'less resistant' by Fine 1 routine (*e. g.* ditch segment D1 in *Figure 7*) is also likely to be identified as such by the other routines.

Such identification is relative to other soils tested in the same conditions, as they were in this case (undisturbed samples drained under a suction of 5 kPa). A soil can then be identified as 'less' or 'more' resistant by inspecting all the curves and deciding if its curve falls below that of the other soils tested. A curve that is below the other curves indicates soil that will detach more than the other soils under the action of the water jets, considering that the curves were generated by using a single CSM routine.

Despite different routines being used in Paper I, parts of the behaviour in the CSM curves were similar. For instance, the curve for the soil from segment D1 indicates that it would detach more than soils from segment C and segment D2, regardless of the CSM routine used (*Figure 7*). However, the same cannot be said to apply when assessing which soil is 'more resistant' to detachment. Soil from segment D2 seemed to be 'more resistant' under routines Mud 9, Sand 17 and Sand 1 but not under routine Fine 1(*Figure 7*).

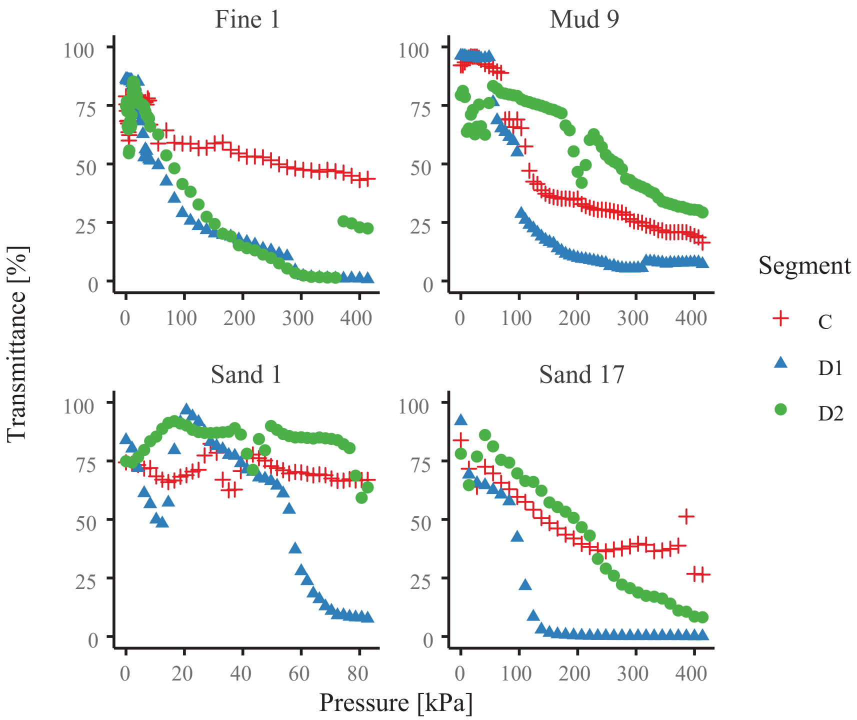

Figure 7. Cohesive strength meter (CSM) curves of applied jet pressure versus light transmittance for segments of the Bäcklösa ditch. C, D1 and D2 indicate the three different segments surveyed and the points are averages (N = 3) (Source: Data from Figure 5 on Paper I).

Based on the results of the CSM tests in Paper I, as summarised in *Figure 7*, it was concluded that the choice of routine is somewhat arbitrary. However, once a routine is chosen, it appears that comparisons of results obtained using that routine are more robust than comparisons of results obtained using several routines. A similar conclusion regarding the use of a single routine was reached by Grabowski *et al.* (2010).

The results thus led to the conclusions that different routines produce different shapes of curve and that the CSM can help distinguish soils that are 'more' likely to detach than others. However, additional evidence that a test soil is, in fact, 'more resistant' to detachment than others was needed. The qualitative description provided in Paper I was useful, but an experiment in which soil resistance to detachment was increased by some other means was needed to test the capability of CSM to detect this increased resistance. An extra requirement was that the means by which resistance was increased in the experiment had to be as meaningful and close to agricultural practices as possible. In the experiment described in Paper II, a soil was subjected to different liming treatments, as commonly performed in practical agriculture, and then tested with the CSM to assess its resistance to detachment.

The hypothesis tested in Paper II was that the CSM curves of soil treated with lime treatments show higher transmittance under a set jet pressure than non-limed soils (Control). This hypothesis was based on the reported relationship between increased erosion resistance of soils and aggregate stability (Amezketa, 1999), and the fact that the liming treatments used have been reported to increase aggregate stability (Blomquist *et al.*, 2017). Based on those findings, higher aggregate stability was hypothesised to translate into increased resistance to detachment, and this 'increased' resistance was expected to be reflected in the CSM test results.

The results in Paper II confirmed that soil with improved structure brought about by field application of lime had higher resistance to detachment. This can be seen in *Figure 8*, which is modified from the original Figure 3 in Paper II (error bars removed for clarity), and shows the CSM curves for soils in the two study plots (Ultuna 3 and Ultuna 9) treated with mixed lime, slaked lime and tunnel kiln slag (see *Table 2*).

It can be seen that the CSM curves for the Control soil are below all the curves corresponding to the other treatments (mixed lime, slaked lime and tunnel kiln slag). This was consistently found for both sites, confirming that the treatments used to improve soil structure also increased soil resistance to detachment by water-induced forces.

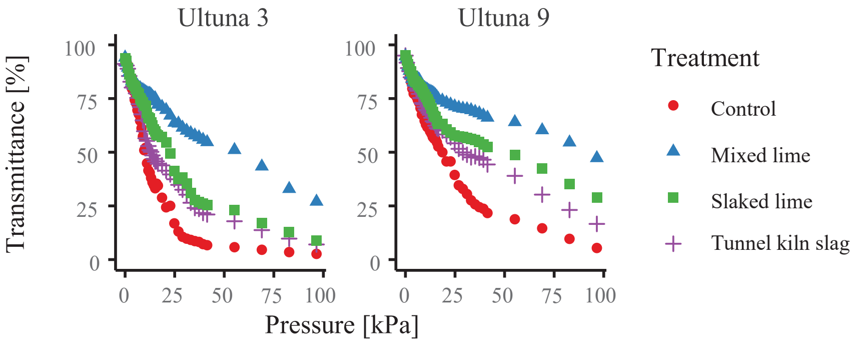

Figure 8. Cohesive strength meter (CSM) curves for soils from the Ultuna 3 and Ultuna 9 plots, treated with different lime products or left untreated (Control). The points are averages (N = 3). (Source: Data from Figure 3 in Paper II).

The CSM results from Paper I (summarised in *Figure 7*) provided the basis to distinguish ditch bank soils showing visual evidence of erosion and soils showing no such evidence, as being 'less' or 'more' resistant to detachment, respectively. The CSM results from Paper II (summarised in *Figure 8*) indicated that the CSM test has the ability to distinguish between soils with weaker (Control) and stronger (limed) structure as being 'less' and 'more' resistant to detachment, respectively. This capability for distinguishing between 'less' and 'more' resistant soils is useful, but more knowledge of the magnitude of forces involved in the detachment process is needed, particularly for modelling erosion and for comparison to potential hydraulic pressures expected from flowing water in ditches. In section 3.2 of this thesis, Eq. (1), which is a common formula for estimating erosion, consider that erosion takes place once a threshold value of shear stress (which is characteristic of the soil) is exceeded. Hydraulic models can provide estimations of the shearing forces acting on the ditch channels. The CSM aims to provide an estimate of the critical shear stress that needs to be exceeded for detachment to occur. In order to establish this critical shear stress, conversion is needed between the CSM jet pressures and the horizontal shear stress that are applied, because of the CSM jet, to the soil. Such conversion is possible by first considering the pressures that act on the soil surface by the action of the CSM water jets. Paper III dealt with this by measuring the pressures at the surface.

In Paper III, two relationships between CSM jet pressures and pressures at the soil surface were obtained, one using measurements made with a pressure sensor (see Figure 5 in Paper III) and one following the method proposed by Vardy *et al.* (2007) (see Figure 6 in Paper III). A linear fit was found to represent satisfactorily the variation in pressure at the surface to CSM jet pressures in both cases. The regression lines obtained were:

$$P_{surface} = 0.005 \cdot P_{jet} \quad (7)$$

$$P_{surface} = 0.012 \cdot P_{jet} \quad (8)$$

where Eq. (7) was obtained from measurements made with the pressure sensor plate and Eq. (8) was obtained following the method proposed by Vardy *et al.* (2007).

The measurements revealed that the CSM jet pressure greatly attenuates by the time it reaches the surface. Pressures at the surface were found to be either 1/200 (Eq. (7)) or 1/84 (Eq. (8)) of the CSM jet pressure, depending on the relationship used. This means that 1 kPa of CSM jet pressure, translates to about 5 Pa or 12 Pa, respectively, of pressure at the surface. Based on the equations, the CSM jet pressure attenuation was even more pronounced than reported in previously published work, which ultimately affects estimations of τ_c. The right-hand column in *Table 4* (summarising the results of Paper III) compares estimates of τ_c obtained from the literature with those derived from the use of Eq. (7) and Eq. (8).

The estimated values of τ_c in Paper III showed that the choice of 'conversion' factor between CSM jet pressures and pressures at the test soil surface produced different estimates of the τ_c. In fact, for the same soil, the estimates of τ_c could be orders of magnitudes apart (*Table 4*). Further, when using Eq. (7) to obtain pressures at the surface, estimates of τ_c obtained with Eq. (4) were lower than previously published values, as for the case of the sand/kaolin mixtures and the mud and mud+eps shown in *Table 4*. Based on Eq. (1) this equates to more soil being eroded.

Regarding the effect of roots and moisture content on soil resistance to detachment, the results from the CSM tests conducted on soils from the agricultural ditch in Jönåker are shown in *Figure 9*. These CSM curves are for soils with different root densities tested with two routines (Sand 1 and Fine 1, see *Table 1*) and two moisture contents present in the soil prior to testing (drainage pressure 5 kPa and saturated conditions). *Figure 9* is based on data for Fine 1 from Figure 3 and Table 4 in Paper IV. Here, the curves corresponding to Sand 1 where added. Here the error bars were removed for clarity.

Table 4. *Implications of the relationships found between cohesive strength meter CSM jet pressures and pressures at the soil surface for estimation of the critical shear stress (τ_c) (Source: Data from Table 3 in Paper III)..*

Material	Description	Pressure [Pa]	Estimated τc [Pa]
Sand/kaolin mixture with clay content of 10%	Pjet	6,100 - 6,600	0.566 - 0.611[(a)]
	Psurface	40 - 45	0.099 - 0.105[(a)]
		73 - 79	0.142 - 0.149[(c)]
		31 - 33	0.087 - 0.089[(d)]
Sand/kaolin mixture with clay content of 30%	Pjet	9,000 - 10,200	0.827 - 0.933[(a)]
	Psurface	70 - 85	0.138 - 0.157[(a)]
		113 - 123	0.193 - 0.206[(c)]
		47 - 51	0.108 - 0.113[(d)]
Mud	Pjet	0 - 10,000	0 - 0.916[(b)]
	Psurface	0 – 230	0 - 0.346[(b)]
		0 - 120	0 - 0.203[(b)]
		0 - 50	0 - 0.112[(b)]
Mud+eps	Pjet	30,000 - 40,000	2.571 - 3.314[(b)]
	Psurface	680 - 900	0.931 - 1.217[(b)]
		360 - 480	0.515 - 0.671[(c)]
		150 - 200	0.242 - 0.307[(d)]

The values of P_{jet} were taken from Grabowski et al. (2010) for the sand/kaolin mixtures and from Vardy et al. (2007) for the mud and mud+eps mixture. Each range of P_{jet} values was used to estimate $P_{surface}$ with tree different equations, the last two estimates were done with Eq. (7) and Eq. (8)

(a) Values of P_{jet} and $P_{surface}$ were estimated from data and equations published by Grabowski et al. (2010). Values of τ_c were estimated using Eq. (2) for P_{jet} and using Eq. (4) for $P_{surface}$.

(b) Values of P_{jet} and $P_{surface}$ were estimated from data and equations published by Vardy et al. (2007). Values of τ_c were estimated using Eq. (2) for P_{jet} and using Eq. (4) for $P_{surface}$.

(c) Values of $P_{surface}$ were estimated using Eq. (8). Values of τ_c were estimated using Eq. (4).

(d) Values of $P_{surface}$ were estimated using Eq. (7). Values of τ_c were estimated using Eq. (4).

From *Figure 9*, can be seen that soils with higher root densities were more resistant to detachment regardless of initial moisture content in the soil. In both cases, drained and saturated, and for the two routines used, the CSM curves for soils with higher root densities were above the curves for soils with lower root densities.

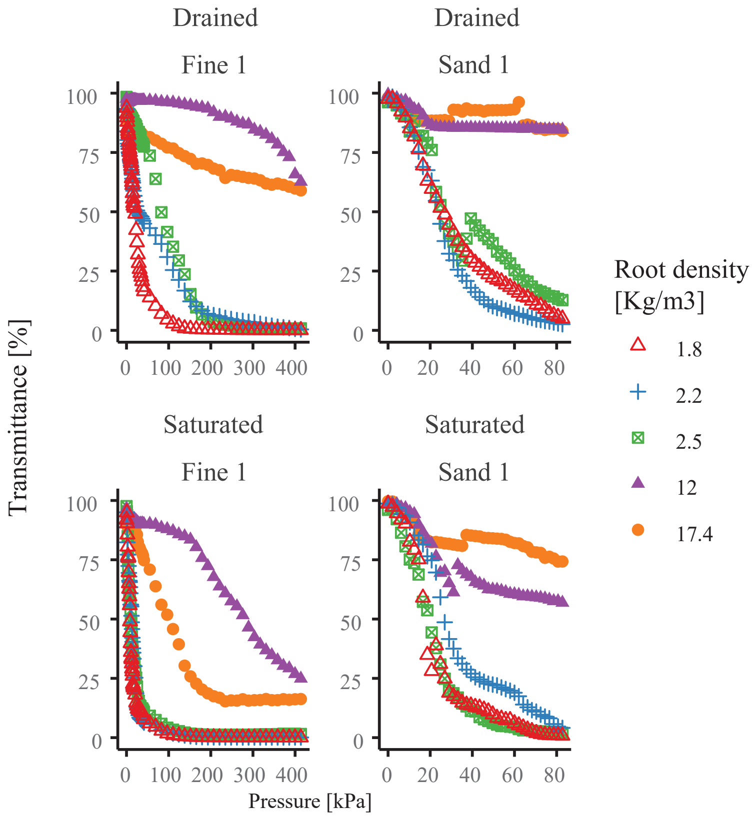

Figure 9. Cohesive strength meter (CSM) curves for soils with different root densities, in two different CSM test routines and two initial saturation conditions (drained to a suction pressure of 5 kPa and saturated). The points are averages of light transmittance (N = 3). Root densities are averages (N =12) (Source: Data from Figure 3 and Table 4 in Paper IV).

With respect to the differences in the CSM results caused by the initial moisture content, a soil that was drained before testing showed a CSM curve that, particularly at higher pressures, was above the CSM curve for the same soil saturated prior to testing. This suggests that a particular soil is more easily detached when initially saturated than previously drained, at least according to the CSM test results.

From *Figure 9*, it can also be said that the reinforcing effect of roots can be detected with the CSM, regardless of initial moisture content of the soil prior to testing. However, the starting moisture content prior to testing appeared to have an effect on the final shape of the CSM curve, with drained soils being less prone to detach than saturated soils. Regardless of the differences induced by the initial moisture content, the distinction among the groups of more or less resistant soils remained the same for the soils in *Figure 9 i.e.* the CSM curves for the three less resistant soils were below those for the two more resistant soils. This is important since if CSM results are used to obtain estimates of τ_c based on values of P_{jet_c} identified by application of the 90% (light transmittance) threshold criterion (Tolhurst *et al.*, 1999) as in *Table 4*, this leads to values of $P_{surface}$ that are similar for drained and saturated conditions. Further, the estimated values of τ_c, would be similar, regardless of whether the soil is drained or saturated before testing with the CSM.

Overall, the results presented in this thesis suggest that the CSM can distinguish soils that are more easily detached than others by the action of water jets of increasing pressure (Papers I and II). The results also suggest that the magnitude of the jet pressure in the CSM test is more attenuated by the time it reaches the surface of the test soil (Eq. (7)) than predicted by the relationship obtained following the method of Vardy *et al.* (2007) (Eq. (8)), an issue that ultimately affects the magnitude of the estimated values of τ_c (Paper III). In addition, the results in this thesis provide evidence that the CSM can still distinguish soils that are more easily detached than others, regardless of degree of saturation and root density in the soil (Paper IV). The question is whether all these findings can be translated into a procedure to identify, in the field and/or in the laboratory, agricultural ditches that are more likely to experience soil erosion. Paper II indicated the possibility to use the entire CSM curve to do this. Comparing curves obtained from different soils could be a starting point for evaluation, at least until a more general relationship between P_{jet_c} and τ_c is developed. However, comparing curves is far from straightforward since CSM curves can have different forms. An alternative to tackle this curve comparison problem is presented in the following section.

5.2.1 CSM parameterization

When considering CSM curves of light transmittance versus applied jet pressure, the usual starting point is to define a criterion for detachment, *i. e.* a threshold that defines the onset of detachment, such as that proposed by Tolhurst et al. (1999). The alternative suggested in Paper II, involves using the whole curve to make relative comparisons among different soils, or perhaps the same soil under different conditions (*e. g.* different root densities, different degrees of saturation etc.). In Paper II the comparison was made by simple visual inspection of the curves, selecting certain pressure and transmittance levels and running statistical analysis on that selection. Somehow, this seems incomplete and raises the obvious question of why these pressures or transmittance values should be used. Some value or set of values obtained from the CSM test output would be preferable for deriving comparisons, but these value/s should have the particular criterion of not being chosen by the person doing the analysis.

One way to avoid picking values from the CSM test is to fit a curve to the data and use the fitting parameters to make comparisons. This was done using Eq. (5) taking the raw data used to produce *Figure 8* (data from Figure 3 on Paper II) as an example. The data depicted in *Figure 8* were reduced to averages of four blocks and limited to pressures below 100 kPa. For illustration purposes, a curve was fitted to the CSM curve for each block in both Ultuna field plots (see *Figure 2*). The resulting curves are presented in *Figure 10* and 11.

From the diagrams, it can be observed that the exponential model (Eq. (5)) seemed to be appropriate (R^2 >0.9 in all cases). The regression parameters derived are shown in *Table 5*. It can be seen that, for all treatments, regression parameter *a* was around 100. This was expected since, at the start of every CSM test, the transmittance has some value above 70% (ideally around 100%). Values below 70% should be taken as an indication that the soil has been heavily disturbed during initial set-up *i. e.* during filling of the test chamber, and it is recommended that the test be started again, choosing a different spot in the soil surface to accommodate the testing chamber (Partrac, 2011).

Regression parameter *b* indicates the 'rate of decay of light transmittance' with increasing pressure. For CSM curves, *b* is always negative. The closer to zero *b* is, the smoother the decay in light transmittance values with increasing pressure, which is an indication that the test soil is less prone to detach. Conversely, the farther values of *b* are from zero, the more pronounced the drop in transmittance values with increasing pressure, which serves as an indication of soil that detaches easily. With all of this in mind, it is apparent that parameter *b* can be used for making comparisons as long as soils are tested with the same CSM routine.

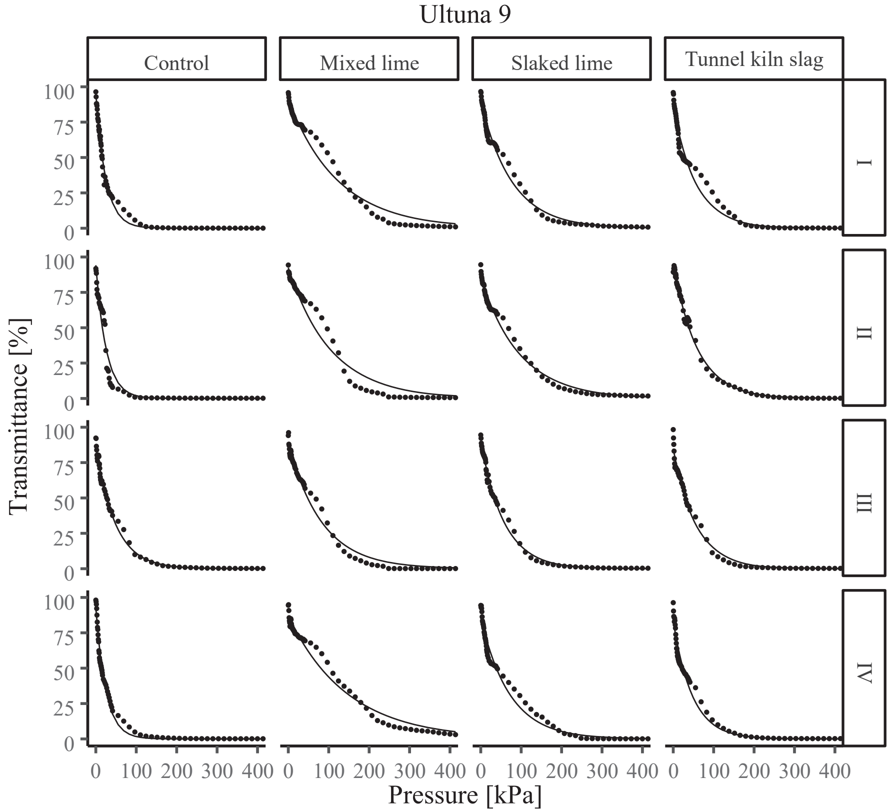

Figure 10. Transmittance as a function of cohesive strength meter (CSM) jet pressure (P_{jet}) for limed and untreated soil from the Ultuna 9 plot (Paper II). The continuous lines are the exponential model fits (Eq. (5)). The points are averages (N = 3) and I-IV are blocks within the plot.

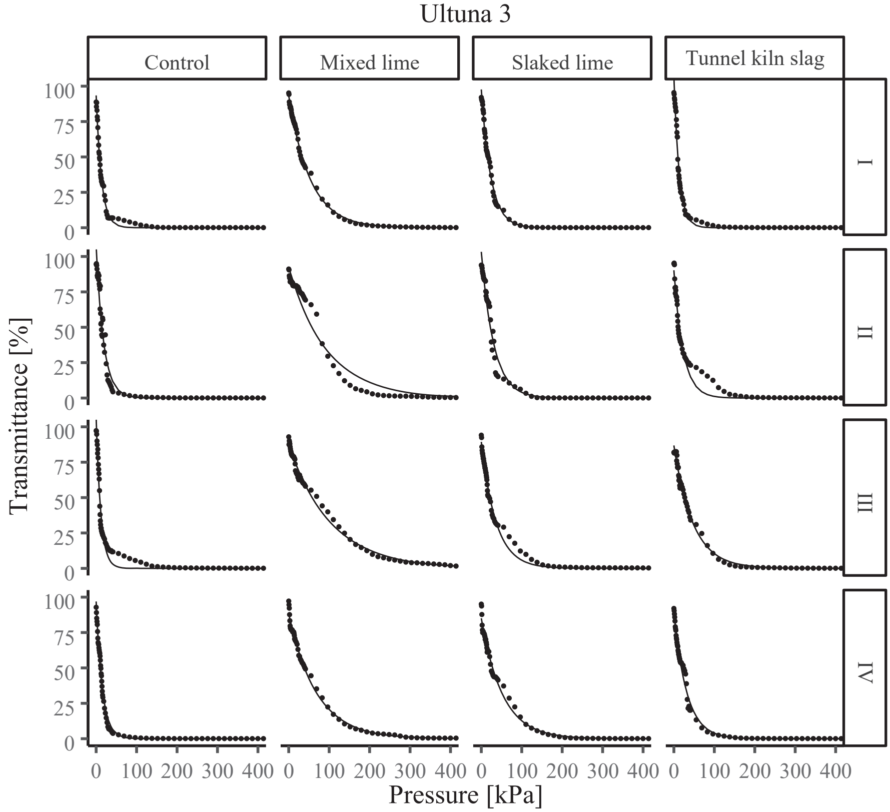

Figure 11. Transmittance as a function of cohesive strength meter (CSM) jet pressure (P_{jet}) for limed and untreated soil from the Ultuna 3 plot (Paper II). The continuous lines are the exponential model fits (Eq. (5)). The points are averages (N = 3) and I-IV are blocks within the plot.

Table 5. *Regression parameters (a, b) obtained for the exponential model (Eq. (5)), applied to cohesive strength meter (CSM) data for the Ultuna 3 and Ultuna 9 plots (Source: Data from Paper II)*

		Ultuna 3		Ultuna 9	
Treatment	Block	*a*	*b*	*a*	*b*
Untreated control	I	99.6	-0.092	96.1	-0.042
	II	108.5	-0.053	97.0	-0.046
	III	112.3	-0.095	89.0	-0.024
	IV	97.2	-0.067	95.2	-0.046
Slaked lime	I	98.0	-0.043	89.7	-0.013
	II	105.0	-0.034	86.8	-0.012
	III	89.6	-0.028	92.0	-0.019
	IV	84.3	-0.019	84.8	-0.014
Mixed lime	I	95.0	-0.021	91.6	-0.009
	II	93.2	-0.011	92.4	-0.009
	III	87.6	-0.009	90.3	-0.013
	IV	89.3	-0.016	87.5	-0.007
Tunnel kiln slag	I	106.6	-0.077	86.4	-0.018
	II	98.6	-0.054	94.2	-0.016
	III	90.1	-0.024	85.1	-0.018
	IV	94.0	-0.039	87.5	-0.029

As an example of how to use the *b* parameter for making comparisons, *Figure 10* and

Figure 11 were compared. Recall that these diagrams are based on the results in Paper II (summarised in *Figure 8*) where limed soils from the two field plots at Ultuna (treated with mixed lime, slaked lime and tunnel kiln slag) were shown to detach less than soils without any amendment (Control soil) when tested with the CSM. It can be observed from the diagrams that soil treated with mixed lime detached least under the action of the CSM water jets. This conclusion is supported by the *b* parameter values shown in *Table 5*, where those for mixed lime were closer to zero than those of the other amendments, for both field plots. This was also the conclusion drawn in Paper II on analysing particular CSM jet pressure levels (see Table 3 in Paper II) and different transmission levels (see Figure 4 in Paper II).

In order to formalise and reinforce the conclusions drawn from the comparisons made using the *b* values, analysis of variance (ANOVA) was performed on the data shown in *Table 5*. It was found that, for the two field plots considered in Paper II, the effect of treatment was not significant for parameter *a* (p>0.05) but was significant for parameter *b* (p<0.001). Dunnett's test was then carried out to compare all treatments with the control soil. It was found that for Ultuna 3, slaked lime and mixed lime were significantly different from the control (p<0.05) but tunnel kiln slag was not. For Ultuna 9, all treatments were significantly different from the control (p<0.05).

A similar analysis was performed, again as an example, on soil from Bäcklösa ditch. CSM test data for the routine Fine 1 depicted in *Figure 7* were used and the exponential model (Eq. (5)) was fitted to the data. The regression parameters are shown in *Table 6* and the graph with the exponential model is shown in *Figure 12*. Similar soil behaviour was observed in this case. The parameter *b* was closest to zero for ditch segment C, which indicates that soil detached less under the action of the CSM water jets than soil in the other two ditch segments analysed (D1 and D2). Of the three segments, D1 was identified as the most likely to detach. A similar conclusion was reached in previous work based on assessment of agricultural drainage ditches using MADRAS (Joel et al., 2015) were the segment was identified as one in poor condition. This method was taken as a starting point in Paper I (see Table 2 on Paper I) where segments D (D1 and D2) of the Bäcklösa ditch were classified as being in poor condition (for details, see "MADRAS" within "Materials and Methods" in this thesis and in Paper I).

Table 6. *Regression parameters (a, b) obtained for the exponential model, Eq. (5), applied to cohesive strength meter (CSM) data on segments C and D of the Bäcklösa ditch obtained using the CSM routine Fine 1 (Source: Data from Paper I (see* Figure 7*)).*

Segment	*a*	*b*
C	74.9	-0.001
D1	90.5	-0.010
D2	80.0	-0.007

From inspection of the curves from the exponential model (*Figure 10* – 11) it can be seen that the model fitted the CSM data fairly well in most cases. More importantly, the results presented could help reduce the information from a CSM test to one value, the *b* parameter in Eq. (5), which seems to be indicate which soils are more easily detached than others.

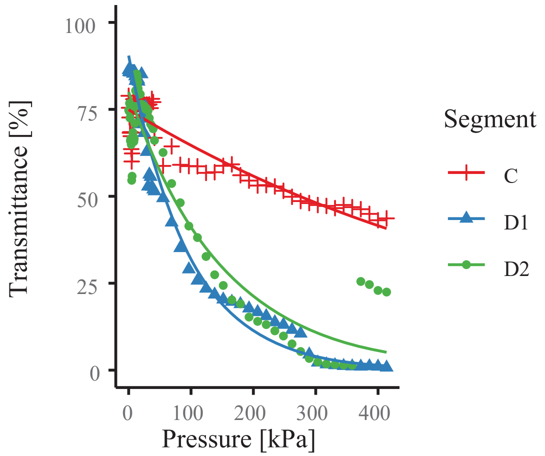

Figure 12. Transmittance as a function of cohesive strength meter (CSM) jet pressure for segments C and D of the Bäcklösa ditch for the routine Fine 1.The continuous lines are the exponential fits (Eq. (5)). The points are averages (N = 3). (Source: Data from Paper I (see *Figure 7*))

5.3 Susceptibility to mass movement (Papers I and IV)

Paper I showed that 'unstable' ditch banks had lower shear strength than 'stable' ditch banks (*Figure 13*). In paper I, a ditch bank was classified as 'stable' if there was evidence of stablished vegetation. A ditch bank was classified as 'unstable' if there was visual evidence of soil at the toe of the bank slope (which was taken as an indication of mass movement) and very sparse or no vegetation cover on the ditch bank surface. As regards soil texture, the soils in 'stable' and 'unstable' banks were practically identical (see Figure 3 in Paper I) and soil conditions were considered similar in each segment of the ditch. It is known that grain size distribution, stress history, presence of fissures, aggregate size, soil structure and void ratio among other factors, control the shear strength of soils (Das & Sivakugan, 2016; Amezketa, 1999). All of these can be assumed to be similar in each segment of the Bäcklösa ditch studied in Paper I. With this in mind the most noticeable difference between the 'stable' and 'unstable' banks was the presence of vegetation (*Figure 13*).

There is one interesting aspect of the results in *Figure 13*, relating to the way in which the presence of roots adds to the shear strength of the soil. The lines representing increasing shear strength with increasing vertical stress for 'stable' and 'unstable' banks were practically parallel. Thus it seems that roots add an almost constant amount of shear strength to the soil. If the soils are considered as being identical in all other regards, the presence of roots displaced the line for ‘unstable’ banks upwards on the vertical axis. This is in agreement with a proposed model which states that roots add to soil shear strength through an increment in cohesion (Chok *et al.*, 2015). This is indicated in *Figure 13* by the intercepts with the vertical axis, which are 10 kPa for ‘unstable’ banks and 24 kPa for ‘stable’ banks. The increment in cohesion due to roots is about 14 kPa. The cohesion values were found to be different ($P < 0.1$) between ‘stable’ and ‘unstable’ whereas the angle of friction values were not found to be different ($P > 0.5$) between ‘stable’ and ‘unstable’.

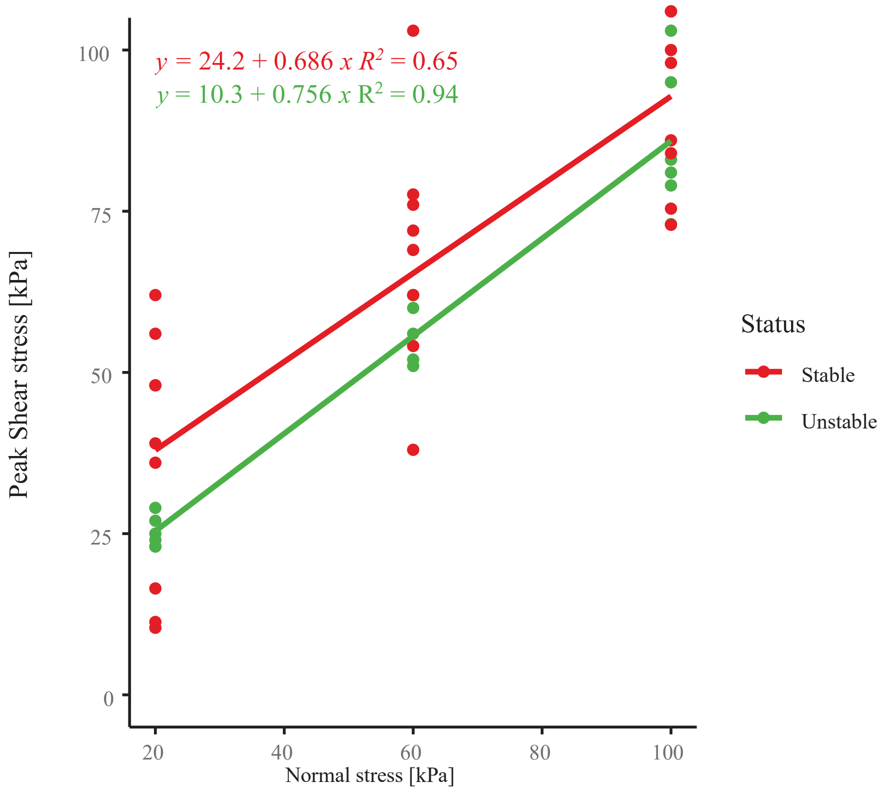

Figure 13. Peak shear stresses for ‘stable’ and ‘unstable’ banks. The soil from ‘unstable’ banks had almost no roots whereas the soil from ‘stable’ banks had considerable amounts of roots. The points are averages (N = 3). (Source: Data from Figure 4 in Paper I)

It has been widely shown that roots add shear resistance to the soil (Bordoni *et al.*, 2016; Li *et al.*, 2016; Zhong *et al.*, 2016; Chok *et al.*, 2015; Leung *et al.*, 2015; Veylon *et al.*, 2015; Baets *et al.*, 2008; Fan & Su, 2008; Tengbeh, 1993). However, before the work in this thesis, this had not been proven by means of testing on undisturbed samples under unsaturated conditions with varying root densities. Since the main premise of Papers I and IV in this thesis was that soils are never completely saturated but in some intermediate state, an unsaturated direct shear test would better represent the shear strength of soil under field conditions. The results from the unsaturated direct shear tests in this thesis showed that soils from ‘stable’ bank ditches with presence of roots had higher shear strength than soils from ‘unstable’ bank ditches with markedly less vegetation roots.

A question raised by the findings in Paper I was whether the amount of roots controls the amount of added shear strength in a soil. Unfortunately the amount of roots was not measured in Paper I and, therefore, it was not possible to determine the relationship between amount of roots in soil and the change in shear strength.

Determining the contribution of roots to soil shear strength was one of the main aims in Paper IV. In the ditch at Jönåker, ‘Stable’ banks were visually identified as those ditch banks with established vegetation and no visual evidence of soil deposited at the toe of the ditch bank. ‘Unstable’ banks were identified as ditch banks with sparse or no vegetation on the surface and visual evidence of soil at the toe of the ditch bank. However, the soils in all banks were similar based on texture analysis (see Table 2 in Paper IV) and the main difference was the amount of roots present in the soil. In *Figure 14* the results from Paper IV are summarised in a graph of peak shear stress versus vertical stresses for the ‘stable’ and ‘unstable’ banks and considering the differences in root density.

Ditch banks considered ‘stable’ had noticeably higher amount of roots and established vegetation. The ‘unstable’ banks contained some roots, but the root densities were lower than in the ‘stable’ banks. The shear strength was found to increase with increased root density (*Figure 14*).

It has been reported that the stabilising effect of roots derives from added cohesion, increasing the shear strength of the soil (Chok *et al.*, 2015). This can be seen in *Figure 14* where the lines are almost parallel and the only difference seems to be increased cohesion (intercept of the lines with the vertical axis) with increasing average root density. Further, it was found that the cohesion values were different ($P < 0.1$) for the ‘stable’ and ‘unstable’ banks, where ‘stable’ banks had higher root densities. This was also evident in *Figure 13*.

The slope stability analysis provided values of the factor of safety (FoS) which are shown in *Table 7*. These values revealed that having a layer of soil with high root density in the ditch bank, with a slope of 1:0.25 and a root depth of 10 cm, was sufficient to bring the ditch bank to a state of marginal stability.

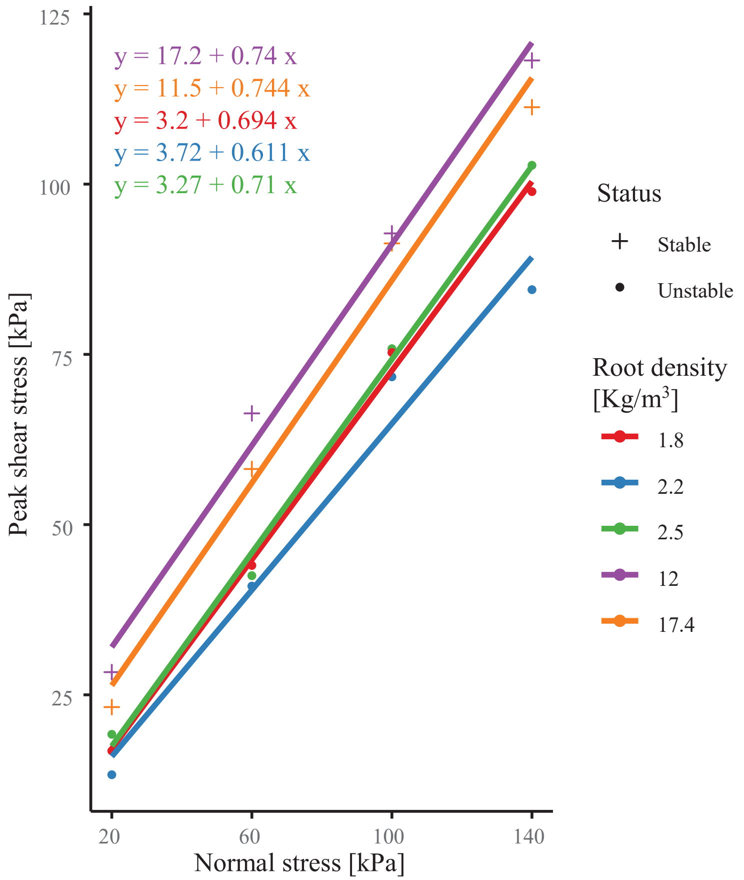

Figure 14. Peak shear stresses for 'stable' and 'unstable' banks with different average root density values. The points are averages of shear stress (N = 3). Root densities are averages (N =12) (Source: Data from Figure 4 and Table 5 in Paper IV).

For example, the FoS increased from 0.9 (entire cross section with soil with low root density) to 1.12 (top and bank slope with a layer of soil with high root density). Increasing the depth of the layer with roots to 60 cm increased the FoS further to 1.73. For a slope of 1:0.25, removing the vegetation from the bank but leaving it on the top left the slope in an unstable state, as can be seen from the FoS value of 0.93 (10 cm roots) (*Table 7)*

The results were similar when the slope of the bank was modified (see *Figure 6* for the geometry of the cross-section), as can occur when carrying out maintenance work. Changing the slope from 1:0.25 to 1:1, without the addition of a layer of vegetation, caused the FoS value to increase from 0.9 (unstable) to 1.56 (stable). At different slopes, vegetation roots also increased the FoS. For a ditch bank with a slope of 1:0.5, the FoS increased from 1.12 to 1.14 with the addition of a 10 cm layer of soil with high root density on the top of the bank slope. The increment was even more (FoS = 1.41) with a 60 cm layer of soil with high root density. For a bank slope of 1:1, the FoS increased from 1.56 to 2.05 with the addition of a 60 cm layer of soil with high root density. It is important to note that depending on the plant species and age of the plants, roots can penetrate even deeper into the soil, which is likely to reinforce the ditch bank even more by adding more cohesion to a larger fraction of the soil. In addition, reducing the slope further would increase the FoS, restricting mass movement. Based on these findings, it can be concluded that the stability of ditch banks can be improved by the presence of established vegetation or by decreasing the slope of the banks (decreasing the angle of slope of the ditch bank).

Table 7. *Factor of safety (FoS) values obtained from slope stability analysis (Source: Data modified from Table 7 in Paper IV)*

Scenario	Depth of the root region [cm]	Slope (V:H)		
		1:0.25	1:0.5	1:1
Entire cross section with soil with low root density.	-	0.9	1.12	1.56
Top of the slope with soil with high root density.	10	0.93	1.14	1.60
Top and slope with soil with high root density.		1.12	1.34	1.63
Top of the slope with soil with high root density.	60	1.17	1.19	1.88
Top and slope with soil with high root density.		1.	1.41	2.05

6 Conclusions

- Visual assessment with MADRAS is a helpful method for assessing ditch status and for identifying the principal processes behind degradation.
- Ditch banks that had experienced mass movement, based on visual assessment, had lower shear strength than ditch banks where no mass movements had taken place. This was mainly explained by the presence of plant roots.
- Slope stability analysis can be used to demonstrate the impact of vegetation in stabilisation of ditches and reduction of mass movement. Simply adding a shallow layer of soil with high plant root density (10 – 20 cm) to the slope of the ditch bank can be enough, in some cases, to transform a ditch bank slope from a state of failure (FoS < 1) to a state of marginal stability (FoS >1).
- Measurements of the pressures exerted by water jets in a CSM test suggest that these pressures are smaller than predicted by a method based on measured water discharges (Q). Estimates of critical shear stress (τ_c) derived from the measured pressures were only 9 to 15% of the values reported by others.
- Results obtained in applying CSM tests to soils with varying root densities indicate that increased root density in the soil results in less soil being detached than from the same soil with lower root density.
- CSM parameterisation suggested that the slope of the CSM curve of light transmittance values versus CSM jet pressure, parameter b in equation (5), can be used to identify soils that are more easily detached than others.

7 Recommendations for future work

Some key issues that should be investigated in future work on developing tools to identify soils that are more likely to experience erosion were identified:

- For CSM tests, it is worth trying to find a procedure to 'wash' the soil surface prior to testing. The idea is to gently remove the loose soil that causes the initial light transmittance value to be lower, with the aim of achieving initial light transmittance values close to 100% while also keeping the soil surface as intact as possible.
- For CSM tests, it would be worth investigating the effect of prolonging the time the water jets act. Lower jet pressures, over longer time, could perhaps cause similar detachment as higher jet pressures achieve over short times. This means modifying the CSM.
- The unsaturated shear tests suggested a positive effect of roots on soil shear strength. It could be useful to run tests with different plant species, controlling for age of the plant, type of roots and better procedures to estimate root density in the soil. This could help to identify species with more pronounced positive effect and to extend the guidelines for maintenance work on agricultural ditches.
- Estimating the erosion quantities obtained from equation (1) requires knowledge not only of the critical shear strength of the soil, which was addressed in this thesis, but also of the magnitude of shear stress caused by the flowing water. Further, water-induced shear stress acts in the water-soil interface, in a region known as the boundary layer. Defining the shear stresses for turbulent boundary layers is a challenging task. Research is needed on methods to quantify the shear stresses in the turbulent boundary layer, especially considering the hydraulic behaviour of agricultural ditches, which is affected by vegetation, land use changes, lateral flow, seepage *etc*. This is important for studying the degradation of agricultural ditches.

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Popular science summary

Deciding where to prioritise expensive maintenance work in agricultural ditches is a difficult task. With multiple sources of instability (*e.g.* soil erosion, soil mass movements etc.), it can be problematic to determine which indicators should be used to decide if work is needed to keep agricultural ditches properly functional and with reduced maintenance needs. This thesis presents a method to evaluate how easily a soil can be detached by the action of the water flowing in the ditch. This method allows comparisons between different soils and can help to identify soils that are more likely to experience soil erosion problems. This information is important for making decisions regarding possible stresses caused by water flow that should be considered when designing ditches.

This thesis also examined the stabilising role of vegetation in increasing ditch bank stability to mass movement (bank failure). It was found that even a thin layer of soil with roots could be enough to stabilise ditch banks against mass movement. This indicates that, during maintenance work, vegetation on ditch banks should be left in place whenever possible or at least plant roots should be left in the soil. This will make the ditch banks more resistant to erosion by flowing water and to mass movement.

Populärvetenskaplig sammanfattning

Att bestämma var man ska prioritera dyrt underhållsarbete i jordbruksdiken är en svår uppgift. Det kan finnas flera orsaker till varför dikesslänter blir instabila. Detta gör det problematiskt att utvärdera var uppmärksamheten bör riktas och vilka indikatorer som ska användas för att besluta om vilken typ av arbete som kan eller bör göras för att behålla dikens funktion att avleda vatten och för att kunna minska underhållsbehovet på lång sikt. Denna avhandling innehåller metoder för att utvärdera hur lätt jordmaterial kan erodera genom inverkan av flödande vatten i jordbruksdiken och metoder för att utvärdera risken för släntras. Denna information är viktig för att fatta beslut om hur man ska utforma ett dike som kan stå emot eventuella påfrestningar orsakade av rinnande vatten.

I detta arbete har det också ingått studier av vegetationens stabiliserande roll för att öka markens skjuvhållfasthet. Av studierna framkom att även ett tunt lager jord med växtrötter kan vara tillräckligt för att stabilisera dikesslänter och skydda mot släntras. Detta tyder på att vegetationen på dikesslänter bör lämnas kvar vid underhållsarbetet när så är möjligt eller åtminstone att växtrötter lämnas i marken. Detta kommer att göra dikesslänterna mer motståndskraftiga mot såväl erosion av strömmande vatten som mot massrörelser under belastningsförändringar.

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Agricultural ditches degrade over time due to soil erosion and mass movement, creating needs for maintenance. This thesis evaluated procedures for assessing soil susceptibility to erosion and mass movement. Variables included were bank slope, plant roots and shear strength, which are important for assessing the status of the ditch and for their design. The proposed methods show that it is possible to assess soils susceptibility to degradation. Results show that plant roots enhance soil resistance to erosion and shear strength.

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